The development of locomotor planning for end-state comfort

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Abstract

Walking through real world environments involves complex choices between alternative routes, and the ability to make such choices must develop through childhood. We examine performance in one such situation. We use a novel paradigm analogous to manual 'end-state comfort' (ESC) planning tasks, where an uncomfortable manouevre at the start of a movement is traded off for comfort at its end. We find that adults show locomotor ESC planning, adjusting feet at the start of a route in order to gain comfort at its end (cross a manageable gap between two stepping stones). 3 – 6 year olds also make this trade-off, but to a lesser degree than adults. The results suggest that end-state comfort is an important determiner of locomotor behaviour, and show an early ability to engage in locomotor end-state comfort planning.

Introduction

One component of successful navigation is accurately perceiving the relations between the physical characteristics of the surrounding environment, and one's own action possibilities. This allows the walker to decide (implicitly or explicitly) which obstacles to avoid and which routes to take. Consider stepping over a puddle – I must know if I can successfully cross it, then choose my route over or round it as appropriate. How do humans acquire these abilities in childhood? 'Visual cliff' experiments showed that children as young as 6 months avoid a large drop (Gibson & Walk, 1960). Likewise we know that 12-14 month olds can reliably decide whether it is safe to walk on a slope (Adolph, 1995) or cross a barrier (Schmuckler, 1996). At first glance then, competence in making locomotor choices seems to be achieved impressively early. However, relatively little is known about children's performance in more complex locomotor situations.

In many natural environments, decisions must be made which require the walker to weigh up different options and balance conflicting motivations. For example one might have to choose between taking a long path over safe ground, or a shorter path over an icy patch. For various reasons, young children might find this kind of task difficult: they may have limited experience of the costs and benefits of different actions, immature executive functioning, or perceptual abilities below adult levels. In the present study we investigate this kind of situation by examining 'planning for end-state comfort'. This is an issue which has emerged from the reaching literature, but has not yet been investigated in walking. An everyday manual example is turning over an upside-down glass to pour wine into it: the glass is typically picked up 'underhand' (thumb pointing downwards) so that it can be put down again in a comfortable 'overhand' position (thumb pointing upwards). Thus planning for end-state comfort (ESC) involves minimising discomfort at the end of a movement by choosing a particular (possibly uncomfortable) posture at the start of the movement (Rosenbaum *et al*, 1990).

Experimental evidence for the tendency to engage in ESC planning comes from a series of manual studies by Rosenbaum and colleagues. In a 'bar' task, participants picked up a horizontally oriented cylinder with distinctively coloured ends, and placed it in one of four vertical target positions: left or right of its original position, and with its dark or light end pointing downwards (Rosenbaum *et al*, 1990). As in the wine-glass example, participants used an overhand or underhand grip to pick up the bar depending on the target position, acting to minimise awkward turns which would result in extreme joint angles, and exploiting the arm's tendency to return to a resting position if an unnatural position at the start was unavoidable. Participants behaved similarly in a 'handle' task (Rosenbaum, Vaughan, Barnes & Jorgensen, 1992). Further studies indicated that participants trade off an awkward starting position for a comfortable end position to ensure that during the crucial end phase of the movement the hand is in a position where it can be finely controlled (Short & Cauraugh, 1999).

ESC planning in manual tasks develops during childhood. On the handle task, adult-like selection of underhand grasps for certain rotations is barely present at 4 years - resulting in very awkward hand positions for these children - but clearly evident by 8 years (Smyth and Mason, 1997). In this study, evidence for such an increase on the bar task is equivocal; though a study by Hughes (1996) with higher demands for accuracy found a significant improvement between 3 and 4 years.

Studies with atypical populations help clarify the factors which underlie this development. Hughes (1996) found significantly less ESC planning in children with autism. In contrast, Smyth and Mason found no impairment on an ESC task in a group of children with Developmental Coordination Disorder (DCD). Taken together these results might suggest that the planning which develops is an executive, perhaps explicit process. However, recent data contradict this view and suggest ESC planning is essentially ‘motor’ in nature. Van Swieten et al (under review, *Dev Sci*) show that even adult performance is highly dependent on the motor subtasks involved, for example the initial rotation the hand must make to reach for the handle, and which hand is used. They also demonstrate that different groups perform according to their motor skill level - for example, children with DCD (but typical executive functioning) make fewer ‘ESC’ trade-offs than age-matched controls when large initial rotations are required; this is also true of typically developing young children. A strong ‘motor’ element to the planning is further suggested by the fact that recent movement history influences grip selection (Kent et al, 2008). Furthermore Newman (2001) shows that a group of children with Williams Syndrome, a rare genetic disorder with known dorsal stream and cerebellar abnormalities (see Bellugi et al, 1999; Atkinson et al, 1997), were impaired on an ESC handle task and that this impairment was not correlated with tests of frontal lobe function. Thus there is some evidence that manual ESC paradigms tap implicit, motor planning processes rather than explicit or executive processes.

In this experiment we developed a locomotor version of the end-state comfort task to test whether end-state comfort planning is present in locomotion, and if so how it develops. This is necessarily very different from any reaching task, but the underlying concept is the same. Participants walked on paths of small wooden 'stepping stones', a technique previously used to examine gaze during walking (Hollands, Marple-Horvat, Henkes & Rowan, 1995; Vickers & Patla, 1999). Our task tested ESC planning by trading off an uncomfortable manoeuvre at the start of the movement for a comfortable one at the end. The uncomfortable manoeuvre at the start was adjusting or crossing over feet; the comfortable movement at the end was stepping over a manageably-sized gap. For participants who were sensitive to end-state comfort, the size of this end gap would influence their initial manoeuvre and chosen route across the stones. We tested adults and 3- to 6-year-olds to examine the development of ESC planning in this locomotor task.

General Methods

Equipment

The equipment for this experiment created a 'river-crossing' scenario (Figure 1), with a blue 'river' made of vinyl sheet flooring [approx 170cm x 500cm] and some 'stepping stones' and planks of wood which could be used to cross it.

[FIGURE 1 ABOUT HERE]

Three small ‘stepping stones’ across the river were wooden blocks (21 x 9 x 2.5 cm each) securely fixed to the vinyl. One stone was the ‘start stone’. The other two were at a distance of 40% stride length and angles ±35° from the forward direction, since these values enabled a comfortable first step. On average participants were able to place one foot comfortably on a single stone, or two feet less comfortably. Two longer planks of wood (180 x 26 x 2.5 cm each) could be slid underneath the far bank to create a gap between the small stepping stone and the plank of wood. A cluster of cardboard ‘flamingos’ were positioned in the centre of the river.

Procedure

The experiment was presented as a river crossing game. Equipment was laid out as described above, and on each trial the planks were arranged so there were two alternative routes, one including a small gap and the other a large gap. These gap sizes were scaled to each participant’s step length (see *Design*). On every trial the task was to cross from the start to the opposite bank, by stepping on the ‘stepping stones’ and planks across the ‘river’. Participants were given no explicit instructions except to “cross the river, without falling in or knocking over a flamingo”. In practice the layout constrained them to stepping onto one of the small stones, then onto one of the longer planks of wood. This meant participants could cross by one of two routes, ‘fixed’ (small gap) or ‘variable’ (usually a larger gap) (see *Design* for gap sizes). On each trial we measured whether participants took the ‘fixed’ or ‘variable’ route.

The flamingos did not obstruct the view of adult or child participants, or constrain their movement except to prevent jumps between the left and right stones, or diagonally across from a small stone to the opposite-side plank. This meant that once on a path, participants were committed to it, and could not change their plans part way through the movement (as has also been the case in manual studies).

If a child successfully crossed the river without ‘falling in’ (touching the blue vinyl) they retrieved a toy animal from the box on the opposite bank, which they added to a toy ‘jungle’ constructed over the course of the study. This procedure encouraged children to follow the rules of the game: in fact this meant they retrieved a reward on almost every trial.

Experiment 1

Since our main task (Experiment 2) required participants to perceptually discriminate between gap sizes at a distance, it was first necessary to show that children of the ages tested were visually sensitive to this difference. Experiment 1 tested children’s ability to make such a discrimination.

Method

Participants

Ten 4.5 year olds (mean 4.54 years, s.d. 0.19 years) took part. In addition, three 3.5 year olds (mean 3.43 years, s.d. 0.26 years) took part in a shortened version of the experiment (one block of trials) after completing Experiment 2. All had normal or corrected to normal vision, and had been recruited from the John Radcliffe Hospital (Oxford, UK) at birth.

Procedure

On each trial the participant was presented with the river-crossing task, with one fixed and one variable route. Participants placed their feet naturally on the footprints on the near bank. Participants were asked which would be the easiest route to take and pointed to one side to indicate their answer. They then crossed the river by that route and, if successful, collected a toy from the box on the far bank.

Design

To enable fair comparison across age groups, gap sizes (between the small stones and the planks) were scaled to each participant's stride length. Before the experiment we measured leg length and multiplied by 1.58 to estimate stride length since for the age range we tested, the ratio (stride length : leg length) is reasonably constant **(Hof & Zijlstra, 1997)**. The size of the fixed gap (distance from the start stone to one plank) was constant at 80% stride length. Two factors were varied within-subjects. These were the size of the variable gap (distance from start stone to other plank), which was 80, 100, 120, or 140% of each participant's stride length); and the side of the variable gap (left or right, 50% trials each). Each participant completed 32 trials (variable gap size (4) x gap side (2) = 8 trials per block, random order, x 4 blocks = 32 trials).

Results

All participants correctly judged which route was easiest to take (i.e. had the smallest gap) on all trials. An inability to make this judgment was therefore unlikely to contribute to the results of Experiment 1.

Experiment 2

This experiment used the layout described in Experiment 1 to test ESC planning in children and adults.

Method

Participants

Twelve 3.5 year olds (mean 3.44 years, s.d. 0.14 years), thirteen 4.5 year olds (mean 4.44 years, s.d. 0.14 years), twelve 6 year olds (mean 6.48 years, s.d. 0.24 years) and thirteen adults (mean 21.17 years, s.d. 0.77 years) took part. All had normal or corrected to normal vision. 3 and 4 year olds had been recruited from the John Radcliffe Hospital (Oxford) at birth and were tested in the laboratory; 6 year olds were recruited and tested in a local school.

Procedure

As before, on each trial the participant was presented with the river-crossing task, with one fixed and one variable route. They were instructed to “cross the river without falling in”; if successful they collected a toy from the box on the far bank. However, in this study we manipulated the starting position of the feet to introduce a need for end-state comfort planning (Figure 2). Participants began each trial with one foot on the first stepping stone and the other behind it on the bank. Adults were told which foot to place on the start stone first; for children, because of difficulties with left-right naming the experimenter tapped the appropriate foot. These initial foot positions biased participants to move in one direction (see Figure 2: the right foot on the bank would naturally move to the right-hand-side small stone).

However, on each trial participants were free to change foot positions or make a cross-over step (back leg crosses past front leg). This kind of movement might be particularly useful if the ‘natural’ movement would lead to the participant being faced with the large gap. In this case, participants would be planning for end-state comfort, since an uncomfortable movement at the start of the trial would result in a more comfortable second step. Given the choice of a large gap which they could take without any foot adjustments, and a small gap which required such adjustments, participants who were planning for ESC would be expected to show an increasing tendency to adjust their feet to cross the small gap, as the size of the large gap was increased. Thus the slope of a function relating gap size to route choice should act as an index of planning for end-state comfort. (This parallels the Smyth and Mason study, where choice was a function of handle position).

Design

Four age groups (3 years, 4 years, 6 years, adult) were tested. The size of the variable gap was varied within subjects: this was 80, 100, 120, or 140% of each participant's stride length (each value occurring on one quarter of the trials). The fixed gap was always 80% stride length. There were two further manipulations: 'start-foot', i.e. which foot was placed on the start stone (left or right, 50% trials each); and the side of the variable gap (left or right, 50% trials each). These manipulations combined to make half the trials 'test' trials, and half 'control' trials. On control trials start foot and variable gap side were the same, i.e. feet were positioned so the most natural route to take (requiring no foot corrections) was the fixed route. On test trials (Fig 2) start foot and distance side were opposite, i.e. feet were positioned so the most natural route to take was the variable route. This means that on test trials, for a large variable gap size, adjusting feet at the start of the movement to take the fixed route (Fig 2b) would lead to better end-state comfort (and perhaps successful crossing) than stepping naturally onto the variable route (Fig 2a). Each participant completed 64 trials (variable gap size (4) x start foot (2) x gap side (2) = 16 trials per block, x 4 blocks = 64 trials).

[FIGURE 2 ABOUT HERE]

Participants were presented with a given layout (gap side and distance) on two consecutive trials. Within a pair of trials one started with the right foot, the other with the left, so that there was always one control trial and one test trial, in random order. Gap side (left or right) and distance (80, 100, 120, 140% stride length) were randomised within each block.

Data analysis

We measured the proportion of trials on which participants took the fixed route. If participants were planning for ESC, this would happen more often as gap size increased. These proportion data were arcsin transformed to enable ANOVA of the non-normal distribution arising from ceiling effects in proportion measures. For each trial type (test, control) we then performed an ANOVA with factors age (3 years, 4 years, 6 years, adult) and variable gap size (80%, 100%, 120%, 140% stride length). To look for development within the children's groups we repeated these ANOVAs with only the age groups 3 years, 4 years, and 6 years.

Results

Adults never 'fell in the river'. Children only did so on a small proportion of trials - around ~3% for all ages, on average 1-2 trials per participant.

Figure 3 presents mean data for different trial types and age groups. Fig 3a shows that on test trials the fixed route was more often taken when the variable gap was large, despite this requiring initial foot adjustments. For test trials there was a main effect of variable gap size ($F[3,138] = 80.5$, $p < 0.001$), a main effect of age (3 years, 4 years, 6 years, adult) ($F[3,46] = 5.6$, $p < 0.003$), and an age x variable gap size interaction ($F[9, 138] = 7.8$, $p < 0.001$). The effect of gap size demonstrates planning for locomotor ESC. The interaction shows that the degree of ESC planning varied with age. The plots in Figure 3 suggest that adults change their behaviour much more steeply in response to the change in gap size, i.e. plan more sensitively for ESC, than children in any of the age groups.

[FIGURE 3 ABOUT HERE]

Across all gap sizes there was a trend for 6-year olds to take the fixed route least often, followed by 4-year olds, 3-year olds, then adults. However a second ANOVA on the age groups of children showed that there were no significant differences between these age groups: there was no main effect of age ($F[2,34] = 1.9$, $p > 0.1$) and no gap size x age interaction ($F[6,102] = 0.38$, $p > 0.9$). Most importantly, there was still a main effect of gap size ($F[3,102] = 28.5$, $p < 0.001$), which demonstrates the existence of ESC planning in children's locomotion taking the three age groups together.

Figure 3b illustrates fixed route choices for control trials. Although on these trials the fixed route was always easiest and most natural to take, children took the fixed route less often than adults, sometimes opting to adjust their feet and cross a larger gap on the other side. On these control trials there were no significant effects of gap size ($F[3,138] = 2.5$, $p < 0.06$), or gap size x age ($F[9,138] = 1.8$, $p > 0.07$), but a main effect of age ($F[3,46] = 6.1$, $p < 0.002$). A second ANOVA on control trials showed that there were no significant differences between the three age groups of children: there was no effect of gap size

($F[3,102] = 2.3$, $p > 0.08$) or age ($F[2,34] = 1.7$, $p > 0.1$) and no gap size x age interaction ($F[6,102] = 1.9$, $p > 0.08$).

This control trial data suggests that children may have been motivated, at least in part by a desire to jump across large gaps. This motivation would conflict with any planning for ESC, which would cause children to avoid large gaps. While we cannot assume the magnitude of the effect was the same on control and test trials, nevertheless to obtain a better measure of ESC planning we calculated planning on test trials relative to a control baseline. Figure 3c plots the measure (proportion fixed route [test trials] - proportion variable route [control trials]). This transformation of the data probably gives a more accurate picture of the underlying behaviour, but does not change its overall pattern.

In choosing whether to take the variable route participants must balance two conflicting motivations: avoiding a large gap, and minimising awkward foot movements. Planning for end-state comfort is the behaviour in which the first of these motivations wins out over the second. Figure 3d illustrates how participants would perform if they were influenced by only one of these factors (gap avoidance and foot adjustment respectively). Comparing these graphs to the actual data makes it clear that at all ages participants did plan for end-state comfort by tending towards gap avoidance: adults tended more towards this pattern than children, who seemed to be more influenced by the immediate discomfort of foot adjustment. The results suggest that the ability to engage in ESC planning must develop further between 6 years and adulthood.

Discussion, Experiments 1 & 2

We used a 'river crossing' paradigm to test whether adults and children would adjust their feet at the start of their walk to avoid crossing a large gap at the end of it. This task is a carefully controlled analogue of many everyday situations where some adjustment would allow avoidance of an obstacle. Since both crossing the obstacle directly and avoiding it entail some cost to the walker, efficient walking requires a carefully balanced choice. These experiments demonstrate that this kind of trade off ('end-state comfort planning'), does occur in locomotion.

How does this ESC planning fit into a broader framework of locomotor planning? In ESC planning, a current route choice is affected by distant environmental features. Some current models of human walking explain this kind of effect, suggesting that walkers can steer through a complex environment guided online by relevant information (Fajen & Warren, 2003; Warren, 2006). At each point, the walker is 'attracted' to goals (which they steer toward) and 'repelled' from obstacles (which they steer away from). The magnitude of these attractive and repulsive forces is largest for nearby objects and drops in a predictable manner with walker-object distance. Under such a model, the large gap in our task should act as a repeller which participants are influenced to avoid, to differing degrees depending on its size. Our results do show that the gap is often avoided, but they also show that one's own body state massively influences choice. In our case, the relevant body state was initial foot positioning. When foot positions lead naturally away from the large gap (control trials), it is rarely taken; when feet lead naturally towards it, it is taken much more often (test trials). Thus, our data suggest that the effect of a repeller is highly dependent on the walker's own body state as well as their location. Nevertheless they are consistent with the modeling of large obstacles as repellers which afford different actions to the walker (Gérin-Lajoie & Warren, 2008).

An alternative framework in which to consider these results is one in which movements are 'planned' rather than controlled online. This may involve more abrupt 'choices' during the walk, more abstract reasoning and even explicit processes in which the walker consciously weighs up their options (e.g. "Although it's a hassle, I will cross over my feet and follow the 'fixed' path since I want to avoid the big gap"). This kind of framework has certainly been applied to reaching ESC tasks (Rosenbaum, Carlson & Gilmore, 2001; Smyth & Mason, 1997; Hughes, 1996) and might equally apply to a walking situation. However, further studies would be needed to directly assess whether this kind of abstract planning framework or a more online, 'motor' framework best describes behaviour in locomotor ESC tasks.

Our data suggest immature ESC planning around 3 – 6 years, and imply a later development of the ability between 6 years and adulthood. Several factors could have influenced performance on the task. First, adjusting or crossing over feet at the start of movement may have been more difficult for the children than the adults. However children's behaviour strongly suggested this was not the case: they made foot adjustments even when it was unnecessary, on control trials. Second, Experiment 1 demonstrated that children were able to judge the relative gap sizes of the fixed and variable routes at a distance. We can therefore exclude both perceptual and motor performance limitations as explanations of behaviour on this task. Rather the immaturity seen in children's performance must be in the planning process, in which perceived gap size and body position influence the course of action taken. The results suggest that planning for end-state comfort is present in some form by three years, and develops further from six years to adulthood. It may be a powerful factor in childrens' locomotor choices which should be compared and contrasted with others such as walking skill or body size.

Although there was clearly development from childhood to adulthood, establishing the pattern of development during childhood was difficult. The slope of the function relating gap size to route choice indicated sensitivity to ESC. There was no significant effect of age on this slope, so ESC planning apparently did not develop from 3-6 years. However, there was certainly a trend for older children to take the fixed route less often than younger children. This may indicate a U-shaped pattern of development in ESC planning. A more likely explanation is that older children enjoyed jumping large gaps on test trials. It might be possible to devise a more suitable test of ESC for children of this age, but in itself this result also suggests that development of end-state comfort use has two components: the ability to predict end-state comfort or use it to guide action, which we were attempting to measure; and the priority assigned to end-state comfort. While 6 year olds may be successfully able to predict end-state comfort, they may not in practice prioritise as much as adults or 3 year olds do: thus they sometimes choose to jump very large gaps on test trials. This makes intuitive sense since at this age it may be important for children to explore their locomotor abilities by taking challenging steps (in this case, crossing large gaps). Thus end-state comfort is to some extent a consideration for children, but there is a fundamental shift in its importance from childhood to adulthood. These two components of end-state comfort should be distinguished in future paradigms.

What processes might underlie the development of planning for end-state comfort? The kind of planning processes described above are complex. They involve looking at least one step ahead; making a relative size judgment of multiple environmental features; making a body-scaled judgment of at least one environmental feature and using this to anticipate future discomfort; and relating these judgments to current movement options. From Experiment 1 we think it unlikely that the size judgment element of the task (either environmental or body-relative) was a problem for our groups; but exclamations midway through the movement (of the form "Oh no, this gap is too big") suggested that failing to look ahead may have contributed to the failure to plan for end-state comfort. The unique feature of end-state comfort is in detecting the impact that distant environmental features should have on current plans, and it is likely that this element of the task also developed between 6 years and adulthood.

Might a common process underlie manual and locomotor ESC planning? Our study does not directly address this question. Nevertheless the results are not immediately suggestive of a common pattern of development across manual and locomotor ESC tasks. Whereas 4-5 year olds in Smyth & Mason's manual study showed virtually no such planning, in our task very young children (3 years) showed quite proficient planning. In both studies 6 year olds performed significantly below adult levels. These comparisons imply that locomotor ESC planning reaches competence earlier than manual ESC planning, and both continue developing over a wide age range. Early development in the locomotor domain could be accounted for by the larger cost of making mistakes in locomotion (putting the whole body in a precarious or dangerous position). This hypothesis could be tested by a carefully designed within-subjects study which uses manual ESC tasks, locomotor ESC tasks, and other tasks to test for the existence of a specific ESC factor in children's motor planning.

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