

Walking skill versus walking experience as a predictor of barrier crossing in toddlers

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Abstract

The aim of this study was to examine the roles of body size parameters, walking skill, and locomotor experience in determining the abilities of 14-, 18-, 24-, and 30-month-old toddlers to cross a barrier varying in height. Thresholds for barrier crossing were measured using a modified psychophysical staircase procedure, walking skill was assessed using a footprint analysis of gait, and locomotor experience via parental report. Overall, older children surpassed younger children in measures of body size, walking skill, locomotor experience, and crossing thresholds. Analyses relating the various body size, skill, and experiential parameters to crossing thresholds revealed that, replicating earlier findings, barrier crossing was most strongly related to walking experience. These findings are discussed in terms of the limitations of different forms of skill assessment as predictors of visually guided locomotor ability. © 2000 Elsevier Science Inc. All rights reserved.

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1. Introduction

The first year of an infant's life represents a period of dramatic change in which a number of important developmental milestones are reached. One particularly important development during this time is the acquisition of independent mobility. Learning to crawl and walk is an incredible accomplishment, and represents a feat not easily achieved (Adolph et al., 1993a). One key aspect in the acquisition of such abilities is a significant growth in motor skill, requiring the maturation of both skeletal and neuromuscular systems (Thelen et al., 1987).

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The ability to move independently throughout the world is not the result of motor development alone, however; perceptual sensitivity to the surrounding environment is also critical (Gibson, 1988; Gibson & Schmuckler, 1989; Schmuckler, 1993, 1996). Haptic, auditory, and visual sources of information all play a role in guiding our actions. For example, vision is useful in choosing the most appropriate mode of locomotion depending upon properties of the ground surface (e.g., Gibson et al., 1987), locating a destination, and picking the actual path to be taken (Gibson & Schmuckler, 1989). Once on the move, visual information is continually useful in maintaining balance in static and dynamic postures (Schmuckler, 1997; Schmuckler & Gibson, 1989), as well as in maintaining one's direction of movement, and picking a path around obstacles (Schmuckler, 1995; Schmuckler & Gibson, 1989) and over barriers (Schmuckler, 1996).

Thus, successful action is a simultaneous function of perceptual sensitivities and motor capabilities, with perception guiding our actions, and action in turn participating in perception (e.g., Gibson, 1988); this functional interdependence between perceptual and motor systems has been called "perception-action coupling" (e.g., Hofsten, 1989; Pick, 1984, 1989; Prinz, 1984; Reed, 1982, 1989; Schmuckler, 1993). One example of this type of inter-relation between perception and action systems is seen in the concept of affordances (Adolph et al., 1993b; Gibson, 1982, 1988; Gibson, 1979; Michaels & Carello, 1981; Stoffregen, 2000). An affordance is the link between perception and action (Gibson, 1982, 1988) in which the performance of a given action is based on the "fit" between the physical capabilities of the actor and the constraints imposed by the environment (Gibson, 1979).

Much research has been conducted with the goal of identifying the basis of this actor-environment fit. Experimental investigations of adult actors' perceptions of the affordances involved in locomotion (e.g., Burton, 1992; Heinrichs, 1994; Heinrichs et al., 1993; Konczak et al., 1992; Warren, 1984; Warren & Whang, 1987) have revealed three main findings. First, successful performance of basic locomotor actions, such as climbing stairs or moving through doorways, is most strongly related to an actor's body size, and not to any absolute measure; accordingly, such action is called "body-scaled" (Heinrichs, 1994; Schmuckler, 1996; Warren, 1984; Warren & Whang, 1987). Second, perceptual judgments of capabilities are categorical; once a critical point has been reached, judgments of capabilities change from "able" to "unable" (Heinrichs, 1994; Warren, 1984). And third, perceptual judgments are related to actual action capabilities, with relatively accurate perceptual assessments of locomotor capabilities (Maraj & Domingue, 1999; Mark & Voegelé, 1987; Warren, 1984). Interestingly, these perceptual judgments appear to be body-scaled as well (Warren, 1984).

Body size is not the only possible candidate for the scaling of action, however; other possibilities include perceptual-motor proficiency (e.g., skill), factors related to physical ability (e.g., leg strength, flexibility, and balance), and perceptual-motor experience (Schmuckler, 1996). Unfortunately, because much of the work investigating the scaling of action has employed adults performing basic, highly overlearned behaviors such as stair climbing or sitting (e.g., Mark, 1987; Mark & Voegelé, 1987; Warren, 1984), skill, experience, and physical ability have not varied to any great extent, making it unlikely that variation in action would be related to such factors. In one notable attempt to assess the role of alternative variables, Konczak et al. (1992) compared the stair climbing abilities of younger and older adults, who presumably had more variability in terms of perceptual-motor

proficiency, and found that the action capabilities of the older age group were determined by both anthropomorphic and ability constraints. One possibility is that experience with their reduced physical abilities increased the older adults' awareness of these constraints, resulting in an increased role of variables such as leg strength and flexibility.

An alternative to looking at the role of anthropomorphic variables, proficiency, and factors such as strength, flexibility, and balance in aging populations is to explore the importance of such variables in young children. Some work on perception-action coupling in older children has found scaling of action to anthropomorphic measures. For instance, Heinrichs (1994) investigated adults' and five-year-old children's ability to cross barriers of increasing height and found that transition points in crossing (e.g., moving over to moving under, or moving under with support to bending under) were a function of leg length. Likewise, Pufall and Dunbar (1992), looking at 6-, 8-, and 10-year-old children's perceptions of affordances for stepping onto versus over objects, found that by age six perceptual judgments of action capabilities were also scaled to leg length.

In contrast, work with younger children has observed that anthropomorphic measurements are less useful predictors for action capabilities; rather, locomotor experience and skill better predict the abilities of toddlers (Adolph, 1995; Schmuckler, 1996; Ulrich et al., 1990). For example, Ulrich et al. (1990) looked at the roles of muscular strength, leg length, and postural constraints in determining the riser heights that afforded stairclimbing in 8- to 20-month-old infants. In this study, infants had to choose one of three staircases, differing in riser height, to climb. For 8- to 15-month-old infants, differences in choices were related to locomotor capabilities such as walking and stair climbing experience and not to variations in body build. In contrast, for 20-month-old infants neither body size nor walking experience predicted stair choices; in fact, no pattern was evident for these infants' initial choice. One possibility is that once a certain level of skill is achieved, the riser heights used in this experiment no longer represented a constraint, or varying degrees of difficulty, for these older infants.

In a similar vein, Schmuckler (1996) investigated the abilities of 1- to 2½ -year-old toddlers to cross barriers varying in height as well as spatial extent and transparency. In this study, Schmuckler calculated the threshold heights at which children successfully (versus unsuccessfully) crossed a barrier and then related these thresholds to various anthropomorphic and experiential variables. In keeping with the previous findings with young children (e.g., Ulrich et al., 1990), but in contrast with the results from older children and adults (e.g., Heinrichs, 1994; Pufall & Dunbar, 1992; Warren, 1984), crossing thresholds were most strongly scaled to variations in walking experience, and not to differences in body size.

Schmuckler (1996) hypothesized that experience (which presumably includes skill) predicted action because the toddlers in these studies varied considerably in their abilities to perform the perceptual-motor task of barrier crossing; this variation in perceptual-motor skill, then, constrained action. In contrast, anthropomorphic variables (such as leg length) will become useful predictors only when ability no longer varies to any great extent, as would occur once a mature level of skill has been reached (Heinrichs, 1994; Schmuckler, 1996).

The hypothesis of walking experience as an explanatory variable for action is limited in some important ways, however. First, because walking experience is frequently measured through retrospective parental reports, it is often difficult to reliably index (e.g., Walk, 1966).

Second and more importantly, walking experience is at best only an approximate indicator of walking skill. Although experience and skill are positively correlated in the development of walking (Bril & Brenière, 1992), they nonetheless represent two distinct concepts.

Walking experience refers to the length of time (measured in days, weeks, or months) between the onset of walking and any particular temporal landmark (i.e., the occurrence of an experimental test), and thus reflects opportunities for learning about action and the environment (Schmuckler, 1996). This particular definition, however, does not make clear what activities contribute to or make up such “learning opportunities” (Adolph, 1995). Nor does it make clear how many learning opportunities a child may have. Although researchers try to match experience levels by holding age constant, this procedure does not guarantee equivalence in actual experience. As such, walking experience is something of a catchall used to define children’s general experience of moving independently throughout the world.

Walking skill, on the other hand, involves the interplay of a number of contributing variables, such as strength, flexibility, balance, and interlimb coordination (Heinrichs, 1994; Schmuckler, 1996), to name a few. And unlike walking experience, it can be reliably and objectively measured (Adolph, 1995). Differences in walking skill between children may reflect differences among any combination of these variables. For instance, regardless of experience, some children are better walkers from the moment they take their first steps. Or, some children may show vast improvements over short periods of time during which others may struggle (Adolph, 1995). Thus, when investigating differences in action capabilities between children, it is important to use measures that both encompass these concepts and reflect any true developmental differences among the sample.

Only two studies to date have specifically addressed the conceptual difference between walking skill and walking experience in young children (Adolph, 1995; Adolph et al., 1993a). Adolph et al. (1993a) looked at 8.5- and 14-month-old toddlers’ perceptual judgments as to whether a hill was safe for climbing up and down, and examined the relative contributions of walking experience, walking skill, and body proportions to these judgments. Four predetermined slopes (10°, 20°, 30°, and 40°) were presented in both ascending and descending order. For the ascending slopes, walking skill was the better predictor for the abilities of the 14-month-old toddlers. For the descending slopes, none of the variables predicted performance, although only two of the four slopes were actually perceived as walkable by the children, with alternative methods of descent (e.g., sliding) used for the remaining two slopes. Because of the greatly reduced data set for the descending slopes, the researchers argued that their finding was exploratory at best. Neither crawling experience nor skill were useful predictors for the behavior of the younger group.

In a follow-up study, Adolph (1995) used a psychophysical staircase procedure to determine the walking boundaries of 14-month-old toddlers. In this procedure toddlers received increasingly steep slopes until an angle was reached at which they either failed or refused to ascend. The process was then reversed, with the angle of the slope becoming less severe until the toddlers could once again successfully descend the slope. Walking boundaries were defined as the steepest slope that children could successfully climb up while failing to ascend the next steepest increment (for details, see Adolph, 1995). Using this procedure, Adolph again found walking skill to be the best predictor for both ascent and descent boundaries.

From the research disentangling the relative roles of skill and experience (e.g., Adolph, 1995; Adolph et al., 1993a), walking skill appears to be better than walking experience at predicting the action capabilities of toddlers. This finding, however, is limited in that it has focused on only a single perceptual-motor action (e.g., ascending and descending slopes) at a single age (i.e., 14 months). To be considered as a fundamental factor in perception-action coupling, it is important that a similar relation be observed across a variety of perceptual-motor feats, and potentially across a range of different ages. Examining this relation is one of the primary goals of this experiment.

This issue was examined by investigating the roles of body size, walking skill, and walking experience in determining the action capabilities of 14- to 30-month-old toddlers for crossing a barrier varying in height. Barrier crossing creates an ideal situation for investigating perceptual-motor behavior and its impact on the perception of affordances. Both physical and perceptual constraints determine an individual's ability to successfully cross a barrier. In choosing the best course of action, an actor must be able to accurately perceive the height and width of the barrier and take into account his/her physical capabilities and limitations in executing the movements needed to cross (Schmuckler, 1996).

Moreover, the actions involved in barrier crossing are very different from those involved in slope ascent and descent—a scaling of action to walking skill for this task would provide further support for its role as a fundamental factor in perception-action coupling. Although the act of crossing a barrier can be accomplished in more than one way (e.g., see Heinrichs, 1994), the primary interest in this study are the movement patterns involved in stepping over a barrier.

For very low barriers, successfully stepping over simply entails taking a higher step than normal. Higher barriers, on the other hand, necessitate a more complicated series of movements and an interplay of strength, flexibility, and balance. For example, now the actor must shift his body weight to one leg, and maintain his balance while raising the other leg up and over the barrier. Once this leg is firmly planted on the other side, he must reshift his weight to bring the lagging leg across. As the height of the barrier continues to increase, so too does the level of difficulty involved. These movement patterns rely, to varying degrees, on the various factors that determine a toddler's skill at walking—as mentioned previously, the interplay of strength, flexibility, balance, and interlimb coordination (Heinrichs, 1994; Schmuckler, 1996).

A second goal of this experiment was to assess whether an existing measure of walking skill (see Adolph, 1995; Adolph et al., 1993a) is useful as a global measure of children's locomotor skill and perceptual-motor proficiency. Previous investigations of walking skill (e.g., Adolph, 1995) have used the footprint method of gait assessment in which the inked footprint sequences of a child's walking pattern are compared to the mature pattern of adults (Adolph, 1995; Adolph et al., 1993a; Adolph et al., 1996; Boenig, 1977). In general, improvements in walking skill are associated with longer steps and strides, shorter step widths, smaller foot rotations, and straighter paths of progression (see Adolph, 1995; Adolph et al., 1996). Greater proficiency in walking reflects the increasing refinement of the skeletal and neuromuscular systems implicated in independent locomotion (Pufall & Dunbar, 1992). For instance, weak leg extensor muscles and poor balance control are believed to underlie the pattern of gait associated with very immature walkers, who, by taking small steps with their feet spread apart, are able to widen their base of support (Adolph et al., 1996).

Because walking and the movements necessary for barrier crossing both rely on similar

factors, such as strength, flexibility, and balance (Heinrichs, 1994; Schmuckler, 1996), it is quite possible that the footprint analysis reflects a global measure of perceptual-motor proficiency in toddlers. As such, this measure should be applicable as a predictor of action capabilities for a variety of locomotor behaviors. In contrast, it might be that the utility of this measure is more specific to tasks involving strict locomotion, and as such will not be applicable as a global measure of locomotor skill. Although each of the variables of interest (e.g., strength, flexibility, and balance) can be measured independently, these tests often require the use of constraining equipment, such as force plates or motion analysis systems, that are impractical when testing very young children. Moreover, even with assessment procedures that are not technologically constraining (see Heinrichs, 1994), such tests often require children to perform tasks (e.g., balance on one leg) that are simply not practical for below about 5 years of age,¹ and have correspondingly not been standardized for such a young group. The footprint analysis of gait assessment provides an alternative and reliable measure (see Adolph, 1995) that can easily be administered to very young children.

2. Method

2.1. Participants

Seventy-six toddlers participated in this study, 16 toddlers (6 male) at 14-months of age and 20 toddlers each at 18 months (8 male), 24 months (14 male), and 30 months (9 male) of age. The mean age of each group was 13.9 months ($SD = 0.50$), 18.0 months ($SD = 0.66$), 24.6 months ($SD = 0.75$), and 30.4 months ($SD = 0.83$), respectively. An additional 55 children (9 fourteen-month-olds, 29 eighteen-month-olds, 9 twenty-four-month-olds, and 8 thirty-month-olds) participated in the study but were not included in the data analysis. These children were excluded from the study because they either did not successfully complete one or both portions of the study. Specific reasons related to the walking assessment portion of the study included: running on the paper (16), refusing to walk (6), stopping halfway or walking off of the paper (6), refusing to wear shoes (1), as well as missing videotapes (2). Reasons related to the barrier crossing assessment portion included: refusing or failing to ever cross the barrier, crawling over the barrier, or becoming too upset to participate such that a threshold could not be determined (11). And finally, a number of children (13) were excluded because of problems with both the walking assessment and barrier crossing portions of the study. All infants were recruited from the Scarborough, Ontario, community and received a toy and certificate for their participation. Detailed information regarding parental socioeconomic status and ethnic identity was not collected.

2.2. Experimental apparatus and procedure

Testing took place in a long hallway with separate areas designated for walking skill and barrier crossing assessments. A video camera mounted on a tripod at one end of the hallway recorded the entire experimental session. Each session began with the assessment of walking skill followed by the barrier crossing procedure.

2.2.1. *Walking skill assessment*

For the assessment of walking skill, a 6 m long strip of paper was placed on the floor, with lines drawn on opposite ends demarcating the starting and finishing point. The child's parent stood at the finishing line and the child was placed at the starting line, and two experimenters positioned themselves on either side of the length of the paper. The child was then encouraged to walk along the paper to the waiting parent. For each test session, several practice trials were run to ensure that the child would walk the length of the paper and not stray from the path. If a child ran, the task was modeled by either the parent or the experimenter to demonstrate that walking was the desired behavior.

After a number of practice trials, inkpads were placed on the child's feet. For ease of application, the inkpads were attached to pieces of cardboard that could be easily taped to the bottoms of a child's shoes, with the bottom edge of each card placed in line with the edge of the child's heel. Each inkpad card was a 10.2×3.8 cm strip of cardboard with a triangular piece of moleskin attached to the top (toe end) edge of the card, and a square piece of moleskin attached to the bottom (heel end) edge of the card. Liquid ink was applied to the moleskin immediately prior to the cards being placed on the child's shoes. Once the inkpad cards were attached, the child was positioned at the starting line and again encouraged to walk towards his/her parent. Upon reaching the finishing line, the parent picked up the child and an experimenter removed the inkpad cards. The trial was repeated with a fresh strip of paper if the child ran along the paper, stopped halfway, or turned around during the trial.

2.2.2. *Barrier crossing assessment*

The barrier crossing component of the study began after the walking skill assessment, using the barrier apparatus employed in previous crossing studies (Schmuckler, 1996). The barrier consisted of two gray, hollow vertical poles, 3.5 cm thick, each supported by a steel base. Each of these poles had notches cut into them in 2.5 cm increments from top to bottom. A gray, plastic dowel, approximately 1.4 m long and 2 cm thick, stretched horizontally between these two poles, supported by the notches. The notches allowed the horizontal dowel to be positioned from 2.5 cm off the ground up to 45.7 cm. A 4.6 m long by 1.5 m wide pathway was created in a hallway; gymnastic mats, 3 cm thick, lined the floor to protect toddlers from falls. The barrier was positioned two-thirds of the way down the pathway and in line with a recessed doorway in the hallway. Again, two experimenters were responsible for running this portion of the experiment. Positioned at opposite ends of the pathway, the first experimenter and one of the child's parents (at the end closer to the barrier) encouraged the child to approach and cross the barrier. The second experimenter, positioned in the recessed doorway and hidden from view, adjusted the barrier's height.

At the beginning of the barrier crossing assessment, the child acclimatized to the experimental situation by playing with a pile of toys at the parent's end of the pathway. Once the child appeared comfortable, she was brought to the experimenter's end of the pathway. The barrier was adjusted to the appropriate height for that trial, and the child was then encouraged to cross the barrier to get a toy from the parent. Receiving a toy at the end of each trial, once the child has crossed the barrier, differs from the Schmuckler (1996) study in which a child carried a toy to their parent. This methodological change grew out of a concern in the Schmuckler study that the child's balance may have been affected by not having her hands

free when crossing the barrier, as well as to avoid the problem that a child may have taken more toys than she could handle; both of these demands may disrupt a child's attention from the act of crossing.

Parents were told they could provide verbal encouragement to their child but were discouraged from either physically helping their child cross, or from sitting too close to the barrier such that the child need not cross the barrier to get a toy. If necessary, the act of crossing was modeled for a child at the beginning of the barrier crossing session. Once the child had crossed, the barrier was removed and the child was induced back to the starting point. The barrier was then placed at its next height (see below), and the entire process was repeated.

At the end of the session, anthropomorphic body size measures (see below) were assessed and parents were questioned as to their child's locomotor experience. The entire experimental session (walking skill and barrier crossing assessments) lasted approximately 45 to 60 min.

2.3. *Dependent measures*

2.3.1. *Walking skill*

Walking skill was quantified using information derived from the inked footprint sequences of the toddlers (Adolph, 1995; Adolph et al., 1993a; Adolph et al., 1996; Boenig, 1977). This analysis focused on the middle portion of each child's traverse down the pathway. It is this section of a continuous gait cycle at which it is believed that children hit their most natural stride (Brenière et al., 1989). A minimum of three footprints per leg were examined for all children. For each footprint, XY coordinates of the tip of the toe print and the midpoint of the heel print were obtained using a transparent grid placed over the footprint sequence. The resolution of the grid was 0.25 cm.

Using the XY footprint coordinates, a variety of skill related measures were calculated, including stride length, step length, step width, foot rotation, and dynamic base. Stride length is the distance between heel prints of the same foot. Step length is the distance between the heel strike of one foot and the heel strike of the other foot. Step width is a measure of the lateral distance between the heel strike of one foot and the heel strike of the other foot. Foot rotation involves the angle of a child's toe relative to their heel (i.e., toe-in or toe-out); children who are more skilled at walking point their feet straight ahead (Adolph, 1995; Adolph et al., 1996). Finally, dynamic base measures the "angle between the stride of one foot and the step on the other foot" (Adolph, 1995); this angle can be obtained from looking at three [dynamic base (3)] or four [dynamic base (4)] step sequences. Dynamic base reflects how well children control their path of progression, with improvements in walking skill indicated by dynamic base angles approaching 180° (Adolph, 1995).

2.3.2. *Barrier crossing*

Barrier crossing thresholds were determined using a version of the modified psychophysical staircase procedure originally developed by Cornsweet (1962). In the original procedure, subjects are presented with stimuli in increasing increments until a change in behavior or response occurs. The process is then repeated in reverse, with the stimuli presented in

decreasing order until a change in responding again occurs. This pattern of alternating between increasing and decreasing increments is continued with each change in response until a predetermined criterion has been met, at which point a measure of threshold is taken (Adolph, 1995; Cornsweet, 1962; Schmuckler, 1996).

In the current situation, crossing behavior was coded on-line as a success (e.g., able to step over the barrier without knocking it down), a failure (e.g., barrier is knocked down during the act of crossing), or a refusal (e.g., a child refuses to approach the barrier and/or makes no attempt to cross). In addition to these three categories, special notations were used for attempts to crawl over the barrier or if the side of the barrier was held while crossing. As the desired action was unsupported barrier crossing (i.e., stepping over without holding on to anything) from an upright stance, trials were repeated following crawling or supported crossing attempts.

Each infant began the session with a low barrier height (7.6 cm). If the child successfully crossed the barrier twice in a row at this height, the barrier was raised two increments (note: each increment equaled 2.5 cm); such increases continued until a failure or refusal to cross occurred.² Following this change in behavior, the barrier height was lowered one increment. If the child remained unable to cross, the barrier height was again dropped one increment. Thus, increases in barrier height occurred if the infant could successfully cross two times in a row; a single unsuccessful cross resulted in a decrease. To avoid frustration at repeated failures and to break up any patterns of supported crossing, trials at a very low height were interspersed throughout the experiment (Schmuckler, 1996).

One consequence of this procedure is that the number of attempts at specific heights varied from child to child depending on ability. For example, some children showed patterns of successively increasing heights before reaching a height they could not cross. Others alternated between successes and failures at similar heights. Interestingly, few refusals to cross were seen; in many cases, a child's refusal signaled the end of the session as opposed to the end of a trial. As such, a child's crossing threshold was determined as the barrier height the child was able to cross (i.e., having at least one success) while failing to cross the next height on all attempts (i.e., no successes).³

An additional consequence of this procedure is that the number of trials completed by each child varied depending on the height of the threshold, attention to the task, and so on. In practice, all children completed a minimum of 7 trials in threshold determination. The mean number of trials was 19.1, 28.0, 31.4, and 37.4 for the 14-, 18-, 24-, and 30-month-old infants, respectively.

2.4. *Body size variables*

Anthropomorphic body size measures included body weight, standing and sitting height, and shoulder, waist, and hip widths. For body weight, the children stood on a standard bathroom scale with a digital readout. For height measurements, a measuring tape was placed on a nearby wall, and the child was induced to stand and sit with his back against the wall. Measures of weight and height were taken with a child's shoes on. Width measurements were obtained by wrapping a measuring tape around the child's shoulders, the area around his navel, and the area above his pelvic bone, for shoulder, waist, and hip measures, respectively.

Using these values, a number of additional body size variables were calculated, including leg length (standing height – sitting height), Ponderal Index (weight/(standing height)³ × 100), and a ratio of shoulder width/waist width. In children, small values of Ponderal Index (kg/cm³) and the shoulder-to-waist ratio are associated with more mature body proportions (Adolph, 1995).

2.5. Locomotor experience

Parents were asked to consult any personal records prior to their visit to the laboratory regarding information concerning the onset of crawling, independent standing, and upright locomotion for their child. Crawling was defined as the age at which children could move across the floor on their hands and knees. Independent standing was defined as the age at which children could stand on their own without support. Upright locomotion was defined as the age at which children could stand on their own, without any help, and walk 10 steps across a room (Schmuckler, 1996).

3. Results

A number of goals were addressed in the data analysis. The first series of analyses determined if, in fact, the various measures of interest differed as a function of age. Although not addressing the primary question of interest (i.e., the scaling of action to measures of body size, skill, or experience), these analyses are important as they demonstrate the validity of the various measures by quantifying developmental change across the ages examined.

The second series of analyses examined the primary question of interest per se, the scaling of action in toddlers. A normalization procedure was used to examine the relation between crossing thresholds and the various anthropomorphic, walking skill, and experiential measures. In this procedure, a child's crossing threshold was divided by each measure, with the resulting normalized thresholds then compared as a function of age using a one-way ANOVA.

This procedure, developed by Schmuckler (1996), was adapted from Warren (1984) who found that differences in the maximum height of perceived stair climbability between short and tall participants were eliminated when these judgments were normalized (divided) by the participants' leg length. In the current context, factors that are most strongly related to crossing thresholds should eliminate differences in threshold, both within and between age groups. In contrast, variables less strongly related to thresholds may reduce, but not eliminate, such differences (Schmuckler, 1996).

Prior to these analyses, however, an initial analysis examined whether the walking skill measures varied as a function of left versus right foot within the four age groups. A series of two-way analyses of variance (ANOVAs) were conducted with the within-subject factor of foot (left vs. right) and the between-subject factor of age (14 vs. 18 vs. 24 vs. 30 months). Of the six walking skill measures, only two significant effects of foot (right vs. left) and one significant interaction between foot and age were found. Overall, larger measures of dynamic base (4) [$F(1, 162) = 10.8$, $MSE = 649.9$, $p < .005$] were found for the left foot [$M =$

145.3°, $SD = 26.2^\circ$) than the right foot [$M = 132.4^\circ$, $SD = 24.6^\circ$]. In contrast, larger foot rotations were found for the right foot [$M = 13.2^\circ$, $SD = 9.1^\circ$] than for the left foot [$M = 10.6^\circ$, $SD = 6.2^\circ$] [$F(1, 162) = 5.2$, $MSE = 53.1$, $p < .05$]; however, this difference was qualified by a significant interaction between foot and age [$F(3, 162) = 2.8$, $MSE = 53.1$, $p < .05$]. Posthoc analyses (Tukey HSD test) revealed that the mean right foot rotation of the 14-month-old toddlers differs significantly from almost all other left and right foot rotation values ($p < .01$); the one exception is a marginal difference with the mean right foot rotation of the 18-month-olds ($p = .07$). Given the general lack of differences as a function of left versus right foot, and of interactions between foot and age for the remaining measures (all $ps > .05$), walking skill measures were averaged across left and right feet for all subsequent analyses.

3.1. Age differences

A series of one-way ANOVAs, using the between-subject variable of age (14 vs. 18 vs. 24 vs. 30 months) compared children on the anthropomorphic, walking skill, and experiential factors, as well as the crossing thresholds; mean values for these variables are given in Table 1. Given the large number of statistical tests employed in this and the following sections, a more stringent level of statistical significance is called for in evaluating these comparisons. Accordingly, only p values less than .01 will be noted as statistically significant. Addressing the anthropomorphic measures first, significant differences were found for standing height [$F(3, 72) = 133.7$, $MSE = 7.8$, $p < .001$], sitting height [$F(3, 72) = 28.2$, $MSE = 5.1$, $p < .001$], leg length [$F(3, 72) = 108.2$, $MSE = 3.8$, $p < .001$], body weight [$F(3, 71) = 23.4$, $MSE = 2.6$, $p < .001$],⁴ waist width [$F(3, 72) = 6.1$, $MSE = 11.9$, $p < .001$], hip width [$F(3, 72) = 4.5$, $MSE = 12.0$, $p < .01$], shoulder width [$F(3, 72) = 11.0$, $MSE = 9.4$, $p < .001$], and Ponderal Index [$F(3, 71) = 12.9$, $MSE = 0.0$, $p < .001$]. Generally, older children were taller, heavier, and larger than younger children. Not all anthropomorphic measures varied as a function of age, however. Specifically, no difference between ages was found for shoulder-to-waist ratio [$F(3, 72) = 0.7$, $MSE = 0.005$].

Analyses of walking skill also showed many significant differences as a function of age; mean values for these variables also appear in Table 1. Significant differences were found for stride length [$F(3, 72) = 11.4$, $MSE = 139.5$, $p < .001$], step length [$F(3, 72) = 9.8$, $MSE = 31.7$, $p < .001$], step width [$F(3, 72) = 4.6$, $MSE = 6.3$, $p < .01$], foot rotation [$F(3, 72) = 4.5$, $MSE = 25.3$, $p < .01$], and dynamic base (3) [$F(3, 72) = 11.5$, $MSE = 126.0$, $p < .001$]. No significant differences were observed for dynamic base (4) [$F(3, 72) = 0.8$, $MSE = 52.1$].

A closer look at the data reveals that the values obtained for the youngest age group are driving these differences. Posthoc analyses (Tukey HSD test) reveals that the 14-month-old toddlers differed from the three older age groups ($p \leq .05$) on numerous measures. Overall, the 14-month-olds had shorter strides, larger step widths, and smaller measures of dynamic base (3) than all three of the older ages. In addition, the youngest age group also had smaller steps and greater foot rotations than the 24- and 30-month-old toddlers. Looking at the older toddlers, few differences between the ages were found. Thirty-month-old toddlers had significantly longer strides and steps than eighteen-month-old toddlers ($p < .05$), with

Table 1

Means (standard deviations) for measures of body size, walking skill, locomotor experience, and crossing thresholds

	14 Months	18 Months	24 Months	30 Months
<u>Body Size</u>				
Standing height (cm)	75.77 (2.52)	81.60 (2.92)	87.72 (2.89)	93.28 (2.73)
Sitting height (cm)	45.08 (2.05)	47.94 (1.72)	50.20 (2.49)	51.62 (2.64)
Weight (kg)	8.62 (1.34)	10.05 (1.57)	12.20 (1.54)	12.52 (1.90)
Leg length (cm)	30.69 (1.49)	33.66 (2.08)	37.53 (2.49)	41.66 (1.50)
Waist width (cm)	48.93 (3.46)	49.69 (3.39)	50.29 (3.52)	53.37 (3.42)
Hip width (cm)	51.95 (3.44)	54.10 (2.90)	55.44 (3.90)	55.88 (3.56)
Shoulder width (cm)	57.98 (3.08)	58.64 (3.38)	60.86 (3.30)	63.15 (2.41)
Ponderal Index (kg/cm ³)	0.002 (0.0002)	0.002 (.0002)	0.002 (.0002)	0.002 (.0002)
Shoulder-to-waist ratio	1.19 (0.06)	1.18 (0.07)	1.21 (0.07)	1.19 (0.08)
<u>Walking Skill</u>				
Stride length (cm)	51.64 (7.64)	62.37 (12.14)	69.08 (13.45)	73.48 (12.42)
Step length (cm)	28.38 (3.20)	32.34 (5.89)	35.95 (6.53)	37.83 (5.89)
Step width (cm)	11.16 (2.37)	8.24 (2.45)	8.95 (2.85)	8.67 (2.32)
Foot rotation (°)	15.38 (7.58)	11.61 (3.88)	10.84 (4.01)	9.38 (4.41)
Dynamic base (3) (°)	132.13 (13.24)	149.11 (10.60)	149.88 (11.78)	152.40 (9.36)
Dynamic base (4) (°)	139.75 (5.13)	139.50 (7.52)	136.69 (7.87)	139.23 (7.64)
<u>Locomotor Experience</u>				
Crawling (months)	7.07 (2.06)	10.46 (1.40)	17.12 (1.90)	22.88 (1.90)
Standing (months)	5.22 (1.86)	8.94 (1.64)	14.55 (2.06)	19.95 (1.77)
Walking (months)	2.84 (1.33)	6.00 (2.04)	12.36 (2.29)	18.45 (1.57)
<u>Crossing Threshold</u>				
Height (cm)	4.44 (2.36)	12.95 (4.51)	22.61 (4.87)	30.99 (5.38)

twenty-four-month-old toddlers in between the two. No other significant differences were observed between the ages.

The experience measures were also found to vary across the ages, with significant differences in crawling [$F(3, 66) = 251.4$, $MSE = 3.3$, $p < .001$],⁵ standing [$F(3, 72) = 226.6$, $MSE = 3.4$, $p < .001$], and walking [$F(3, 72) = 254.1$, $MSE = 3.5$, $p < .001$] variables. Overall, and not surprisingly, older children had more locomotor experience than younger children. Again, mean values for these variables appear in Table 1.

Finally, crossing thresholds varied as a function of age [$F(3, 72) = 118.1$, $MSE = 20.41$, $p < .001$], with posthoc analyses (Tukey HSD test) revealing significant differences between all four ages (all $ps < .001$); mean thresholds appear in Table 1. Older children were successfully able to cross barriers much higher in height than younger children.

Thus, differences within all of the categories (body size, skill, experience, and thresholds) were found between the ages. Although skill measures showed less variation than the others, the fact that some measures varied does suggest face validity of the measures. One of the subsidiary goals of this study was to obtain normative data documenting changes in walking skill as a function of age using the footprint analysis of gait assessment. Although few age differences were found between the three older age groups, the mean values obtained are

Table 2

Results of one-way ANOVAs on normalized crossing thresholds as a function of body size, walking skill, and locomotor experience

Variable	14, 18, 24, and 30 months
<u>Body Size</u>	
Standing height	$F(3, 72) = 100.08$
Sitting height	$F(3, 72) = 103.03$
Weight	$F(3, 71) = 57.75$
Leg length	$F(3, 72) = 89.13$
Waist width	$F(3, 72) = 103.00$
Hip width	$F(3, 72) = 103.95$
Shoulder width	$F(3, 72) = 96.67$
Ponderal Index	$F(3, 71) = 96.64$
Shoulder-to-waist ratio	$F(3, 72) = 95.87$
<u>Walking Skill</u>	
Stride length	$F(3, 72) = 59.62$
Step length	$F(3, 72) = 66.56$
Step width	$F(3, 72) = 32.63$
Foot rotation	$F(3, 72) = 26.56$
Dynamic base (3)	$F(3, 72) = 100.95$
Dynamic base (4)	$F(3, 72) = 103.09$
<u>Locomotor Experience</u>	
Crawling	$F(3, 66) = 14.15$
Standing	$F(3, 72) = 8.94$
Walking	$F(3, 72) = 2.01^{**}$

Note: Except where noted $p < .001$; $** p = .120$.

indicative of improvements in skill relative to the younger age previously investigated (Adolph, 1995).

3.2. Normalization analyses

As described earlier, normalized crossing thresholds were created by dividing each child's crossing threshold by the various body size, skill, and experience variables. These normalized thresholds were then analyzed using a series of one-way ANOVAs, with the between-subject factor of age (14-, 18-, 24-, and 30-months); Table 2 presents the results of these analyses. Replicating Schmuckler (1996), walking experience successfully normalized crossing thresholds across age (i.e., removed age differences). Of the remaining variables, body size consistently failed to eliminate group differences; a finding at odds with the literature based on adults (e.g., Heinrichs, 1994; Heinrichs et al., 1993; Konczak et al., 1992; Warren, 1984) and older children (Heinrichs, 1994; Pufall & Dunbar, 1992), but one in keeping with previous studies of infants (Adolph, 1995; Adolph et al., 1993a; Schmuckler, 1996; Ulrich et al., 1990). Interestingly, and in contrast to Adolph's (1995; Adolph et al., 1993a) findings, walking skill was similarly ineffective in removing threshold differences across the ages.

4. Discussion

To summarize, this experiment compared the efficacy of body size, walking skill, and locomotor experience measures as predictors of the barrier crossing abilities for 14-, 18-, 24-, and 30-month-old toddlers. The principle result was that barrier crossing was strongly predicted by experiential variables, specifically, walking experience; this result is consistent with Schmuckler's (1996) findings. Somewhat surprisingly, however, measures of walking skill were ineffective as predictors of crossing thresholds, a finding at odds with previous work addressing the difference between walking skill and walking experience (i.e., Adolph, 1995; Adolph et al., 1993a). Finally, as in previous studies with infants, measures of body size were also ineffective as predictors of crossing thresholds.

One disturbing explanation for this apparent dichotomy with respect to the roles of walking experience and walking skill is that our skill measures may not have been properly assessed, and as such, may be off relative to Adolph's (1995) measures. An informal comparison of the walking skill measures obtained for the 14-month-olds in the current study with the values obtained by Adolph (1995; see p. 744), however, suggests that this is not the case. For example, the values obtained for stride length in the current study ranged from 33.44 cm to 61.97 cm; Adolph reports a similar range of 30.66 cm to 61.37 cm. A range of 7.50 cm to 16.71 cm was found for step width; again, these values are very much in keeping with Adolph's report of a range of 6.13 cm to 18.20 cm. Likewise, the pattern of intercorrelations between the skill measures is also similar between the two studies.⁶ For instance, Adolph (1995; see Table 4, p. 745) reports an intercorrelation of .99 between measures of step length and stride length, $-.46$ between stride and step width, and $-.86$ between step width and dynamic base. Values of .95, $-.27$, and $-.84$, respectively, were obtained for these same measures in the current study. These findings are encouraging as they further suggest that the proper steps were taken in assessing each of the skill measures; moreover, they indicate that the youngest age group in the current study is comparable in skill level to the toddlers in Adolph's study.

Assuming there is reasonable confidence in the current skill measures, why was skill so ineffective in predicting barrier crossing? One obvious possibility is that the footprint measure of skill is simply not reflective of the physical demands required in barrier crossing. Although slope ascent and descent, and barrier crossing may rely on the same underlying variables (strength, flexibility, and balance), they likely do so to differing degrees. The key actions involved in barrier crossing vary depending upon the height of the barrier (see Heinrichs, 1994). Stepping over very low barriers simply involves taking a slightly higher step than normal. For somewhat higher barriers, the actor must execute a series of more complicated movements to successfully maneuver herself over the barrier. As the height of the barrier continues to increase, so too does the level of difficulty involved; eventually, a height will be reached at which it is no longer physically possible for an individual to step over the barrier.

In contrast, successfully walking up and down slopes involves repeating a similar set of actions (the basic leg actions used to walk across a flat surface), although the direction and angle of the slope do place different physical demands on these familiar actions. For instance, when walking up a slope, the actor leans forward, an action that aids in his acceleration up

the slope; however, when walking down a slope, the actor must lean backwards to avoid increasing his forward momentum and toppling forwards (Adolph et al., 1993a).

Given these different demands, the walking skill assessment used (Adolph, 1995; Adolph et al., 1996; Boenig, 1977), may, in truth, be more closely attuned to the motor demands of walking up and down slopes than to the motor demands of barrier crossing. For example, walking on flat ground does not require the actor to balance on one foot while swinging a leg across an obstacle. Thus, when used as a measure of toddlers' general locomotor skill, the information provided by the footprint method of gait analysis appears to be relevant to particular locomotor activities.

Adolph's (1995) own findings seem to support this very idea. For example, walking up and down slopes differ in terms of the level of control required to maneuver oneself. Whereas walking up a slope may be more physically tiring, it requires less physical control than walking down a slope. With respect to the amount of control required, walking on flat ground would be similar to walking up a slope, in that it too requires lower levels of physical control than walking down a slope. Interestingly, Adolph observed a stronger relation between the footprint skill measure and slope ascent (as opposed to descent), supporting the hypothesis that the strength of the relation between the measure of walking skill and the task being predicted is dependent on how similar the two are in physical makeup.

This argument concerning the fit between the demands of the skill measure and the demands of the perceptual-motor behavior being studied is, in many ways, comparable to a theoretical model put forth by Bril and Brenière (1992) concerning the development of walking in young infants. According to these researchers, the development of walking occurs in two phases. The first phase, lasting between 3 to 6 months after the onset of walking, is a learning period in which children learn to integrate the necessary physical components needed to initiate their first steps. During this period, dramatic visible changes in children's gait occur. The second phase is a period in which children's abilities become more finely tuned; it is characterized by a stabilizing of the gait parameters and takes place during the 18 months following the end of the first phase (Bril & Brenière, 1992).

Bril and Brenière (1992) further suggest that during the first developmental phase of walking, the child must not only learn how to maintain sufficient postural control to remain upright, but she must do so while propelling her body forward. Until a child has adequately mastered this process, upright locomotion is limited. Thus, the process of maintaining postural control while walking is a complicated one that can only be successfully achieved through the integration of a number of interdependent elements. One consequence of the complexity of this process is that the abilities of a child displayed during this first phase are very sensitive to external influences. As a result, situations that are posturally demanding for a child may lead to a visible regression in the child's ability to maintain her balance (Bril & Brenière, 1992). As an aside, support for this model can be found in a study by Schmuckler and Gibson (1989), who observed that younger, more novice walkers showed significantly greater postural perturbations in response to imposed optical flow when walking around obstacles, relative to walking in a straight path; in contrast, imposed optical flow produced no differences in postural perturbations for the most highly experienced group of walkers.

Bril and Brenière's (1992) model does suggest an intriguing developmental progression, with locomotor behavior scaled to different factors at different ages and experience levels.

Thus, during the first stage, when gait is being learned (i.e., the first 6 months of walking), locomotor behavior could well be driven by explicit skill variables (as, for example, evidenced by Adolph, 1995). Once gait has stabilized and children are fine-tuning their walking (i.e., the next 18 months of walking), experiential factors, both global and specific, may well play more of a role. Finally, subsequent to the conclusion of this second stage (i.e., after about 24 months of walking), both skill and experiential factors will be less important in determining locomotor behavior. It is at this point that body size variables may well play more of a role.

Given this suggestion, Bril and Brenière's (1992) framework has a number of implications for the current situation. For example, it suggests that one should see that scaling of action for barrier crossing might well vary across the ages in the present study, with the 14-month-olds (who have less than 3 months of walking experience) scaled to skill variables, and the 18- and 24-month-olds (who have between 6 and 12 months of walking experience) scaled to experiential variables. The 30-month-olds (who have about 18 months of walking experience) are trickier, and might well represent a group transitioning between experience and body size variables.

Of course, the most obvious problem for this pattern is that the abilities of all the infants, including the 14-month-old infants, were scaled to walking experience and not to any of the measures of skill. In this sense, however, it is worth remembering that the skill measures assessed in this study are clearly more aligned with the task of locomotion itself, and not necessarily with barrier crossing. Put differently, in Bril and Brenière's (1992) framework, crossing a barrier would qualify as a posturally demanding task, particularly for a very young child. Thus, measures of a child's walking skill on flat ground, a task that is presumably less posturally demanding than barrier crossing and consequently, would not disturb postural control to the same degree, may not be strongly related to crossing thresholds.

What is needed, then, is a measure of skill that more accurately assesses the critical elements involved in crossing a barrier. Possibilities in this vein include assessments of parameters such as strength, flexibility, and balance, all of which can be measured independently (see Heinrichs, 1994). Unfortunately, and as mentioned previously, there is little information concerning how such variables change as a function of increasing age and walking skill, presumably due to the inherent difficulty in quantifying these parameters in young children. Until a better measure of skill can be obtained, a number of questions remain unanswered. For example, it may be that, unlike adults, the motor abilities of young children are not determined by a single fundamental factor (e.g., body size), but rather by different variables (e.g., skill or experience) predicting different actions (e.g., slope ascent versus barrier crossing). Alternatively, and as described in the developmental sequence above, it may be that the importance of skill, experience, and body size variables change with age. In fact, such a developmental sequence does have precedents in work on motor control. Research with older adults, for example, has found a change from the scaling of action solely to anthropomorphic measures to a combination of anthropomorphic and physical ability variables resulting from movement constraints arising as a consequence of aging (Konczak et al., 1992).

In sum, the current study looked at the development of perception-action coupling within the context of a common visual-guidance situation encountered by young infants—the need

to locomote over a barrier in one's path. In attempting to disentangle the importance of various factors (e.g., body size constraints versus skill variables versus experiential factors) that may drive or underlie this perceptual-motor behavior, the current study found some tentative support for a model of locomotor development in which the various factors of importance may change as a function of different experience and levels of perceptual-motor skill. In truth, however, these results represent only the first few tentative steps towards understanding the influences important for the acquisition of the critically important developmental milestone of independent mobility. Future work in this vein can, and should, continue to pull apart such influences, and thus hopefully shed light on the growth of a skill that has considerable consequences for the general development of the child.

Notes

1. In fact, preliminary work in the current project attempted to assess a variety of relevant physical ability factors using, for example, tests of lower body strength (Standing Broad Jump), flexibility (Sit and Reach), and balance (standing on one foot) [for details, see Heinrichs, 1994]. Unfortunately, after extensive pilot testing, these attempts were abandoned because even the oldest children in our sample were simply unable to adequately perform any of the necessary behaviors.
2. A slight modification of this procedure was necessary to accommodate the much more limited motor abilities of the youngest age group. For the 14-month-old toddlers, the barrier was initially positioned at a height of 2.5 cm and the barrier was raised a single increment following two successful attempts to cross.
3. The decision to base crossing thresholds on actual abilities as opposed to perceptual judgments arose because of the general lack of refusals during barrier crossing. One reason there were few refusals stems from a consequence of using only an ascending psychophysical staircase. Because this procedure tends to produce trials that hover close to threshold (within about 2 barrier increments), and barrier height was only systematically increased from an initial low level, as opposed to decreasing from an initial high level, there were, in fact, very few trials at which the barrier height significantly exceeded the child's crossing threshold. Unfortunately, Schmuckler (1996) found that it was only when barriers were higher than crossing thresholds did refusals to attempt to cross become prominent. Moreover, the tendency to not refuse to attempt to cross was likely exacerbated given the fact that, due to safety considerations, the barrier was designed to collapse during an unsuccessful attempt. Thus, there was little danger involved in attempting barrier crossing, and accordingly arising from failures in crossing. Most children seemed unconcerned about any negative consequences; Adolph (1995) suggests that such "learning by doing" is one of the most direct ways to obtain information about affordances. In cases where greater danger is involved, more prudent strategies are required.
4. The degrees of freedom for body weight and Ponderal Index differ from the remaining anthropomorphic measures as one child refused to stand on the scale.
5. The degrees of freedom for crawling experience differs from the remaining two forms

of locomotor experience as five children in the study were reported to never have crawled.

6. Intercorrelations between the skill measures were also examined for the remaining three age groups as well as for the combined age group. Reasonably similar values were also found, providing further support that our measures are internally consistent.

In addition to looking at the relation between the individual skill measures, the reliability of this measure was also examined. For the youngest age group, attempts were made to obtain two walking skill trials. Nine of the sixteen 14-month-old toddlers provided two useable trials; the remaining seven, only one useable trial. A series of two-way ANOVAs were conducted with the within-subject factors of foot (left vs. right) and trial number (first vs. second) for each skill measure for these nine children. No significant effects of foot, trial number, or interactions between foot and trial number were found (all $ps > .05$).

Correlations between trials were also examined for each skill measure. Significant correlations between trials were found for measures of stride length (.80), step length (.66), step width (.79), foot rotation (.84), and dynamic base (3) (.93) [all $ps < .005$]. The correlation between trials was not significant for dynamic base (4) ($p > .05$).

Given the lack of significant differences within and between these factors (i.e., foot and trial number), as well as the strong relation between trials, we are confident that the walking skill measures obtained from the remaining children in the study are reliable and moreover, that they provide an accurate assessment of their walking patterns.

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