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# Out of the Toolbox: Toddlers Differentiate Wobbly and Wooden Handrails

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This study examined whether 16-month-old walking infants take the material composition of a handrail into account when assessing its effectiveness as a tool to augment balance. Infants were encouraged to cross from one platform to another via bridges of various widths (10, 20, 40 cm) with either a "wobbly" (foam or latex) or a wooden handrail available for assistance. Infants attempted to walk over wider bridges more often than narrow ones, and attempts were more frequent when the sturdy wooden handrail was available. Infants tailored their exploratory behaviors, bridge-crossing strategies, and handrail-use strategies to the material properties of the rail.

## *Escape From the Toolbox*

What comes to mind when you hear the word "tool"? Most people think of a handheld object like a hammer or a screwdriver—an item found in a toolbox or hanging from a handyman's belt. What makes hammers, screwdrivers, and other handheld implements tools is that they function to extend bodily capabilities. Tools make it possible to perform actions that otherwise would have been impossible or difficult to perform (Connolly & Dalgleish, 1989; Lockman, 2000). Hammers augment arm strength and direct forces onto a concentrated area, screwdrivers increase turning force and provide a precision grip, wrenches increase leverage, and so on.

A classic example of handheld tool use is Köhler's (1925) chimpanzees recognizing that a stick could extend their reach. After frustrated attempts to reach a distant food lure with their bare hands, the chimps noticed a nearby stick and used it to rake in the fruit. Köhler's chimps also fit two short sticks together and used the elongated stick to rake in bananas that were beyond the reach of a short stick. Inspired by Köhler's famous chimps, McGraw (1935), in her own classic study, showed that 2-year-old human twins, Jimmy and Johnny, could also reach with a stick through the bars of a specially built cage to rake in a piece of fruit. The boys even figured out how to use a very short stick to retrieve another one long enough to reach the fruit. In the tradition of Köhler and McGraw, dozens of studies have shown that non-human primates and human infants can use handheld implements such as canes, rakes, sticks, spoons, and levers as tools to bring distant objects within reach (Chen & Siegler, 2000; Connolly & Dalgleish, 1989; Hauser, Kralik, & Botto-Mahan, 1999; Hauser, Pearson, & Seelig, 2002; Hauser, Santos, Spapen, & Pearson, 2002; Koslowski & Bruner, 1972; Steenbergen, van der Kamp, Smitsman, & Carson, 1997).

However, tools do not need to be relegated to a toolbox. Although tool use is not often conceived as a whole-body, locomotor behavior, Köhler's (1925) famous chimps used objects to extend their abilities in ways that were unlike the usual handheld methods. For example, Köhler's chimps recognized that a pole could be used as a means of extending the range of their whole bodies and not just the reaching distance of their arms. They pole vaulted themselves up into the air to grab bananas hanging from the ceiling on their way down. Comparable to connecting short sticks to create a long raking tool, the chimps also stacked short boxes on top of each other to create a means of reaching the ceiling. Similarly, McGraw (1935) started training Jimmy and Johnny in some of

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Köhler's tasks when they were 20 months old. Less than 4 months later, they too had learned to stack and climb boxes to reach a lure hanging from the ceiling. It took Johnny 2 months to learn how to seriate a set of stools of different heights to reach the ceiling lure. Eventually he learned that shorter stools, which he could climb easily, were the intermediate means of reaching the taller stools, which in turn were the direct means of reaching the goal.

More recently, we showed that infants could demonstrate some of the elements of spontaneous whole-body tool use without special laboratory training (Berger & Adolph, 2003). We tested 16-month-old walking infants' ability to use a handrail as a tool for keeping balance. Infants were encouraged to walk over both wide and narrow bridges, with a handrail available for assistance on half of the trials. Infants' decisions to walk or not were based on both bridge width and handrail presence. On wide bridges, infants ran straight to the finishing platform regardless of handrail availability. Narrow bridges were a different story. On trials without a handrail, infants steadfastly refused to cross. On trials with a handrail, babies walked slowly and carefully to the finishing platform gripping tightly onto the rail to augment their balance.

### *Cognitive Underpinnings of Tool Use*

We propose that the same cognitive abilities underlie successful performance in traditional demonstrations of handheld tool use and in the less conventional studies of whole-body tool use. In fact, whole-body tool use highlights the integration of both perceptual-motor skills (adaptive control of motor action) and cognitive skills (means–ends problem solving) in the service of achieving a goal. Tool use requires mentally coordinating and motorically executing a series of three steps, each in itself a noteworthy psychological achievement. First, infants must recognize a physical limitation that creates a discrepancy between their bodily abilities and the desired goal—that narrow bridges, for example, do not afford walking or that a bunch of bananas are beyond arms' reach. It is this discrepancy between the current and desired state of affairs that prompts infants to search for alternative means. In our original handrails study (Berger & Adolph, 2003), infants demonstrated that they possessed this knowledge: on trials without a handrail, they refused to walk over the narrow bridges.

The second step in tool use is the most studied and the most contentious as it involves a fundamental component of problem solving: the cognitive ability to find alternative means to achieve an otherwise unattainable goal. Tool use involves a special kind of means–ends problem solving because infants must resolve the discrepancy between their own abilities and the goal by noticing the utility of an external object for carrying out their action plan. On most accounts, bona fide tool use requires infants (or chimps) to demonstrate that they have mentally linked the tool to the goal by bringing the tool into physical proximity of the target and placing it in the appropriate spatial configuration, as when infants select a cane and orient the head to rake in a toy or when toddlers drag a box to the base of a pedestal to use it as a stepping stool to reach a high lure (Chen & Siegler, 2000; Lockman, 2000; McGraw, 1935). Although the differential use of handrails demonstrates means–ends problem solving via an external object, the handrails are stationary and do not require infants to bring them into proximity with the target.

Despite the central role of means–ends problem solving in dozens of previous studies, researchers focused primarily on the ages at which infants first learned to use tools (Connolly & Dalgleish, 1989; McCarty, Clifton, & Collard, 2001; Steenbergen et al., 1997). Few studies examined *how* infants figure out that certain tools are available and useful. One exception was our previous handrail studies (Berger & Adolph, 2003) in which we documented the details of infants' exploratory behaviors before they stepped onto the bridges. Infants did not display the sudden moments of insight that Köhler (1925) described with chimps in locomotor and handheld tool-use tasks. Nor were infants' behaviors reminiscent of the "trial-and-success" random thrashing that Thorndike (Chance, 1999) described with cats as they escaped from puzzle boxes. Instead, on trials with narrow bridges, infants stopped at the brink of the precipice and concertedly sought out information about the handrails by touching them and testing their utility before making a decision about crossing.

The final step in successful tool use involves the perceptual-motor skills necessary for implementing the tool: not just knowing that a pole can be used to vault oneself into the air, but figuring out *how* to swing oneself forward and up into the air; not simply recognizing that a spoon can transport food but knowing to hold the handle rather than the bowl-end and to grasp it with a radial grip (McCarty, Clifton, & Collard, 1999; McCarty et al., 2001; McCarty & Keen, in press). Furthermore, implementing a tool may require infants to modify their typical strategies to meet situational demands, such as using a less mature ulnar grasp rather than a radial grip to eat with a bent-handled spoon or to fit a spoon into an altered container (Achard & von Hofsten, 2002; Steenbergen et al., 1997). Likewise, in the handrails study (Berger & Adolph, 2003), infants modified their step length and velocity, turned sideways, and held the handrail with both hands to incorporate the handrail into their locomotor plan successfully.

### *Material Properties*

A critical component of the means–ends problem solving involved in the second step two is identifying an appropriate tool for the task. In studies of handheld tool use, researchers have demonstrated that infants and nonhuman primates attend to the relevant structural properties of potential tools and ignore irrelevant features such as color. Infants and monkeys, for example, consistently choose a hooked stick over a straight one and a long stick over a short one, suggesting that they understand that some properties make objects better tools for reaching than others (Brown, 1990; Hauser, 1997; Hauser et al., 1999, 2002).

In addition to structural properties, the material composition of a tool may also determine its effectiveness (Bushnell & Boudreau, 1991; Lockman, 2000). For example, ''a flexible cloth must be pulled to bring a distant toy within reach, but a rigid support may be pulled, lifted, or rotated to achieve the same result'' (Willatts, 1999). Despite a rich literature on infants' understanding of tools' structural properties, researchers know little about infants' understanding of the relevance of material properties. Would human infants recognize that a flexible cloth can only be pulled but that a rigid support can be pulled, lifted, or rotated? Would they understand that a flimsy piece of string would not be appropriate for raking but that a rigid stick would be?

On the one hand, there is some evidence to suggest that infants might take material properties into account when gauging the effectiveness of a tool. Dozens of studies have demonstrated infants' perceptual discrimination of material properties (e.g., Bushnell & Boudreau, 1991, 1993, 1998; Klatzky, Lederman, & Metzger, 1985; Klatzky, Lederman, & Reed, 1987). For example, 6-month-olds engage in differential visual exploration when presented with displays of a deforming sponge and a rigid cube (Gibson & Walker, 1984). Similarly, they engage in differential oral and manual exploration when presented with rigid and nonrigid pacifiers, objects, and table-top surfaces (Bourgeois, Khawar, Neal, & Lockman, in press; Gibson & Walker, 1984; Palmer, 1989). The haptic exploration of 9- to 10-month-olds has become as sophisticated as adults—tailored to the object being explored and designed to gather specific types of information (Bushnell & Boudreau, 1991, 1993, 1998; Lederman, Summers, & Klatzky, 1996). For instance, to assess an object's rigidity, infants and adults apply pressure to the surface by squeezing (Bushnell & Boudreau, 1991; Klatzky et al., 1987; Lederman et al., 1996).

On the other hand, there is reason to suggest that infants might be oblivious to material properties when gauging the effectiveness of a tool. Material properties such as rigidity, deformability, elasticity, brittleness, flimsiness, and so on require different information-gathering behaviors than structural properties such as shape and size. Structural properties can be specified by static visual cues. In contrast, material properties like rigidity must be specified in motion information, from direct haptic exploration of the object or by watching an event occur with the object. Thus, infants might fail to gather haptic information about potential tools, they might mistakenly attribute certain material properties to objects based solely on visual cues (the object has sharp edges so it must be rigid), or after gathering haptic information they may simply fail to understand the significance of material properties for tool use. In walking tasks, for example, toddlers, preschoolers, and adults fail to gather haptic information about the deformability of the ground surface and consequently attempt to walk and fall (Joh & Adolph, in press).

### *Goals of the Current Study*

Although infants discriminate subtle material properties in the course of object exploration, experimenters have rarely asked whether babies can use such information to make adaptive decisions about action. The current study was designed to examine the sophistication of infants' tool-use knowledge. Our first aim was to determine whether infants' means/ends understanding in tool use extends to the role of material properties—that a tool must be made of materials that are appropriate for the demands of the task. In previous studies, infants may have correctly matched the orientation of a cane or rake, for example, with its usefulness as a tool without taking material properties into account (Brown, 1990; Connolly & Dalgleish, 1989). Similarly, in the original bridges and handrail studies (Berger & Adolph, 2003), infants may have recognized that the handrail spanned the gap between their current position and the goal without recognizing that its material properties rendered it sufficiently sturdy to augment their balance. Thus, we designed a new study in which we varied the rigidity of an available handrail as infants walked over wide and narrow bridges. On some trials, the handrail was sturdy enough to support infants' weight; on other trials, the handrail wobbled and gave way when infants leaned on it. If infants take material properties into account when assessing a handrail as a means for augmenting balance, then they should cross narrow bridges with a wooden handrail but avoid them with a wobbly handrail.

Our second aim was to provide a rich description of the normally undocumented three-step process of tool use: discovering the necessity of a tool, searching for the existence of a tool, and success at implementing the tool. Toward that end, we observed infants' visual and haptic exploration of bridges before touching the handrail, their haptic exploration of the handrail before crossing the bridge, and their strategies for crossing the bridge while holding the handrail. Although adults and infants can adjust their postural sway by lightly touching a handrail while standing still (Barela, Jeka, & Clark, 1999, 2003; Jeka & Lackner, 1994; Metcalfe, Chen, Chang, & McDowell, 2005), infants' task in the current experiment was to maintain balance under the more precarious condition of walking along a narrow beam. Thus, we compared infants' use of "light touch," where they grazed their hand along the rail, with their use of "heavy touch," where they leaned or pulled on the rail, and their consequent success at crossing the bridges.

Finally, we used an age-matched control design, keeping infants' age constant at 16 months while measuring the effects of developmental differences in the duration of infants' walking experience, level of walking skill, and the size of their body dimensions. Previous work showed that infants with several months of walking experience gauge possibilities for walking based on their level of walking skill and body dimensions (Adolph, 1997; Adolph & Avolio, 2000). Here, we asked whether infants with more walking experience might be more likely to recognize the importance of material substance for augmenting balance (e.g., show more material exploration of the handrails and be less likely to use the wobbly handrails on narrow bridges), more skillful walkers might succeed at crossing narrower bridges, and larger infants might resort to using the handrail on wider bridges than smaller infants.

## Method

### *Participants*

Twenty-three 16-month-old infants (± 1 week; $M = 16.03$ months) participated (11 boys, 12 girls). Two additional infants did not complete testing because of fussiness and data from 1 infant could not be used because of experimenter error. Infants were recruited through a commercial mailing list of families living in the New York City metropolitan area. All babies were healthy and born at term. Most were White and middle class. All could walk at least 10 feet continuously without help. Parents reported their infants' locomotor experience in a structured interview (Adolph, Vereijken, & Shrout, 2003). Walking experience (dating from the day they could walk approximately 10 feet across the room) ranged from 35 to 169 days ($M = 121.5$ days, $SD = 33$ days). Twenty infants had previous exposure to handrails going up or down stairs (4 infants), on playground equipment (7 infants), or both (9 infants). Babies received a diploma and photo as souvenirs of their participation.

### *Bridges and Handrails*

One of 3 bridges (40, 20, or 10 cm) connected a starting platform (76 cm wide × 106 cm long) to a finishing platform (76 cm wide × 157 cm long) over a crevasse (74 cm deep × 76.2 cm long) lined with 13.5 cm of foam padding along the sides and bottom (see Figure 1). The bridges fit between the two platforms via a locking tongue and groove system and could be quickly changed between trials. A sturdy or wobbly handrail could be attached to support posts (43.5 cm high) on the starting and landing platforms so that it ran the length of the walkway alongside the bridge. The wooden handrail (302 cm long × 13.5 cm wide × 4 cm thick) had a pale wood grain pattern and was identical to the one used in previous research (Berger & Adolph, 2003). After extensive pilot testing to identify appropriate materials, we constructed wobbly handrails out of latex and foam. The latex handrail (246.38 cm long × 2.8575 cm in diameter × 0.635 cm thick) was made from yellow, stretchy, hollow tubing with a hard, rubbery, outer shell. It felt solid to a light touch. The foam handrail (246.38 cm long × 4.445 cm diameter) was made from blue, spongy rubber. It felt springy when pressed lightly with a finger. Both wobbly handrails looked rigid and stretched from one platform to the other without sagging or moving; however, they gave way when leaned on, stretched outward when pulled on, and swung back and forth when pressed.

### *Procedure*

We tested infants on the 9 combinations of 3 bridge widths crossed with 3 handrail types. Trials

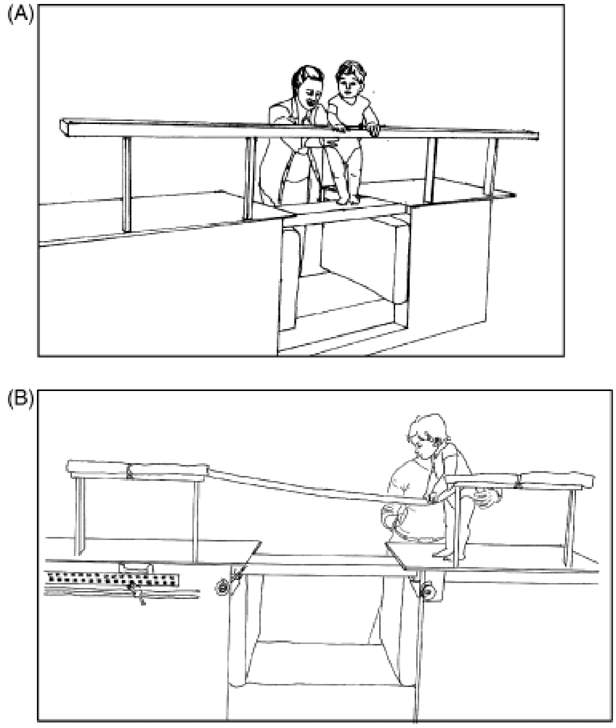

*Figure 1.* Walkway with adjustable bridge widths and removable (A) wooden and (B) wobbly (foam or latex) handrails (shown with a 20 cm bridge). The drop-off beneath the bridge was lined with foam padding. Infants began each trial on the starting platform. Parents (not shown) stood at the far end of the finishing platform offering encouragement. An experimenter (shown) followed alongside infants to ensure their safety. An assistant (not shown) adjusted the bridges and switched the handrails (reprinted with permission from Berger & Adolph, 2003).

were presented in sets of 3, always beginning with the 40 cm bridge to maintain infants' motivation to walk, followed by the 20 and 10 cm bridges in random order. Each bridge in the set was paired with a different type of handrail. Six presentation orders were counterbalanced across boys and girls. After presenting each of the 9 combinations, we repeated the sequence so that infants received each bridge–rail combination twice for a total of 18 trials. A final 40 cm bridge was presented at the end of the session to ensure that prior refusals to walk were not due to fatigue or boredom. All of the infants walked on the final trial and the data were not used in analyses.

Parents stood at the end of the finishing platform and encouraged their children to cross the bridges by offering toys and cereal, but did not draw infants' attention to the handrail, instruct them how to cross, or tell them to be careful. A highly trained experimenter followed alongside infants to ensure their safety if they began to fall. Trials ended when infants reached the finishing platform, fell off the bridge, or remained on the starting platform for 45 s, whichever occurred first. Sessions were videotaped with two camera views mixed in real time onto a single videotape. One camera panned to provide a side view and a second ceiling-mounted camera provided an overhead view.

After testing on the walkway, an experimenter measured infants' body dimensions (recumbent height, leg length, crown–rump length, trunk length, arm span from fingertip to fingertip, and weight). Infants' step length and walking velocity across the no-handrail 40-cm trials served as measures of their walking skill. Step length was calculated from videotape by dividing the distance between two points on the walkway by the number of steps it took infants to walk from one point to the other. Walking velocity was the time to travel between the two points. The entire session, including trials and body measurements, lasted 45–90 min.

## Results

Data from each test session were coded from videotapes using MacShapa, a computerized video coding system that records frequency and duration of specified behaviors (Sanderson et al., 1994). A primary coder scored 100% of all trials. A second coder independently scored 25% of each infant's trials. Interrater reliability ranged from .85 to 1.0 for categorical and frequency measures; $p$ values for all Cohen's kappa coefficients were $< .01$. Correlation coefficients for measures of duration ranged from $r = .94$ to $r = 1.0$. Discrepancies between coders were resolved through discussion.

One child was missing seven trials from the second run through the conditions and a second child was missing one trial from the second run (due to fussiness); a third child received an extra trial in two conditions and was short by a trial in two conditions (due to experimenter error) and a fourth child was missing a trial from the camera view (when the tape ran out). As a result, for analyses involving trial number, the data set consisted of 405 rather than 414 trials and the number of participants included in analyses was reduced from 23 to 19. In addition, the number of available trials was further reduced for some measures because portions of trials were momentarily obscured from the camera view (by the experimenter's arms or parts of the walkway) or because the measures were contingent on infants attempting traversal. Thus, we report omnibus tests using trial number as a factor only for analyses where at least 17 children contributed data and where the pattern of effects for bridge width and handrail type replicates the full sample. Main effects and interactions were followed up with paired *t* tests. For each set of comparisons, we used a Bonferroni-adjusted alpha level to correct for experimentwise error rates (overall $p = .05$).

### *Attempts to Walk*

The critical test of whether infants differentiated the utility of handrails based on material substance was whether their *attempts* to walk over the bridges (scored as stepping onto the bridge with both feet) were geared to handrail type. Table 1 presents the data averaged over trials. As shown in row A of the table, infants always attempted to walk over the 40 cm bridge, regardless of handrail type. However, on the 10 and 20 cm bridges, infants attempted to walk more frequently when the handrails were wooden rather than wobbly. As illustrated in Figure 2A, attempts on the narrow bridges increased from the first to second trials. With no variance in attempts at the 40 cm bridge width, we restricted statistical analyses to the two narrower bridges. A 2 (bridge width) × 3 (handrail type) × 2 (trial) repeated measures analysis of variance (ANOVA) on attempts to walk confirmed main effects for bridge width, $F(1, 18) = 48.87$, $p < .01$, handrail type, $F(2, 36) = 7.15$, $p < .01$, and trial number, $F(1, 18) = 4.73$, $p < .05$. Post hoc tests revealed differences between the two wobbly rails versus the wooden handrails (all $p < .013$). On most trials when infants did not attempt to walk, they waited out the trial on the starting platform (87.4%); for the remaining refusal trials, infants held onto the experimenter while stepping onto the bridge, backed off the platform into the gap, slid off the platform into the gap in a sitting position, and crawled over the bridge.

We were surprised by two related findings: (a) that the rate of attempts was so high on trials at the 20 cm bridge with the wobbly handrails ($M = .61$, $SD = .32$) and (b) that nearly all attempts with the wobbly handrails were successful (64% at 10 cm, 92.5% at 20 cm, and 100% at 40 cm). Infants walked from one platform to the other without falling or requiring assistance on 92.5% of all attempted trials. The 19 falls in the data set were divided evenly between the 10 and 20 cm bridge widths and among the three handrail types and between trials when they did and did not use the handrail while crossing. To investigate the surprisingly high rate of infants' successful attempts with wobbly handrails, we considered the possibility that we had miscalculated the dimensions of infants' bodies relative to the rails such that the handrails might not have depressed beneath infants' weight.

The data on infants' body dimensions, however, were inconsistent with this explanation. On average, infants were 78.95 cm tall (range = 70.08–84.60 cm), meaning that the handrail fell between the infants' breast bone and belly button, approximately at most infants' elbow height. When infants pushed down on the foam or latex handrails with all of their weight, they displaced it so far that it fell to midthigh and they had to bend over to hold on. Infants' mean shoulder width was 16.27 cm (range = 11.15–21.60 cm), too wide for them to fit comfortably on the narrowest 10 cm bridge while facing forward.

Table 1
*Mean Values (and Standard Errors) of Toddlers' Behaviors Prior to Embarking onto Bridges*

| | Wood (cm) | | | Foam (cm) | | | Latex (cm) | | |
|---|---|---|---|---|---|---|---|---|---|
| | 10 | 20 | 40 | 10 | 20 | 40 | 10 | 20 | 40 |
| Walking | | | | | | | | | |
| A. Attempts to walk (proportion trials) | 0.28 (0.08) | 0.83 (0.07) | 1.00 (.00) | 0.17 (0.07) | 0.61 (0.08) | 1.00 (.00) | 0.15 (0.06) | 0.61 (0.08) | 1.00 (.00) |
| Exploration | | | | | | | | | |
| B. Latency (s) | 37.03 (2.79) | 17.29 (2.63) | 4.14 (.48) | 39.86 (2.12) | 23.55 (2.93) | 5.20 (.79) | 40.26 (1.96) | 23.00 (2.88) | 4.22 (.55) |
| C. Bridge exploration (proportion trials) | 0.48 (0.07) | 0.43 (0.08) | 0.02 (.02) | 0.48 (0.09) | 0.57 (0.07) | 0.11 (.04) | 0.48 (0.08) | 0.50 (0.08) | 0.02 (.02) |
| D. Gap exploration (proportion trials) | 0.70 (0.08) | 0.35 (0.07) | 0.02 (.02) | 0.72 (0.08) | 0.48 (0.08) | 0.04 (.03) | 0.63 (0.08) | 0.35 (0.07) | 0.02 (.02) |
| E. General handrail exploration (proportion trials) | 0.89 (0.04) | 0.96 (0.03) | 0.54 (.08) | 0.89 (0.06) | 0.91 (0.05) | 0.57 (.10) | 0.89 (0.05) | 0.93 (0.04) | 0.33 (.08) |
| F. Material handrail exploration (proportion trials) | 0.76 (0.07) | 0.54 (0.09) | 0.02 (.02) | 0.87 (0.06) | 0.72 (0.07) | 0.17 (.06) | 0.87 (0.06) | 0.74 (0.06) | 0.07 (.05) |

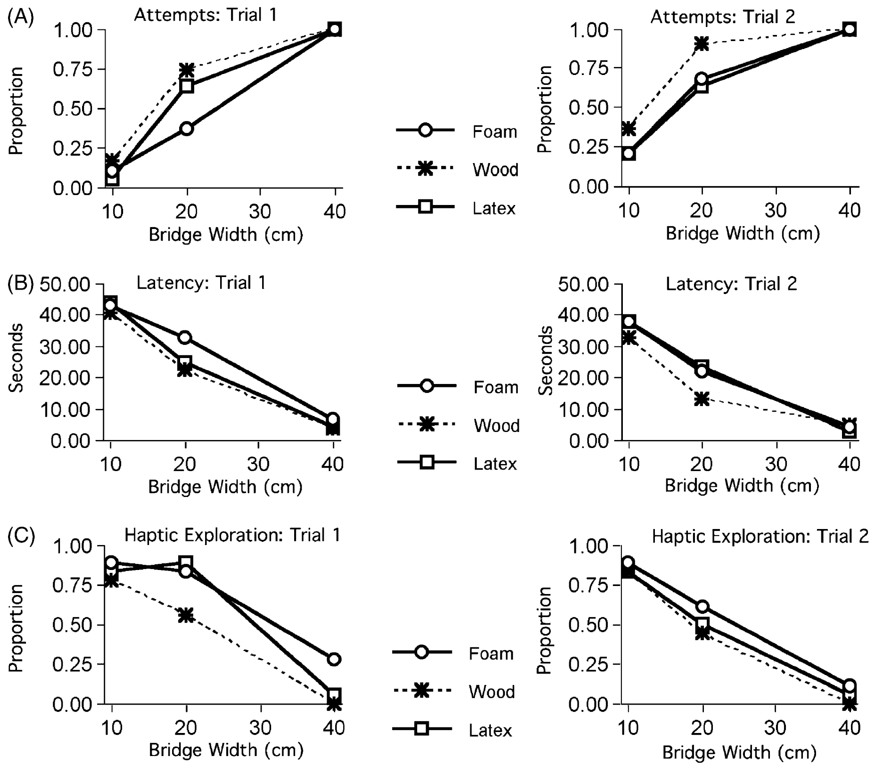

*Figure 2.* (A) Infants' attempts to walk over bridges at each bridge width and with each handrail type at each trial. (B) Infants' latencies to step onto the bridges at each bridge width and with each handrail type at each trial. (C) Infants' material exploration of the handrail at each bridge width and with each handrail type at each trial.

Infants' mean weight was 10.81 kg (range = 9.49–12.16 kg). Infants' body dimensions were not correlated with attempts to cross, success at crossing, or exploratory behaviors, suggesting that the handrails wobbled for lightweight as well as heavier babies, smaller infants did not have an advantage over larger ones in fitting onto the bridges more easily, and larger infants could not reach the handrail more easily.

A second explanation for infants' success at walking with the wobbly rails is that they used the rails in unexpected ways. We consider this possibility in the section below, describing how infants implemented the handrail as a tool for augmenting balance.

### *Bridge Exploration*

The first prerequisite for tool use is recognizing that a desired goal cannot be achieved using the typical means. In this case, to examine whether infants recognized the perils of walking over narrow bridges, coders scored three measures of their reticence to leave the starting platform: *latency* to step onto the bridge, *touching the bridge* with feet or hands, and *exploring the gap* between the two platforms by peering over the edge of the walkway down into the gap, dipping their hands and feet into the gap, and balancing on or curling their toes over the edge of the crevasse.

As shown in Table 1, row B, latency increased on narrower bridges and increased on the trials with wobbly handrails. As illustrated in Figure 2B, latency decreased from the first to the second trial block. A repeated measures ANOVA with 3 (bridge width) × 3 (handrail type) × 2 (trial) on latency confirmed main effects for bridge width, $F(2, 44) = 158.50$, $p < .01$, handrail type, $F(2, 44) = 3.74$, $p < .04$, and trial number, $F(1, 16) = 6.38$, $p < .03$. Post hoc comparisons revealed differences between each of the three bridge widths and between the two wobbly rails versus the wooden handrails (all $p < .02$). Rows C and D of the table show that the frequency of touching the bridge and exploring the gap also decreased with bridge width. Neither bridge nor gap exploration changed over trials. Repeated measures ANOVAs with 3 (bridge widths) × 3 (handrail types) × 2 (trial number) on touching the bridge and gap exploration confirmed main effects for bridge width only, $F(2, 44) = 31.88$, $p < .01$ and $F(2, 44) = 55.68$, $p < .01$, respectively. Post hoc comparisons revealed that infants explored more often on the two narrow bridges (10 and 20 cm) than on the wide bridge (40 cm) (all $p < .01$).

### Handrail Exploration

The second step to successful tool use is recognizing that something in the environment can serve as a means to reach an otherwise unobtainable goal, that is, recognizing that a sturdy handrail could augment balance control. Thus, we paid special attention to how infants explored the end of the handrails while standing on the starting platform. Coders scored *general exploration* of the handrail if infants touched the handrail before stepping onto the bridge. Coders scored *material exploration* of the handrail if infants touched the handrail in a way that could yield information about its material composition and ability to support their weight: pushing (bending and straightening the elbows while leaning onto the rail), tapping (hitting the same spot repeatedly on the handrail), squeezing (clenching the hand around the rail with movement of the fingers around the knuckles), rubbing (engaging in lateral or vertical hand motions along the rail), and mouthing (putting their mouths on or biting the handrail).

As shown in Table 1, row E, general exploration of the handrail decreased as bridge width increased. A repeated measures ANOVA with 3 (bridge width) × 3 (handrail type) × 2 (trial) on handrail exploration confirmed a significant effect only for bridge width, $F(2, 34) = 26.46$, $p < .01$. Post hoc comparisons showed that infants explored the handrails on the 10 and 20 cm bridges more often than the 40 cm bridge (all $p < .01$). Although the frequency of general handrail exploration did not differ according to handrail type, material exploration depended on whether the handrail was wooden or wobbly. A 3 (bridge width) × 3 (handrail type) × 2 (trial) repeated measures ANOVA on material exploration showed main effects for bridge width, $F(2, 34) = 65.62$, $p < .01$, handrail type, $F(2, 34) = 4.39$, $p < .01$, and trial, $F(1, 17) = 12.88$, $p < .01$ (see Table 1, row F). Post hoc tests revealed differences between the two narrow versus wide bridges and between the two wobbly versus wooden handrails (all $p < .016$). As illustrated in Figure 2C, infants explored the material composition of the handrails less frequently during the second block of trials.

Table 2

*Proportion of Trials (and Standard Errors) on Which Toddlers Engaged in Material Exploration of the Handrails*

| | Wood | Wobbly |
|---|---|---|
| Pushing | .54 (.06) | .72 (.05) |
| Tapping | .24 (.06) | .11 (.04) |
| Squeezing | .18 (.04) | .61 (.05) |
| Rubbing | .10 (.04) | .35 (.06) |
| Mouthing | .03 (.02) | .05 (.02) |

The particular manner of material exploration depended on whether the handrails were wooden or wobbly. As shown in Table 2, infants tapped the wooden handrail as if to ensure its sturdiness, but they pushed, squeezed, or rubbed the wobbly ones as if to figure out what they were made of and to test the limits of the rails' ability to support their weight. Infants rarely mouthed the handrails. Because infants showed no differences in general haptic exploration between the 10 and 20 cm bridges and no differences in material exploration between the foam and latex handrails, we collapsed the data over the two narrow bridge widths and the two wobbly rails for subsequent analyses. As infants rarely explored the handrail on the 40 cm bridge, we did not consider trials at the widest bridge in tests of the various exploratory procedures. Paired samples $t$ tests comparing the proportion of trials on which infants displayed different types of material exploration (pushing, tapping, rubbing, squeezing) revealed differences for handrail type (all $p$ values $< .02$). Moreover, on the most difficult trials (narrow bridges with wobbly handrails), infants who used material exploration to gather information about the rigidity of the handrails were more likely to make it successfully across the bridge than those who did not; $r(23) = .55$, $p < .01$.

### Using the Handrail

The third requirement for successful tool use is the ability to implement the tool, in this case, to use the handrail effectively. On trials where infants attempted to cross, coders scored *handrail use* (touching the handrail after stepping onto the bridge) to distinguish the trials on which infants might have used the handrails as a tool. Three measures described modifications to infants' walking gait that could accompany handrail use: number of *preparatory steps* on the starting platform before stepping onto the bridge, number of *steps* to walk across the bridge, and *time* to cross the bridge. More preparatory steps reflects prospective control of gait modifications; increased step number and longer crossing times reflect increased caution (Gill-Alvarez & Adolph, 2005). Because so few infants attempted to cross the 10 cm bridge, we collapsed data over the 10 and 20 cm bridges for subsequent analyses.

Infants indeed used the handrail for assistance on narrow bridges. A 2 (bridge width) × 3 (handrail type) repeated measures ANOVA for handrail use

Table 3
*Mean Values (and Standard Errors) of Toddlers' Behaviors After Stepping onto Bridges*

| | Wood | | Foam | | Latex | |
|---|---|---|---|---|---|---|
| | Narrow | Wide | Narrow | Wide | Narrow | Wide |
| A. Handrail use (proportion trials) | 0.90 (0.05) | 0.41 (.09) | 0.84 (0.08) | 0.61 (.08) | 0.90 (0.06) | 0.39 (.09) |
| B. Number of preparatory steps | 8.85 (0.76) | 4.70 (.36) | 8.28 (0.59) | 4.30 (.29) | 9.40 (0.72) | 4.67 (.40) |
| C. Number of steps to walk across bridge | 11.66 (0.69) | 6.68 (.28) | 12.36 (0.82) | 7.35 (.27) | 13.89 (1.03) | 7.28 (.32) |
| D. Time to walk (s) | 10.51 (1.96) | 2.33 (.21) | 7.94 (1.06) | 2.99 (.46) | 7.23 (0.78) | 2.93 (.48) |

showed a main effect only for bridge width, $F(1, 16) = 46.41$, $p < .01$ (see Table 3, row A). All 23 children used the handrail on at least one attempt and 2 infants used the handrail on 16 of their 18 total trials. In addition, infants modified their walking patterns to accommodate narrower bridge widths. A series of 2 (bridge width) × 3 (handrail type) repeated measures ANOVAs on number of preparatory steps on the starting platform, number of steps on the bridge, and time to cross the bridge revealed main effects for bridge width (all $p$ values $< .01$). Step number on the bridge also depended on handrail type, $F(2, 30) = 3.34$, $p < .05$, and there was a significant interaction between bridge width and handrail type for the time it took infants to walk across the bridge, $F(2, 30) = 3.52$, $p < .04$, suggesting that some gait modifications accompanied handrail use. Post hoc analyses confirmed that on the narrow bridges, infants took shorter, more careful steps before stepping onto the bridges, and took more steps and more time to walk across than on the wide bridge (all $p < .01$; see Table 3, rows B–D).

To investigate infants' unexpected success at crossing the narrow bridges on trials with wobbly handrails, coders scored *light-touch* (gently resting, grazing, or gliding the hand along the rail without leaning onto or pulling up on the rail) and several *heavy-touch* strategies for using the handrail (ways of gripping the handrail and positioning the body that involved leaning onto and pulling up on the rail). Eleven infants exhibited light touch on successful trials with wobbly handrails on the 10 and 20 cm bridges and 17 infants exhibited heavy touch. Light touch occurred on 27.5% of successful trials on the narrow bridge with wobbly rails and heavy touch on 62.1% (on 8.6% of trials, infants succeeded without using the handrail). Light touches were generally brief ($M = 1.94$ s, $SD = 1.54$ s, range = 0.50–4.73 s) with the hand grazing the surface in multiple bouts, and heavy touches tended to last longer ($M = 3.26$ s, $SD = 3.48$ s, range = 0.60–14.93 s) because infants could not let go without falling.

Altogether, we documented five heavy-touch strategies (see Figure 3). Ten children used a "hunchback" strategy, where they walked sideways, stooped over, pressing down on the handrail so that it depressed to their knees (45% of successful attempts with wobbly handrails on 10 and 20 cm bridges where infants used the handrail). Seven children used a "snowshoe" strategy (19% of successful attempts), where they faced forward and distributed their weight by resting their entire arm on the handrail to prevent it from dipping too deeply, just as snowshoes prevent walkers from plunging through the snow. Six children used a "mountain-climbing" strategy, where they faced forward, leaned backward, and pulled up on the handrail like a rope, dragging themselves along hand over hand (11% of successful attempts). Three babies used a "windsurfing" strategy, where they leaned backward and pulled up on the handrail as high as it would go with both hands (9% of successful attempts). Unlike the "mountain climbers" who walked forward facing the landing platform,

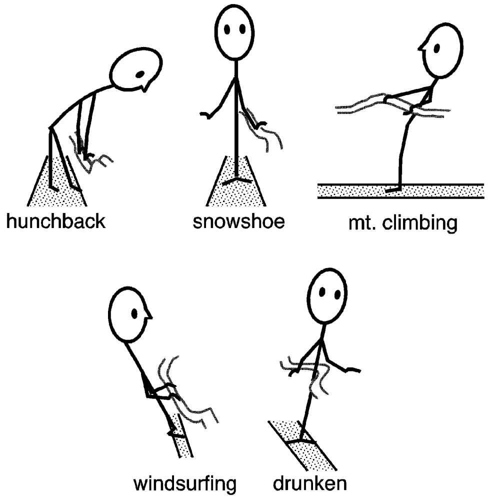

*Figure 3*. Schematic of infants' special strategies for using the wobbly handrails.

"windsurfers" walked sideways facing the handrail. Three infants used a "drunken" strategy, where they faced forward and leaned sideways against the railing, sliding their torsos along the handrail (6% of successful attempts). On 16.7% of successful, narrow bridge/wobbly handrail trials on which babies used a special handrail strategy, babies used multiple strategies in the same trial.

The data were consistent with the possibility that infants outmaneuvered our experimental manipulations by devising clever new strategies for using the wobbly handrails despite the tendency of the handrails to shake or give way when infants placed their weight on them. Heavy touches were far more frequent on the narrow 10 and 20 cm bridges than on the wide one (only 5.4% of trials on 40 cm; light touch was comparable at 29.3% of trials and infants succeeded without using the handrail on 65.2% of trials). The more information infants acquired about the handrails via material exploration, the more likely they were to use a heavy-touch strategy for implementing the handrail, $r(23) = .43$, $p < .05$. In addition, adopting one of the special strategies for handrail use was positively correlated with successful bridge crossing, $r(23) = .79$, $p < .01$.

### *Developmental Differences*

Walking experience was not related to infants' material exploration of the handrails, but it did predict infants' attempts and success at walking such that more experienced infants were more likely to attempt to walk over the 10 cm bridge ($r(22) = .42$, $p < .05$) and more experienced infants were less likely to fall off the 20 cm bridge ($r(22) = .49$, $p < .03$). Our measures of walking skill were crude and were not related to infants' success at walking over the bridges. Individual differences in infants' body dimensions did not predict their use of the handrail—nearly all infants used the handrail on trials when they attempted the 10 and 20 cm bridges.

## Discussion

### *Material Substance*

Previous work on the development of tool use assessed whether infants realize that a tool can be used to fill a gap in their ability (e.g., Brown, 1990; McCarty et al., 2001; Steenbergen et al., 1997). Infants' decisions about the appropriateness of different tools were based on static structural properties that they could see, such as the curvature of a tool's handle, the shape of a tool's head, or the location/orientation of the tool relative to the target (Brown, 1990; Chen & Siegler, 2000; Leeuwen, Smitsman, & Leeuwen, 1994). In contrast to shape, size, distance, and ori entation, rigidity is not well specified by static visual cues (Adolph, Eppler, Marin, Weise, & Clearfield, 2000; Joh & Adolph, in press). Determination of material substance requires dynamic information revealed by an event, as in haptic exploration. Previous work on the development of haptic exploration described differential touching and mouthing of rigid and deformable objects in the course of spontaneous open-ended object manipulation (Bourgeois et al., in press; Bushnell & Boudreau, 1998; Gibson & Walker, 1984; Palmer, 1989; Rochat, 1987, 1989; Ruff, 1984).

The current experiment aimed to extend the scope of previous tool use and haptic exploration studies. We asked whether infants take into account the material properties of an object when assessing its usefulness as a means to achieve a goal. In particular, would toddlers discriminate wooden and wobbly handrails by their haptic exploration and would they realize that a sturdy wooden handrail is more effective for augmenting balance than a deformable wobbly one?

Our findings showed that by the middle of infants' second year of life, haptic exploration of object rigidity serves more than a discriminatory function. Toddlers can assess the appropriateness of a tool based on its material attributes as well as its structural properties. On the narrow bridges, where a handrail could create new affordances for action, infants crossed more frequently when the handrail was wooden rather than wobbly. Although the three handrails had different colors and visible textures (tan woodgrain, yellow latex, blue foam), all looked solid before a touch. Haptic exploration was prompted by narrow bridge widths and was geared toward determining the handrails' deformability and potential to support their weight—applying pressure to the handrail by squeezing, tapping, rubbing, pulling, or pushing (Bushnell & Boudreau, 1998; Klatzky et al., 1987). Although mouthing was too infrequent to discern differences based on material substance, in very young infants mouthing is analogous to manual exploration and can be used to differentiate rigid and deformable objects (Bushnell & Boudreau, 1991; Gibson & Walker, 1984). Handrail exploration decreased over repeated trials, suggesting that infants may have learned to rely on static cues such as color to signal the handrails' composition. Infants treated the wobbly latex and foam handrails as functionally equivalent for every outcome measure, despite their different colors and textures, and as functionally distinct from the sturdy wooden handrail.

Typically, the more diverse the range of infants' exploratory behaviors, the greater their success at problem solving (Caruso, 1993). Many forms of material exploration were not displayed in the previous bridge and handrail studies where only the wooden handrail was provided, suggesting that infants do not use the exploratory procedures in their repertoires indiscriminately (Berger & Adolph, 2003). Instead, infants recognized the need for particular exploratory procedures to assess the handrails' rigidity efficiently and they tailored their procedures to suit the particular handrails. For instance, they were more likely to tap the wooden handrail but to squeeze the wobbly ones. Thus, once infants noticed the potential of the handrail to help them maintain balance based on its static structural configuration, they tested material attributes that would determine whether it could really do so. These findings attest to the sophistication of infants' tool-use knowledge.

### *Inventive Tool Users*

Köhler (1925) described two approaches to problem solving in his chimpanzees as they figured out how to use tools for reaching food lures. In some cases, such as when the chimps discovered that a stick could help them to reach some food outside of their cage, the discovery was sudden and apparently effortless. At other times, such as when the chimpanzees learned to stack boxes one on top of the other to reach food hanging from the ceiling, their attempts were effortful and riddled with mistakes. The chimps precariously balanced boxes on their edges and attempted to stack boxes open end up, resulting in unstable, ineffectual towers. Success on one trial did not guarantee success on subsequent trials.

Like Köhler's colorful descriptions of his chimps' problem-solving behaviors, our detailed behavioral coding made observable the usually hidden cognitive steps of tool use. However, infants' problem solving in the bridges and handrails task matched neither of Köhler's descriptions. Rather than a moment of quiet thinking resulting in a sudden flash of insight, infants tested a variety of means for using the handrails within the course of a single trial and continued to discover new crossing strategies over trials. Rather than a haphazard, error-prone search, infants' means–ends exploration never resulted in ineffectual strategies (e.g., holding the rail behind their back). Instead, infants' experimentation was intentional, directed, and meticulous. The information that infants gathered through exploration served as the basis for devising appropriate bridge-crossing and handrail-use strategies when typical strategies would no longer suffice. Specialized material exploration was correlated with alternative strategies for using the wobbly handrails.

Infants' high level of success, regardless of handrail type, was an unexpected but important finding. Infants used the wobbly handrails successfully on 92.5% of attempted trials on the 20 cm bridges. In contrast, in our previous research (Berger & Adolph, 2003), when no handrail was available infants succeeded on only 58% and 83% of attempted trials at 18 and 24 cm bridges, respectively. The difference in infants' success rates in the two experiments, despite similar bridge widths, suggests that a suboptimal wobbly handrail was not equivalent to no handrail at all. Inspection of infants' body dimensions and reexamination of the videotapes indicated that the wobbly handrails were appropriately designed to give way beneath infants' weight and to sag below waist height when depressed.

Infants' high success rate with wobbly handrails was due to the inventiveness of their problem solving (and a failure on the part of the experimenters to anticipate such ingenuity). Infants used both a light-touch strategy (27% of trials), grazing their hands along the rail so as to generate somatosensory information for controlling posture (e.g., Barela et al., 1999, 2003; Metcalfe et al., 2004), and a heavy-touch strategy (62% of trials), where they exploited the deformability of the handrail for discovering hunchback, snowshoe, mountain-climbing, and other bridge-crossing methods. Cognitive flexibility about the conventional uses of objects coupled with the urge to move may have inspired babies' inventive use of the handrails. Infants may have inadvertently benefited from their ignorance about the conventional uses of handrails. Babies may have a "wider criteria for what can count as an object's function than do adults" or older children (German & Defeyter, 2000). For example, when 5- to 7-year-olds were posed the problem of retrieving an object from a high shelf using everyday objects such as storage boxes, building blocks, pencils, or a ball, only the 5-year-olds came up with a workable solution—turning over a box to stand on. The 6- and 7-year-olds could not overcome their functional fixedness, or inability to get past an object's conventional function, which hindered their ability to see the box as anything other than a place to store things.

Unlike adults and older children whose prior knowledge can restrict what they are willing to conclude about objects' functions (Matan & Carey, 2001), our toddlers displayed no preconceived ideas about the correct way to use a handrail and made no a priori inferences about their use. Like German and Defeyter's (Defeyter & German, 2003; German and Defeyter, 2000) 5-year-olds who could devise novel uses for familiar objects in a problem-solving task, the infants in our study found creative ways to make the novel wobbly handrails work as effective tools. In contrast, we, as the experimenters who designed the wobbly handrails, were more like German and Defeyter's (Defeyter & German, 2003) 6- and 7-year-olds who could not overcome their functional fixedness. Just as they could not see that a box could be used both for storage and as a stool to reach an object, we had not anticipated that infants could invent new locomotor strategies allowing them to use a wobbly handrail for balance control.

In addition to their cognitive flexibility, the joy of movement may have inspired infants to devise new handrail strategies. Harlow and Mears (Harlow & Mears, 1979; Mears, 1978) coined the term peragration to describe infants' urge to move their body to a new location simply to delight in the exercise of movement. They described infant rhesus monkey's persistence in active locomotor play, even after their playrooms were stripped of all toys and accessories. The infants turned a small knob in the wall into a piton, like a mountaineering tool for launching themselves onto a ceiling ledge, for the sheer pleasure of transporting themselves to the new location (Mears, 1978). Reminiscent of such peragration, human infants in the bridges/handrails study persisted in solving the problem of crossing the bridges even when only the wobbly handrails were available.

### *Out of the Toolbox: What Develops?*

Traditionally, polemics about tool use center around the cognitive underpinnings of using handheld objects as a means to achieve a goal: for example, nonhuman primates' use of a stick to rake in a food lure (Hauser et al., 2002; Köhler, 1925) or to collect insects from a termite mound (Nash, 1982); babies' use of a rake or cane to retrieve a toy; children's mastery of conventional tools such as spoons and writing implements (Brown, 1990; Chen & Siegler, 2000; Leeuwen et al., 1994; Lockman, 2000; McCarty et al., 1999, 2001; Steenbergen et al., 1997). We have argued that whole-body tool use requires the same three critical psychological achievements as those involved in using handheld tools. Infants must recognize a discrepancy between their bodily abilities and the desired goal. They must find an alternative means to achieve the goal via an object in the environment and transport and/or orient the tool appropriately relative to the target. Morever, infants must implement the appropriate perceptual-motor behaviors to incorporate the external object into the action plan.

Accordingly, infants in this study demonstrated many of the components of whole-body tool use. They treated the narrow bridges as barriers to reaching their goal and recognized that they could not walk over them using their typical locomotor method. Individual differences in walking experience predicted infants' attempts to cross the 10 cm bridge and failures on the 20 cm bridge. Presumably, a younger sample of infants with less walking experience would not have perceived affordances as accurately and would have rashly attempted to walk over impossibly narrow bridge widths. New walkers, for example, do not scale their walking attempts to the slant of a slope or the size of a gap in the floor (Adolph, 1997, 2005; Adolph & Berger, 2005).

In this study, after recognizing the necessity of a tool, infants searched for alternative means by exploring the structural and material properties of the handrails that spanned the walkway. Certainly, much younger infants also demonstrate means–ends problem solving by pulling cloths to retrieve objects, lifting covers to reveal hidden objects, pushing buttons to drop barriers, and so on (Munakata, McClelland, Johnson, & Siegler, 1997; Piaget, 1952; Willatts, 1999). Expanding on previous work, this study demonstrated that infants take material properties into account for assessing the adequacy of an object as a means for achieving a goal. Unfortunately, due to practical constraints in the design of our bridge apparatus, we could not assess whether infants could create a relationship between tool and target by bringing the handrail to the bridge and orienting it appropriately to span the precipice from starting to finishing platforms. However, in a comparable task, McGraw's (1935) work with Jimmy and Johnny showed that by approximately 16 months infants demonstrate the wherewithal to bring a stepping stool to the location of an overhead lure, suggesting that they have in their repertoires the basic array of necessary skills for bona fide tool use (although they may not yet be able to solve more complicated problems involving seriating stools to reach the lure).

Finally, infants in this current study were able to incorporate even the wobbly handrails into their plan for reaching the goal by devising clever, new, bridge-crossing strategies on narrow bridges. On trials with the rigid handrail, infants typically faced the rail, grasped the rail with both arms while leaning forward, and inched along sideways. However, on trials with the wobbly rails, infants used both light- (grazing the hand along the rail) and heavy-touch strategies (leaning backward, pulling up on the rails, facing forward, etc.) for crossing successfully. Such inventive and skillful implementation of a tool may lag behind perceiving affordances and means–ends problem solving in the development of tool use. For example, 21-month-olds sometimes selected appropriate rakes and canes to retrieve a lure, but still failed to retrieve the target. By 31 months of age, children's implementations were largely successful (Chen & Siegler, 2000).

In sum, the infant tool user displays a sophisticated capacity to discover means for augmenting whole-body actions. This capacity involves a series of exploratory behaviors. Visual inspection of the barrier to a goal prompts tactile exploration of material substance. Means–ends exploration precedes selection of an appropriate strategy. Such a capacity for whole-body tool use may even provide the foundation for exploiting the sorts of handheld implements found in a toolbox or hanging from a handyman's belt.

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