Early Development and Parenting, Vol. 6, 149–157 (1997)

Visual Guidance of Passing Under a Barrier

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The theory of affordances proposes that organisms control their actions according to the fit between the organism and the environment. This study set out to examine the proposal that actions are attuned to environmental demands on the basis of body-scaled information and how modifications to such actor–environment synergies might be influenced by speed of locomotion and locomotor ability. The paradigm task was walking and running under a barrier set at different heights. The subject groups comprised normal adults, nursery school children, cerebral palsied children, and infants with less than 6 weeks' independent walking experience. A body-scaled critical point, at which they began to duck under the barrier, was observed for all but the infant subjects. In addition, the nursery school children were found to be more cautious in their behaviour than adults both when walking and running. The cerebral palsied children compensated for their poorer ability to control vertical position in space by allowing an even greater safety margin when passing under the barrier. The results provide support for an affordance theory of perception, in which body size, speed of locomotion and level of motor control are considered important properties of the actor–environment fit. ©1997 John Wiley & Sons, Ltd.

Early Dev. Parent. **6**: 149–158, (1997)
No. of Figures: 4. No. of Tables: 2. No. of References: 21.

Key words: affordances; perceptual and motor development

How do humans and animals control their actions so efficiently within their cluttered environment? A person can adjust immediately and appropriately to accommodate changes in his or her surroundings—avoiding obstacles and negotiating uneven surfaces—without even needing to think about it.

It is precisely this unconscious nature of action control that underlies Gibson's (1958, 1966, 1979, 1983) theories of behaviour where the environment is said to constitute a collection of possibilities for action—*affordances*—which the organism needs to detect. The affordance of a surface, object, or event in the environment is the opportunity that it provides for (inter)action. Thus, the same surface, object, or event may afford different things to different organisms. For example, the same tree might afford living-in to a bird and eating-from to an elephant.

The behaviourally relevant properties of the environment must, in these terms, be analysed in terms of the capabilities for action possessed by the animal. For example, surface contours must be

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Contract grant sponsor: Medical Research Council, UK.
Contract grant sponsor: Scottish Office (Home and Health Department).

CCC 1057-3593/97/030149–09$17.50

Received 1 December 1996
Accepted 15 July 1997

judged in relation to gait potential, object size in terms of grip potential, and aperture width in terms of body dimensions.

Such a departure point led Warren (1984) to propose that the critical (maximum) and optimal values of an environmental property, relevant to performing an action, are an invariant proportion of some aspect of each actor's body scale, and that these critical and optimal points can be expressed in terms of a dimensionless ratio of the relevant properties (pi number) of both actor and environment, i.e.:

$$\pi = E/A$$

where E is some property of the environment and A is the corresponding property of the actor. In Warren's (1984) study of stair climbing these represented riser height and leg length, respectively. Using those parameters, ratios were determined for the action of stair climbing which was most 'comfortable', and for when it became impossible unless a hands-and-knees gait were to be adopted. Subjects were highly accurate at judging these points on the basis of visual perception alone.

In addition to stair climbing, optimal and critical points have been determined for many other actions. For example, Mark (1987) found that adults could visually determine comfortable sitting height, and Warren and Whang (1987) found a critical ratio for judgements of aperture width relative to shoulder width. In addition, these authors provided empirical evidence showing that these ratios are, in fact, perceived as a function of the observer's eye height.

Species other than humans have also been shown to gear their actions to ratios of this kind. Ingle and Cook (1977) found that, in visually guided jumping through apertures by frogs, the frequency of jumping dropped from 75% to 25% when the width of the opening approached 1.3 times the width of the frog's head. Also, Branch (1979) discovered that whether limpets attacked or retreated from whelks was dictated by the relative size of these two organisms.

Within the theoretical framework of 'affordances' (Gibson, 1979), the first research question of the present study was concerned with identifying a critical, body-scaled, point at which behaviour changed for a particular action. These findings would then be used as a baseline for comparison with other groups of subjects. This question was prompted by the work of Warren and Whang (1987), who reported that when aperture width was less than 1.3 times the shoulder width of the subject, the aperture no longer afforded walking straight through, but rather a phase transition in behaviour was needed such that the subject rotated his shoulders when passing through. The task of the present research was passing under a horizontal barrier placed at different heights relative to that of the subject. Previous findings suggest that a body-scaled value would be found, somewhere a little above head height, at which value all adult subjects, travelling at roughly the same speed, would duck under the barrier, regardless of absolute size. The critical ratio ($\pi_{\max}$) would, therefore, be expressed as an intrinsic measurement, directly related to head height, i.e.:

$$\pi_{\max} = B/H > 1$$

When barrier height B decreases towards head height H, a phase transition in behaviour would be expected to occur from a normal upright gait to a ducking response, giving a critical ratio $\pi_{\max}$ expressed in terms of the actor's head height.

The fact that these critical ratios for affordances are said to be scale independent for *physically similar systems* (Rosen, 1978) was crucial to the two central questions on which this research focused. Firstly, what happens if the organism behaves in a physically *different* way?

Gibson *et al.* (1987) found that a wobbly surface afforded locomotion to crawling infants, but not to walking ones, with the implication that mode of locomotion might affect the perception of affordances. Warren and Whang (1987) found that the critical ratio for shoulder rotation was very slightly increased when subjects travelled at higher speeds. This they attributed to greater lateral oscillations of the upper body or greater caution at higher speeds. An affordance theory, however, can accept and, in fact, requires both of these explanations. The fact that the task of running involved greater variability of position meant that the aperture afforded the need for greater caution on the fast trials.

In the present study, speed of locomotion was investigated as a factor affecting the critical ratio for ducking under a barrier with the expectation that, at higher speeds, subjects would show more caution in order to allow for the possibility of compensation for the greater vertical oscillation.

The second question involved the comparison between organisms that are in fact, for these purposes, physically dissimilar—adults and children. Much work has been carried out showing that affordances are very different for children, but not because they are incapable of detecting them (for an overview, see Adolph *et al.*, 1993a). For example, Gibson *et al.* (1987) showed that toddlers could perceive whether or not a surface afforded walking. Adolph (1995) showed that toddlers also take dynamic constraints, such as level of walking proficiency, into account when negotiating going up and down slopes.

However, infants and young children often do not behave adaptively. Their exploratory behaviour suggests that they discriminate differences in surface properties, but that they do not perceive affordances for action or understand the consequences of errors. For example, babies plunge over cliffs (e.g., Bertenthal *et al.*, 1984) and over impossibly risky slopes (Adolph *et al.*, 1993b). Moreover, infants, (nursery) school children, and adults sometimes overestimate their abilities (see, for example, Carello *et al.*, 1989; McKenzie *et al.*, 1993; Plumert, 1995).

The difficulty of the detection of affordances by children may have much to do with the necessity for this to take place parallel with, and be relevant to, the fast-changing capabilities of the child. A good illustration of this point is Ulrich *et al.*'s (1990) work on the detection of stair 'climbability' in infants, which revealed no anthropometric measurements related to the choice of step height, a finding contrary to that of Warren and Whang (1987) and Mark (1987) using adult subjects. This result can, however, be accommodated if it is realized that differences in action capabilities of infants and toddlers may be due more to differences in dynamic properties such as postural control, muscle strength, etc., reflected in their level of motor ability, than to differences in body dimensions *per se*.

Previous research has shown that adults take constraints other than their body dimensions into account when judging possibilities for action. For example, Konczak *et al.* (1992) showed that young and older adults take leg strength and flexibility into account when judging possible stair heights. In the present study, the barrier was more liable to afford the need for caution when the subjects had less reliable control of their own vertical position in space. It was expected, therefore, that children, with their still-developing, poorer, postural control (Woollacott and Shumway-Cook, 1989) would show a greater critical ratio for ducking under the barrier. In order to pursue those predictions about the mediating effects of postural control and changes in eye height (cf. Mark, 1987), hemiparetic cerebral palsied (CP) children with their typical asymmetrical gait and infant walkers were included as additional groups of subjects. It was expected that both groups of subjects would be even more cautious in their ducking behaviour when compared, for example, to the baseline conditions for the adults and older, non-handicapped, children.

METHOD

Design

Body-scaled ratios were calculated for the point at which adults and nursery school children, at running and walking speeds, and CP children and young babies at walking speed, begin to duck under a barrier.

Subjects

Thirty subjects participated. Twelve were males, 18 years of age or older, of whom six were 191 cm in height or taller, and six were 175 cm in height or shorter. Six subjects were nursery school children, four girls and two boys, aged between 4 and 5, their heights ranging between 105 cm and 114 cm. Six subjects were hemiparetic CP children, two girls and four boys, aged between 4 and 7, their heights ranging between 100 cm and 122 cm. All the CP children could walk unaided, albeit with a pronounced limp due to stunt growth on the affected side of the body, with four wearing corrective splints. Six subjects were young babies with less than 6 weeks of independent walking experience, three girls and three boys, ranging in age from 11 to 15 months (see Figure 1).

Apparatus and Procedure

A horizontal barrier which could be varied in height was constructed using high-jump equipment. The height of the barrier was adjusted by moving the support on the vertical post. Along the outside edge of the upright strut was a measurement scale. Infrared light-emitting diodes (LEDs) were attached to the subject's right temple and to the end of the barrier (see Figure 2). The LEDs were viewed from the side by a Selspot camera, from a distance of 6 m. The *y*-axis in the camera's view was lined up perpendicular to the walkway. The Selspot data were recorded on a computer at 62.5 frames per second. A video camera, placed

Figure 1. The tallest and shortest subjects taking part in the experiment. Note the difference in leg length and, consequently, eye height.

Figure 2. A nursery school child taking part in the experiment. In order to monitor subjects' ducking motions in fine detail, a Selspot camera placed perpendicular to the walkway viewed the infrared light-emitting diodes (LEDs) glued to the temple and to the end of the barrier. The children and babies carried small toys to and fro so as to keep them interested in the task.

beside the Selspot camera, also viewed the subjects, so that a complete record of the subjects' ducking behaviour was obtained.

Before the trials began, standing height of each subject was recorded using a standard tape measure attached to the wall with a horizontal moveable part resting on the head. Subjects, including the babies, stood with their heels against the wall and looked straight ahead. For the adults and nursery school children, the fast and slow trials were presented in blocks in a randomized order. In the walking condition, subjects were asked to walk naturally at a constant speed under the barrier towards a wall, approximately 7 m (2 m for the babies) further beyond, and in the running condition they were asked to do the same using a comfortable running gait.

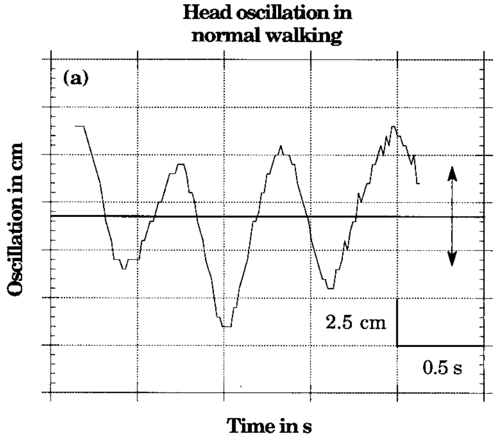
On each trial, the subject began at a point approximately 5 m (3 m for the babies) in front of the barrier, and walked forwards, passing underneath it and continuing towards the wall. All subjects then returned to the starting point, but the children and babies picked up a small toy first, so as to keep their interest in the task. One experimenter then ensured that the subject's back was turned whilst the height of the barrier was altered, by engaging the subject in conversation or, in the case of the children, by playing with them. This was to ensure that the subjects were not using memory and extrinsic calculation to guide their behaviour.

In each condition, the subject carried out eight trials, resulting in a total of 16 trials (eight slow and eight fast) per subject. In one trial, no barrier was used, in order to obtain data about normal uninterrupted walking patterns. The barrier height was then varied between 0, 5, 7.5, 10, 12.5, 15 and 20 cm above the subject's own height (these values having been determined in a pilot study that indicated that most people duck between 5 and 10 cm above their head height), the order in which these were presented being randomized.

RESULTS

The Selspot y-coordinates of the LED on the temple were analysed and all trials for each subject were judged as to whether the subject had ducked or not. 'Ducking' was determined by comparing the data on the test trials to the no-barrier trial. The mean y-coordinate, a measure of the average location of the temple, was calculated for this trial, as well as the standard deviation of the y-coordinate, a measure of the natural vertical oscillation in gait along the y-axis (see Figure 3a). If the data, during a test trial, close to the x-position of the barrier showed a y-position value lower than twice the standard deviation below the mean on the no-barrier trial, a positive duck was recorded (see Figure 3b). For each subject, the critical barrier height was obtained for the walking and, if relevant, running conditions. This was the maximum barrier height at which a duck was identified.

None of the subjects erred by touching the barrier or knocking it down. One of the CP children, however, developed in the initial stages of the experiment some kind of apraxia, where he did not seem to know how to go under the barrier and just stopped short of it. After the experimenter had shown him once how to solve this problem, he completed the experiment without further problems.



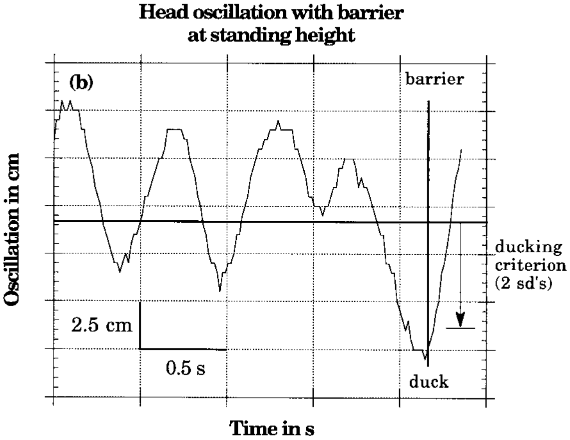


Figure 3. Typical Selspot record showing vertical oscillation of the y-coordinate of the temple LED over time for an 194 cm tall subject walking when (a) no barrier was present, and (b) the barrier was set at standing height. In the no-barrier trial (a) the mean y-coordinate, a measure of the average location of the temple during uninterrupted gait, is represented by the thick horizontal line, while the standard deviation of the y-coordinate, a measure of the natural vertical oscillation in gait along the y-axis (in this case about 2.5 cm), is indicated by the vertical arrows. In the test trial with the barrier set at standing height (b) it can be seen that the data, close to the x-position of the barrier, show a y-position value lower than twice the standard deviation (vertical arrow) below the mean on the no-barrier trial (thick horizontal line). According to this ducking criterion, a positive duck with a depth of just over 10 cm was recorded.

Short Versus Tall Adults

Table 1 shows the means and standard deviations for the critical ratio for adult subjects, running and walking. These intrinsically expressed values were similar for both groups in both conditions, $F(1, 10)=0.06$, n.s., with significantly higher values in the running condition, $F(1, 10)=14.40$, $p<0.005$. This supported the hypotheses that the critical point is a constant regardless of scale changes in the size of the actor, and that faster speeds result in subjects being more cautious in their ducking behaviour.

Adults Versus Nursery School Children Versus CP Children

Table 2 shows the means and standard deviations of the $\pi_{\max}$ (B/H) values for adults and nursery school children when walking and running, and for CP children when walking. The difference in standard deviations suggests that the children's ducking behaviour was more variable than that of the adults. The nursery school children were

Table 1. Means and standard deviations of critical barrier-height-to-head-height ratio (π_{max}) for tall and short adult subjects walking and running

	Short Mean (SD)	Tall Mean (SD)
Walking	1.037 (0.013)	1.038 (0.014)
Running	1.055 (0.019)	1.057 (0.015)

Table 2. Means and standard deviations of critical barrier-height-to-head-height ratio (π_{max}) for adults and nursery school children running and walking, and for hemiparetic cerebral palsied children walking under the barrier

	Adults, tall and short Mean (SD)	Nursery school children Mean (SD)	Cerebral palsied children Mean (SD)
Walking	1.038 (0.013)	1.114 (0.025)	1.144 (0.024)
Running	1.056 (0.017)	1.141 (0.044)	n/a

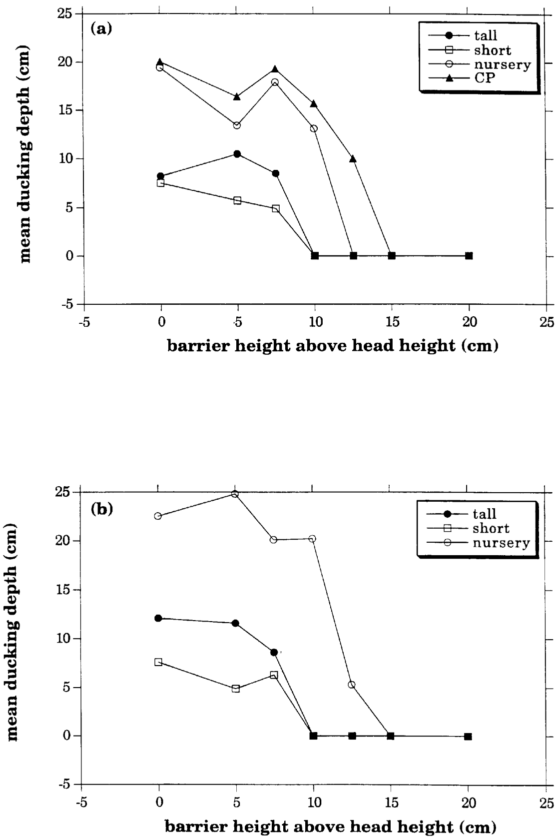


Figure 4. Mean ducking depth plotted as a function of barrier height for the different groups of subjects when (a) walking and (b) running under the barrier. In (a) it can be seen that the nursery and CP children need about 20 cm headroom to safely pass under a barrier set at their own height, whereas both short and tall adults only need about 7.5 cm to perform the same task successfully. Note that a mean ducking depth of 0 cm indicates there is no difference in mean y-values passing under high barriers compared with walking or running without a barrier.

found to be more cautious (indicated by the higher π_{max} values) than the adults, both when walking and running under the barrier, $F(1,16)=120.02$, $p<0.0001$. In addition, both adults and nursery school children were observed to have higher π_{max} values when running under the barrier, $F(1,16)=6.13$, $p<0.03$. Finally, the barrier was found to afford ducking at significantly higher positions with respect to head height in the CP children than in the nursery school children when walking under it, $t(10)=2.14$, $p<0.03$.

The mean ducking depths at different barrier heights when walking and running for the different groups of subjects are shown in Figure 4. It can be seen that when walking under the barrier, nursery school children and CP children allow approximately the same amount of headroom when passing the barrier set at different heights, $t(12)=0.54$, n.s., and that this is significantly more than for the adults, $t(26)=2.84$, $p<0.01$. When comparing the walking and running conditions, it was found that the nursery school children consistently allowed more headroom than the adults, both when walking and running, $F(1,19)=6.49$, $p<0.02$. In addition, it was shown that the nursery children ducked deeper when running, whereas the adults kept the amount of headroom more or less constant irrespective of whether they walked or ran under the barrier, $F(1,19)=10.48$, $p<0.005$.

Toddlers

It was not possible to determine a π_{max} (B/H) value for the toddlers. Even though they all had 6 weeks or less walking experience, the variation in locomotor ability was staggering. One very agile toddler showed very cautious ducking behaviour and was observed to duck at the waist at a π_{max} value of 1.23. Two other toddlers had π_{max} values of 1.18 and 1.21, respectively. This supported the hypothesis that the barrier affords more cautious behaviour to subjects who have less reliable control of their own position, for example, because they had only just learned to walk.

However, three of the toddlers were not capable of ducking at all. Nevertheless, their actions were always appropriate to the task at hand. When the barrier was above head height, they would reduce their speed (all the other subjects were verbally instructed to maintain a constant speed) and minimize vertical oscillation so as to just squeeze themselves under the barrier without touching it. When the barrier was at head height, however, they correctly perceived that this strategy would not work and that a different kind of action was required, and the three non-ducking toddlers each solved the problem successfully in their own way. One toddler would walk up to the barrier, lower herself onto all fours, and crawl under it. Another toddler avoided the barrier by walking around it so as to get to the toys on the other side. The third toddler walked up to the barrier while sticking out his hands and, without slowing down, lifted the barrier up a little so as to pass under it without ducking.

DISCUSSION

This experiment set out to investigate the existence of body-scaled information in the affordance of passability of a barrier. It was found that critical values of $\pi_{\max}$ did exist for adults, nursery school children, and CP children at which ducking began. For adults, the critical points occurred at a ratio of $\pi_{\max} \approx 1.038$ when walking and at $\pi_{\max} \approx 1.056$ when running. These values appear to be constant across adults, regardless of body size. This result supports the contention that such critical points are scale-independent constants for the organism–environment system and, thus, was consistent with the findings of Warren (1984) and Warren and Whang (1987).

In addition, critical points were found for nursery school children and for CP children when passing under the barrier. The nursery school children had higher $\pi_{\max}$ values than the adults both when walking and running. This supported the hypothesis that children behave more cautiously, compensating for their poorer motor control, and lends support to the claim that, in addition to static body dimensions, dynamic properties, reflected in level of locomotor ability, may also be crucial to the actor–environment fit. In addition, because of ongoing rapid growth children might be less certain about their vertical position in space and therefore display more cautious ducking behaviour.

The hemiparetic CP children who, because of their handicap resulting in asymmetric gait, were only capable of walking under the barrier, behaved even more cautiously than the nursery school children. Again, this finding lends support to the idea of compensation for poorer motor control: each individual actor's lack of ability to control his or her position in space being compensated for by a greater safety margin in his or her perception of passability.

The above statement might also help to explain the difference in affordance of passability between running and walking in adults and children. The fact that subjects behave more cautiously on the running trials due to greater vertical oscillation of position is also accommodated by a postulate of compensation due to uncertainty of position.

An additional problem the CP children encountered was with the timing of the ducking action. It appeared that all adults and nursery school children timed their locomotion pattern so that a downward undulation of the head naturally coincided with ducking under the barrier. The CP children seemed incapable of controlling this aspect of their behaviour, and in about half of all trials they would have to superimpose a duck on a natural upward undulation. As a result, the CP children's ducking actions were less smooth and looked clumsy. This problem will be investigated in more detail in a later paper.

No obvious critical point could be observed for the babies. This result was consistent with the findings of Ulrich *et al.* (1990), who failed to find a geometric relation between preferred riser height and body dimensions for stair climbing in infants and toddlers. Geometric relations between environmental dimensions and body dimensions are only useful for describing affordance boundaries when subject variability is primarily due to differences in size and mass. In the study by Ulrich *et al.* (1990) the differing stages of motor development of the infants would have been the predominant source of subject variability. In the present study, an attempt was made to solve this problem by only recruiting babies with 6 or less weeks of independent walking experience. Nevertheless, the differences in dynamic action capabilities such as postural control, dynamic balance on two legs, and muscle strength varied widely, with half of the infant subjects not being able to duck at all. Testing for exact affordance ratios for toddlers would obviously involve more careful control of these variables. However, consistent with Gibson *et al.*'s (1987) results, it was found that all babies perceived the passability of the barrier in terms of their own action capabilities and, as a result, acted appropriately—even though this meant that one baby who lacked the locomotor ability to duck avoided the barrier by walking around it!

It seems, therefore, that in previous research the importance of dynamic variables such as degree of motor control and mode of locomotion have, in general, been underestimated. The present study suggests that it is not possible to determine critical values for actions purely in terms of static body dimensions. Instead, the affordance of passability of a barrier is influenced not only by body size as such, but also by mode of locomotion, degree of motor control, and level of development. When subjects have less reliable control of their own vertical position in space (because they are running, are cerebral palsied, or have only just learned to walk), a barrier affords more cautious ducking behaviour.

ACKNOWLEDGEMENTS

Thanks are due to the adult, child and baby subjects (and their parents) for their enthusiastic participation, and to Christine Caldwell for help with all aspects of the study. I would also like to thank Scott Johnson, John Whiting, and two anonymous reviewers for their helpful comments on an earlier version of this paper. The work was supported in part by grants from the Medical Research Council (UK) and the Scottish Office (Home and Health Department).

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