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PAPER

No bridge too high: Infants decide whether to cross based on the probability of falling not the severity of the potential fall

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Abstract

Do infants, like adults, consider both the probability of falling and the severity of a potential fall when deciding whether to cross a bridge? Crawling and walking infants were encouraged to cross bridges varying in width over a small drop-off, a large drop-off, or no drop-off. Bridge width affects the probability of falling, whereas drop-off height affects the severity of the potential fall. For both crawlers and walkers, decisions about crossing bridges depended only on the probability of falling: As bridge width decreased, attempts to cross decreased, and gait modifications and exploration increased, but behaviors did not differ between small and large drop-off conditions. Similarly, decisions about descent depended on the probability of falling: Infants backed or crawled into the small drop-off, but avoided the large drop-off. With no drop-off, infants ran straight across. Results indicate that experienced crawlers and walkers accurately perceive affordances for locomotion, but they do not yet consider the severity of a potential fall when making decisions for action.

Introduction

Would you walk across the Brooklyn Bridge? A log over a creek? An Inca rope bridge suspended over the Río Apurimac gorge? For adults, deciding whether to cross a bridge depends both on the probability of falling and on the severity of the potential fall. The probability of falling depends on the properties of the bridge: whether it is wide or narrow, sturdy or rickety, rigid or compliant, stable or swaying, slippery or dry – in short, whether the bridge affords walking (Franchak & Adolph, in press; J.J. Gibson, 1979). The severity of the fall depends on the properties of the drop-off, and can range from getting wet feet or a sprained ankle to being swept away by a raging river and certain death. An important determinant of fall severity is the height of the drop-off: More time accelerating due to gravity results in a higher force of impact with the ground. For adults, the drop-off height is especially salient: The higher the drop-off, the more anxious adults are about standing at the edge of a precipice (Davis, Campbell, Adkin & Carpenter, 2009), the more reticent they are to step over a gap in the ground (Jiang & Mark, 1994), and the more carefully they traverse a climbing wall (Pijpers, Oudejans, Bakker & Beek, 2006). Therefore, adults might walk over a challenging bridge if the drop-off were relatively small – say, at knee height – but avoid the same narrow bridge if the drop-off were relatively large – say, at standing height or higher.

Do infants, like adults, respond both to the probability of falling and to the severity of the potential fall? There is clear evidence that experienced walking infants respond to the probability of falling based on variations in bridge width. When tested on bridges spanning a 62-cm high precipice, infants run straight across wide bridges within their abilities, walk carefully across narrower bridges near the limits of their abilities, and refuse to cross impossibly narrow bridges beyond their abilities (Berger & Adolph, 2003; Berger, Adolph & Kavookjian, 2010; Berger, Adolph & Lobo, 2005). Similarly, experienced infants are mindful of falling into a gap spanning a 76-cm high drop-off; they attempt to reach across small gaps within their abilities but refuse to lean over larger gaps slightly beyond their abilities (Adolph, 2000).

There is also abundant evidence that infants are sensitive to the probability of falling at different drop-off heights. In the classic visual cliff paradigm, infants crawl over the visually specified surface on the ‘shallow’

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side of the apparatus and avoid the apparent drop-off on the 'deep' side (Adolph & Kretch, 2012; Campos, Hiatt, Ramsay, Henderson & Svejda, 1978; E.J. Gibson & Walk, 1960). On a real, adjustable drop-off, infants show exquisite sensitivity to the probability of falling: Experienced crawlers and walkers make 1-cm discriminations between drop-offs that afford descent and those that are too large for crawling and walking safely (Kretch & Adolph, in press). Attempts decrease sharply on drop-offs beyond infants' abilities (15 cm, on average) and infants never attempt to crawl or to walk over a 90-cm drop-off.

Moreover, infants are especially averse to falling into a precipice compared with falling on flat ground, falling uphill, or penalties other than falling. Crawlers fall, on average, 17 times an hour during spontaneous locomotion over flat ground and walkers of the same age average 32 falls per hour (Adolph, Cole, Komati, Garciaguirre, Badaly, Lingeman, Chan & Sotsky, 2012); infants rarely cry and are back in motion a few seconds later. Infants refuse to walk down slopes that are impossibly steep, where an experimenter must rescue them to prevent injury. But the same infants fall repeatedly while attempting to walk up the same slopes, where they can safely catch themselves (Adolph, 1995, 1997; Adolph, Eppler & Gibson, 1993). Infants refuse to walk along impossibly narrow ledges where the penalty for error is falling off the edge of a 65-cm high platform, but they repeatedly attempt to squeeze through impossibly narrow openings where the penalty for error is entrapment (Franchak & Adolph, 2012). Thus, like adults, the possibility of falling from a height is an especially salient factor for infants when deciding how to navigate obstacles.

Despite evidence that infants gauge the probability of falling and are averse to falling from a height, we do not yet know whether infants take the severity of a potential fall into account because fall severity has never been manipulated independently of the probability of falling. In studies where infants crossed bridges or gaps, the height of the drop-off did not vary. In studies where infants descended cliffs or slopes, drop-off height did vary, but the severity of the potential fall necessarily covaried with the probability of falling. Thus, infants may have avoided larger drop-offs and steeper slopes simply because they perceived that falling was more likely, not because they perceived that the potential fall would be worse.

To determine whether infants' motor decisions at the edge of a precipice are based on the severity of the potential fall, we must manipulate fall severity independently of the probability of falling. In the current studies, we manipulated the probability of falling by varying bridge width, and manipulated fall severity by varying drop-off height.

Experiment 1. Walkers: large and small drop-offs

In Experiment 1, 14-month-olds confronted wide and narrow bridges (2–60 cm) spanning a large (71-cm) and small (17-cm) drop-off. Wider bridges afforded walking and narrower bridges did not, but neither drop-off height was walkable. The large drop-off was nearly infants' standing height – slightly higher than the precipice used previously in studies of infants walking over bridges (Berger & Adolph, 2003; Berger *et al.*, 2010; Berger *et al.*, 2005); the small drop-off was at infants' knee height – about the size of a household stair and beyond the walking ability of the average 18-month-old (Kretch & Adolph, in press).

If infants take both the probability of falling and the severity of the potential fall into account, then their behavior should vary with both bridge width and drop-off height. Specifically, on wide bridges when the probability of success is close to 100%, infants should always attempt to cross, and on narrow bridges when the probability is near 0%, infants should never attempt to cross. But when success is uncertain, infants may attempt in the small drop-off condition and refuse in the large drop-off condition. Moreover, if infants are more wary of falling from a larger height, they should walk more slowly and carefully, hesitate longer, and explore more in the large drop-off condition than the small drop-off condition.

Method

Participants

We tested 37 infants within a week of their 14-month birthday; 18 infants (11 boys, seven girls) were randomly assigned to the large drop-off condition and 19 (10 boys, nine girls) to the small drop-off condition. Infants were recruited via advertisements and visits to maternity wards of local hospitals, and received small souvenirs as compensation for participating. Most families were White or Asian and middle class. Parents reported infants' walking experience in the context of a structured interview based on the first day infants walked 10 feet continuously: M walking experience = 2.15 months, SD = 1.08. An additional nine infants were tested but did not complete the procedure due to fussiness (n = 5), experimenter error (n = 3), or because the parent terminated the data collection (n = 1).

Bridge and drop-off apparatus

Infants were tested on an adjustable wooden apparatus (Figure 1). A starting platform (76 cm wide × 106 cm long × 86 cm high) and landing platform (76 cm wide × 157 cm long × 86 cm high) flanked a 76-cm long gap in the surface of support. The walls and floor of the gap were padded with high-density foam to ensure infants' safety and covered in a black and white checkerboard material to provide salient visual information for depth (as on the visual cliff). In the large drop-off condition, the floor of the gap was 71 cm below the platform surface, and in the small drop-off condition, the floor was 17 cm below. Pilot data confirmed that infants could not step into the 17-cm drop-off without falling. We varied bridge width from 2 to 60 cm in 2-cm increments from trial to trial by sliding bridges of different widths into a locking tongue-and-groove mechanism between the two platforms.

Procedure

Each session lasted approximately 60 minutes. At the beginning of each trial, the experimenter stood infants on the starting platform. An assistant drew infants' attention to the bridge using a small toy; trials began after infants saw the bridge. Trials lasted until infants crossed the bridge or remained on the starting platform for 30 s, whichever happened first. Parents stood at the far side of the landing platform and encouraged infants to cross, using toys and snacks as incentives. The experimenter followed alongside infants and caught them if they began to fall. Sessions were videotaped from stationary overhead and front views, and a panning side view, and digitally mixed online for later coding.

First, infants walked four times across the 60-cm bridge to become comfortable on the raised platform and to learn the game of walking toward their parents. Then, as in previous studies (e.g. Adolph, 1995; Adolph, 2000; Kretch & Adolph, in press), we used a psychophysical staircase procedure to estimate each infant's ability to walk across bridges. An assistant coded each trial online as a success (infant walked safely over the bridge), failure (tried to walk but fell or got stuck midway), or refusal (avoided crossing, crawled over the bridge, or descended into the drop-off). Protocols began with an easy 50-cm baseline bridge. After each successful trial, the assistant presented infants with a bridge 6 cm narrower (e.g. success at 44 cm was followed by the 38-cm bridge). After unsuccessful trials (failures or refusals), the assistant repeated the same bridge width. After a second unsuccessful trial, infants received a trial on the 50-cm baseline bridge to maintain their motivation to walk. Then, the assistant presented a bridge 4 cm wider than the last unsuccessful increment (e.g. two consecutive failures at 20 cm were followed by the 50-cm bridge and then the 24-cm bridge). This procedure continued until the assistant determined each infant's *affordance threshold* – the narrowest bridge they walked successfully on at least two out of three trials, and failed or refused on at least two out of three trials at each of the next three narrower increments.

Then, infants were presented with additional test trials normalized to their individualized threshold: two trials each on bridges 2 and 6 cm wider than their affordance threshold; 2, 6, and 12 cm narrower than their

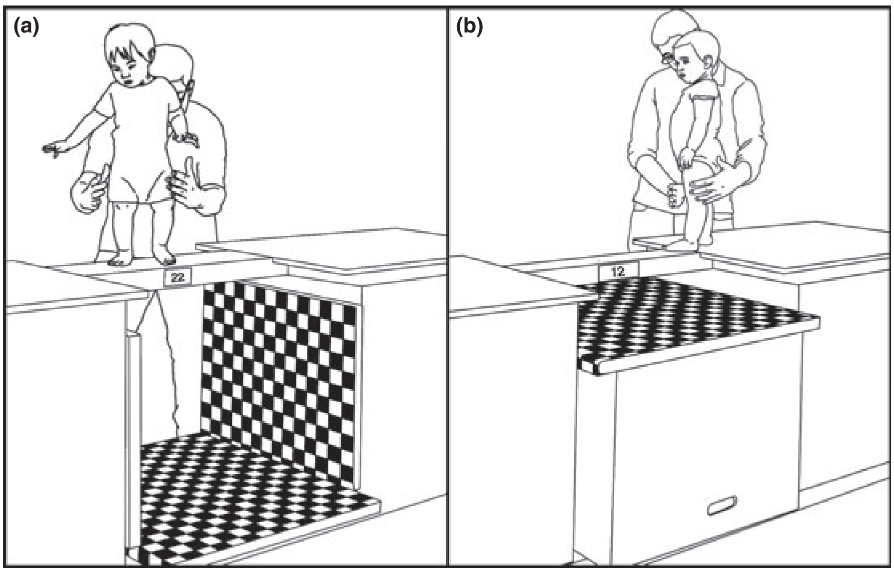

Figure 1 *Adjustable bridge and drop-off apparatus used in Experiments 1 and 3. (A) Large drop-off condition, with the floor 71 cm below the bridge. (B) Small drop-off condition, with the floor 17 cm below the bridge. Wooden bridges 2–60 cm in width were locked between the two platforms for each trial.*

affordance threshold; and two trials on the narrowest, 2-cm bridge. In total, the staircase protocol and test trials required $M = 42.4$ trials. Then, if infants were not too tired or fussy, we raised or lowered the floor of the gap and ran another protocol in the opposite condition. Of the 18 infants assigned to the large drop-off condition, 11 also completed the small drop-off condition. Of the 19 infants assigned to the small drop-off condition, eight also completed the large drop-off condition. Thus, a subsample of 19 infants participated in the study as a within-subjects design. Note, infants were not less likely to complete both protocols if they received the large drop-off first.

Data coding

A primary coder scored all outcome measures from video using OpenSHAPA software (www.openshapa.org). A second coder scored 25% of each infant's trials for inter-rater reliability. Correlation coefficients for continuous measures were >.99, and Kappa coefficients for categorical codes were >.91. Disagreements between coders were resolved through discussion.

Infants' *motor decisions* were recoded from video according to the same criteria for success, failure, and refusal used online; 100% of thresholds agreed with those calculated online. For success trials, coders scored *gait modifications*: number of steps to cross the bridge, crossing time (from the first step on to the first step off the bridge), and whether infants walked with alternating steps (one foot in front of the other) or changed their gait pattern by walking with one foot leading and the other following. Number of steps indexes step length (more steps reflects a smaller average step length), crossing time indexes walking speed (shorter crossing times reflect faster speeds), and the leading-following gait pattern decreases step width. Coders also scored *exploratory activity* on the starting platform to determine how infants generated perceptual information for their decisions. If infants attempted to walk, coders scored latency from the beginning of the trial to the moment infants started onto the bridge. For all trials, coders scored haptic exploration: touching the bridge with hands or feet.

Results and discussion

Primary analyses were calculated using data from all infants in between-groups comparisons. If infants completed both drop-off conditions, only their initial condition was used. Within-subjects analyses are reported at the end of this section. One infant completed both conditions, but the video recording was lost. This infant is included in analyses of thresholds and motor decisions, which could be determined from online codes.

For analyses of the various outcome measures, we combined data from staircase protocols and test trials to take advantage of all available data. Following previous work (e.g. Adolph, 2000; Kretch & Adolph, in press), we binned data into five groups normalized to affordance thresholds: bridges 10, 12, and 14 cm smaller than threshold (denoted by the midpoint −12 cm), bridges 4, 6, and 8 cm smaller than threshold (−6 cm), bridges at threshold and the two surrounding increments (0 cm), bridges 4, 6, and 8 cm larger than threshold (+6 cm), and bridges larger than 10 cm above threshold (+12 cm). We tested effects of bridge width and drop-off height using mixed design ANOVAs (bridge width group × drop-off condition) with repeated measures on the first factor. We also performed linear and quadratic trend analyses to determine how behavior varied with bridge width.

For analyses of attempts and touching, we compared data from all 5 normalized bridge groups and performed separate *t*-tests for the 2-cm bridge. Two infants (one in each condition) did not receive trials at the −12-cm bridge group due to fussiness; those data points were replaced with group means. Only 22 infants contributed data at 2 cm. For latency, there were very few attempts at the 2-cm bridge and the −12-cm bridge group, so we compared the −6, 0, +6, and +12 bridge groups only. Seven infants never attempted the −6-cm bridge, and therefore did not have latency data in the −6 bridge group; those infants were dropped from the ANOVA. For measures of gait modifications, there were rarely successful trials at the −12-cm and −6-cm bridge groups,

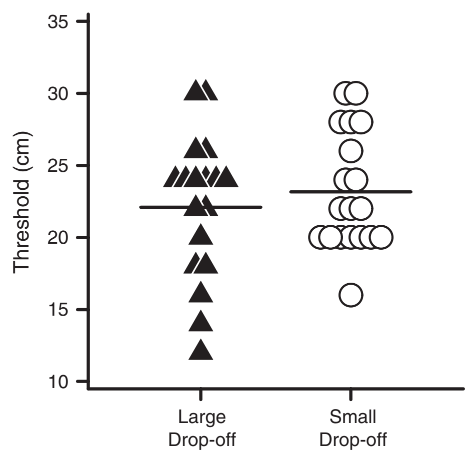

Figure 2 *Affordance thresholds for walkers in the two drop-off conditions. Each symbol represents one infant, and solid lines represent group means.*

so we compared the 0, +6, and +12 bridge groups only. Data from the 50-cm baseline bridges are plotted in figures for comparison, but are not included in analyses.

Infants base crossing decisions on the probability of falling, not the severity of the potential fall

Affordance thresholds varied widely, from 12 to 30 cm (Figure 2), and reflected infants' walking skill: Infants with more walking experience walked successfully over narrower bridges, $r(35) = -.62$, $p < .01$. It was important to establish that the probability of falling did not differ for the two drop-off conditions. If infants' balance was perturbed by sparse visual cues in the large drop-off condition (Giacalone & Rarick, 1985), then affordance thresholds may have been smaller in the small drop-off condition. However, drop-off height did not affect affordance thresholds ($M = 22.11$, $SD = 5.00$ for the large drop-off, $M = 23.16$, $SD = 4.07$ for the small drop-off condition), $t(35) = 0.70$, $p = .49$.

Given that the probability of falling was based solely on bridge width and did not vary between the two drop-off conditions, we could ask whether infants responded to the probability of falling, the severity of the fall, or both. Differential responses between the conditions would indicate that infants were responding to the differences in fall severity between the large and small drop off. But to our surprise, motor decisions, gait modifications, and exploratory behaviors were scaled only to bridge width; we found no effects for drop-off condition (Figure 3, Table 1).

Infants walked over bridges within their abilities and refused to walk over impossibly narrow bridges. Attempt rates (successes and failures divided by the total number of trials) varied with the probability of success, as confirmed by a main effect for bridge width (Figure 3A, Table 1 rows 1–3). Trend analyses revealed significant linear and quadratic trends, indicating that attempts were scaled to bridge width. However, there was no effect of drop-off condition and no interaction. Similarly,

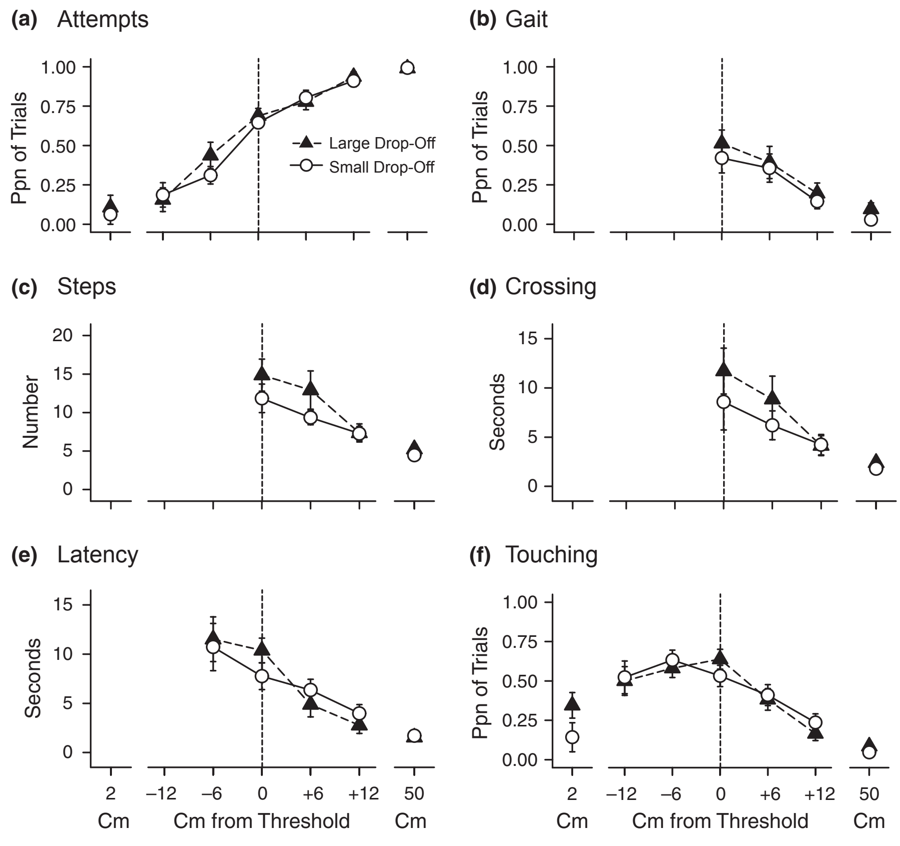

Figure 3 *Walkers' behaviors by bridge width and drop-off height. (A) Proportion of trials on which infants attempted to walk across the bridge. (B) Proportion of trials on which infants used a leading-following gait pattern rather than the typical alternating pattern. (C) Number of steps infants took to cross the bridge. (D) Time infants took to cross the bridge. (E) Latency to begin crossing the bridge. (F) Proportion of trials on which infants touched the bridge with hands or feet. Error bars denote standard errors. The dashed line represents infants' affordance thresholds, and the increments −12, −6, +6, and +12 represent bridge widths normalized to threshold. 2 cm and 50 cm represent absolute increments.*

Table 1 *ANOVA main effects, trends, and interactions for walkers in Experiment 1: Between-subjects comparisons*

	Bridge Width		Drop-off Height		Interaction	
	F	partial η^2	*F*	partial η^2	*F*	partial η^2
Attempt Rate						
effect	80.528**	0.697	0.411†	0.012	0.729†	0.02
linear trend	178.843**	0.836				
quadratic trend	4.562*	0.115				
Gait Pattern						
effect	13.388**	0.283	0.393†	0.011	0.124†	0.004
linear trend	25.607**	0.43				
quadratic trend	1.216	0.035				
Steps						
effect	19.76**	0.368	1.109†	0.032	1.88	0.052
linear trend	26.933**	0.442				
quadratic trend	1.6	0.045				
Cross Time						
effect	9.315**	0.215	0.687†	0.02	0.785†	0.023
linear trend	11.511*	0.253				
quadratic trend	0.232†	0.007				
Latency						
effect	15.897**	0.371	0.011†	<0.001	1.06†	0.038
linear trend	27.999**	0.509				
quadratic trend	0.845†	0.03				
Touch Bridge						
effect	15.389**	0.312	0.064†	0.002	0.672†	0.019
linear trend	23.447**	0.408				
quadratic trend	19.573**	0.365				

Note: $^{**}p \leq .001$. $^{*}p \leq .05$. $^{\dagger}p \geq .3$.

infants showed no condition effect on the 2-cm bridge, $t(20) = 0.39$, $p = .70$.

Although attempt rates did not differ between conditions, if infants were concerned about the severity of the fall, they should have walked more carefully in the large drop-off condition. They did not. Infants modified their gait only in accordance with bridge width. They took more steps, more time to cross, and were more likely to use a leading-following gait on narrower bridges (Figure 3B–D, Table 1 rows 4–12). Gait modifications were pervasive, indicating that infants strove to avoid falling into the drop-off: All but two infants showed evidence of shortening step length and decreasing walking speed, and 82% of infants switched to the leading-following strategy. On some trials, they faced forward and inched along to avoid dangling the trailing leg over the edge of the bridge; on others, they turned sideways with their feet perpendicular to the bridge. However, infants did not walk more carefully on bridges spanning the large drop-off, and there was no interaction between drop-off condition and bridge width.

Despite similarity in motor decisions and gait modifications, infants may have been more motivated to make the correct decision when the penalty for falling was more severe, and therefore spend more time exploring in the large drop-off condition. This was not the case. Exploration prior to starting onto bridges was related only to bridge width, not drop-off height (Figure 3E–F, Table 1 rows 13–18). Latency decreased linearly with bridge width, and touching showed both linear and quadratic effects, as haptic exploration was highest on both risky and ambiguous bridges. While hesitating, infants peered over the edge, touched the bridges, implored parents and experimenters for help, and paced back and forth on the starting platform. Most touches (89%) were with the feet: Infants typically placed a foot partially on the bridge, shifted their weight over it for several seconds, and then either retreated to the safety of the starting platform or started crossing. However, latency and touching did not differ between drop-off conditions and there was no interaction between drop-off condition and bridge width. Rates of touching were lowest on the 2-cm bridge, suggesting that infants did not need additional perceptual information to determine that the bridge was impossible. However, touching did not differ significantly between the drop-off conditions on the 2-cm bridge, $t(19) = 1.53$, $p = .14$.

Within-subjects analyses

Analyses of the subset of 19 infants who completed both drop-off conditions replicated every finding (Figure 4, Table 2). Regardless of whether infants received the large or small drop-off condition first, attempts to walk, gait

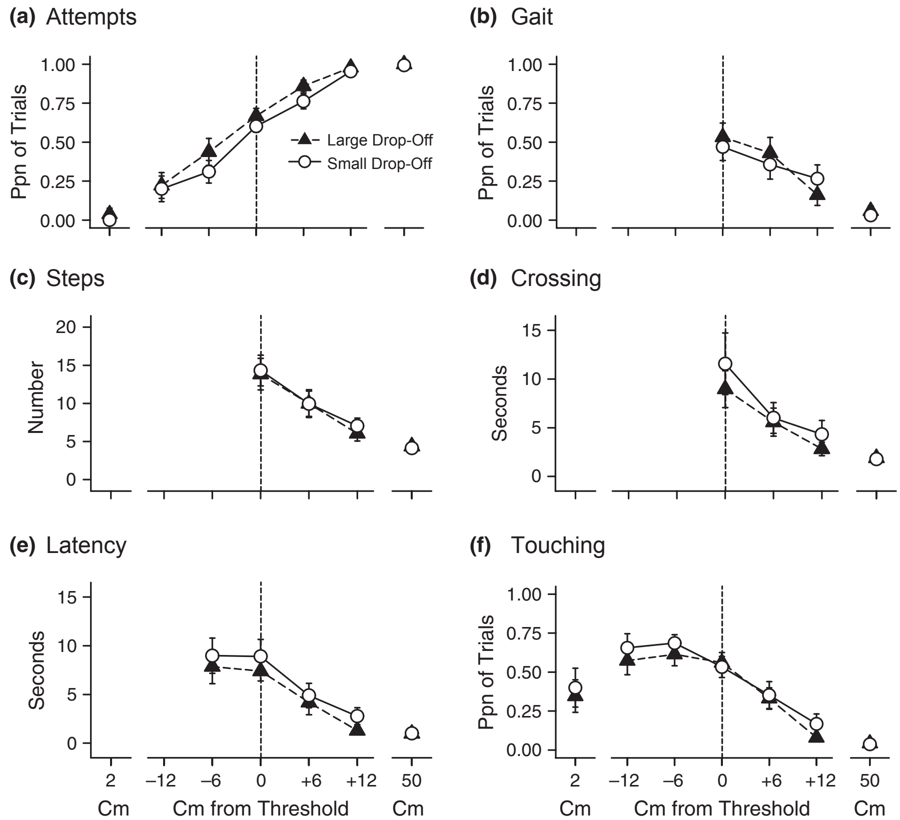

Figure 4 *Within-subjects comparisons for infants who completed both drop-off conditions. (A) Proportion of trials on which infants attempted to walk across the bridge. (B) Proportion of trials on which infants used a leading-following gait pattern rather than the typical alternating pattern. (C) Number of steps infants took to cross the bridge. (D) Time infants took to cross the bridge. (E) Latency to begin crossing the bridge. (F) Proportion of trials on which infants touched the bridge with hands or feet. Error bars denote standard errors. The dashed line represents infants' affordance thresholds, and the increments −12, −6, +6, and +12 represent bridge widths normalized to threshold. 2 cm and 50 cm represent absolute increments.*

modifications, and exploration were scaled to bridge width, but were unaffected by drop-off condition. In fact, Figure 4A shows a slight tendency for infants to attempt walking more frequently in the *large* drop-off condition, and the main effect – going in the opposite direction from what we expected – for drop-off condition was marginally significant (p = .095). Although Figure 3C–D indicated a small but nonsignificant increase in step number and walk time in the between-subjects analyses, this difference disappeared in the within-subject comparisons illustrated in Figure 4C–D, suggesting that individual differences were responsible for the small discrepancy in between-subjects comparisons.

Infants base descent decisions on the probability of falling from different drop-off heights

Although infants treated bridges identically regardless of drop-off height, they did show sensitivity to the height of the drop-off on refusal trials, consistent with previous research (Kretch & Adolph, in press). When bridges were too narrow for walking, infants occasionally descended into the drop-off by stepping, backing, crawling, or scooting rather than waiting out the trial on the starting platform. Nine infants descended in the small drop-off condition (M = 19.2% of refusal trials overall), by backing (8.8%), stepping (7.7%), or crawling (2.8%). Six infants descended in the large drop-off condition (M = 7.7% of refusal trials overall), but those who descended did so only once, and mostly by stepping (5.4%), compared with scooting (2%) or backing (0.4%); inspection of the videos suggests that some of the stepping trials may have been failed attempts to step onto the bridge. Descent was more frequent in the small drop-off condition, $F(1, 34) = 4.98$, $p = .03$, partial $\eta^2 = .13$ in the between-subjects analysis and $F(1, 17) = 4.20$, $p = .06$, partial $\eta^2 = .20$ in the within-subjects analysis. Therefore, as in previous research, infants in

Table 2 *ANOVA main effects, trends, and interactions for walkers in Experiment 1: Within-subjects comparisons*

	Bridge Width		Drop-off Height		Interaction	
	F	partial η^2	*F*	partial η^2	*F*	partial η^2
Attempt Rate						
effect	62.761**	0.777	3.107	0.147	0.716†	0.038
linear trend	114.776**	0.864				
quadratic trend	0.71†	0.038				
Gait Pattern						
effect	20.084**	0.542	0.032†	0.002	2.068	0.108
linear trend	28.807**	0.629				
quadratic trend	1.276	0.07				
Steps						
effect	29.97**	0.638	0.212†	0.012	0.382†	0.022
linear trend	38.439**	0.693				
quadratic trend	0.391†	0.023				
Cross Time						
effect	15.785**	0.481	1.455	0.079	1.018†	0.057
linear trend	15.944**	0.484				
quadratic trend	12.488*	0.424				
Latency						
effect	15.511**	0.66	3.135	0.282	1.594	0.166
linear trend	41.709**	0.839				
quadratic trend	0.047†	0.006				
Touch Bridge						
effect	28.024**	0.622	0.708†	0.04	0.366†	0.021
linear trend	60.012**	0.779				
quadratic trend	11.281*	0.399				

Note: $^{**}p \leq .001$. $^{*}p \leq .05$. $^{\dagger}p \geq .3$.

the current study responded differently to the two drop-offs when the task was descent and the height of the drop-off affected the probability of success.

Summary

In the current study, as in previous work, infants responded to the probability of falling based on bridge width (through crossing behaviors) and drop-off height (through descent behaviors on refusal trials). Infants were less likely to attempt narrower bridges, crossed narrower bridges more carefully, and increased exploratory activity on narrow and ambiguous bridges, indicating that they perceived affordances for walking over bridges and took measures to reduce the probability of falling. Infants also perceived the different affordances of the two drop-offs: On the narrowest bridges where walking was impossible, infants descended into the small drop-off more frequently and avoided the large drop-off more frequently.

However, infants did not respond to the severity of the potential fall. We found no differences in attempts, gait modifications, or exploratory activity between the large and small drop-off conditions. Given infants' strong aversion to falling into a precipice, this result is surprising and counterintuitive.

A potential alternative explanation is that infants did not have sufficient visual information about the differences in drop-off height. The drop-off was lined with a patterned fabric to highlight depth cues, but we only required that infants fixate the bridge at the start of each trial, not the drop-off. Perhaps infants were too distracted by the bridge to register the drop-off height. To investigate where infants directed their visual attention, we observed two infants (one in each drop-off condition) in a modified version of Experiment 1, and monitored their eye gaze using a head-mounted eye-tracker (Franchak, Kretch, Soska & Adolph, 2011). Infants received two trials each at the 50-, 30-, 22-, and 10-cm wide bridges. Both infants showed similar looking behaviors. At every trial, the drop-off was in the field of view when we showed infants the bridge, suggesting that they could always see the drop-off at the start of the trial. On the 50-cm bridge, neither infant looked directly at the drop-off, but on the 22- and 30-cm bridges, they looked into the drop-off on one of two trials, and on the 10-cm bridge, they looked into the drop-off on both trials. Thus, failure to respond differently to the two drop-off heights did not likely result from lack of visual information.

Another possibility that must be ruled out is that infants saw the drop-off but simply ignored it. Infants' motor decisions, gait modifications, and exploratory behavior suggest that they were motivated to stay on the bridges. Was this truly to avoid falling into the drop-off below the bridge, or was it simply due to experimental artifacts? Infants may have preferred walking in the center of the walkway where bridges were located, or they may have walked over the bridges due to the salient contrast of the wooden surface against the checkerboard background. Moreover, calling infants' attention to the bridge at the start of each trial may have cued infants to devote their attention solely to the bridge. If infants did not care about the presence of the drop-off, we would expect them to behave identically regardless of whether a drop-off was present or not. That is, we would expect them to refuse to cross bridges that were too small, modify their gait on smaller bridges, and explore smaller bridges even when there was no drop-off below the bridge. We tested this hypothesis in Experiment 2.

Experiment 2. No drop-off

In Experiment 2, we presented infants with similar visual information to Experiment 1, but eliminated the drop-off by creating a 'visual bridge' apparatus.

Method

Participants and visual bridge apparatus

We tested eight 14-month-olds (five boys, three girls). Their average walking experience was 2.82 months (SD = 1.58), comparable to the infants in Experiment 1.

We constructed a visual bridge apparatus using the same starting and landing platforms arranged as in Experiment 1 (Figure 5). To eliminate drop-off height, we inserted a 76-cm wide bridge into the gap to create a continuous platform. We covered the bridge with a 76 cm wide × 76 cm long Dycem high-friction mat attached securely to the sides of the bridge with velcro. The mat was covered in three alternating strips of patterned contact paper: The strip in the middle contained a wood pattern that matched the rest of the apparatus, and the outer strips contained a black and white checkerboard pattern similar to the fabric that covered the floor of the drop-off in Experiment 1. The mat therefore resembled the bridge and drop-off apparatus except that they presented no actual visual or haptic cues for depth. We constructed three mats that contained three different sized 'bridges': 32, 20, and 6 cm, representing bridges that would have been easy, challenging, and impossible (respectively) had they spanned a true precipice.

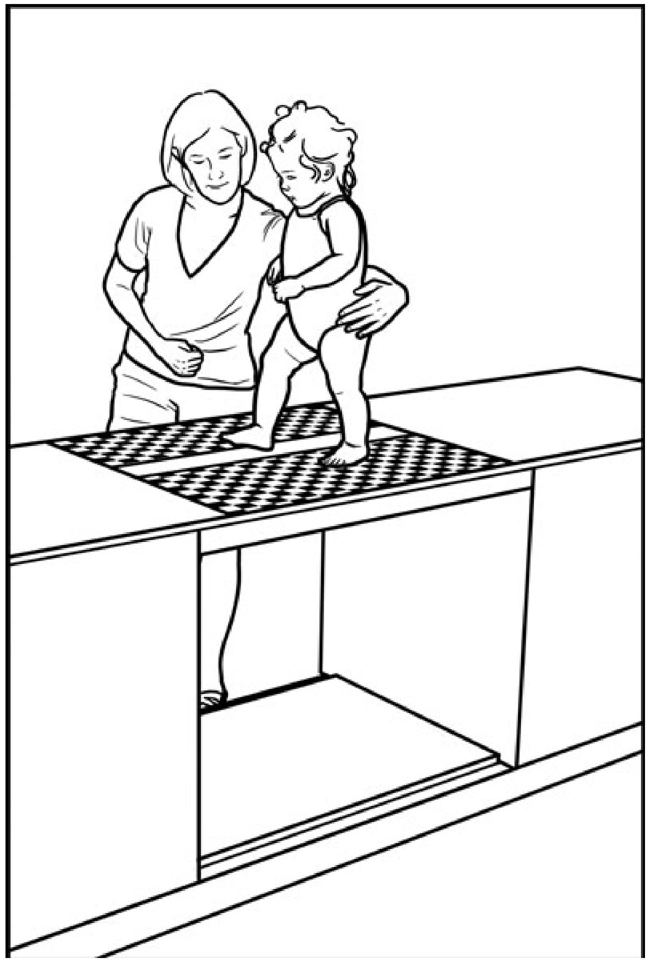

Figure 5 *Visual bridge apparatus used in Experiment 2.*

Procedure and data coding

The procedure was designed to mimic the critical elements in Experiment 1. We first presented infants with four warm-up trials over the continuous wooden platform to teach them the game of walking over to their parents. Then, we placed the first visual bridge mat over the middle of the platform and encouraged infants to cross. The bridges were presented in descending order as in the early stages of the staircase protocols in Experiment 1. Infants received two trials on the 32-cm 'bridge', then two trials on the 20-cm 'bridge', and finally two trials on the 6-cm 'bridge'. This sequence was repeated two times for a total of 12 trials per infant (one infant completed only one block of trials). At the beginning of each trial, an assistant called infants' attention to the bridge area of the mat using a small toy, and trials began after infants had seen the bridge.

We scored attempts and refusals, gait modifications, latency, and exploratory touching as in Experiment 1. In addition, since we could not score successes and failures (walking was possible at all three increments), we scored whether infants stayed on the bridge area of the mat, or took steps with at least half of the foot on the checkerboard area because on an actual bridge, these steps would have resulted in a fall.

Results and discussion

In contrast to Experiment 1 where infants showed sensitivity to bridge width, when we removed the drop-off in Experiment 2, infants did not respond differentially to bridge width. They walked across the platform on every trial without trying to stay on the bridges; they walked over the checkerboard area of the platform on 58.9% of trials. Infants did not modify their gait for smaller bridges: Number of steps ($F(2,14) = 1.80$, $p = .20$) and time to cross ($F(2,14) = 2.61$, $p = .11$) did not differ significantly based on bridge width – if anything, infants were fastest on the narrowest bridge – and infants used the leading-following gait pattern on only 3/90 trials. Infants paused before crossing on 10/90 trials (latency did not differ based on bridge width, $F(2,14) = 0.84$, $p = .45$) and touched the surface on only 3/90 trials.

Together, Experiments 1 and 2 illustrate that toddlers' decisions about bridge crossing depend on bridge width, but only if failing to remain on the bridge will result in falling into a drop-off. Infants attend to the drop-off and are averse to falling into the drop-off, but they respond identically to bridges spanning a small and a large drop-off.

Experiment 3. Crawlers: large and small drop-offs

In Experiment 3, we examined the generalizability of this counterintuitive finding. We tested a sample of crawling infants on the same bridge and drop-off task used in Experiment 1. Recent evidence indicates that walking infants usually cannot see much of the ground near their feet, but crawlers, with their heads close to the floor and tilted down, have nearly constant visual access to the ground near their hands (Kretch, Franchak, Brothers & Adolph, 2012). We therefore asked whether crawling infants, who would have continuous information about drop-off height, would respond to the severity of a potential fall with differential attempts to cross, gait modifications, and exploratory activity.

Testing crawlers in this task also allowed us to investigate whether the different biomechanical constraints of crawling influence affordances – and perception of affordances – for crossing bridges. Whereas walkers must balance their entire body over two limbs, crawlers must coordinate the movements of four limbs, two of which are unavailable to vision. Therefore, locomoting over a narrow surface of support is a different and potentially more difficult task for crawlers. Do crawlers respond to the probability of falling with as much precision as walkers?

Method

Participants and procedure

Twenty-seven healthy, term infants participated within a week of their 11-month birthday. Fourteen infants (six boys, eight girls) were tested in the large drop-off condition and 13 (six boys, seven girls) in the small drop-off condition. Infants were recruited and compensated in the same manner as in the previous experiments. Although younger than the walking infants in Experiment 1, infants were even more experienced in their method of locomotion ($M = 3.11$ months crawling experience, $SD = 1.02$). Previous work showed that infants with similar durations of crawling experience perceive affordances just as accurately as experienced walkers (Adolph, 1997; Kretch & Adolph, in press). An additional five infants were tested but did not complete the study due to fussiness (three in the large drop-off condition and two in the small drop-off condition). The procedure was the same as in Experiment 1.

Data coding

Coders re-scored infants' *motor decisions* (success, failure, or refusal) from video; 100% of thresholds agreed with those calculated online. With twice the number of limbs recruited for locomotion, infants had more ways to err than walkers, so for each failure trial, coders scored *failure type*: misplaced hand, misplaced leg, or getting stuck in the middle of the bridge. For success trials, coders scored *gait modifications*: the number of steps with each leg and crossing time. Coders also scored measures of *exploratory activity*: Latency, touching the bridge, and whether infants explored the drop-off by reaching into the precipice with their hands and then retracting their arms (Adolph, 2000). Correlation coefficients for continuous measures were >.97, and Kappa coefficients for categorical codes were >.84.

Results and discussion

Video data were lost for one infant in the large drop-off condition; her data are included in analyses of thresholds and motor decisions based on the online codes. Three infants (two in the large drop-off condition and one in the small) did not receive trials at the −12-cm bridge group due to fussiness; these data were replaced with group means for attempts and touching. Six infants never attempted the −6-cm bridge and dropped out of the ANOVA for latency. Sixteen infants contributed data at 2 cm.

Crawlers respond to the probability of falling, not the severity of the potential fall

Crawlers proved remarkably adept at crossing bridges. Although they had to fit a larger portion of their bodies on the bridge than walkers, their affordance thresholds fell into a similar range (16 to 32 cm, compare Figures 2 and 6). Like walkers, crawlers' thresholds were correlated with crawling experience, $r(25) = -.47$, $p = .01$. Also like walkers, crawlers' balance was not disrupted by visual information in the large drop-off condition: Affordance thresholds were similar between the large ($M = 20.71$) and small ($M = 23.23$) drop-off conditions, $t(25) = 1.67$, $p = .11$.

Did greater visual access to the drop-off compel crawlers to respond with greater wariness to the large drop-off? It did not. Like walkers, crawlers scaled their motor decisions only to bridge width, not drop-off condition (Figure 7A, Table 3 rows 1–3). There was no difference in attempt rates on the 2-cm bridge, $t(14) = 0.76$, $p = .46$. However, like walkers, infants perceived the different affordances of the small and large drop-offs, as evidenced by their behavior on refusal trials. Although the small drop-off was impossible for walking down, it did afford crawling down. Crawlers perceived this, and descended into the small drop-off on $M = 51.5\%$ of refusal trials (21.5% crawling, 18.4% backing, 11.5% scooting) compared with only $M = 3.9\%$ of refusal trials in the large drop-off condition (all backing), $F(1, 25) = 7.37$, $p = .01$. Nine of the 13 infants in the small drop-off condition descended at least once (compared with only two infants in the large drop-off condition).

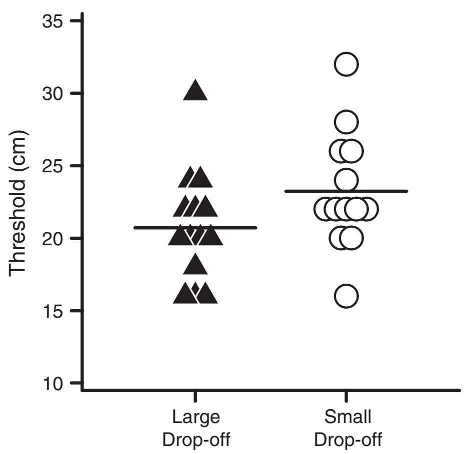

Figure 6 *Affordance thresholds for crawlers in the two drop-off conditions. Each symbol represents one infant, and solid lines represent group means.*

Although crawlers were less likely to attempt smaller bridges than larger ones, they still erred by attempting the −6-cm bridges – that is, they did not always correctly gauge the probability of falling. Why did experienced crawlers, who perform near ceiling in perceiving affordances of slopes and drop-offs (Adolph, 1997; Kretch & Adolph, in press), have a more difficult time with bridges? Crossing bridges differs from descending slopes and drop-offs because bridge crossing relies on precise limb placement to avoid falling whereas the descent tasks do not. An examination of infants' failures suggests that limb placement is the culprit. In both conditions, infants were more likely to fall because they misplaced a leg (66.4% of failure trials) than because they misplaced a hand (22.2% of failure trials) or got stuck on the bridge (11.4% of failure trials). Possibly infants erred because they had difficulty monitoring the placement of back limbs that were obscured from their view.

We expected that having the precipice in view would make the severity of a potential fall more salient, prompting crawlers to cross more carefully in the large drop-off condition. This was not the case. Infants took more crawling steps and more time to cross on narrower bridges, but steps and crossing time did not differ between conditions, and there was no interaction (Figure 7B–C, Table 3 rows 4–9). Similarly, exploration was largely unaffected by drop-off condition. Like walkers, crawlers hesitated longer and touched more on narrower bridges (Figure 7D–F, Table 3 rows 10–18). Crawlers also explored the drop-off by reaching down with their hands. The ANOVAs revealed no significant effects of drop-off condition and no interactions for latency, touching the bridge, or reaching into the drop-off. However, on the 2-cm bridge, infants touched the bridge more in the large drop-off condition, $t(14) = 2.16$, $p = .05$. This may be partly due to the fact that infants were stuck on the starting platform for 30 s in the large drop-off condition and had more opportunity to touch the bridge, whereas in the small drop-off condition they had the option of descending into the drop-off. Reaching into the drop-off did not differ between the conditions on the 2-cm bridge, $t(14) = 0.62$, $p = .55$.

Summary

Crossing bridges over small and large drop-offs posed different challenges for crawlers compared with walkers. Whereas walkers have more of the walls in their field of

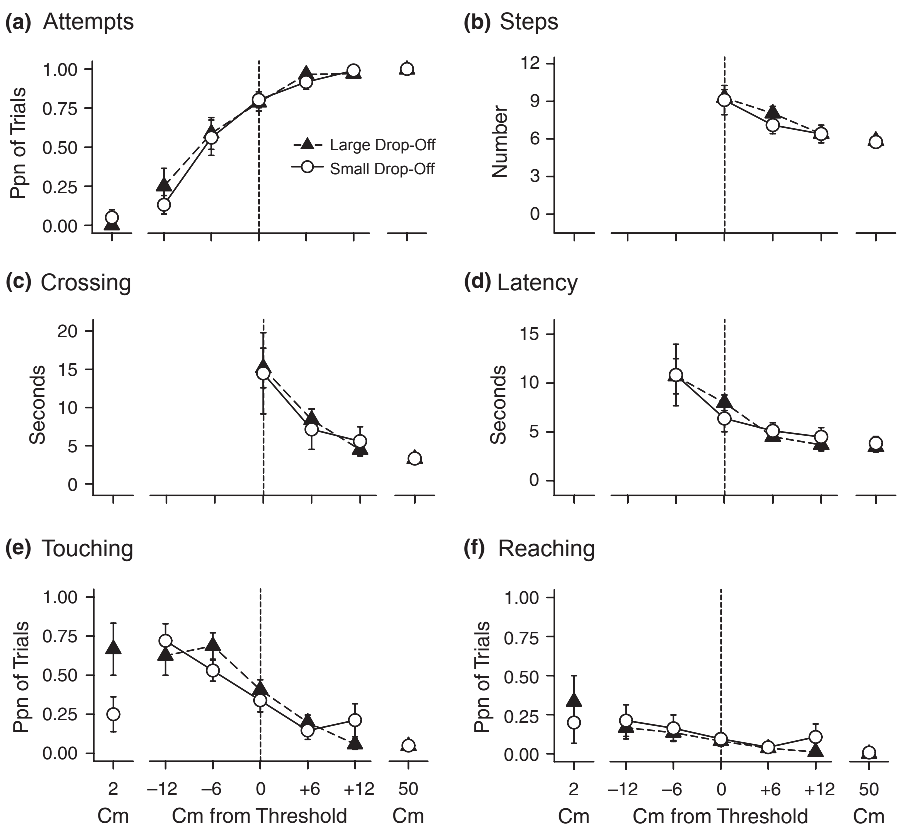

Figure 7 *Crawlers' behaviors by bridge width and drop-off height. (A) Proportion of trials on which infants attempted to crawl across the bridge. (B) Number of steps infants took to cross the bridge. (C) Time infants took to cross the bridge. (D) Latency to begin crossing the bridge. (E) Proportion of trials on which infants touched the bridge with hands or feet. (F) Proportion of trials on which infants explored the drop-off by reaching an arm into the gap and then retracting it. Error bars denote standard errors. The dashed line represents infants' affordance thresholds, and the increments −12, −6, +6, and +12 represent bridge widths normalized to threshold. 2 cm and 50 cm represent absolute increments.*

view, crawlers see more of the ground; presumably, they had visual access to the height of the drop-off as they approached the bridge and crawled over it. Rather than facing two impossible drop-offs for walking, crawlers were confronted with an impossibly large drop-off and a difficult but possible drop-off for crawling. Whereas walkers had to keep two limbs on the bridge, crawlers had to find space for all four limbs.

Despite these differences, crawlers showed the same pattern of responding as walkers: They responded to the probability of falling, but not to the severity of the potential fall. Crawlers' attempts to cross, gait modifications, and exploratory activity varied only with bridge width, not drop-off condition. Crawlers erred more than walkers, but they erred equally in both drop-off conditions, indicating that the similarity between conditions in Experiment 1 was not merely a ceiling effect. The only outcome measure for which drop-off condition had an effect was in infants' refusal strategies: They avoided the large drop-off where descent was impossible but crawled or backed into the small drop-off, where the probability of falling was low.

General discussion

What information do infants use to make decisions about action? In particular, do infants, like adults, consider both the probability of falling and the severity of a potential fall when deciding what to do at the edge of a precipice? Previous work could not address this question because the height of the drop-off was constant (Adolph, 2000; Berger & Adolph, 2003; Berger *et al.*, 2010; Berger *et al.*, 2005) or covaried with the probability of falling (Adolph, 1995, 1997; Adolph *et al.*, 1993; Kretch & Adolph, in press). Here, we disentangled the probability of falling and fall severity by varying bridge width and drop-off height independently. Three experi-

Table 3 *ANOVA main effects, trends, and interactions for crawlers in Experiment 3*

	Bridge Width		Drop-off Height		Interaction	
	F	partial η^2	*F*	partial η^2	*F*	partial η^2
Attempt Rate						
effect	59.302**	0.703	0.301†	0.012	0.458†	0.018
linear trend	148.864**	0.856				
quadratic trend	25.478**	0.505				
Steps						
effect	22.936**	0.489	0.182†	0.008	0.704†	0.028
linear trend	36.218**	0.601				
quadratic trend	0.553†	0.023				
Cross Time						
effect	13.133**	0.344	0.107†	0.004	0.28†	0.011
linear trend	18.733**	0.428				
quadratic trend	2.285	0.084				
Latency						
effect	12.611**	0.399	0.507†	0.026	0.69†	0.035
linear trend	17.897*	0.485				
quadratic trend	3.893	0.17				
Touch Bridge						
effect	22.545**	0.484	0.014†	0.001	1.496	0.059
linear trend	53.098**	0.689				
quadratic trend	0.198†	0.008				
Touch Drop-off						
effect	2.743*	0.103	0.907†	0.036	0.221†	0.009
linear trend	6.122*	0.203				
quadratic trend	0.735†	0.03				

Note: **$p \leq .001$. *$p \leq .05$. †$p \geq .3$.

ments showed that infants base their decisions only on the probability of falling, not on the severity of a potential fall. The findings were robust in between- and within-subject comparisons and in crawlers and walkers. Attempts to cross, gait modifications, and exploration were geared to bridge width, but did not differ between drop-off conditions.

Although robust, these findings are counterintuitive. Infants are averse to falling into a drop-off, and one would expect them to perceive the consequence of falling into a large drop-off as more severe than falling into a small drop-off. But they did not. Moreover, at first blush, the current findings appear to contradict decades of previous work showing differential avoidance of large and small drop-offs at the edge of a visual cliff or real cliff (Campos *et al*., 1978; E.J. Gibson & Walk, 1960; Kretch & Adolph, in press). However, the findings are not contradictory. Consistent with previous work, on refusal trials infants showed sensitivity to drop-off height. They backed or crawled into the small drop-off but avoided the large drop-off. The results seem counterintuitive and contradictory because our commonsense intuition is that infants should be more wary of a large drop-off. However, the real surprise from the current experiments is not that infants weren't wary of crossing bridges over a large drop-off, but that they were equally wary of crossing bridges over a small drop-off that was just barely too high to walk down.

Probability of falling

Infants perceived affordances for locomotion based both on bridge width and drop-off height. In terms of bridge width, attempts decreased on narrower bridges. Infants also hesitated longer and engaged in more haptic exploration before starting onto narrower bridges, suggesting that they were loathe to err and thus generated additional information before deciding whether to cross. When they did attempt narrow bridges, both crawlers and walkers shortened step length and decreased speed, and walkers switched to a leading-following gait pattern.

But walkers perceived the probability of falling more accurately than crawlers: Walkers attempted $M = 32\%$ of impossibly narrow bridges and crawlers attempted $M = 46\%$. Why more errors in experienced crawlers? Although thresholds were comparable, affordances for crawling over bridges differ from affordances for walking. Crawling involves balancing the full width of the body on the bridge and managing placement of four limbs, whereas walking allows turning the body to narrow its dimensions. For adults, some affordances are more difficult to perceive than others, depending on the dynamic factors influencing the particular action (Cole, Chan & Adolph, in press). The current studies suggest that actions that preclude visual guidance, such as precise placement of hind limbs on a narrow surface, may be especially difficult to predict.

Infants also perceived the probability of falling based on drop-off height. The 0-cm drop-off on the 'visual bridge' was perfectly safe for walking; accordingly, infants walked without hesitating, touching, modifying their gait, or keeping their feet on the 'bridge'. The 17-cm drop-off afforded descent in crawling, backing, and scooting postures; infants used these strategies to descend, but rarely attempted to walk. Crawlers descended more frequently than walkers, suggesting that starting in a crawling position may bias infants to perceive affordances for crawling and similar actions. The 71-cm drop-off was too high for descent in any posture and both crawlers and walkers avoided descent. Like experienced crawlers and walkers on an adjustable drop-off (Kretch & Adolph, in press), infants in the current study differentiated the affordances of the various drop-offs and responded based on the probability of falling.

Severity of the fall

In adult decision-making, optimal choices are based on both perception of the probability of success and consideration of cost or penalty (Kording & Wolpert, 2006; Trommershäuser, Maloney & Landy, 2003, 2008). Like adults, infants can take both the probability of success and the penalty for error into account (Franchak & Adolph, 2012). Infants' attempts to pass through openings depend on the size of the opening relative to their bodies and whether failed attempts would result in entrapment or falling off a ledge.

Again, our findings seem to contradict previous work. Why did infants respond differently to entrapment and falling in Franchak and Adolph, but not to falling from two different heights in the current study? Both the ledge and bridge paradigms clearly show that infants are averse to falling into a large precipice: They responded cautiously to a 65-cm drop-off beneath a ledge and to a 71-cm drop-off beneath a bridge. The key difference is that infants disregard the penalty of entrapment but not the penalty of falling into a small (17-cm) precipice. The current experiments indicate that infants consider falling from *any* height to be a serious penalty.

Apparently, infants' problem is that they do not understand that falling from different heights leads to differences in the severity of the potential fall. Viewed in this way, the results are perhaps not so surprising. How *would* infants know that the longer an object (or baby) falls, the harder it hits the ground? Certainly by adulthood, we understand this intuitively. An open question is how and when this understanding develops. Although falling is a leading cause of accidental injury in children, fortunately most children do not experience a severe fall (Mathers & Weiss, 1998).

Role of attention and emotion

Could attention have played a role in infants' equally wary responses in both drop-off conditions? The eye-tracking data indicate that infants directed their gaze to the drop-off in both conditions. But perhaps after seeing the drop-off, infants' attention was consumed by the motor demands of crossing the narrow bridges and this prohibited them from processing information about the severity of the potential fall. Previous work indicates that the attentional demands of planning difficult motor actions may inhibit expression of infants' perceptual and cognitive abilities (Berger, 2004; Berthier, Bertenthal, Seaks, Sylvia, Johnson & Clifton, 2001; Boudreau & Bushnell, 2000).

However, previous work also shows that infants can process multiple sources of information in demanding locomotor tasks such as descending slopes, navigating openings, and crossing bridges. Eighteen-month-olds attend to perceptual information from their own exploratory activity and social information from their mothers when deciding whether to walk down slopes (Tamis-LeMonda, Adolph, Lobo, Karasik & Dimitropoulou, 2008). Seventeen-month-olds consider information about affordances for fitting through openings and information about the penalties for errors (Franchak & Adolph, 2012). And 16-month-olds simultaneously take multiple dimensions of the environment into account, integrating information about bridge width and the presence, composition, and location of a handrail that can augment their balance (Berger & Adolph, 2003; Berger *et al.*, 2010; Berger *et al.*, 2005). Notably, the infants in those studies were a few months older than the infants in the current studies; perhaps the ability to integrate multiple sources of information in the context of a difficult locomotor task develops between 14 and 16 months of age.

In some sense, appreciation of the height of the drop-off is a prerequisite for the bridge-crossing task. A bridge, by definition, is a path that spans an otherwise uncrossable precipice. To realize that the bridge was necessary, infants had to register the height of the drop-off from the beginning. Perhaps, rather than integrating information about bridge width and drop-off height simultaneously, infants processed information sequentially. First, they considered the drop-off. If there was no drop-off, they ran straight across the platform (as in Experiment 2). If there was a drop-off, they turned their attention exclusively to the bridge and considered whether crossing was possible. If so, they crossed quickly if the bridge was wide and carefully if the bridge was narrow. If not, they turned their attention back to the drop-off and reconsidered its affordances: If they could crawl or back into it, they did so, if not, they stayed put.

Another factor that might have affected infants' decisions at the edge of a precipice is fear of heights. In adults, this common emotional response is instigated by the loss of motion parallax cues for balance when objects are farther away (Brandt, Arnold, Bles, & Kapetyn, 1980; Coelho & Wallis, 2010; Huweler, Kandil, Alpers & Gerlach, 2009). As such, emotional arousal is a graded response that increases linearly with drop-off height in adults (Davis *et al*., 2009). Therefore, we might expect infants to incur stronger anxiety or fear with a larger drop-off height than a smaller one. As in previous work, we found clear evidence that infants are averse to falling from a height (Adolph, 1997, 2000; Kretch & Adolph, in press), but no evidence of adult-like anxiety that increases with drop-off height. Even crawling infants, who had the drop-off continuously in view, were equally likely to cross bridges over the large and small drop-off. Possibly, the 71-cm drop-off in the current study was not large enough to elicit fear. We believe this explanation is unlikely – the large drop-off was approximately infants' standing height, analogous to a six-foot drop-off for an adult – but perhaps an even larger drop-off would have elicited greater expressions of wariness compared with both drop-offs. Alternatively, the development of fear of heights may accompany learning about the severity of a potential fall.

Conclusions

Perceiving affordances means perceiving whether an action is possible or impossible (Franchak & Adolph, in press). Perceiving affordances for crossing a bridge means perceiving whether you can walk safely or whether you will fall. However, perceiving affordances does not necessarily include knowledge about the severity of the penalty if the action is impossible. For adults, motor decisions include consideration of both affordances and penalties. The current study suggests that, at least by 14 months, infants have mastered the former but not the latter.

Learning to perceive affordances is a primary task of infancy (E.J. Gibson, 1988). The ability to perceive affordances for locomotion develops slowly, and requires a protracted period of experience with each posture in development (Adolph, 1997, 2000; Kretch & Adolph, in press). Reasoning about the severity of action consequences may come later in development. Infants might require a more sophisticated naive physics to realize that a fall from a large height is worse than a fall from a small height. Or, they may learn from caregivers' messages to be more wary of larger drop-offs. Whatever the later stages of the process, perception of affordances is the starting point for learning to guide actions adaptively.

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