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Infants Use Handrails as Tools in a Locomotor Task

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In 2 experiments the authors demonstrated that adaptive locomotion can involve means–ends problem solving. Sixteen-month-old toddlers crossed bridges of varying widths in the presence or absence of a handrail. Babies attempted wider bridges more often than narrow ones, and attempts on narrow bridges depended on handrail presence. Toddlers had longer latencies, examined the bridge and handrail more closely, and modified their gait when bridges were narrow and/or the handrail was unavailable. Infants who explored the bridge and handrail before stepping onto the bridge and devised alternative bridge-crossing strategies were more likely to cross successfully. Results challenge traditional conceptualizations of tools: Babies used the handrail as a means for augmenting balance and for carrying out an otherwise impossible goal-directed task.

Although independent locomotion is heralded as a setting event for important cognitive developments in object search, spatial skill, and causal and social relationships (e.g., Bertenthal, Campos, & Barrett, 1984; Bremner, 1993; Campos et al., 2000; Campos, Hiatt, Ramsay, Henderson, & Svejda, 1978), researchers typically treat locomotion itself as a low-level perceptual–motor activity. For example, researchers in the biomechanical tradition have focused on infants' postural adjustments, changes in their crawling and walking patterns, interlimb coordination, and muscle actions (e.g., Adolph, Vereijken, & Denny, 1998; Bril & Breniere, 1993; Clark & Phillips, 1987; Thelen, Ulrich, & Niles, 1987). Researchers in the perception–action tradition have focused on infants' use of perceptual information via visual and haptic exploration to inform their motor decisions (e.g., Adolph, 1997; Adolph, Eppler, Marin, Weise, & Clearfield, 2000; Gibson et al., 1987; Schmuckler, 1996). Gibson, for example, described infants' everyday activity on the playground as a "revelation of attention to affordances" (from K. Adolph's notes on a presentation given by Gibson, 1992), meaning that everyday playground encounters involve gathering perceptual information so as to determine new possibilities and constraints on action.

Means–Ends Problem Solving in Manual and Locomotor Tasks

In this article, we argue that locomotion can involve more than low-level perceptual–motor skills. Infants' everyday, goal-directed locomotor activities can involve higher level cognitive processes such as means–ends problem solving, strategy selection, inhibition, and sequencing a series of actions into a complex motor plan as they cope with obstacles in their path, coordinate the components of a plan to navigate the jungle gym or bouncing bridge, and inhibit compelling behaviors as they wait their turn on the slide. Moreover, we argue that problem solving that involves using environmental means to extend locomotor abilities may even represent a hallmark of human intelligence: tool use.

Since Piaget's (1954) descriptions of his children's sensorimotor behaviors, researchers of cognitive development have been comfortable using manual motor tasks as indices from which to infer infants' cognitive skill. For example, infants' abilities to manually search for a hidden object provide evidence about their understanding of object permanence (e.g., Butterworth, 1977; Wellman, Cross, & Bartsch, 1986), their spatial and temporal concepts (e.g., Bremner & Bryant, 1977), and their understanding of number (Feigenson & Carey, in press). Using one object to retrieve another, such as retrieving a toy by pulling a blanket on which it rests, provides evidence for means–ends problem solving and a primitive sort of tool use (e.g., Chen, Sanchez, & Campbell, 1997; Willatts, 1984).

Despite the prevalence of manual means–ends tasks in the literature, there is a precedent for locomotor problem solving involving more of the body than the hands and arms. For example, Köhler's (1931) chimpanzees performed locomotor tasks, such as pole vaulting or building platforms, to obtain food that was out of

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reach. To pole vault, chimps had to recognize that the lure was beyond the reach of their jumps, notice the pole on the other side of the room, and seize on the pole as a means for vaulting their bodies to the appropriate height to grab the bananas. To build platforms, the chimps had to similarly recognize that boxes were available and potentially useful, seriate them to stack them appropriately, and then climb up to get the bananas. Both tasks are clever cognitive accomplishments that demonstrate sophisticated means–ends problem solving via the coordination of several substeps into a plan. Replicating Köhler's (1931) observations, McGraw (1935) trained twin toddlers, Jimmy and Johnny, to climb on furniture, stack boxes, or use sticks to reach a goal that was out of reach. Recent research indicates that even without several months of practice in a special training regimen, toddlers may be capable of using environmental support to solve gross locomotor problems as successfully as they use them in fine motor tasks. Adolph (1995, 1997) observed newly walking infants spontaneously grasp onto support posts prior to descending steep slopes, suggesting that they recognized the function of the posts as aids for maintaining balance while placing a foot out to explore the sloping surface. To use the poles in this way, infants had to recognize that they were in a potentially risky location, realize that a pole was available and could be used to augment balance, and then implement use of the pole. However, because the poles were out of reach once infants stepped onto the slope, infants' ability to use them as a means for completing a locomotor task could not be tested systematically.

Means–Ends Problem Solving and Tool Use

A pinnacle achievement for means–ends problem solving is tool use (Connolly & Dalgleish, 1989). Culling from several descriptions of infant and primate tool use, researchers seem to agree that tool use is a multistep process requiring users to (a) recognize a gap between their own abilities and their typical means for achieving the goal, (b) notice that a tool is available that can supply the missing means to fill the gap, and (c) modify their typical means to incorporate the role of the tool in obtaining the goal (e.g., Bushnell & Boudreau, 1998; McCarty, Clifton, & Collard, 1999, 2001; Tomasello & Call, 1997). Meeting these criteria may demand spatial skills because it requires coordination of the locations of the goal and the tool (Lockman, 2000). Indeed, infants frequently fail to make the connection between implements and their uses when the tools are not directly touching the target object, though they may lie next to each other on a table, and even 5-year-olds sometimes have difficulty when the tool and goal are on opposite sides of a room (Bates, Carlson-Luden, & Bretherton, 1980; Shapiro & Gerke, 1930/1991; van Leeuwen, Smitsman, & van Leeuwen, 1994). However, the tool use problem may not be about coordinating two points of spatial reference per se, but about coordinating multiple pieces of information simultaneously. For example, tool use requires mentally linking the tool to a goal if the relationship is not direct, or envisioning the desired outcome plus knowing how to use the tool as an aid to achieve it. This mental jump implies that the tool user can mentally coordinate the steps en route to the complete event (van Leeuwen et al., 1994). Prospective tool use involves inhibiting behaviors that would be unsuccessful without the aid of a tool, thereby eliminating inefficient trial and error.

Based on Köhler's (1931) famous chimpanzees piecing sticks together to rake in a banana through the bars of their cages (and perhaps our everyday use of the word *tool* to refer to those hand-held objects in a toolbox), our classic vision of infant tool use involves hand-held implements. Consequently, the literature on tool use has focused on manual tasks. For example, by 10 months, infants use sticks, hooks, rakes, and rings to drag over an object that is out of reach, and they adapt their behavior according to the implement provided (Bates et al., 1980; Brown, 1990; Chen & Seigler, 2000; van Leeuwen et al., 1994). By the time they are 2 years old, infants can use tools that are self-directed (eating with a spoon, brushing their hair) and can adjust their strategies to continue using tools that have been altered structurally, such as changing the way they grasp a spoon with a bent handle to continue scooping food from a bowl (Connolly & Dalgleish, 1989; McCarty et al., 2001; Steenbergen, van der Kamp, Smitsman, & Carson, 1997).

The locomotor problem-solving tasks described above (Adolph, 1995, 1997; Köhler, 1931; McGraw, 1935) are akin to these manual tool-use tasks where an implement found in the environment is used as an aid for achieving a goal. To date, however, no clear criteria have been established for what should and should not be considered a tool. For example, Parker and Gibson (1977) would likely have classified the pole vaults and stackable boxes only as *prototools*. In prototool use, only the object of change is freely mobile, such as when primates (agents of change) bang nuts in their shell (objects of change) on a hard surface, such as the ground (implement of change) to break them open. On their definition, Köhler's (1931) vaulting chimps did not engage in tool use to move themselves in reach of the bananas, because an object (the chimp) was moved by means of a fixed implement (the vault) rather than by a detached one. In contrast, other definitions suggest that the pole vault, for example, may indeed count as a tool because it made an otherwise impossible action possible—it changed the relationship between the environment and the vaulter so that the reward became reachable (e.g., Connolly & Dalgleish, 1989; Steenbergen et al., 1997; van Leeuwen et al., 1994; Wagman & Carello, 2001). This discrepancy creates an ambiguous distinction between piecing together sticks to rake in food versus piecing together sticks to vault oneself to food hanging from the ceiling. Indeed, previous tool use discussions have typically not included examples in which the agent of change was also the object of change, that is, when infants or nonhuman primates use environmental support to make their way from one location to another.

Goals of the Current Study

This research had three primary goals. Our first goal was to extend the classic conceptualization of tool use into a new locomotor task domain. To determine whether infants could demonstrate the hallmarks of tool use, we designed a locomotor task that challenged infants' developing balance control—walking over wide and narrow bridges spanning a deep precipice. On the basis of previous research showing that toddlers respond adaptively to variations in ground surface (e.g., Adolph, 2000; Adolph & Avolio, 2000; Campos, Bertenthal, & Kermoian, 1992; Gibson & Walk, 1960; Richards & Rader, 1981, 1983; Schmuckler, 1996), we expected infants to scale their locomotor responses to bridge width. On narrow bridges they should recognize the discrepancy between their own limited abilities to keep balance and the possibility of walking to the goal.

We included environmental support that could serve as a means to achieve the goal—a handrail was present on some trials for infants to use as a means to navigate the bridges. We reasoned that if infants could recognize the handrail as a means for augmenting balance control, they should ignore the handrail when walking over wide bridges but should notice and use it more frequently to walk over narrow bridges. In addition, we assessed whether means–ends analysis extends to the motor plan itself by observing whether infants update their motor plan by switching from one bridge-crossing strategy to another as they walk over the bridges. By placing a task with such strong cognitive demands in a locomotor context, this work highlights the integrated nature of different developmental domains. Although these domains are traditionally studied separately, success at this kind of task requires the coordination of both cognitive skills and lower level perceptual–motor skills into a plan of action.

Our second goal was to use infants' observable behaviors as a window onto underlying cognitive processes. Previous problem-solving research has been criticized for its inability to demarcate "the activity of planning from the activity of execution of the plan" (Bauer, Schwade, Wewerka, & Delaney, 1999, p. 1336). To address this concern, we examined how infants obtained information for making motor decisions via their exploratory behaviors and collected descriptions of infants' various handrail and bridge-crossing strategies to document how infants figured out how to use the handrail as a tool. We expected that infants would explore more and expend more effort figuring out how to use the handrail on the narrower bridges, where it was more difficult to walk.

Our third goal was to examine sources of individual differences. We kept age constant as a crude control for maturational factors and measured likely sources of individual differences in infants' means–ends problem solving on the basis of locomotor experience (e.g., Adolph, 1997, 2000; Bertenthal et al., 1984; Kingsnorth & Schmuckler, 2000; Schmuckler, 1996), body dimensions (e.g., Adolph & Avolio, 2000), or walking skill (e.g., Adolph, 1995). We also predicted that infants who did not spend time planning their locomotor decision before executing it or take the time to update their motor plan in the face of new information would be less accurate than those who explored the bridge and handrail to make informed decisions.

Experiment 1: Bridges and Handrails

Method

Participants. Twenty-four 16-month-old (± 1 week; $M = 16.03$ months) toddlers participated (12 girls and 12 boys). All could walk 10 feet (3.05 m) across a room without falling. Most infants were White and of middle-class socioeconomic status. All were healthy and born at term. A highly trained experimenter interviewed parents about infants' cruising and walking experience, prior handrail experience (on stairs and playground equipment), and serious falls. Interviewers followed a strict protocol used in previous studies (e.g., Adolph & Avolio, 2000), which involved a series of probing questions regarding dates of events. Parents used "baby books" or calendars to help provide milestone dates. Prior to walking onset, infants' cruising (i.e., walking sideways holding onto furniture) experience ranged from 0 to 5.65 months ($M = 2.76$ months). Infants' walking experience ranged from 0.76 to 6.87 months ($M = 3.89$ months). Eighteen infants had experience using a handrail on the playground or on stairs.

Bridges and handrails. The experimental apparatus was composed of wooden starting (76 cm wide × 106 cm long) and finishing platforms (76 cm wide × 157 cm long) connected by 74-cm-long wooden bridges of various widths (18 cm, 36 cm, 48 cm, and 72 cm). The bridges spanned a 76-cm-deep crevice between the two platforms padded with 13.5 cm of foam. They fit between the two platforms via a tongue-and-groove system and locked into place. When unlocked, they could be pulled out and quickly changed between trials. Lines down the length of the bridges' surface marked 2-cm increments. A 302-cm-long × 13.5-cm-wide × 4-cm-thick handrail could be installed on a permanent support structure on the starting and finishing platforms, creating a continuous handrail spanning the platforms along one side of the bridge (top panel, Figure 1), or the handrail could be removed to create a gap extending the length of the bridge plus 23.5 cm on each end (bottom panel, Figure 1).

Procedure. Each infant was presented with each bridge width three times with a handrail and three times without for a total of 24 trials. Trial order was counterbalanced across six combinations of bridge width and handrail presence (2 boys and 2 girls per order). Trials were blocked into six groups of four. Each block began with the widest (72-cm) bridge to maintain infants' motivation, and the next three trials included each of the other three bridge widths. Two trials in each block were handrail trials, and two were no-handrail trials. Parents called to their babies from the far side

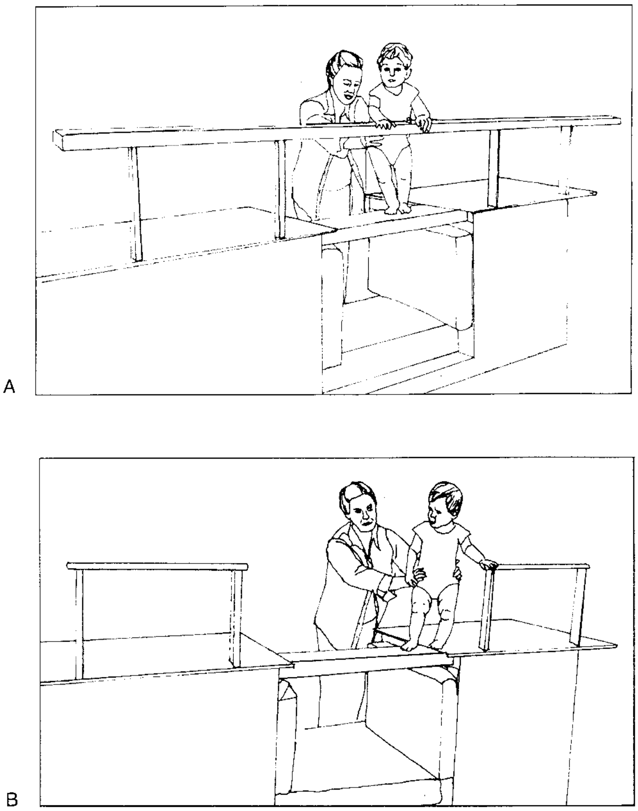

Figure 1. Walkway with adjustable bridge widths and removable handrail. Infants began on the starting platform. Parents (not shown) stood at the far end of the finishing platform, offering encouragement. An experimenter (shown) followed alongside infants to ensure their safety, and the area underneath the bridge was lined with padding. An assistant (not shown) adjusted the bridges in 18-cm (Experiment 1) or 12-cm (Experiment 2) increments. (A) On handrail trials, a handrail spanned the length of the bridge and rested on permanent support posts. (B) On no-handrail trials, the permanent support posts remained on the starting and finishing platforms.

of the landing platform but did not tell children how to cross or caution them to be careful. An experimenter followed alongside infants to ensure their safety if they began to fall. The experimenter ended a trial if the infant did not start onto the bridge within 45 s. The session was videotaped with one camera that panned to provide a view of the baby on the starting platform, bridge, and finishing platform and one ceiling-mounted camera providing an overhead view of the bridge/handrail section of the walkway. Both views were mixed in real time onto a single videotape.

Results and Discussion

Data coding. A primary coder scored outcome measures from video. Based on coding criteria used in earlier studies (e.g., Adolph, 1997), the coder scored trials as *attempts to walk* if infants stepped off the starting platform with both feet on the bridge and as *refusals to walk* if they remained on the starting platform, crawled over the bridge, stepped onto the bridge holding the experimenter's arm, or slid off the starting platform into the crevice. She scored attempted trials as *successful* if infants reached the finishing platform without assistance or as *failures* if they tried to walk but fell or grabbed the experimenter's arm midbridge. She counted *handrail use* on the basis of whether infants touched the handrail after stepping onto the bridge. The coder also scored details of infants' bridge and handrail strategies after embarking onto the bridge to document the components of infants' motor plans (*hand and body positions*, *duration of handrail use*, *walk time*, and *step number*). She scored infants' exploratory behaviors on the starting platform to determine how they decided whether bridges were safe for walking and when to use the handrail (*latency* to begin traversal, *touching* the bridge and handrail support posts, and *shifts* in body position).

A second coder independently scored 25% of trials from each infant. Interrater agreement for categorical measures ranged from 97% to 100%. Correlation coefficients for durations ranged from .98 to 1.00. Discrepancies between coders were resolved through discussion.

Attempts to walk and handrail use. Infants appeared to recognize both the discrepancy between their own ability and the likelihood of reaching the goal and that the handrail could augment their physical ability. All infants attempted to walk over the three wider bridges regardless of handrail presence, but they were more likely to walk over the narrow 18-cm bridge when a handrail was available and more likely to avoid it when a handrail was not available (see Table 1, Row 1, and Figure 2A, Experiment 1). A 4 (bridge width) × 2 (handrail presence) repeated measures analysis of variance (ANOVA) on attempts to walk revealed main effects for bridge width, $F(3, 69) = 33.59$, $p < .01$, and handrail presence, $F(1, 23) = 13.32$, $p < .01$, and an interaction between the two factors, $F(3, 69) = 9.47$, $p < .01$. Planned comparisons between handrail and no-handrail trials at each bridge width showed significant differences in attempts only on the 18-cm bridge, with more attempts in the handrail condition, $t(23) = 3.50$, $p < .01$.

Infants' handrail use increased on narrower bridges, suggesting that they were aware of the handrail and that they recognized it as a means for augmenting balance control (see Table 1, Row 5, and Figure 2B, Experiment 1). On narrower bridges, infants were more likely to hold on with both hands than with only one hand, and they were more likely to hold onto the handrail for longer periods of time before they moved forward along the bridge (see Table 1, Rows 6 and 7). Repeated measures ANOVAs on the proportion of trials on which infants used the handrail, on the number of hands with which infants held the handrail, and on the duration of their first handrail touch at each of the four bridge widths showed main effects for bridge width: $F(3, 69) = 55.79$, $p < .01$; $F(3, 69) = 57.39$, $p < .01$; and $F(3, 69) = 10.69$, $p < .01$, respectively. Infants who used the handrail were more successful at walking over the 18-cm bridge ($r = .56$, $p < .01$).

Overall, infants were very accurate in judging their abilities to walk over bridges. Only 6% of trials were failures, most of which occurred on the narrowest (18-cm) bridge (see Table 1, Row 2). Although 16 children failed at least once, there was no evidence of within-session learning; failures were split equally between the first and second halves of the session ($p > .10$). Furthermore, there was no evidence that infants were more hesitant to cross on trials immediately following one on which they failed: They refused to walk on 8% of trials following trials on which they fell and on 11.5% of trials following trials on which they crossed successfully.

On wide bridges, infants walked normally, but on narrow ones, they modified their gait to walk successfully. On some walk trials, infants took more than 25 baby steps and longer than 30 s to reach the finishing platform (see Table 1, Rows 3 and 4). Repeated measures ANOVAs testing the effect of bridge width on step number and time to cross the bridge could not be performed because some infants contributed no gait data at the narrowest bridges. Planned comparisons at each bridge width, comparing infants' walk time with a handrail and without, revealed no statistically significant differences. That is, the time infants took to walk across the bridges depended on the width of the bridge but not on the presence of the handrail.

In addition to modifying step length and step number, infants devised other ingenious strategies to navigate the narrowest (18-cm) bridge. Sometimes they turned sideways (33% of trials; number of children = 18), took a giant step when they neared the end of the bridge (22% of trials; $n = 17$), crawled over the bridge (3% of trials; $n = 3$), or grabbed the experimenter's arm or shoulder (5% of trials; $n = 7$). They used the handrail by facing forward and holding the rail with one hand (51% of handrail trials; $n = 20$), facing the rail and holding it with two hands (45% of handrail trials; $n = 14$), and—most surprising—one child turned her back to the rail and held on with her hands behind her back (3% of handrail trials; $n = 1$).

On 15% of all trials, 23 infants began traversing the bridge using one method, then updated their plan by switching to another method midbridge. On 74% of trials in which infants switched locomotor methods, they went from a more difficult strategy to a more effective one for walking over narrow bridges. For example, they started out walking forward, but then crawled or walked sideways the rest of the way across, or they started out holding onto the rail with one hand before grabbing on with both hands. If infants had only been trying out different possible strategies without attempting to make their progress more effective, then the order in which strategies were performed would have been random. However, because they generally started out with their typical strategies and then refined them, it appears that infants updated their locomotor plans as they realized that their current method would decrease their chances of crossing safely.

Exploratory behaviors. We considered behaviors to be exploratory only while infants were still on the starting platform before

Table 1

Experiment 1: Mean Values of Toddlers' Behaviors on Bridges With and Without Handrails

	With handrail								Without handrail							
	18 cm		36 cm		54 cm		72 cm		18 cm		36 cm		54 cm		72 cm	
Behavior	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Walking																
1. Attempts to walk (prop. of trials)^{a,*,**,†}	.71	.40	1.00		1.00		1.00		.43	.41	.94	.16	.99	.07	1.00	
2. Failed attempts (prop. of trials)^{b,*}	.29	.37	.01	.07	0		0		.42	.44	.08	.18	0		0	
3. Walk time (s)^{b,*}	9.07	6.42	2.54	1.38	1.59	0.77	1.30	0.33	6.59	4.48	2.92	2.50	1.53	0.64	1.32	0.37
4. Mean number of steps taken^{b,*}	12.09	4.83	7.11	2.18	5.60	1.08	5.25	0.61	11.50	5.11	7.56	2.66	5.57	1.18	5.32	0.73
Handrail																
5. Handrail use (prop. of trials)^{c,*}	.86	.31	.72	.34	.25	.32	.07	.17								
6. Mean number of hands on rail^{c,*}	1.57	0.43	1.06	0.22	1.00		1.00									
7. Duration of first touch (s)^{d,*}	5.03	3.69	1.63	1.35	0.96	0.86	0.58	0.51								
Exploration																
8. Latency (s)^{a,*,**,†}	20.51	14.67	4.03	1.79	2.59	0.87	2.30	0.78	29.49	15.88	7.77	7.60	3.48	3.08	2.37	0.75
9. Bridge exploration (prop. of trials)^{a,*,**,†}	.51	.35	.10	.18	.01	.07	0		.51	.35	.24	.35	.04	.11	0	
10. Rail/post exploration (prop. of trials)^{a,*,**,†}	.74	.33	.44	.38	.15	.22	.04	.11	.54	.34	.25	.34	.11	.23	.01	.07
11. Mean number of position shifts^{a,*,**,†}	1.01	0.86	0.04	0.15	0		0		1.07	1.06	0.19	0.42	0.07	0.34	0	

Note. prop. = proportion.

[a] Calculated for all trials. [b] Calculated for all attempted trials. [c] Calculated for all handrail available trials. [d] Calculated for all handrail used trials.

* Significant main effect for bridge width, all p values $< .01$. ** Significant main effect for handrail presence, all p values $< .01$. † Significant interaction between bridge width and handrail presence, all p values $< .04$.

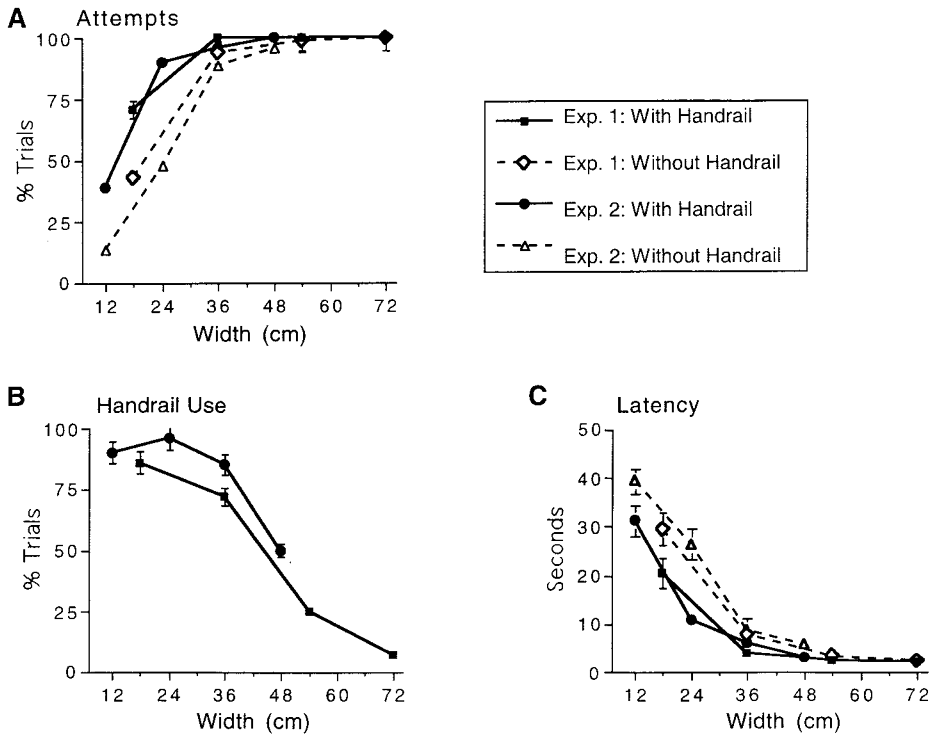

Figure 2. Experiments 1 (Exp. 1) and 2 (Exp. 2): effects of bridge width and handrail presence on infants' locomotor decisions. A: infants' attempts to walk over bridges. B: the proportion of trials when the handrail was used on each bridge width (calculated only for trials in which a handrail was available). C: latency to embark onto the bridge.

they stepped onto the bridge. Infants' latency to leave the starting platform increased sharply on the 18-cm bridge, especially on trials with no handrail (see Table 1, Row 8, and Figure 2C, Experiment 1). A 4 (bridge width) × 2 (handrail presence) repeated measures ANOVA showed main effects for bridge width, $F(3, 69) = 61.72$, $p < .01$, and handrail presence, $F(1, 23) = 11.03$, $p < .01$, and an interaction between the two, $F(3, 69) = 6.40$, $p = .01$. Planned comparisons between handrail and no-handrail trials at each bridge width showed significant differences in latency between the handrail and the no-handrail conditions only on the 18- and 36-cm bridges, $t(23) = 3.01$, $p < .01$, and $t(23) = 2.32$, $p < .03$, respectively. Latency was longer when the handrail was not available, suggesting that infants required more time to figure out how to reach their goal when walking was most difficult.

During the time that infants hesitated, they were not simply standing still and avoiding the bridge. Rather, they actively gathered information by touching the bridges and/or the section of the handrail or supporting post that spanned the starting platform (see Table 1, Rows 9 and 10). Infants touched bridges by probing the surface with one foot or by bending down and pressing it with their hands. A 4 (bridge width) × 2 (handrail presence) repeated measures ANOVA on the proportion of trials in which infants touched the bridge revealed only a main effect for bridge width, $F(3, 69) = 47.44$, $p < .01$. A post hoc Scheffé test with a significance level of .05 revealed that infants explored the 18-cm bridge width on a significantly greater proportion of trials than they explored all other bridge widths. Furthermore, infants explored significantly more often on the 36-cm bridge than on the 72-cm bridge.

Infants touched the handrail or supporting post by gripping or patting it. Because exploratory behaviors were coded only while infants were on the starting platform, it was possible to code handrail exploration even when the handrail was not spanning the bridge. Permanent posts built into the walkway to support the handrail allowed infants to test whether they needed support to keep balance as they stepped onto the bridge, even on no-handrail trials (see Figure 1B). For example, when only the supporting post was available, they sometimes held it while stretching one foot out as far as they could onto the bridge to test whether they could hold on and embark. Thus, we were able to code handrail/post exploration for all trials, regardless of handrail presence. A repeated measures ANOVA on touching the handrail/support post before stepping onto the bridge revealed main effects for bridge width, $F(3, 69) = 51.75$, $p < .01$, and handrail presence, $F(1, 23) = 11.50$, $p < .01$, and an interaction between the two variables, $F(3, 69) = 2.64$, $p = .05$. Planned comparisons between handrail and no-handrail trials showed increased touching of the supporting posts in the handrail condition on the 18-cm bridge, $t(23) = 2.70$, $p < .02$. A post hoc Scheffé test at the .05 significance level revealed that babies explored the handrail significantly more often on the 18-cm bridge than on all other bridge widths. Additionally, babies explored significantly more often on the 36-cm bridge than on the 72-cm and 54-cm widths. If babies had only reached for the handrail after they were already on the bridge, we might infer that they were simply reacting to being stuck in a precarious situation. However, the fact that they touched the handrail or supporting post before stepping onto the narrow bridges suggests that they recognized the environmental support as a tool to augment their balance.

Before stepping onto narrow bridges, infants frequently shifted their body positions to determine the best way to embark or to gather additional information (see Table 1, Row 11). They sometimes turned sideways to use the handrail, bent down to touch the bridges with their hands, or shifted from upright to other positions to test alternative methods of traversal. A 4 (bridge width) × 2 (handrail presence) repeated measures ANOVA on number of shifts in body position revealed only a main effect for bridge width, $F(3, 69) = 38.98$, $p < .01$. A post hoc Scheffé test at the .05 significance level revealed that babies shifted their body positions significantly more often on the 18-cm bridge than on any of the other bridge widths.

Individual differences. What distinguished the infants who displayed accurate judgments from those whose decisions were inaccurate? Because nearly all failures occurred on the 18-cm bridge, we analyzed potential sources of individual differences in infants' failure rate (the proportion of each infant's trials that were coded as failures) on the narrowest bridge. Previous studies have found that infants' locomotor experience (e.g., Adolph, 1997, 2000; Bertenthal et al., 1984; Kingsnorth & Schmuckler, 2000; Schmuckler, 1996), locomotor skill (e.g., Adolph, 1995), and body dimensions (e.g., Adolph & Avolio, 2000) predicted the adaptiveness of their responses in novel locomotor tasks. For the current study, parents' reports of infants' walking experience, prior handrail experience, and serious falls were not related to any of the behaviors that we coded on the narrowest (18-cm) bridge (i.e., attempts, successes, exploration). Possibly, walking experience was unrelated to bridge performance because infants were not pushed to their physical limits; even on the narrowest (18-cm) bridge, infants were proficient enough to cross successfully on more than half of the trials. Infants' body dimensions (height, weight, head circumference, shoulder width, and arm and leg lengths) and walking skill on solid ground (step velocity and step length) were also not related to their failure rate on the narrowest bridge, suggesting that the problem was not having a body too clumsy or too large to fit on the bridge.

The cause of failure appeared to depend in part on infants' ability to integrate information into an effective plan of action and to update their locomotor plans in accordance with new information. Lower levels of exploration were associated with higher failure rates in bridge crossing, suggesting that infants who neglected to gather information before deciding to cross were more likely to fail. Longer latencies and frequent shifts in body position predicted higher rates of success ($r = -.68$, $p < .01$, and $r = -.48$, $p < .02$, respectively). Moreover, of the 82 trials on which infants attempted to cross the 18-cm bridge, the failure rate was lower (23%) on trials where infants updated their locomotor plans (switched strategies midbridge) than on trials where infants never switched strategies (60%). There was no correlation between failure rate and the average number of times infants switched strategies on the bridge ($r = .10$, *ns*), suggesting that falling off the bridge did not preclude infants from switching. Rather, not knowing to update their strategies for crossing the bridge prevented infants from crossing successfully.

Infants' handrail use on attempted handrail trials was also related to their exploratory behaviors. When stepwise multiple regression was used, bridge width significantly predicted handrail use when it was entered into the equation first ($R^2 = .65$), $F(1, 90) = 170.08$, $p < .01$. On the next step, the proportion of trials on which infants explored the handrail before stepping onto the bridge explained significant additional variance ($R^2 = .73$), $F(2, 89) = 119.91$, $p < .01$. Therefore, infants who knew to explore the handrail before stepping onto the walkway were more likely to use it for assistance. Experience with handrails prior to visiting the laboratory was not associated with handrail use ($r = .17$, *ns*).

Summary

In sum, infants showed sophisticated means–ends problem solving behavior. They recognized the limits of their own abilities (i.e., they scaled walking attempts to bridge width), they noticed the availability of the handrail to augment their abilities (as shown by exploratory touching of the handrail while on the starting platform), and they perceived the relationship between themselves and the rail (as demonstrated by the interaction between bridge width and handrail condition). Infants' use of the handrail was toollike in these experiments because infants recognized that when their ability to walk across narrow bridges was limited, the handrail could assist them by extending their motor skill. Infants used the handrail to achieve goals that would have been impossible otherwise. Infants' recognition of the handrail as a tool appeared to result from direct, concerted exploration, both within and across trials. When bridge widths were wide enough that a handrail was unnecessary for successful crossing, prolonged exploration was infrequent. However, in more precarious situations, when infants needed to use the handrail for success, they appeared to figure out the role of the handrail in real time using information they obtained through active exploration. Infants explored the bridge and handrail before stepping onto bridges, constructed various strategies for using the handrail to cross the bridges, and modified handrail and crossing strategies midbridge. Higher levels of exploration predicted infants' success at walking over the narrowest bridge.

In the next experiment, we tested infants with narrower bridge widths, ranging from 12 cm to 48 cm. Our aim was to examine whether more infants would show differential use of the handrail to walk over narrower bridges and whether they could recognize that some bridges are too narrow for walking even with the help of a handrail.

Experiment 2: Narrower Bridges and Handrails

Method

Twenty-four healthy, term 16-month-olds (± 1 week; $M = 16.08$ months) participated (12 girls and 12 boys). All could walk 10 feet across a room without falling. Most infants were White and of middle-class socioeconomic status. Parents were interviewed about the same information and using the same protocol described in Experiment 1. Prior to walking onset, infants' cruising experience ranged from 0 to 6.71 months ($M = 2.70$ months). Walking experience ranged from 0.89 to 7.10 months ($M = 4.30$ months). Twenty-one infants had experience using a handrail on the playground or on stairs. We tested babies on the same walkway apparatus as in Experiment 1 with four bridge widths (12 cm, 24 cm, 36 cm, and 48 cm wide). The 36-cm width replicated an increment from the first experiment, allowing direct comparisons between the studies.

Results and Discussion

Data coding. A primary coder scored all outcome measures from video as in Experiment 1. A second coder independently scored 25% of the trials from each infant. Interrater agreement for categorical measures ranged from 96% to 100%. Correlation coefficients for measures of duration ranged from .99 to 1.00. Discrepancies between coders were resolved through discussion.

Attempts to walk and handrail use. As predicted, narrower bridge widths elicited fewer attempts to walk and more frequent handrail use. As in Experiment 1, infants attempted to walk over wider bridges regardless of handrail presence but attempted the narrower bridges more often when the handrail was present (see Table 2, Row 1, and Figure 2A, Experiment 2). Without a handrail, 19 infants refused to walk over the 12-cm bridge on every trial, 8 refused all 24-cm bridge trials, and 2 refused all 36-cm bridge trials. A 4 (bridge width) × 2 (handrail presence) repeated measures ANOVA revealed main effects for bridge width, $F(3, 69) = 84.13$, $p < .01$, and handrail presence, $F(1, 23) = 21.97$, $p < .01$, and an interaction between the two factors, $F(3, 69) = 8.90$, $p < .01$. Planned comparisons at each bridge width showed significant differences between handrail and no-handrail trials, with more attempts in the handrail condition only on the 12-cm and 24-cm bridges, $t(23) = 3.00$, $p < .01$, and $t(23) = 4.81$, $p < .01$, respectively.

Infants used the handrail more often, held the rail with two hands, and held the rail for longer periods of time on narrower bridges (see Table 2, Rows 5, 6, and 7, and Figure 2B, Experiment 2). Repeated measures ANOVAs on proportion of trials on which the handrail was used, number of hands used to hold on, and duration of first touch of the handrail at each of the four bridge widths revealed main effects for bridge width, $F(3, 69) = 20.66$, $p < .01$; $F(3, 69) = 41.99$, $p < .01$; and $F(3, 48) = 20.26$, $p < .01$, respectively.[1] A post hoc Scheffé test at the .05 significance level revealed significant differences between handrail use at the 48-cm bridge and all other bridge widths, with infants using the handrail less often on the wide bridge.

As in the previous study, infants accurately judged their abilities to walk over bridges. Failures occurred on only 6% of trials and were relegated primarily to the narrowest (12-cm) bridge (see Table 2, Row 2). As in Experiment 1, failures were split evenly between infants' first 12 and second 12 trials, and infants showed no wariness on trials immediately following trials on which they failed. On successful trials, infants modified their gait on narrower bridges by increasing walk time and step number (see Table 2, Rows 3 and 4). Again, planned comparisons revealed no significant differences between the time it took infants to walk at each bridge width with a handrail and without a handrail.

Exploratory behaviors. As in Experiment 1, infants hesitated longer on the narrower bridges, especially in the no-handrail condition (see Table 2, Row 8, and Figure 2C, Experiment 2). A 4 (bridge width) × 2 (handrail presence) repeated measures ANOVA on latency to embark showed main effects for bridge width, $F(3, 69) = 98.67$, $p < .01$, and handrail presence, $F(1, 23) = 24.36$, $p < .01$, and an interaction between the two, $F(3, 69) = 8.80$, $p < .01$. Planned comparisons at each bridge width between handrail and no-handrail trials showed longer latencies in the no-handrail condition only at 12-cm and 24-cm widths: $t(23) = 3.03$, $p < .01$, and $t(23) = 5.01$, $p < .01$, respectively.

Before stepping onto bridges, infants gathered information by touching the bridge with their hands or feet (see Table 2, Row 9). A 4 (bridge width) × 2 (handrail presence) repeated measures ANOVA revealed main effects for bridge width, $F(3, 69) = 14.66$, $p < .01$, and handrail presence, $F(1, 23) = 5.04$, $p < .04$, and an interaction between the two, $F(3, 69) = 6.78$, $p < .01$. Unlike in Experiment 1, however, planned comparisons between handrail and no-handrail conditions showed more bridge touching when the handrail was unavailable at 24 cm, as if to figure out how to cross the bridge without assistance: $t(23) = 2.87$, $p < .01$. Exploration of the 12-cm bridge did not depend on handrail presence because it was difficult to walk regardless of handrail availability. A post hoc Scheffé test at the .05 significance level revealed that infants touched the two narrower bridges (12 cm and 24 cm) significantly more often than they touched the two wider bridges (36 cm and 48 cm). Infants also touched the handrail prior to stepping onto the bridges (see Table 2, Row 10). A 4 (bridge width) × 2 (handrail presence) repeated measures ANOVA revealed only main effects for bridge width, $F(3, 69) = 54.60$, $p < .01$, and handrail presence, $F(1, 23) = 5.15$, $p < .04$. A post hoc Scheffé test at the .05 significance level revealed that infants explored the handrail significantly less often on the 48-cm bridge than on each of the three narrower bridges. In addition, infants explored the handrail significantly more often on the 12-cm bridge than they did on the 36-cm bridge.

Infants executed more shifts in body position (2–3, on average) in this experiment compared with the last one (1–2) (see Table 2, Row 11). A 4 (bridge width) × 2 (handrail presence) repeated measures ANOVA on the number of times infants shifted body position before embarking revealed main effects for bridge width, $F(3, 69) = 64.22$, $p < .01$, and handrail, $F(1, 23) = 10.41$, $p < .01$, and an interaction between the two factors, $F(3, 69) = 3.53$, $p < .02$. Planned comparisons at each bridge width between handrail and no-handrail trials showed more body shifts in the no-handrail condition only for the 12-cm and 24-cm bridges, $t(23) = 2.55$, $p < .02$, and $t(23) = 2.34$, $p < .03$, respectively. A post hoc Scheffé test at the .05 significance level revealed that the number of times infants shifted their position was significantly greater on the 12-cm bridge than on all others. Furthermore, infants shifted their body position significantly more often on the 24-cm bridge than they did on the 48-cm or 36-cm bridges.

Individual differences. We analyzed potential sources of individual differences in infants' rate of failing on the 12-cm and 24-cm bridges. As in Experiment 1, locomotor experience, handrail experience, and body dimensions were not related to failures on the narrow bridges. However, in contrast to Experiment 1, locomotor skill was predictive of infants' attempts to walk. Infants who walked faster and took longer steps on solid ground were more likely to attempt to walk over the narrowest bridges than poorer walkers ($r = .59$, $p < .01$, and $r = .78$, $p < .01$, respec-

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[1] Degrees of freedom in the analysis for duration of first handrail touch reflect only the subset of handrail trials in which the handrail was actually used. The other analyses of handrail use were based on proportions of behaviors of all handrail trials.

Table 2

Experiment 2: Mean Values of Toddlers' Behaviors on Bridges With and Without Handrails

	With handrail								Without handrail							
	12 cm		24 cm		36 cm		48 cm		12 cm		24 cm		36 cm		48 cm	
Behavior	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Walking																
1. Attempts to walk (prop. of trials)[a,*,**,†]	.39	.41	.90	.18	.96	.11	1.00		.14	.29	.48	.40	.89	.29	.96	.11
2. Failed attempts (prop. of trials)[b,*]	.46	.48	.09	.19	.01	.07	0		1.00		.17	.29	.02	.07	.02	.10
3. Walk time (s)[b,*]	31.23	19.90	8.24	9.09	2.94	1.57	2.08	1.16			5.22	5.37	3.33	2.78	2.37	1.83
4. Mean number of steps taken[b,*]	21.56	4.53	12.73	6.36	7.41	1.93	6.40	1.86			10.68	4.66	7.95	2.77	6.95	2.17
Handrail																
5. Handrail use (prop. of trials)[c,*]	.93	.17	.96	.11	.85	.23	.50	.41								
6. Mean number of hands on rail[c,*]	1.67	0.40	1.47	0.41	1.13	0.25	1.06	0.30								
7. Duration of first touch (s)[d,*]	5.23	3.70	2.47	1.53	1.36	1.21	0.90	0.60								
Exploration																
8. Latency (s)[a,*,**,†]	31.19	15.51	10.63	8.20	6.10	6.15	3.15	1.65	39.27	12.37	26.47	15.70	8.70	12.60	5.77	5.56
9. Bridge exploration (prop. of trials)[a,*,**,†]	.57	.39	.33	.35	.15	.24	.04	.15	.47	.38	.60	.37	.26	.34	.11	.25
10. Rail/post exploration (prop. of trials)[a,*,**]	.86	.22	.67	.42	.58	.38	.24	.29	.82	.29	.61	.36	.31	.39	.17	.32
11. Mean number of position shifts[a,*,**,†]	1.96	1.04	0.73	0.65	0.28	0.45	0.07	0.34	2.64	1.52	1.27	1.09	0.33	0.61	0.08	0.28

Note. prop. = proportion.

[a] Calculated for all trials. [b] Calculated for all attempted trials. [c] Calculated for all handrail available trials. [d] Calculated for all handrail used trials.

* Significant main effect for bridge width, all *p* values < .01. ** Significant main effect for handrail presence, all *p* values < .01. † Significant interaction between bridge width and handrail presence, all *p* values < .04.

tively). Furthermore, failure was correlated with poor walking skill ($r = -.43$, $p < .04$, and $r = -.51$, $p < .02$, for step time and step length respectively). The discrepancy between correlates of infants' performance in the two experiments is likely due to the greater sensitivity of Experiment 2. Walking over narrower bridges was physically more difficult, so that smaller differences in motor proficiency between subjects may not have been captured until the bridge widths were made more narrow. Apparently, infants took their own level of skill into account when planning a course of action that involved some risk and when determining whether to augment their abilities via alternative means (i.e., the handrail).

As in Experiment 1, lower levels of exploration were associated with increased rates of failure on the 12-cm and 24-cm bridges, suggesting that infants who did not gather information about environmental supports for action made less accurate decisions than children who spent time exploring. Failures on the 12-cm bridge were associated with shorter latencies ($r = -.84$, $p < .01$), less frequent shifts in body position ($r = -.47$, $p < .02$), and less exploratory touching of the handrail ($r = -.49$, $p < .02$). Failures on the 24-cm bridge were associated only with shorter latencies ($r = -.44$, $p < .04$). As in Experiment 1, the ability to update a locomotor plan predicted a lower failure rate on narrow bridges. On trials when infants attempted to cross the 12-cm (number of trials = 38; strategy data missing for 2 trials) and 24-cm (number of trials = 99; strategy data missing for 1 trial) bridges, there was a lower failure rate when infants updated their locomotor plans. One hundred percent of the 12-cm bridge trials on which infants did not update their crossing or handrail strategies resulted in failures. In contrast, only 32% of trials on which infants changed their strategies resulted in failed attempts. Similarly, on the 24-cm bridge, trials on which infants did not update their strategies resulted in failures more often (22%) than trials on which infants did update (5%).

When stepwise multiple regression was used, exploratory behaviors again predicted handrail use on attempted handrail trials. When bridge width was entered into the equation first, it accounted for a significant proportion of the variance of handrail use ($R^2 = .34$), $F(1, 83) = 43.15$, $p < .01$. On the next step, the proportion of trials on which infants explored the handrail before stepping onto the bridge was entered. Exploring the handrail before attempting to cross the bridge explained significant additional variance ($R^2 = .44$), $F(2, 82) = 32.76$, $p < .01$. Experience with handrails prior to visiting the laboratory was not associated with handrail use ($r = .28$, *ns*).

Overlaying the data figures from the two experiments (see Figure 2) illustrates that infants' responses were scaled neatly across experiments. On every primary outcome measure, infants treated the 36-cm bridge width common to both studies similarly. In both studies, infants were less likely to walk and more likely to use the handrail on narrower bridges.

General Discussion

Adaptive locomotion is not simply a matter of muscles, biomechanics, and lower level perceptual–motor skills. In two experiments we demonstrated that adaptive locomotion can involve higher level cognitive abilities—namely a sophisticated form of means–ends problem solving. We encouraged 16-month-old infants to walk over wide and narrow bridges in the presence or absence of a handrail. On the wide bridges, infants always attempted to walk regardless of whether the handrail was available, they rarely touched the handrail while crossing when it was available, they did not modify their gait to walk over the bridges, and exploratory activity on the starting platform was minimal. In contrast, on the narrow bridges, infants attempted to walk more often when the handrail was available than when it was absent, they used the handrail more often while crossing when it was available, they modified their gait by taking smaller, slower steps, and they spent more time on the starting platform exploring the handrail/posts and the bridges. These findings suggest that infants recognized the handrail as a means for augmenting their balance control in a precarious situation. That is, they viewed the handrail as a structure in the environment, separate from themselves, and separate from the bridges, which could be used as an intervening step to achieve the goal of crossing to the landing platform. Moreover, infants adopted multiple strategies for using the handrail successfully and updated their motor plan as they walked over the bridges by switching from less to more efficient strategies (e.g., from walking frontward to facing sideways while holding the rail), suggesting that their means–ends analysis extends to the motor plan itself. Thus, infants' handrail use was not simply a result of finding themselves stranded on a bridge but rather a central component of a planful attempt to reach a goal.

A primary aim of this research was to extend the classic conceptualization of tool use into a new locomotor task domain. By doing so, we attempted to clarify our understanding of the literature's central constructs, specifically, the constraints placed on the types of implements that are typically classified as tools and the types of behaviors that are considered tool use. To what extent is the means–ends problem solving demonstrated by infants in the bridges/handrails studies an example of tool use? Or put more broadly, is using a handrail to walk over bridges, down stairs, or along icy pavement an example of bona fide tool use, the pinnacle of means–ends problem solving? Is a crutch a tool? What about a blind person's cane or an elderly person's wheeled walker?

Traditionally, tool use has connoted an actor's manipulation of one object upon another, such as a hammer hitting a nail, or a hook pulling an out-of-reach object closer (e.g., Bates et al., 1980; Brown, 1990; McCarty et al., 2001). Tradition, however, does not provide a satisfactory rubric for understanding what should and should not count as a tool. On Parker and Gibson's (1977) more restrictive definition, intentionally augmenting one's abilities via a handrail, crutch, cane, walker, or pole vault would likely not be considered an example of tool use because the means are not freely mobile extensions of the actor's body. On others' less restrictive definitions (e.g., Connolly & Dalgleish, 1989; van Leeuwen et al., 1994; Wagman & Carello, 2001), handrails and other objects used to augment balance and locomotion might be considered examples of tool use because they restructure the relationship between the actor and the environment to facilitate the completion of an action.

Like scientific traditions, definitions and criteria are useful only when they include and exclude the appropriate phenomena. On the one hand, the data from the current studies suggest that Parker and Gibson's (1977) definition may be overly narrow. Infants' elaborate, systematic, and prospective exploration of the bridges and handrail and their discovery of appropriate strategies for using the handrail suggest that their cognitive understanding surpasses that of monkeys who throw nuts at the hard ground to crack them open.

On the other hand, the data from the current studies suggest that the less restrictive definitions might be overly inclusive. For example, on the less restrictive definitions, the bridges spanning the precipice and the experimenter spotting the infants—and similarly in other contexts, wheelchairs, wheelchair ramps, ladders, stairs, step stools, cleats, and so on—might be considered examples of tools because they augment actors' bodily abilities by enabling new affordances for action.

Like earlier investigators, we propose that the critical essence of tool use concerns its function and the underlying cognitive mechanisms. At its most fundamental level, the function of a tool is to enable the completion of a task that could not be accomplished otherwise. The heart of tool use is the cognitive understanding that an object external to oneself can serve as a means for connecting oneself to an otherwise unattainable goal, not simply the behavioral incorporation of an external object into a sequence of actions (McCarty et al., 2001). We suggest that the current studies offer a fresh approach to the problem of evaluating means–ends problem solving in terms of tool use: to observe participants in nontraditional tasks, gather rich descriptions of participants' exploratory behaviors and action strategies, and then assess the behavioral evidence on a case-by-case basis for the functional and cognitive hallmarks of tool use (Adolph & Lockman, 2002).

The second goal of this research was to examine individual differences in infants' performance as a way of identifying developmental and behavioral correlates of means–ends problem solving. With our age-held-constant design, we could examine walking experience, prior exposure to handrails on stairs and playground equipment, walking skill on flat ground, body dimensions, and real-time exploratory behaviors as predictors of success in the bridges/handrails task. In contrast to previous work (e.g., Adolph, 1997; Adolph & Avolio, 2000; Kingsnorth & Schmuckler, 2000), infants' locomotor experience and body dimensions were not predictive of performance. As in previous studies (e.g., Adolph, 1995), when the task pushed the limits of toddlers' physical abilities, their motor skill predicted their performance (i.e., walking skill on flat ground predicted success at crossing the narrowest 12-cm bridges). Consistent with previous studies (e.g., Adolph, 1995; Gibson et al., 1987), the most important predictor of success on this task was infants' real-time exploratory behaviors, selection of locomotor strategies, and updating of strategies midbridge. Exploration of the handrail significantly predicted its use, lack of exploration was significantly associated with failing, and choosing an effective locomotor strategy was related to successful bridge crossing. Apparently, the gathering of crucial information, the ability to understand and integrate the information into an effective plan of action, and the adoption of appropriate strategies were the most critical factors for means–ends problem solving. Thus, cognitive and perceptual–motor factors together determine the difficulty of a task, which in turn fluctuates according to continuously developing cognitive and locomotor systems.

The third goal of this research was to examine the processes underlying infants' invention, coordination, and execution of their locomotor plans. Whereas manual means–ends tasks have often lacked behavioral evidence for the underlying cognitive processes that they purport to measure, the current locomotor task provided a rich source of evidence concerning the processes underlying means–ends problem solving in infancy. For example, the sight of the narrow bridges elicited concerted visual and haptic exploration as infants assessed the likelihood of crossing the bridge successfully. On trials in which they did eventually walk, infants took the narrower bridge width into account by modifying their gait patterns. On trials in which they did not eventually walk, infants searched for alternative means of crossing by exploring the handrail and testing various locomotor positions. After discovering viable alternatives, infants reassessed the likelihood of crossing successfully by holding onto the handrail and stepping partway onto the bridge prior to leaving the starting platform or by executing a long first touch prior to beginning movement along the bridge. While crossing, infants continued to consider the effectiveness of their strategy, as evidenced by changes in strategy midbridge.

All of infants' observed behaviors—their exploratory behaviors, gait modifications, crossing strategies, and handrail use—helped to delineate the planning and execution components of general problem solving. After initially evaluating a goal as being unattainable (i.e., crossing the overly narrow bridge), infants subsequently reevaluate the goal as being attainable via the discovered means (i.e., the handrail). The search for and discovery of new means is prompted by the impasse between a desire to reach the goal and an inability to do so using typical methods. Adaptive locomotion may require infants to decide at each new locomotor situation whether walking is possible, but after deciding that a goal is currently unattainable, they should be able to fall back on an alternative strategy or tool that they have used in previous trials or similar contexts (Adolph, 1997). Indeed, the pattern of infants' behaviors in the current study—systematic, organized, intentional, and flexible with respect to bridge width and handrail presence—suggests true strategy use as defined in classic instances of children's problem solving, such as reading, mathematics, memory, and so forth (Bjorklund, 1990).

Thus, the development of adaptive locomotion may involve higher level cognitive changes that improve infants' ability to assess possibilities for locomotion and to discover new means and incorporate them into a plan of action, as well as concurrent lower level perceptual–motor changes that introduce new possibilities for locomotion and more finely honed exploratory movements. As Campos and colleagues (2000) so aptly pointed out, infants' travels may help to broaden their minds; reciprocally, we have tried to show that infants' minds may enrich their travels.

References

Adolph, K. E. (1995). A psychophysical assessment of toddlers' ability to cope with slopes. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 734–750.

Adolph, K. E. (1997). Learning in the development of infant locomotion. *Monographs of the Society for Research in Child Development, 62*(3, Serial No. 251).

Adolph, K. E. (2000). Specificity of learning: Why infants fall over a veritable cliff. *Psychological Science, 2,* 290–295.

Adolph, K. E., & Avolio, A. (2000). Walking infants adapt locomotion to changing body dimensions. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 1148–1166.

Adolph, K. E., Eppler, M. A., Marin, L., Weise, I. B., & Clearfield, M. W. (2000). Exploration in the service of prospective control. *Infant Behavior and Development: Special Issue on Perception-Action Coupling, 23,* 441–460.

Adolph, K. E., & Lockman, J. J. (2002, April). *How tools expand the* *potential for action: Hands, handles and handrails.* Symposium conducted at the International Conference on Infant Studies, Toronto, Ontario, Canada.

Adolph, K. E., Vereijken, B., & Denny, M. A. (1998). Learning to crawl. *Child Development, 69,* 1299–1312.

Bates, E., Carlson-Luden, V., & Bretherton, I. (1980). Perceptual aspects of tool using in infancy. *Infant Behavior and Development, 3,* 127–140.

Bauer, P. J., Schwade, J. A., Wewerka, S. S., & Delaney, K. (1999). Planning ahead: Goal-directed problem solving by 2-year-olds. *Developmental Psychology, 35,* 1321–1337.

Bertenthal, B. I., Campos, J. J., & Barrett, K. C. (1984). Self-produced locomotion: An organizer of emotional, cognitive, and social development in infancy. In R. Emde & R. Harmon (Eds.), *Continuities and discontinuities in development* (pp. 175–210). New York: Plenum.

Bjorklund, D. F. (Ed.). (1990). *Children's strategies: Contemporary views of cognitive development.* Hillsdale, NJ: Erlbaum.

Bremner, J. G. (1993). Motor abilities as causal agents in infant cognitive development. In G. J. P. Savelsbergh (Ed.), *The development of coordination in infancy* (pp. 47–77). Amsterdam: North-Holland/Elsevier Science.

Bremner, J. G., & Bryant, P. E. (1977). Place versus response as the basis of spatial errors made by young infants. *Journal of Experimental Child Psychology, 23,* 162–171.

Bril, B., & Breniere, Y. (1993). Posture and independent locomotion in early childhood: Learning to walk or learning dynamic postural control? In G. J. P. Savelsbergh (Ed.), *The development of coordination in infancy* (pp. 337–358). Amsterdam: North-Holland/Elsevier Science.

Brown, A. (1990). Domain specific principles affect learning and transfer in children. *Cognitive Science, 14,* 107–133.

Bushnell, E. W., & Boudreau, J. P. (1998). Exploring and exploiting objects with the hands during infancy. In K. J. Connolly (Ed.), *The psychobiology of the hand* (pp. 144–161). London: Mac Keith Press.

Butterworth, G. (1977). Object disappearance and error in Piaget's Stage IV task. *Journal of Experimental Child Psychology, 23,* 391–401.

Campos, J. J., Anderson, D. I., Barbu-Roth, M. A., Hubbard, E. M., Hertenstein, M. J., & Witherington, D. (2000). Travel broadens the mind. *Infancy, 1,* 149–219.

Campos, J. J., Bertenthal, B. I., & Kermoian, R. (1992). Early experience and emotional development: The emergence of wariness and heights. *Psychological Science, 3*(1), 61–64.

Campos, J., Hiatt, S., Ramsay, D., Henderson, C., & Svejda, M. (1978). The emergence of fear on the visual cliff. In M. Lewis & L. Rosenblum (Eds.), *The development of affect* (pp. 149–182). New York: Plenum.

Chen, Z., Sanchez, R. P., & Campbell, T. (1997). From beyond to within their grasp: The rudiments of analogical problem solving in 10- and 13-month-olds. *Developmental Psychology, 33,* 790–801.

Chen, Z., & Seigler, R. S. (2000). Across the great divide: Bridging the gap between understanding of toddlers' and older children's thinking. *Monographs of the Society for Research in Child Development, 65*(2, Serial No. 261).

Clark, J. E., & Phillips, S. J. (1987). The step cycle organization of infant walkers. *Journal of Motor Behavior, 19,* 421–433.

Connolly, K., & Dalgleish, M. (1989). The emergence of a tool-using skill in infancy. *Developmental Psychology, 25,* 894–912.

Feigenson, L., & Carey, S. (in press). Tracking individuals via object-files: Evidence from infants' manual search. *Developmental Science.*

Gibson, E. J. (1992). *Perceptual learning and development.* Presentation to the Indiana University Psychology Department Colloquium, Bloomington, IN.

Gibson, E. J., Riccio, G., Schmuckler, M. A., Stoffregen, T. A., Rosenberg, D., & Taormina, J. (1987). Detection of the traversability of surfaces by crawling and walking infants. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 533–544.

Gibson, E. J., & Walk, R. D. (1960). The "visual cliff." *Scientific American, 202,* 64–71.

Kingsnorth, S., & Schmuckler, M. A. (2000). Walking skill versus walking experience as a predictor of barrier crossing in toddlers. *Infant Behavior and Development, 23,* 331–350.

Köhler, W. (1931). *The mentality of apes.* London: Percy Lund, Humphries & Co.

Lockman, J. J. (2000). A perception-action perspective on tool use development. *Child Development, 71,* 137–144.

McCarty, M. E., Clifton, R. K., & Collard, R. R. (1999). Problem solving in infancy: The emergence of an action plan. *Developmental Psychology, 35,* 1091–1101.

McCarty, M. E., Clifton, R. K., & Collard, R. R. (2001). The beginnings of tool use by infants and toddlers. *Infancy, 2,* 233–256.

McGraw, M. B. (1935). *Growth: A study of Johnny and Jimmy.* New York: Appleton-Century.

Parker, S. T., & Gibson, K. R. (1977). Object manipulation, tool use and sensorimotor intelligence as feeding adaptations in cebus monkeys and great apes. *Journal of Human Evolution, 6,* 623–641.

Piaget, J. (1954). *The construction of reality in the child.* New York: Free Press.

Richards, J. E., & Rader, N. (1981). Crawling-onset age predicts visual cliff avoidance in infants. *Journal of Experimental Psychology: Human Perception and Performance, 7,* 382–387.

Richards, J. E., & Rader, N. (1983). Affective, behavioral, and avoidance responses on the visual cliff: Effects of crawling onset age, crawling experience, and testing age. *Psychophysiology, 20,* 633–642.

Schmuckler, M. A. (1996). The development of visually-guided locomotion: Barrier crossing by toddlers. *Ecological Psychology, 8,* 209–236.

Shapiro, S. A., & Gerke, E. D. (1991). The process of adaptation to environmental conditions in a child's behavior. *Soviet Psychology, 29*(6), 44–90.(Original work published in Russian in 1930)

Steenbergen, B., van der Kamp, J., Smitsman, A. W., & Carson, R. G. (1997). Spoon-handling in two- to four-year-old children. *Ecological Psychology, 9,* 113–129.

Thelen, E., Ulrich, B. D., & Niles, D. (1987). Bilateral coordination in human infants stepping on a split-belt treadmill. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 405–410.

Tomasello, M., & Call, J. (1997). *Primate cognition.* New York: Oxford University Press.

van Leeuwen, L., Smitsman, A., & van Leeuwen, C. (1994). Affordances, perceptual complexity, and the development of tool use. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 174–191.

Wagman, J. B., & Carello, C. (2001). Affordances and inertial constraints on tool use. *Ecological Psychology, 13,* 173–195.

Wellman, H. M., Cross, D., & Bartsch, K. (1986). Infant search and object permanence: A meta-analysis of the A-not-B error. *Monographs of the Society for Research in Child Development, 51*(3, Serial No. 214).

Willatts, P. (1984). The Stage IV infants' solution of problems requiring the use of supports. *Infant Behavior and Development, 7,* 125–134.

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