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RESEARCH NOTE

# The affordance of barrier crossing in young children exhibits dynamic, not geometric, similarity

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**Abstract** Previous research has shown that adults perceive affordances like the passability of apertures, climbability or crossability of steps and graspability of objects. In this study, the affordance for stepping over or onto barriers was examined in young children. This was done by placing three distinct barriers (a foam obstacle, a gap, and a single step up), which were scaled to body size, in the walking paths of 4- and 6-year olds and adults, and observing how they crossed the barriers. Age-related differences in the scaling of these actions corresponded to levels of movement variability, indicating that children as young as 4 years old are sensitive to their own constraints and scale their actions accordingly. These results indicate that affordances are not directly related to leg geometry, but rather entail the dynamics of the developing perception–action system.

**Keywords** Motor development · Walking · Barrier crossing · Affordance

## Introduction

Imagine walking down a sidewalk and encountering a tree branch, puddle or crack in the sidewalk obstructing your path. As a proficient walker, you are sensitive to what the obstructions allow (is the puddle narrow enough that it can be stepped over or does it have to be jumped over) and you can use this information to make the appropriate changes to your gait, to step or jump over the barrier and continue on your way. We perform such tasks with relative ease, because we have extensive experience walking in cluttered environments. It is through such experiences that one develops the ability to detect the relevant properties of the environment, then plan, modulate and scale one's movements to accommodate environmental constraints or demands (Adolph et al. 2003; Bojczyk and Corbetta 2004). That is, one becomes sensitive to affordances or what the environment allows (Gibson 1979).

Studies performed with adults, using tasks such as walking through apertures (Warren and Whang 1987), up stairs (Mark 1987; Warren 1984), over gaps (Burton 1992) and over obstacles (Patla et al. 1996), illustrate how well tuned the perception–action system is to affordances. Warren (1984), for example, demonstrated that the perceived limit of stair climbability was invariant between tall and short individuals when considered as a ratio between stair riser height and leg length; critical stair height was 0.88 (stair height/leg length). Moreover, Warren demonstrated that optimal stair height as determined by both energetics and visual preference tests corresponds to about one-quarter of the leg length. Warren postulated that these ratios were invariant because the proportional geometry of adults' legs was invariant despite overall differences in stature, meaning that the length of each leg segment is a constant proportion of the total leg length.

Pufall and Dunbar (1992) investigated Warren's (1984) findings in a study of children 6-, 8- and 10 years old. In one part of the study, children selected the highest step that was climbable; that is, the highest step onto which they could step. Pufall and Dunbar predicted that the ratio between the critical step height and leg length would be the same for 6–10-year-old children and adults, because the proportional geometry of children's legs is the same as

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the proportional geometry of the adults' legs: the geometric similarity hypothesis proposed by Warren. Indeed, children selected the step for which the ratio between maximum step height and leg length was 0.88. In the second part of the study, children selected the highest step over which they could step. The results from this portion, too, supported the geometric similarity hypothesis, as the children chose steps, the heights of which were in a constant ratio to leg length. This ratio, nevertheless, was different from that for step climbability.

Later, however, it was shown that the geometric similarity hypothesis does not extend to older adults (Cesari et al. 2003; Konczak et al. 1992) and/or to individuals with varying levels of joint flexibility (Meeuwsen 1991). Konczak et al. (1992), for instance, demonstrated that older adults perceived and achieved a lower critical limit for the climbability of steps when compared to younger adults. Konczak et al. suggested that action capabilities such as step climbability required scaling of factors other than leg geometry (leg strength and hip flexibility). Cesari et al. (2003) replicated this result. In this experiment, children, young adults and older adults visually identified the highest climbable steps from an array and then climbed the sets of steps to find the actual highest climbable step. Results revealed that older adults, who were less flexible than children and young adults, also perceived a lower critical step height.

Anthropometrics are also poor predictors of action capabilities or action scaling for infants and young children (Adolph 1995; Adolph et al. 1993; Kingsnorth and Schmuckler 2000). Previous research, for instance, has indicated that movement experience is related to infants' sensitivities to affordances like the traversibility of surfaces with different rigidities (Gibson et al. 1987) and different slopes (Adolph 1995; Adolph et al. 1993) and the climbability of stairs (Ulrich et al. 1990). Specifically, movement experience has been shown to be the best predictor of infants' abilities to cross barriers (Kingsnorth and Schmuckler 2000; Schmuckler 1996) and gaps (Zwart et al. 2005). That is, infants' and toddlers' actions are experientially scaled (Schmuckler 1996). Nevertheless, the question remains: what, if anything, relates the scaling in performance of young children to adults? In this paper, we will propose the hypothesis that it is not limb geometry, but is the effectiveness or reliability of motor performance. This could, in turn, be a function of movement experience, but we do not explore this possibility in the current study.

## Stepping onto and over barriers

Previous studies have discussed stepping onto (Konczak et al. 1992; Pufall and Dunbar 1992; Warren 1984) and over (Pufall and Dunbar 1992) barriers in terms of the components of each task. When stepping onto a step, the performer has to step up with the first or leading foot, shift weight to that foot and then pull up the second or trailing foot. When stepping over a barrier, the performer has to step over the barrier with the lead foot, shift weight to that foot and then swing the trail foot over the barrier. To be successful at both tasks under typical circumstances, however, the performer must not make contact with the front edge of the step as the leading foot is guided onto or over the step. This is not necessarily the case for the trailing foot, though, as dragging the trail foot up and over or onto a barrier can be used as a strategy to prevent tripping. In order to avoid making contact, the performer must employ a safety margin that allows foot trajectory variability. Barriers reliably afford crossing only when foot clearances over the barrier includes a margin of safety.

The problem is essentially the same as the passability of apertures, as discussed by Warren and Whang (1987). Warren and Wang contended that apertures (e.g., doorways) afford passage when they are wider than the smallest horizontal body dimension (i.e., shoulder width). To pass through an aperture that is smaller than this, the performer has to turn the shoulders to fit through it. Warren and Whang found that the critical point at which performers turned their shoulders to pass through was at an aperture-to-shoulder-width ratio of 1.3. They indicated that the critical point was greater than one to allow for a margin of safety; it is possible to pass through an aperture equal to one's shoulder width, but is quite difficult to do while walking because of the natural lateral or side-to-side variations in the trajectory of the trunk during gait. That is, performers were adopting a fairly large aperture-to-shoulder-width ratio to avoid colliding with the surfaces defining the aperture.

Collision avoidance and the targeting required to do so, however, are not unique to passing through apertures; targeting and avoiding collisions also constrain stepping, reaching and grasping behaviors (Rosenbaum et al. 2001a, b). When reaching to grasp, the maximum distance between the thumb and finger (grip aperture) is larger than, but scaled to, the size of the target and occurs during the deceleration phase of the reach (Jeannerod 1984, 1988). While producing a grip aperture wider than the target may be energy inefficient, it allows the performer to adjust to the target in advance of arriving at the target, thereby avoiding collision (this is especially important when reaching to grasp dangerous objects such as saws and knives or fragile ones like teacups). In this way, maximum grasp aperture can be viewed as providing a margin of safety.

### Present study

The purpose of this study was to determine how affordances for action were similar between older (6 years old) and younger (4 years old) children and adults when stepping onto or over barriers below the critical limit. This aim was important to assess because there is recent evidence that leg geometry is similar between children of 3–10 years old, and not just children of 6–10 years old. Specifically, Smith (2007) observed roughly linear long bone growth for 3–10-year olds and high correlations between bone length and stature ($r^2 \geq 0.95$). This purpose was addressed by examining action scaling as 4-, 6-year olds and young adults stepped onto or over barriers below the critical height.

In the current study, we hypothesize that the margin of safety is key to understanding invariance of action scaling between children and adults. The leading hypothesis about scale invariance, the geometric similarity hypothesis, predicts that children will scale their actions in a manner similar to adults, because proportional leg geometry is similar. However, the main constraints in the development or learning of effective actions in this context are that actions must be functionally effective. To be functionally effective (which requires targeting and collision avoidance), the reliability with which the task can be performed must be considered. Hence, we expect variability of behavior in the context of margin of safety to be important and not limb geometry.

## Methods

### Participants

A total of 11 4-year olds (4 years ± 15 days; 5 male, 6 female), 11 6-year olds (6 years ± 15 days; 5 male, 6 female), and 10 adults (18–30 years old; 5 male, 5 female) participated in this experiment. Children's names were identified using the birth announcements published in the local newspaper. Using these names, parents were called to solicit participation. The adults were recruited via flyers posted throughout the community. The children were given gift certificates for ice cream, while the adults were compensated with $10 for their participation. All participants had normal or corrected-to-normal vision and were free from any known neurological defects or motor disabilities.

### Apparatus

Infrared emitting diodes (IREDs) were placed bilaterally onto the participants' toes, heels, ankles, knees and hips; IREDs were also placed on all barriers and on the walkway in the location where the barriers would be placed. Movement kinematics was collected at a sampling frequency of 60 Hz using three Northern Digital Optotrak sensors. Behavioral recordings were made with a video camera, which was placed perpendicular to the walkway. All tasks were performed on an elevated walkway that was approximately 4 m in length, 15 cm in height and of 1 m width.

### Task

The participants performed the same tasks: (1) gap, the participants took two steps and then stepped over a gap in the walkway; (2) foam obstacle, the participants took two steps and then stepped over a piece of foam on the walkway; and (3) single step up, the participants took two steps and then stepped onto an elevated section of the walkway. Data from another condition, baseline (where the participants walked normally across the 4 m walkway) was collected, but not analyzed. The gap was created by separating one of the sections of the walkway from the others and was 20–25% of the participants' leg length. The obstacle was a piece of foam that spanned the width of the walkway. The step up was created by placing wooden supports underneath the center and the ends of the walkway. Both the obstacle and single step were 20–25% of the participants' leg length in height; that is, near optimal height as determined by Warren (1984).

### Procedure

All procedures were approved by the Institutional Review Board at Purdue University and were conducted in the Biomechanics Laboratory located in the Lambert Gymnasium at Purdue University. Once the children and their parents, or the adult participants arrived, the purpose of the study was explained and the approved consent form was completed. After receiving assent from the children and consent from the children's parents, or from the adult participants, height, mass and leg length measurements were taken and IREDs were placed onto the participants' joints using hypoallergenic tape. After the IREDs were in place, the participants walked across the walkway a few times. This was done to familiarize the participants with the task and to determine the starting location. The starting location was determined in the following manner: participants walked across the walkway a few times, starting at a predetermined location that was marked by a piece of tape. The piece of tape was adjusted in the anterior–posterior direction so that at the end of the second step, the participants' toe landed just before the place on the walkway where the barrier would be located (pilot testing revealed that this method, combined with constraining the starting distance between the participant and barrier, enabled the children to stay on task). Participants then performed ten trials with no barrier, and then trials in blocks of ten for each barrier condition. The order of conditions was counterbalanced between participants.

### Data processing and analysis

Small gaps (<20 Hz or frames) of missing kinematic data were interpolated using a linear-spline interpolation technique. The kinematic data were then filtered at 8 Hz using a double-pass second-order Butterworth filter. Trials where foot–barrier contact was made were removed from the analysis; this represented less than 3% of all trials. The following variables were calculated for the leading foot for each participant: toe clearance (vertical distance between the toe and the leading edge of the barrier at the first instance the toe crosses the leading edge of the barrier), toe clearance variability (TCV) (standard deviation of toe clearance). Only data from the lead foot were analyzed because participants could not use vision to guide the trail foot over the barriers (Patla and Rietdyk 1993; Mohagheghi et al. 2004; Rietdyk and Rhea 2006).

In keeping with the ecological perspective, the dependent variables were transformed into pi numbers by dividing by leg length (Warren 1984; Warren and Whang 1987; Pufall and Dunbar 1992). To be clear, toe clearance is a measure indicating the margin of safety and TCV assesses the level of control that one has when crossing barriers. This is similar to Warren and Whang's aperture-to-shoulder-width ratio, when toe clearance approaches or equals zero, then safe crossing is no longer possible; when variability is large, the effective margin of safety is reduced.

Toe clearance (TC) and TCV were analyzed separately using two-way mixed factor repeated measures analysis of variance (ANOVAs) with the following factors and levels: condition (gap, obstacle, step up), age (4 years, 6 years, adult).

To determine the relationship between the margin of safety and level of control (TC and TCV, respectively), regressions were computed for each condition. To determine whether any relation between TC and TCV was consistent across conditions, the differences in slope were tested. Slopes for the conditions (gap, obstacle, step up) were contrasted, two conditions at a time requiring three analyses (Pedhazur 1982). Multiple regressions on TC were performed using the following independent variables: TCV and coded vectors (±1) for condition, with an additional vector representing the interaction between condition and TCV. This later vector tested the slope difference. All post hoc analyses were performed using Duncan's multiple range test (MRT).

Finally, to confirm that the variability that we see in stepping and toe clearance reflects general variability in the control of locomotion and stepping, we report the variability in step length (difference in forward displacement of the heels between successive heel contacts) and width (difference in lateral displacement of the heels between successive heel contacts) of the walking in approach to the gaps, obstacles or step.

## Results

### Toe clearance

Figure 1a reports normalized toe clearance (TC) for all participants during all barrier (gap, obstacle, step up) conditions. There was no condition by age interaction ($F_{(4,58)} = 1.41$, $P = 0.24$). There were, however, main effects of both age ($F_{(2,29)} = 6.30$, $P < 0.01$) and condition ($F_{(2,58)} = 75.75$, $P < 0.001$). Post hoc analyses revealed that the 4-year olds had higher TCs than adults, with the 6-year olds being equal to the 4-year olds and adults ($P < 0.01$). In addition, TCs were highest in the obstacle condition followed by the step up condition and then the gap condition.

### Toe clearance variability

Figure 1b reports the standard deviation for toe clearance (TCV) for all participants during each condition. There was a significant condition by age interaction ($F_{(4,58)} = 3.21$, $P < 0.02$). There were also main effects of both age ($F_{(2,29)} = 31.94$, $P < 0.001$) and condition ($F_{(2,58)} = 31.84$, $P < 0.001$). Post hoc analyses revealed that the 4-year olds had higher TCV than both adults and 6-year olds; the 6-year olds had higher variability than adults ($P < 0.01$). In addition, TCV was highest in the obstacle and step up conditions, followed by the gap condition.

### Relation between toe clearance and toe clearance variability

For each condition, the resulting regression was significant indicating that TC is related to and can be predicted by TCV. Gap condition: $TC = 2.28 \times TCV + 0.06$ ($F_{(1,30)} = 64.52$, $R^2 = 0.68$, $P < 0.01$). Obstacle condition: $TC = 2.02 \times TCV + 0.13$ ($F_{(1,30)} = 5.38$, $R^2 = 0.15$, $P < 0.05$). Step up condition: $TC = 2.12 \times TCV + 0.08$ ($F_{(1,30)} = 36.59$, $R^2 = 0.55$, $P < 0.01$).

Comparison of TCV in Fig. 1b with variability in step length, shown in Fig. 1c, and in step width, shown in Fig. 1d, reveals that the variability is general to the control of locomotion and stepping. This supports the inference that mean TC is a function of TCV, to provide a sufficient

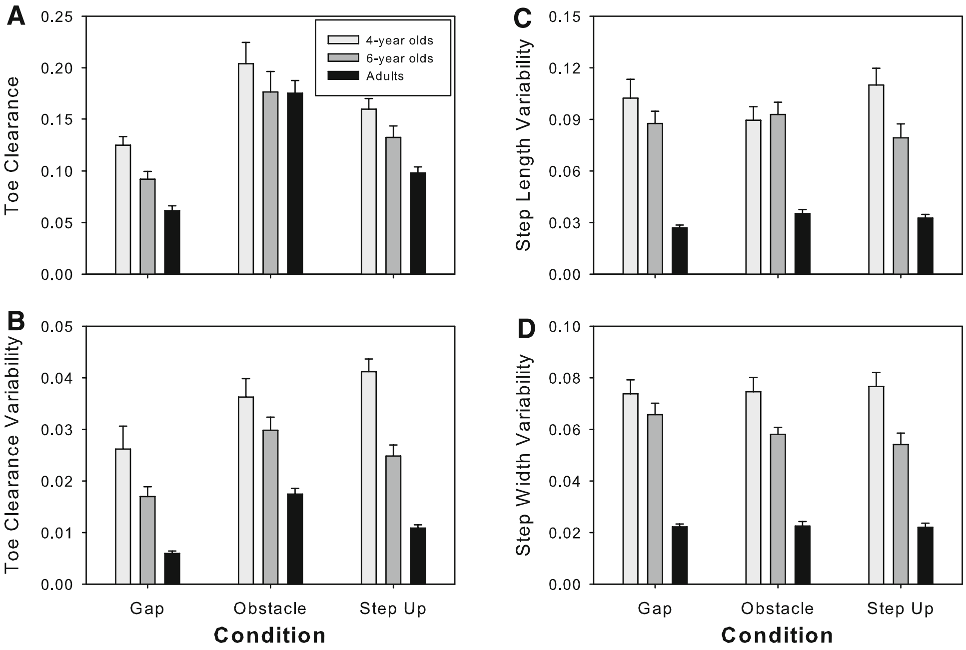

**Fig. 1** **a** Normalized toe clearance by age and condition; **b** toe clearance variability; **c** normalized step length variability; **d** normalized step width variability

margin of safety, rather than the reverse. That is, it was not the case that participants simply produced a larger mean TC and, thus, this allowed them the leeway to be sloppy in the control of their clearance. Instead, the variability is a general feature of their locomotor control and necessitates larger TC to avoid tripping.

### Consistency across conditions

We tested the differences in slope between conditions to determine the consistency of relation between TC and TCV. In this set of analyses, no difference in slope indicates that the relationship between TC and TCV was constant across conditions. For the obstacle versus gap comparison, the resulting regression was significant ($F_{(3,60)} = 33.71$, $R^2 = 0.63$, $P < 0.001$) as was the intercept difference (partial $F$ value $= 9.64$, $P < 0.01$), but there was no difference in slope ($P > 0.05$). For the gap versus step up comparison, the resulting regression was significant ($F_{(3,60)} = 43.82$, $R^2 = 0.69$, $P < 0.001$). There were, however, no differences in intercept or slope ($P > 0.05$). For the obstacle versus step up comparison, the resulting regression was significant ($F_{(3,60)} = 15.87$, $R^2 = 0.44$, $P < 0.001$), but there were no differences in intercept or slope ($P > 0.05$). The scaling of the safety margin is thus: $\mathrm{TC} = 2.14 \times \mathrm{TCV} + 0.09$, that is, roughly twice the variability.

## Discussion

Young children and adults are different in a great many ways, especially when it comes to physical aspects such as stature. But, do they also differ in how they perceive themselves in relation to the environment? Previous research from Pufall and Dunbar (1992) and Cesari et al. (2003) indicates that older children perceive the critical limit for the climbability of stairs in the same way as adults, that is, in relation to the length of their legs. The findings from the present study, however, do not support the geometric similarity hypothesis proposed by Warren (1984). Rather, the findings from the present study indicate that young children scale their actions dynamically when stepping onto or over barriers below critical height, that is, in relation to production variability.

In the present study, the actions of stepping onto and over barriers were scaled to physical dimensions and, unlike previous work from Pufall and Dunbar (1992) and Cesari et al. (2003), the behavioral outcomes were not similar between children and adults. Thus, these results do not support the geometric similarity hypothesis (Warren 1984). However, these results indicate that children and adults are similar when the constraints and capabilities of the individual performers are considered (Munhall and Kelso 1985). Previous work from Konczak et al. (1992) indicated that populations of greatly different ages can be similar functionally or dynamically when additional factors such as leg extensor strength and hip flexibility are considered. In this study, measures of leg strength and hip flexibility were not assessed, so it is not possible to directly investigate the relevance of these factors to action scaling. However, there are several reasons why these specific factors may not be ideal candidates for exploring affordance relations between children and adults. First, previous research from Cesari et al. demonstrated that children

(5+ years old) and young adults have similar levels of joint flexibility. Scaling stepping behaviors by a factor that is roughly constant would have no effect and the behaviors would still be dissimilar. Similarly, though there are numerous studies that have reported that children's absolute leg strength is less than that of adults (De Ste Croix et al. 1999; De Ste Croix 2007; Round et al. 1999), there is evidence that the relative strength is similar. For example, Hedin and Larsson (2003) suggested that peak torque-to-body weight ratios (the measure of strength used by Konczak et al.) are similar for children (5+ years old) and adults. In addition, Damiano et al. (2001) reported on children's (4+ years old) peak torque-to-body weight ratios (eccentric exertion, 0.75 ± 0.18; concentric exertion, 0.61 ± 0.15) and these values were similar to those reported by Konczak et al. for shorter adults (unspecified exertion, 0.75 ± 0.19). So, if the stepping behaviors in this study were scaled to relative strength, it is likely that there would be little effect and behaviors would also still be dissimilar.

How, then, are children and adults similar? The results from the present study indicate that children and adults are similar when their capabilities, including action variability or stability, are considered. The children in this study had higher levels of variability both in the approach to the barriers (see Fig. 1c, d) and in the crossing, and also had the highest clearances (when scaled to size), whereas the adults exhibited lower levels of variability and lower clearances. That is, children and adults scale their actions in relation to their stature and production variability or dynamic stability. This is a perceptual–motor process and, as in cats, likely requires the contribution and coordination of multiple cortical and subcortical structures. For instance, many studies detail how the motor cortex is involved in modifying muscle activity during obstructed gait (for an example see Friel et al. 2007). However, there is a body of evidence that suggests it is the posterior parietal cortex, not the motor cortex, which is involved in planning gait modifications, along with subcortical structures such as the cerebellum (Drew et al. 2007; Friel et al. 2007).

The idea that actions are dynamically scaled is also supported by previous work. Warren and Whang (1987), for instance, found that the passability of apertures was related to shoulder width plus a safety margin to allow for the lateral variations in the trajectory of the trunk (which includes both mean deviation or displacement and variability in this displacement) that are present during gait. Stepping onto or over barriers also requires an allowance for variability. For an individual to successfully cross barriers, one must raise the foot high enough, on average, to allow for vertical deviations in the trajectory of the foot, as it is being swung over the barrier. If one has poor control of the foot, and the trial-to-trial deviations are large, one must increase the clearance over the barrier to avoid repeatedly hitting the barrier. If one has good control of the foot, and the trial-to-trial deviations are low, the clearance over the barrier can be lower. In this way, the findings from the present study indicate that children and adults are similar. Young children are sensitive to their inconsistent performance and compensate for this by increasing the margin of safety relative to body size.

This is consistent with previous research that indicates that even young infants control their actions in relation to their capabilities (Schmuckler 1996): as barrier height increases, infants first fail to cross and then eventually refuse to cross. Taken together, the findings from this study along with those from other developmental studies (Adolph 1995; Cesari et al. 2003; Konczak et al. 1992; Schmuckler 1996; Ulrich et al. 1990; Zwart et al. 2005) support the notion of transitions in the relative importance of experience, skill or capability factors and body dimensions in the development of affordances. Previous research indicates that when infants or toddlers acquire new skills, experience is the most important single factor (Adolph 1995; Schmuckler 1996; Zwart et al. 2005). Once children are relatively skilled, however, body size and capabilities become increasingly pertinent, defining how they interact with the environment. Across the lifespan, these more global aspects of the organism continue to be important (Cesari et al. 2003; Konczak et al. 1992); the specific factors relating to the capabilities of the organism, however, may become more or less relevant.

More research will be needed to further examine the development of affordances in children. Most obvious is the apparent discord between the results of the present study and those from Pufall and Dunbar (1992) and Cesari et al. (2003). Specifically, it is important to assess why affordances are similar between children and adults when step height is at the critical limit, but children and adults scale their actions differently when the step height is lower. A potential solution would be to examine action scaling over a wide range of step heights: from a low percentage of leg length to critical height. Given the results from the present study, one would expect to find similar patterns of action scaling, between children and adults, for steps of lower heights with mean clearance being related to clearance variability. But, is this relationship preserved as step height increases? The answer is probably 'no'. As step height increases, so does the cost associated with raising the foot over the barrier: mechanical stability is compromised and energy expenditure is higher. At some point, this cost becomes too high and the central nervous system trades cost for increased tripping risk. This is particularly relevant when crossing steps close to or at critical height. Use of a safety margin is likely precluded by a loss of degrees of freedom needed to produce the margin.

## Conclusions

The findings from the present study indicate that affordances are not directly related to leg geometry, but rather entail the dynamics of the developing perception–action system. Young children are sensitive to their action production limitations and compensate appropriately. That is, by 4 years of age, children perceive affordances for stepping onto and over barriers and demonstrate appropriate coupling of perception and action.

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