When an object appears unexpectedly: foot placement during obstacle circumvention in children and adults with Developmental Coordination Disorder

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Abstract

Adjustments to locomotion to avoid an obstacle require a change to the usual pattern of foot placement, i.e. changes to step length and/or step width. Previous studies have demonstrated a difficulty in individuals with Developmental Coordination Disorder (DCD) in controlling stability while both stepping over and while circumventing an obstacle. In a previous study we have considered the way in which individuals with DCD prepare for the possibility of an obstacle appearing (Wilmut and Barnett, 2017). Using a parallel data set from this same task on the same individuals the aim of the current study was to investigate the exact nature of changes in foot placement during obstacle avoidance, as this was not clear from previous work. Children and adults aged from 7 to 34 years of age took part in the study. Forty-four met the criteria for a diagnosis of DCD and there were 44 typically developing (TD) age and gender matched controls. Participants walked at a comfortable pace down an 11m walkway; on 6 out of 36 trials a 'gate' closed across their pathway which required circumvention. These 6 'gate close' trials were analysed for this study. The number and magnitude of step length and step width adjustments were similar across the DCD and TD groups, however, the younger children (7-11yrs) made a greater number of early adjustments compared to the older children and adults (12-34 years of age). In contrast the adults made a greater number of adjustments later in the movement compared to the children. In terms of foot placement adjustments a clear preference was seen across all participants to use adjustments which resulted in reducing step length, stepping away from the obstacle and a combination of these. Apart from subtle differences, the individuals with DCD make step placements to circumvent an obstacle in line with their peers. It is suggested that the choice of foot placement strategy in individuals with DCD, although in line with their peers, may not be optimal for their level of motor ability.

Keywords

Stability, circumvention, foot placement, constraints-based-approach

Introduction

In order to safely pass through the environment everyday movement requires us to do more than to walk in a straight line using a uniform locomotor pattern, for example, we might need to change direction, raise the foot higher to step over or change step length/width to avoid obstacles. These adaptations to basic patterns of locomotion occur in response to demands of the environment, individual ability and task goals (Moraes, 2014)). A key part of successful adaptive locomotion is the ability to place the foot appropriately in response to an obstacle (Moraes, 2014). When quantifying this, researchers have measured the re-positioning of the foot when faced with an obstacle with respect to where that foot would have landed if no obstacle were present.

Patla, Prentice, Rietdyk, Allard, & Martin (1999) asked participants to walk along a designated path and avoid stepping on light spots as they appeared. They compared the landing position of the foot in the presence of a light spot to the landing position of the foot in the absence of a light spot and classified these adjustments into 8 strategies: long, short, medial, lateral, long medial, long lateral, short medial and short lateral. From their data Patla et al. (1999) concluded that the choice of these strategies was not random, but rather participants chose a response depending on the conditions of the trial. Based on their findings Patla et al. (1999) suggested that the selection of alternative foot placement is driven by three key criteria: *efficiency*, movements are chosen which result in the least energy expenditure; *stability*, movements are chosen which prevent loss of balance; and *maintenance of forward progression*, movements are chosen which optimise the speed at which the body moves forward. Subsequent studies have demonstrated that no one of these criteria is used as a default, but rather each is a single determinant in the decision process.

For example, Weerdesteyn, Nienhuis, Mulder, & Duysens (2005) used virtual obstacles which allowed them to project a ‘to be stepped over’ obstacle onto the pathway of a group of older females. Participants could either adopt a short-step over strategy or a long-step over strategy. Findings demonstrate a clear preference for lengthening their strides over shortening. Step lengthening has also been shown to be the preferred strategy in individuals recovering from stroke (Den Otter, Geurts, de Haart, Mulder, & Duysens, 2005) and in adults without motor difficulties (Moraes et al. 2007). In light of these findings it would seem that participants are biased towards maintenance of forward progression (illustrated by the preference for step lengthening). However, Chen, Ashton-Miller, Alexander, & Schultz (1994) considered stepping over in a group of young and elderly adults. The timing of obstacle appearance was altered to give participants more or less time to respond. Chen and colleagues found that as response time decreased participants tended towards using the short-step, whereas when more time was available all participants adopted the long step strategy. This latter study demonstrates a clear shift in criteria as task demands change; moving from a default of ‘maintenance of forward programme’ when there are no time constraints to ‘stability’ when forced to respond quickly. When the task is changed from stepping over to circumvention we see a clear preference for shortening step length in adults (Wilmut, Du, & Barnett, In Press) and children (Vallis and McFayden, 2005), once again demonstrating that the way in which foot placement adaptations are made depends on the demands of the task. This idea of different factors constraining or changing movement patterns is the backbone of the constraints-based-approach to motor control which advocates that the environment, the task and the individual are all possible constraints on a motor response (Newell, 1986). This is a helpful framework in which studies on alternative foot placement can be considered.

The constraints-based-approach has also been advocated as a useful framework in which to consider the movement patterns of individuals with Developmental Coordination Disorder (DCD) (Sugden & Wade, 2013). DCD is thought to occur in approximately 2% of the UK population (Lingam, Hunt, Golding, Jongmans, & Emond, 2009) with individuals presenting with both fine and/or gross motor difficulties (Sugden, 2006). Research has demonstrated that children with DCD do not simply grow out of their motor difficulties, but rather that these can persist into adolescence and early adulthood with associated emotional and behavioural difficulties (Kirby, Edwards, Sugden, & Rosenblum, 2010). Anecdotal evidence from parents of children with DCD and the professionals working with them suggests that they are prone to colliding with obstacles in their pathway (Geuze, 2007). Given the key role that adaptive locomotion plays in obstacle avoidance it is surprising that there is a paucity of data regarding this skill. Deconinck, Savelsberg, De Clercq, & Lenoir (2010) considered the nature of approaching and stepping over an obstacle in a group of children with DCD. They showed no differences in step length and step width compared to typically developing controls but they did exhibit difficulty in controlling medio-lateral velocity when stepping over. Although this study suggests adequate anticipatory control (i.e. obstacle collision was avoided), it is not clear why an increase in medio-lateral velocity is seen or exactly what changes in foot placement these individuals make during obstacle avoidance.

In a recent study we measured the approach towards and circumvention around an obstacle (Wilmut & Barnett, 2017). The primary aim of this previous study was not to consider the exact nature of obstacle circumvention per se but rather to look at how individuals prepared for such a movement, in other words when faced with an environment where an obstacle could or could not appear do individuals change their movement in anticipation of that possibility. This previous paper primarily focused on movement prior to the obstacle appearing and did not consider exactly how the obstacle was circumvented. The aim of the current study was, therefore, to further analyse these data in order to describe the nature of foot placement during obstacle circumvention in children and adults with and without DCD. Previous studies have shown that children and adults with DCD tend to start an adjustment to locomotion earlier than their peers during both an aperture crossing task where we see them start to turn when further from the aperture (Wilmut et al, 2016) and a circumvention task where we see them starting to adjust their path further from the obstacle (Wilmut and Barnett, 2017). Therefore, we considered adjustments to foot placement during four steps prior to and during obstacle circumvention. As the literature has demonstrated similar step length and step width in children with DCD whilst walking on an even terrain (Du, Wilmut, & Barnett, 2015) and whilst stepping over an obstacle (Deconinck et al., 2010) we did not expect large group differences in terms of these measures. However, it was expected that individuals with DCD would start their movement adjustments earlier in their movement and that they may use different strategies for obstacle avoidance and may weight the three key criteria identified by Patla et al (1999) differently to their peers.

Method

Participants

This project was approved by Oxford Brookes University Research Ethics Committee. Forty-four participants with DCD were recruited for this study and divided into three age groups: adults (N=15, aged from 19 to 34 years), older children (N=15, aged from 12 to 17 years) and younger children (N=14, aged from 7 to 11 years). In addition, 44 age (to within 6 months) and gender matched typically developing individuals were recruited and divided into the same groups. Details regarding these participants can be found in Table 1. Participants with DCD were recruited from two sources: from a group known to the authors from previous studies and from a local support group for individuals with DCD and their families. All participants with DCD were assessed and selected in line with the DSM-5 criteria for DCD and recent UK guidelines (Barnett, Hill, Kirby, & Sugden, 2015).

To determine motor skill below the level expected for the individual's chronological age (criterion A) we used the test component of the Movement Assessment Battery for Children second edition (MABC-2; Henderson, Sugden, & Barnett, 2007) for individuals ≤17years of age and a combination of this and the Bruininks-Oseretsky Test of Motor Proficiency, Second Edition, Brief Form (BOT-2 Brief; Bruininks & Bruininks, 2005) for individuals > 17 years. Individuals with DCD scored below the 16th percentile on the MABC-2 and below the 18th percentile on the BOT-2 Brief. To determine that the motor impartment significantly impacted on daily living (criterion B) the MABC-2 Checklist, the DCD-Q (Wilson, Kaplan, Crawford, Campbell, & Dewey, 2000) and a telephone interview with the parent was used for individuals ≤17yrs of age while the Adult Developmental Coordination Disorder Checklist (ADC; Kirby & Rosenblum, 2008) and a telephone interview with the participant was used for individuals >17yrs. Telephone interviews were also used to determine that the onset of that difficultly was in early childhood (criterion C) and that the difficulties were not due to a known neurological impairment or intellectual disability (criterion D). The typically developing (TD) individuals or their parents completed a telephone interview and the MABC-2 Checklist / ADC (depending on age) to confirm that no movement difficulties were present.

Given the co-occurrence of motor difficulties and attention difficulties all participants or their parents completed either the Strengths and Difficulties Questionnaire (SDQ; Goodman, 1997) or the Conners' ADHD adult rating scales (CAARS; Conners, Erhardt, & Sparrow, 1999). Only 10 of the individuals with DCD had high or very high scores on the hyperactivity / inattention subscale compared to none of the typically developing individuals. Running analyses both with and without these individuals with high or very high scores did not alter the outcome of the findings and so they were included in the study.

Table 1. Descriptive information for the six cohorts

	Adults		7-11years		12-17years	
	TD	DCD	TD	DCD	TD	DCD
N	15	15	15	15	14	14
Mean age (yrs:mo)	23:3	25:5	14:7	14:11	9:3	9:3
Gender ratio (F:M)	2:3	2:3	1:3	1:3	1:6	1:6
MABC-2 test mean percentile (range in brackets)	-	1.54 (0.1-5)	-	2.55 (0.1-5)	-	3.71 (0.5-9)
BOT-2 test mean percentile (range in brackets)		7.07 (1-18)	-	-	-	-
MABC-2 checklist total score	-	-	0.7	27.6	3.0	25.9
DCD-Q total score	-	-	70.2	33.1	65.5	34.6
ADC total score	21.7	65.9	-	-	-	-

2.2 Apparatus and procedure

Participants walked barefoot at a comfortable pace along an 11m by 1m walkway made from high density foam sports mats. Two rectangular ‘gates’, 60cm wide and 30cm high and constructed from the same high density foam material, were positioned on each side of the walkway (see Figure 1) 8m from the start point. A motion sensor was positioned 5m from the start point (3m in front of the gates) and this when crossed could trigger either the right or left gate to close, partially blocking the pathway. When the motion sensor was activated there was a delay of ~16ms prior to the gate starting to move and the gate took ~1250ms to fully close[1].

A Vicon Nexus 3D motion capture system with 16 cameras running at 100Hz was used to track the movement of reflective spherical markers (9mm in diameter) attached to the skin at five bony landmarks: the sacral wand, the second metatarsal head on left and right foot (left and right toe marker), and the lateral malleolus on left and right foot (left and right ankle marker). Participants were instructed to walk from the start to the stop point for each trial, and then return to the start by the

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[1] As walking speed tends to differ between individuals with DCD and typically developing individuals and also across age this resulted in a different time-to-contact (TTC) for the different groups. Using the walking speed from the ‘no gate’ trials the range of TTC was 0.89 seconds to 1.66 seconds for the typically developing individuals and 1.29 seconds to 1.62 seconds for the individuals with DCD.

return path. In ‘gate close’ trials the motion sensor was switched on so that it was triggered as the participant walked by, causing one of the gates to close across the pathway and forcing them to circumvent the gate to avoid collision and continue their passage. Circumvention of a closed gate was first demonstrated to participants, who were instructed to walk around the gate while continuing their passage along the walkway. On ‘gate open’ trials, unbeknown to the participant, the motion sensor was deactivated so that the gates remained stationery and parallel to the walkway throughout the trial allowing for unobstructed passage. Participants completed 6 ‘gate close’ and 30 ‘gate open’ trials with the former interspersed randomly and the side of closure (right or left) also random. This ensured that presence of the obstacle in the pathway was unpredictable. The start point was varied by ±20cm to avoid the participant starting at a consistent distance from the obstacle and hence using a predictable stepping pattern. In this paper only the ‘gate close’ trials are considered and only data after the gate actually closed are analysed. In addition to these ‘gate open’ and ‘gate close’ trials each participant completed 6 ‘no gate’ trials where they walked down the same pathway but without the presence of the gates. These 6 trials were used to calculate ‘standard’ foot placement measures (i.e. standard step length and step width when no obstacle was present) against which those from the ‘gate close’ trials could be compared.

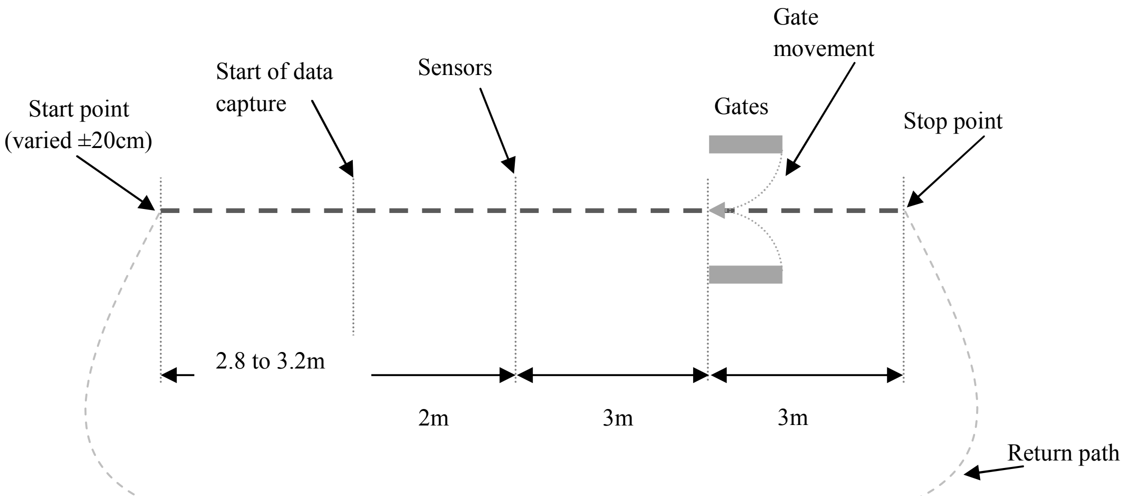

Figure 1. A. bird’s eye view of the set up including the walking path, the return path and the location of the sensors and gates. N.B. the gate measured 60cm wide and so when closed it only partially blocked the pathway.

Data analysis

All participants successfully circumvented the obstacle without any trips or falls on any of the trials. Therefore all data were included in the analysis. VICON movement data was smoothed using an optimized low-pass Woltring filter with a 12Hz cut-off point and was then processed using tailored Matlab routines. Measurements of foot placement were taken. A trial ended at the point that the sacral wand crossed the position of the closed gate. The four steps preceding this point were analysed in this study, these are referred to as the crossing step (cross) and the three steps preceding this (cross-1, cross-2 and cross-3); referred to as step number. Heel strike (HS) and toe off (TO) events were determined based upon an adapted foot velocity algorithm (O'Connor, Thorpe, O'Malleya, & Vaughana, 2007), it was adapted so that the ankle marker rather than the heel marker was used. From the timing of the HS and TO events two measures pertaining to foot placement were determined: *Step length,* the anterior-posterior distance between the front foot ankle marker and the back foot ankle marker at each HS, this was normalised to leg length; *Step width,* the medio-lateral distance between the two ankle markers at each HS, this was normalised to hip width. Data from both the 'gate close' trials and the 'no gate' trials were analysed in this way and the latter formed the standard step length and step width, i.e. the step length and width used when no obstacle was present. We were only interested in actual adjustments to step length and step width, so initially we classified each 'gate close' step as either an adjustment or a no adjustment step. A step was classified as an adjustment step if the step width and/or step length fell above or below three standard deviations[2] of the standard step length/width. Three measures were then calculated for each participant at each step number (cross, cross-1, cross-2, cross-3): *Percentage of adjustment steps* was simply the number of adjustment steps at each step number divided by the number of steps at each step number * 100; *Percentage change in step length and step width,* for all trials the percentage change (as compared to the 'no gate' standard) in step length and step width was calculated for each of the four steps, with a positive number indicating an increase in step length / width and a negative number indicating a decrease (if a given participant on a given step number did not show a step adjustment, i.e. step length / width was not above or below three standard deviations, then this value was set to 0); and *Categorisation of step adjustments*, the adjustment steps were each assigned to one of 8 categories: an increase in step length (long), a decrease in step length (short), an adjustment taking the participant towards the gate (toward), an adjustment taking the participant away from the gate (away), an increase in step length which also took the participant towards (long-towards) or away (long-away) from the gate or a decrease in step length which also took the participant towards (short-towards) or away (short-away) from the gate. In each case the percentage of steps falling into each strategy at each step number was calculated. This categorisation is illustrated in Figure 2.

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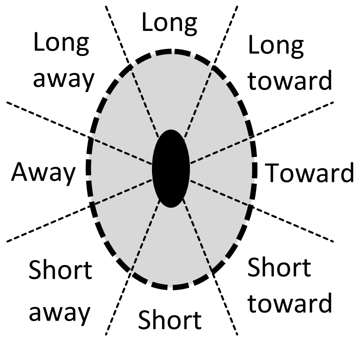
[2] Three standard deviations were chosen based on our observations in previous studies that step length and step width variability is higher in young children compared to older children and in individuals with DCD compared to typical individuals. Our previous data demonstrated that two standard deviations from the mean did not always account for this natural variability in foot placement.

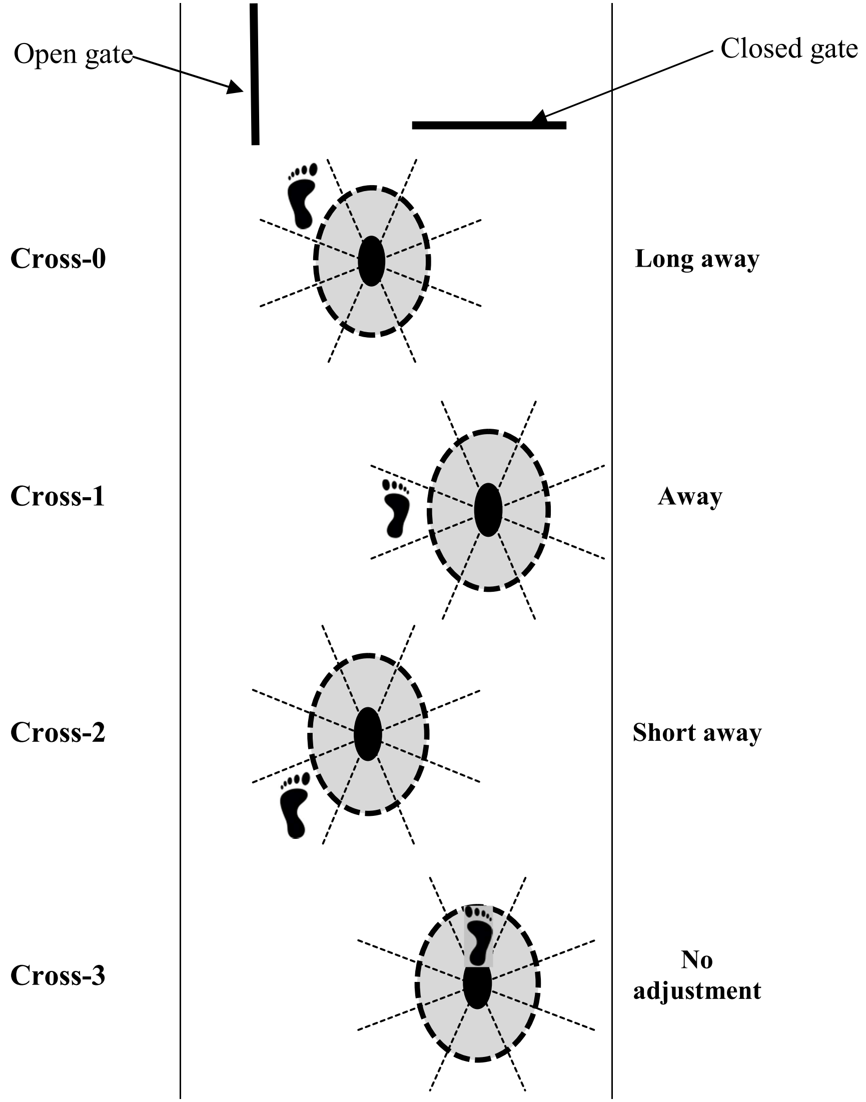
The black oval represents the standard position of the foot with respect to the previous foot placement, i.e. where we would have expected the foot to land if no obstacle was present

The dotted oval and grey area represent foot placements within 3SD of the standard foot placement, only step placements outside this area were considered to be adjustment steps.

Steps falling in the white area would be considered step adjustments and these were classified into eight types, see diagram (assumes the RIGHT gate closes, if the left gate closes the ‘away’ and ‘toward’ strategies would appear on the other side).



Step placements were categorised for the four steps leading up to the gates. An example is given below. The black oval present standard foot placement and pictures of feet the actual foot placement



Statistical analysis

The percentage of adjustment steps and the percentage change of step length and step width was considered across the four step numbers (cross-3, cross-2, cross-1 and cross), the three ages (adults, 12-17yrs, 7-11yrs) and the two groups (TD and DCD) using a 4 x 3 x 2 ANOVA. For the categorisation of step adjustments, the percentage of times each category was chosen was considered across the three ages (as above) and the two groups (as above) for each step number separately using a 3 x 2 ANOVA. In this latter case analyses were carried out for each step number separately due to missing data caused by participants not making step adjustments at each step number. For all statistical analyses Greenhouse-Geisser was reported when the assumption of sphericity was violated. Significant main effects were followed up with post-hoc tests using a Bonferroni correction to adjust for multiple comparisons and significant interactions were followed up with a Pillai's Trace simple main effects test. Partial eta-squared is reported as a measure of effect size and the significance level set at 0.05.

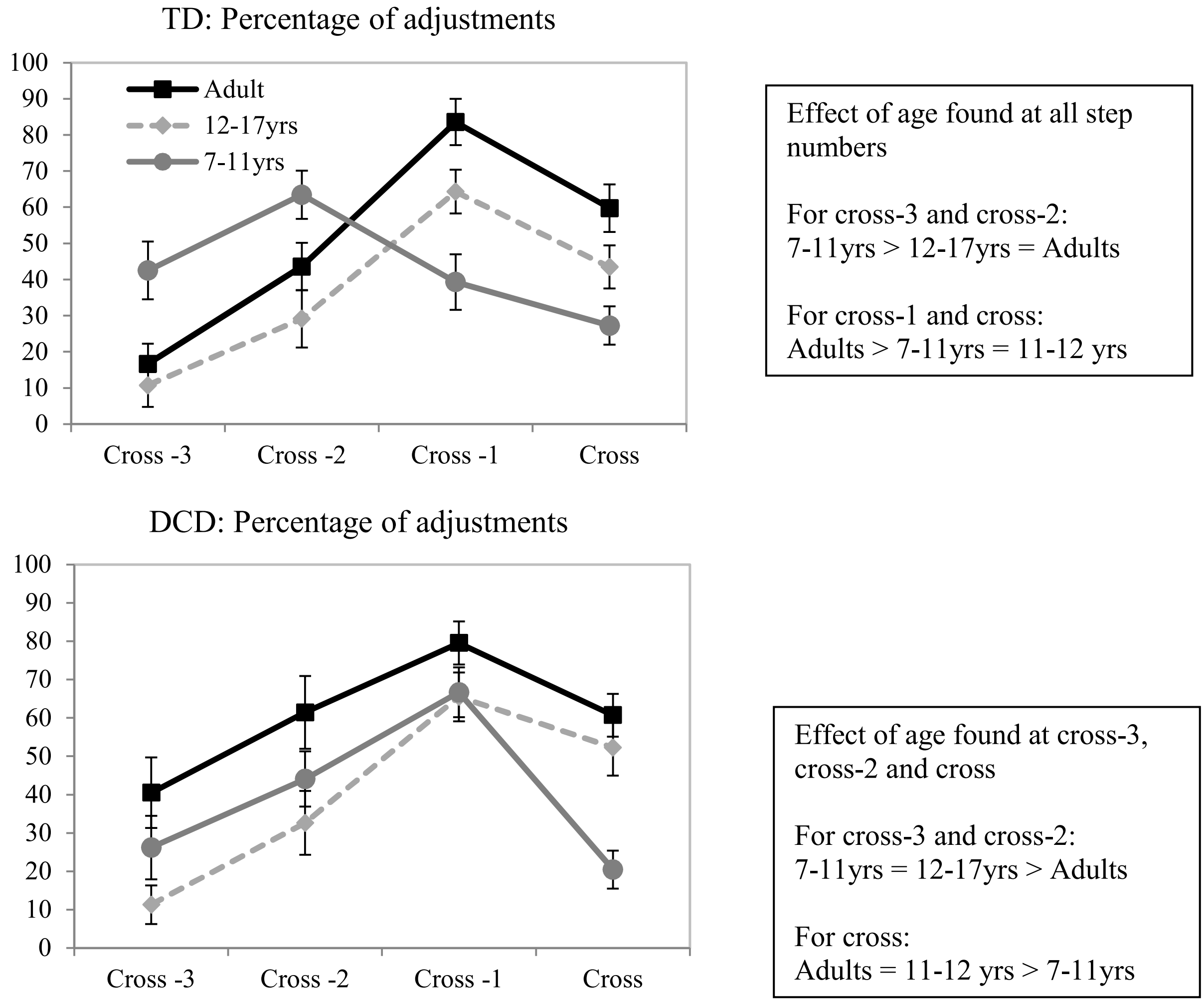
Results

All participants successfully completed all conditions without collision and participants followed the instructions and circumvented the obstacle rather than stepping over it.

Percentage of adjustment steps

Data can be found in Figure 3. An ANOVA (step number x age x group) found significant interactions between step number and age [F(6,246)=7.54 p<.001 η^2=.16] and step number, age and group [F(6,246)=2.56 p=.02 η^2=.06]. These were then the focus of further analyses. To unpick these interactions we considered step number and age for each group separately. Both groups demonstrated a significant effect of step number [TD: F(2.541,104.188)=16.80 p<.001 η^2=.29, DCD: F(2.331,95.575)=24.47 p<.001 η^2=.37] which was due to a greater percentage of adjustments for cross-1 compared to the other steps (cross-1 > cross-2=cross = cross-3). A significant effect of age was also found for both groups [TD: F(2,41)=3.69 p=.034 η^2=.15, DCD: F(2,41)=7.94 p=.001 η^2=.28] with a greater number of adjustments in the adults compared to either of the child groups (adults>7-11yrs=12-17yrs). Finally, both groups demonstrated an interaction between step number and age [TD: F(6,123)=6.47 p<.001 η^2=.24. DCD: F(6,123)=3.42 p=.004 η^2=.14]. To unpick these we ran simple main effects for each step number. For the typically developing group we found an effect of age for each step number [cross-3: F(2,41)=4.34 p=.015 η^2=.18, cross-2: F(2,41)=7.23 p=.002 η^2=.26, cross-1: F(2,41)=6.20 p=.004 η^2=.23, cross: F(2,41)=4.04 p=.025 η^2=.17], for cross-3 and cross-2, this was due to a greater percentage of adjustments in the 7-11yr-olds compared to the other two groups (7-11>12-17=adult), for cross-1 and cross this was due to fewer adjustments in the child groups compared to the adults (7-11=12-17<adult). For the DCD group an effect was found for cross-3,

cross-2 and cross [cross-3: F(2,41)=4.28 p=.021 η^2=.17, cross-2: F(2,41)=3.76 p=.032 η^2=.16, cross: F(2,41)=14.17 p<.001 η^2=.41]. For cross-3 and cross-2 this was due to a greater percentage of adjustments in the child groups compared to the adults (7-11=12-17>adult), for cross it was due to fewer adjustments in the 7-11yr-olds compared to the other two groups (7-11<12-17=adult).


TD: Percentage of adjustments

Effect of age found at all step numbers

For cross-3 and cross-2:
7-11yrs > 12-17yrs = Adults

For cross-1 and cross:
Adults > 7-11yrs = 11-12 yrs

DCD: Percentage of adjustments

Effect of age found at cross-3, cross-2 and cross

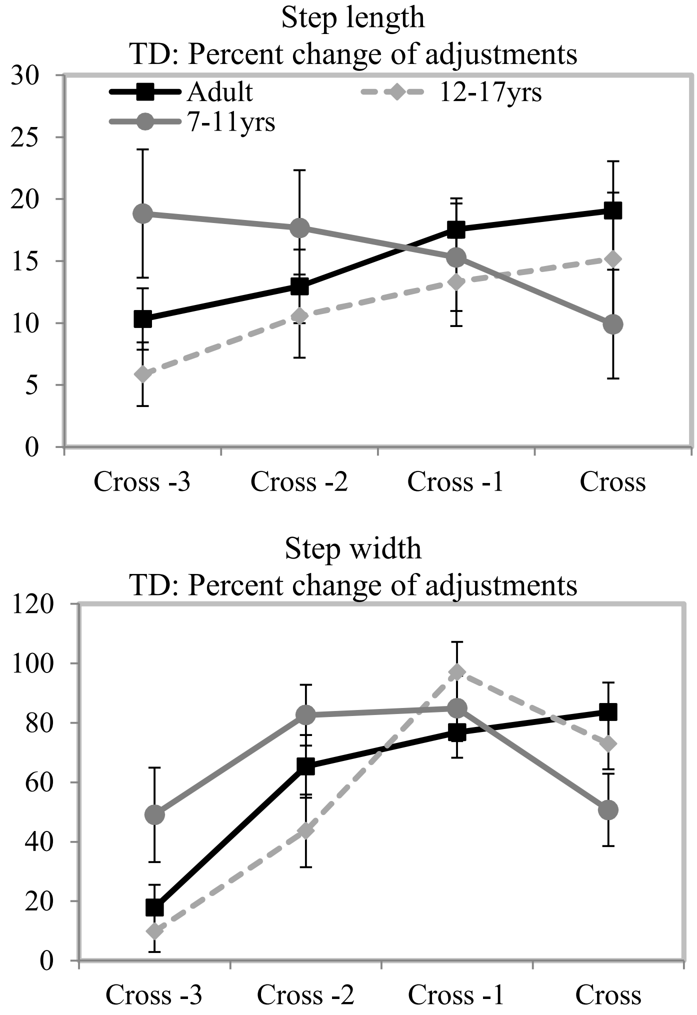
For cross-3 and cross-2:
7-11yrs = 12-17yrs > Adults

For cross:
Adults = 11-12 yrs > 7-11yrs

Figure 3. Percentage of adjustment steps: given for each step number, age and group. Error bars represent standard error.

Percentage change in step length and step width

In terms of the percentage change we found no significant effects of group, therefore the data depicted in Figure 4 is collapsed across group. For step length a significant interaction between step and age was found [F(6,246)=3.19 p=.005 η^2=.12]. To unpick this interaction simple main effects tests were used to compare age for each step number, a significant effect of age was found for cross-3 only where there was a significantly greater change in step length for the 7-11yr-olds children compared to the adults or 12-17yr-olds [F(2,82)=6.34 p=.003 η^2=.13, 7-11yrs>12-17yrs=adults]. For step width there was a significant interaction between step and age [F(6,246)=6.08 p<.001 η^2=.13]. To unpick this interaction simple main effects tests were used to compare age for each step number. A significant age effect was found for cross-3 [F(2,82)=6.94 p=.002 η^2=.15], cross-2 [F(2,82)=5.87 p=.004 η^2=.13] and cross [F(2,82)=5.03 p=.009 η^2=.11]. For cross-3 and cross-2 this was due to a greater change in step width in the 7-11yr-olds compared to the 12-17yr-olds or the adults (7-11yrs>12-17yrs=adults) while for cross this was due to a smaller change in step width in the 7-11yr-olds compared to the 12-17yr-olds or the adults (7-11yrs<12-17yrs=adults).


Step length
TD: Percent change of adjustments

Step width
TD: Percent change of adjustments

Effect of age found at cross-3:
7-11yrs > 12-17yrs = Adults

Effect of age found at cross-3, cross-2 and cross:

For cross-3 and cross-2:
7-11yrs > 12-17yrs = Adults

For cross:
Adults=12-17yrs > 7-11yrs

Figure 4. Percentage change in step length and step width: given for each step number and age, graphs are collapsed across group. Error bars represent standard error.

Categorisation of step adjustments

Initially all eight strategies of adjustments were considered (long, long-toward, toward, short-toward, short, short-away, away, long-away). The percentage time each of these eight strategies for each of the 6 participant cohorts and each step number is shown in Figure 5. From this it is clear that most participants preferred to use short, short-away and away strategies, with some groups not showing any instances of the other strategies. In addition, the use of the short, short-away and away strategies appears to change over the four step numbers. To determine whether some groups used these 'preferred' strategies more than others we started by comparing the combined percentage use of these three preferred strategies across group and age, these data can be found in Figure 5. For cross-3 and cross-2 there were no significant effects of age or group demonstrating that all ages and both groups used these preferred strategies equally often. For cross-1 a significant interaction between age and group was found [F(2,79)=3.79 p=.027 η^2=.09], which was due to a significant effect of age in the typically developing group [F(2,79)=4.56 p=.013 η^2=.10], with adults using these preferred strategies less (adult < 12-17 yrs = 7-11yrs) and no significant effect in the group with DCD (p>.05). For cross only a significant effect of age was found [F(2,71)=4.683 p=.012 η^2=.12,], with the adults and 12-17yr-olds using the preferred strategies less than the 7-11yr-olds, this effect was the same for both groups.

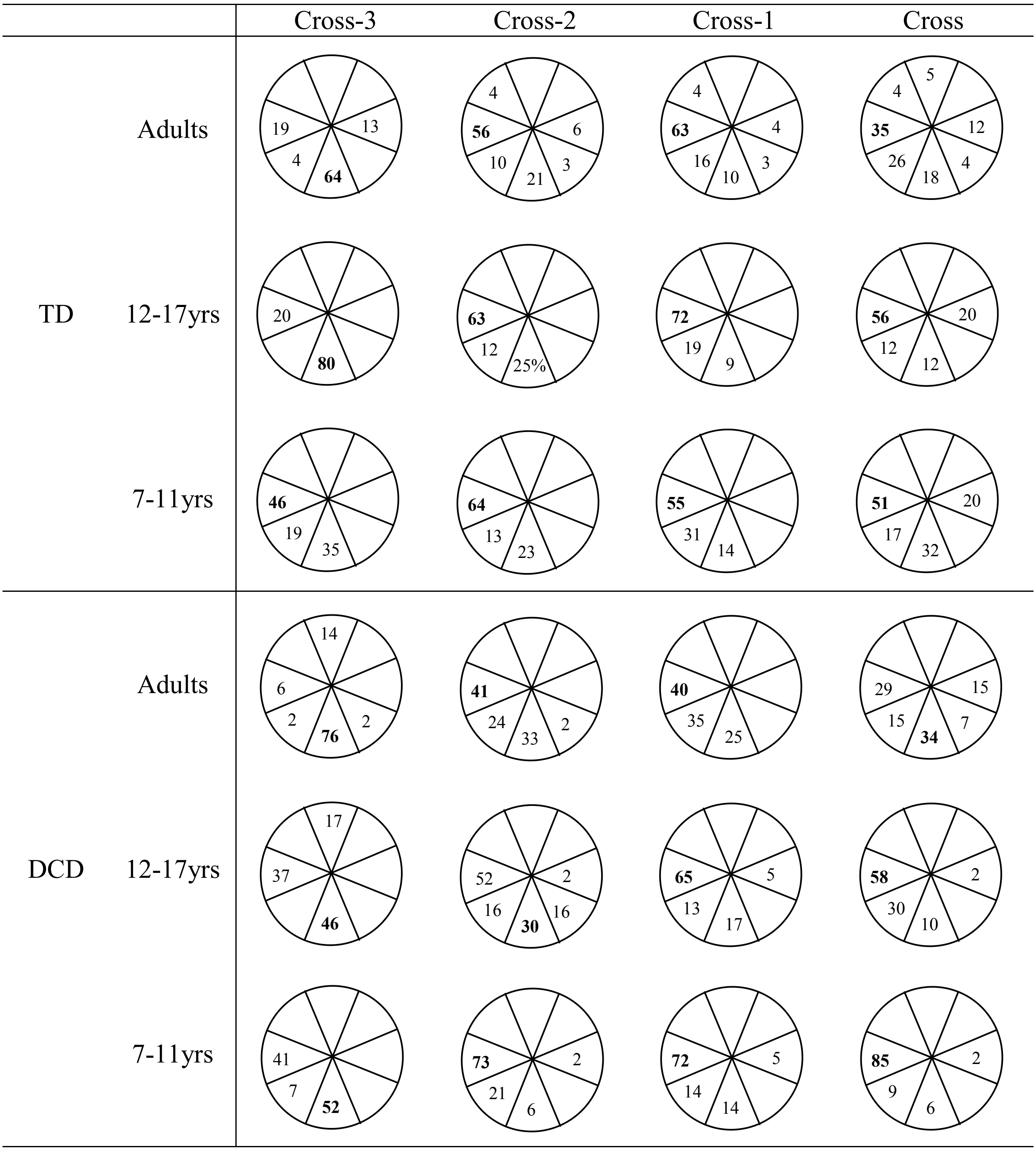
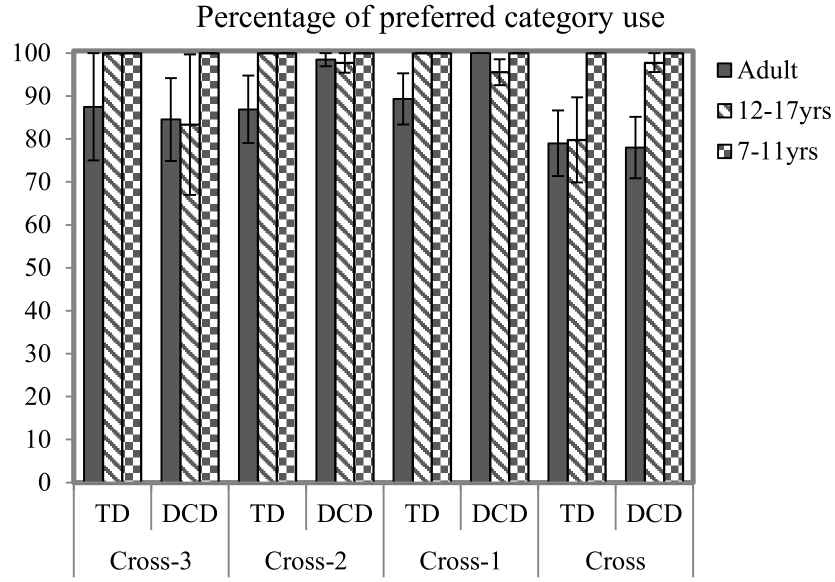


Figure 5. Categorisation of step adjustments, using the same key as shown in Figure 2: An illustration of the use of each strategy, shown across each step number and for each age group and each group. The values given are percentages and where no value is provided it indicates that strategy was never used. The most commonly used strategy at each step number is in bold.



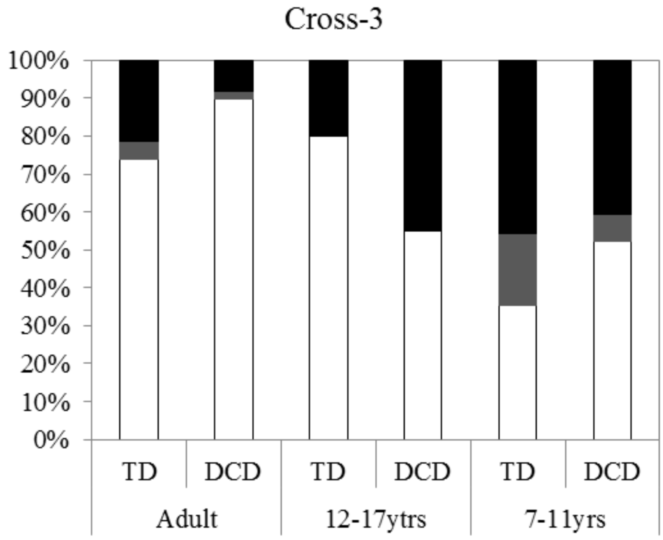
For cross-3 and cross-2:
NS effect of age or group

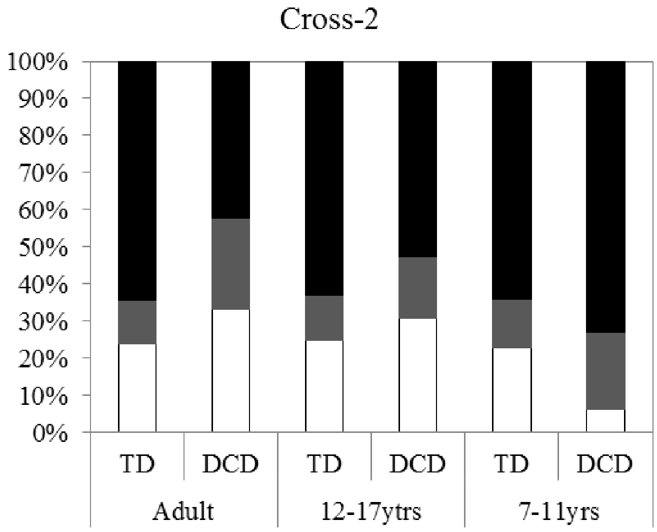
For cross-1:
TD: significant effect of age
12-17yrs=7-11yrs > Adults
DCD: NS effect of age

For cross:
Significant effect of age for both groups
7-11yrs > 12-17yrs = Adults

Figure 6. Categorisation of step adjustments: Graph showing the percentage of steps on which one of the three preferred categories were used for circumvention (short, short-away, away). Given for each step number, each group and each age group. Error bars depict standard error.

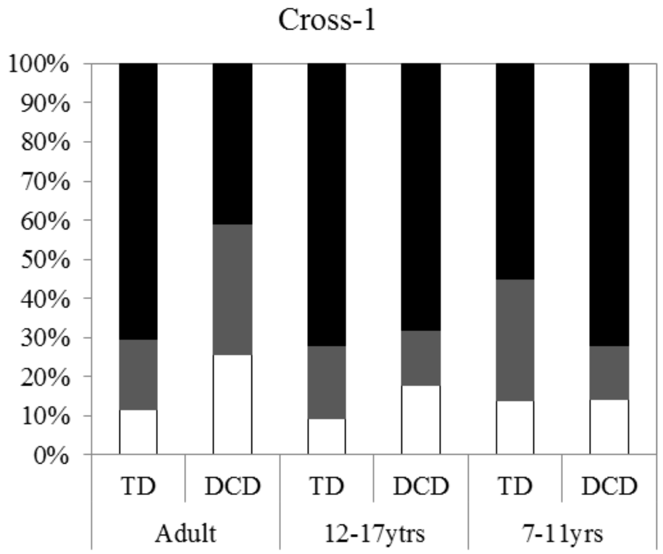
Our final analysis considered a more detailed examination of use of the short, short-away and away strategies. For this analysis, the percentage of times each of the short, short-away and away strategies were used in relation to the total times the preferred strategies were used was calculated for each participant. Separate ANOVAs [category (short, short-away, away) x age (7-11, 12-17, adult) x group (DCD, TD)] were carried out for each step number. For all step numbers a significant effect of category was found [cross-3: $F(1.221,48.827)=20.34$ $p<.001$ $\eta^2=.34$, cross-2: $F(1.60,102.563)=29.23$ $p<.001$ $\eta^2=.31$, cross-1: $F(1.583, 125.066)=48.08$ $p<.001$ $\eta^2=.38$ and cross: $F(2,140)=19.08$ $p<.001$ $\eta^2=.21$]. For cross-2, cross-1 and cross this was due to a preference for away adjustments compared to the other categories (away > short = short-away), for cross-3 this was due to a preference for short adjustments compared to the other adjustments (short>away>short-away). Cross-3 and cross-2 showed no other effects while cross-1 and cross both showed an interaction between category, group and age [$F(4,158)=2.75$ $p=.030$ $\eta^2=.07$ and $F(4,158)=2.47$ $p=.048$ $\eta^2=.07$ respectively]. To unpick these interactions two-way ANOVA (category x age) were run for each group. The TD group showed only a main effect of category for both cross-1 and cross [cross-1: $F(1.635,65.396)=28.59$ $p<.001$ $\eta^2=.42$, cross: $F(2,68)=8.26$ $p<.001$ $\eta^2=.20$] in both cases this was due to a greater percentage of away adjustments compared to short and short-away (away > short = short-away). The DCD group also showed a main effect of category for cross-1 [$F(1.518,62.231)=18.14$ $p<.001$ $\eta^2=.31$] and cross [$F(2,72)=10.95$ $p<.001$ $\eta^2=.23$] again this followed the same pattern described above (away > short = short-away). In addition, an interaction between category and age was found for cross-1 [$F(4,82)=2.51$ $p=.048$ $\eta^2=.11$] and cross [$F(4,72)=4.61$ $p=.002$ $\eta^2=.20$]. Simple main effects demonstrated that for both cross-1 and cross this interaction was due to the presence of an effect of category (away > short = short-away) in the child groups [cross-1, 12-17yrs: F(2,40)=7.05 p=.002 η^2=.26, cross-1, 7-11yrs: F(2,40)=7.70 p=.001 η^2=.28, cross, 12-17yrs: F(2,35)=4.80 p=.014 η^2=.22, cross, 7-11yrs: F(2,35)=8.71 p=.001 η^2=.33] and not the adults (p>.05).

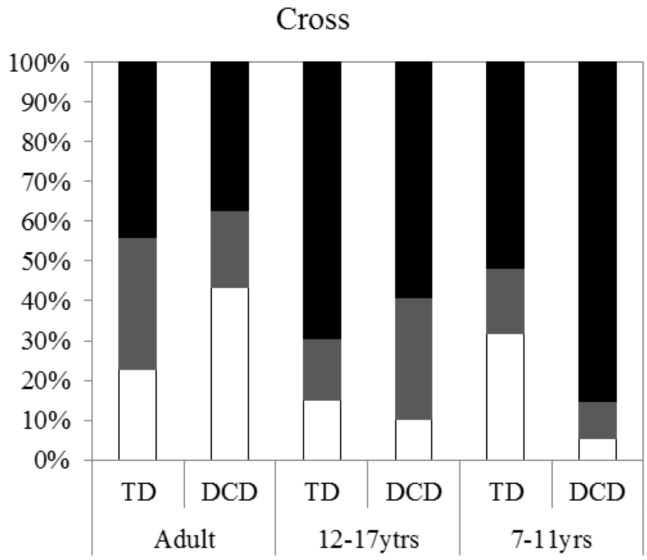

Cross-3


Cross-2

Significant effect of category:
Short > Away > Short-away

Significant effect of category:
Away > Short = Short-away


Cross-1


Cross

For both cross-1 and cross

TD group
Significant effect of category: Away > Short = Short-away

DCD group
Significant effect of category: Away > Short = Short-away
Significant interaction between category and age: Child groups showing the effect of category described above while the adults group showed no effect of category

Figure 7. Categorisation of step adjustments: Percentage of times the three key avoidance strategies were used across the three age groups and two groups. Data is broken down by step number.

Discussion

This study aimed to describe step placement strategies used to circumvent an obstacle by children and adults with DCD. We did this firstly by considering the number of adjustment steps and their size and secondly by considering the nature of those adjustments.

In terms of the number of adjustment steps and their size, the majority of adjustments were made one step prior to the obstacle and those made at this point were the largest. The fewest adjustments, which were also the smallest, were made three steps prior to the obstacle. When considering age differences in the number of adjustments made we found that the typically developing young children (7-11yrs) made a greater number and larger adjustments two and three steps prior to the obstacle compared to the older children or adults, this pattern then reversed in both child groups (7-11 and 12-17yrs) making fewer adjustments one step prior and on the step of crossing compared to the adults. This finding contrasts with that seen previously. Vallis and McFadyen (2005) considered obstacle circumvention in children (8-12years) and adults. Although the focus of their paper was not specifically to describe foot placement, they found that the adults and older children started adjusting foot placement to allow for circumvention well in advance of the obstacle (over 3 steps leading up to the obstacle) while the young children only started to make such adjustments in the last step. From this Vallis & McFadyen (2005) described the children as using ‘last minute’ step adjustments. In the current study we found the opposite; that the children (7-11yrs) preferred to make early rather than late adjustments. Although both studies used circumvention tasks, there are a number of key differences between these studies. In the current study the obstacle was not present from the start of the trial, and the gate did not close on all trials so the need for circumvention was random (although only the ‘gate close’ trials are considered for this paper). This may have meant that the children were quick to react due to the change in the environment while the adults may have delayed their adaptation, in contrast to Vallis and McFayden where a stable environment was measured. Although it may be advantageous to adjust movement as soon as one knows an adjustment is needed, it could also lead to a less than optimal body position if another change were to occur in the environment (unlikely in a lab setting but possible in a natural environment). These findings give an interesting insight into how anticipatory control develops. In line with the adults, the older children (12-17 years) show fewer adjustments early in the movement compared to the younger children. However, later in the movement the number of adjustments the older child group use is in line with the younger children and not the adults. It is thought that anticipatory control starts to develop from 8-12 years of age

(Vallis & McFadyen, 2005). The current finding supports this notion with the older children (12-17yrs) moving towards an adult like system but not demonstrating fully mature anticipatory control.

Both the typically developing individuals and the individuals with DCD followed a similar pattern of step adjustments. One subtle distinction, however, relates to the development of these adjustments. When we consider step characteristics two and three steps away from the obstacle we see the typically developing 7-11yr-olds have a higher number of adjustments compared to the other age groups, we fail to see this heightened number of adjustments in the 7-11yr-olds with DCD. Essentially this shows us that the youngest typically developing children tended to start their adjustments while further from the obstacle while the youngest children with DCD waited until they were closer. Given previous findings that children and adults with DCD start a movement adjustment earlier in the movement (Wilmut & Barnett, 2017; Wilmut, Du, & Barnett, 2015; Wilmut et al., 2016) it is surprising that this has not also been shown in the current study. However, the previous studies have considered adjustments to movement in terms of the path of the trunk or the speed of locomotion. These measures are distinctly different from those in the current study; an individual may slow down but this does not necessarily result in a marked change to foot placement.

In terms of the nature of the adjustment steps we considered eight strategies which describe all of the possible alternative foot placements. We have demonstrated a clear preference in all participants to use three of these: reducing step length, stepping away from the obstacle and combining these (reduction in step length whilst stepping away). Despite the preference to use these strategies, we do see some use of the other five strategies in both the typically developing adults when they are close to the obstacle and in both the typically developing adults and the adults with DCD during the crossing step. This finding demonstrates flexibility in alternative foot placement in the typically developing adults and to a lesser extent in the adults with DCD as they approach the obstacle. This flexibility may reflect a mature adaptive control system.

When comparing the use of these preferred strategies, participants showed a preference for shortening of the step when three steps away, but then focusing on changing step width to move the participant away from the obstacle on subsequent steps. These results are in line with previous findings which used the same task in typically developing adults (Wilmut et al., 2017). As with this previous study we saw very few instances of step lengthening, despite this being the preferred adjustment while stepping over an obstacle in healthy adults (Moraes, Allard, & Patla, 2007), older females (Weerdesteyn et al., 2005) and individuals recovering from stroke (Den Otter et al., 2005). The key difference here is the type of navigation task used. In a circumvention task there is a necessity for an adjustment to step width, which is not necessary when stepping over. However, biomechanically there is a need to trade off between step width and step length, as step width increases step length decreases in order to ensure a stable base of support (for example see Bierbaum, Peper, Karamanidis, & Arampatzis, 2010). Supporting this, Vallis and McFadyen (2003) found a tendency to decrease or shorten step length as step width was increased when adults were circumventing an obstacle. Based on Patla et al.'s (1999) criteria for the selection of foot placement it would seem that the participants in this study are focusing on stability rather than maintenance of forward progression (which is seen in stepping over tasks) due to the constraints of the task.

Apart from subtle differences, the individuals with DCD make alternative foot placements during circumvention of an obstacle in line with their peers, i.e. using the same strategies. This finding would suggest that both the typically developing individuals and the individuals with DCD are weighting the criteria (efficiency, stability, maintenance of forward progression) to select alternative foot placements in a similar way. What needs to be considered is whether these chosen strategies provide an optimal adaptation to locomotion for the individuals with DCD given their reduced level of motor control. Previous studies have shown an increased medio-lateral velocity whilst stepping over (Deconinck et al. 2010) and during circumvention (Wilmut & Barnett, 2017) in individuals with DCD. In fact, in our previous paper which is based on the same task and the same individuals (Wilmut & Barnett, 2017) we demonstrate that a lack of anticipatory movement in response to the possibility of an obstacle appearing seems to be related to a higher medio-lateral velocity during circumvention, i.e. poorer balance control. Furthermore, medio-lateral velocity during circumvention is higher for the DCD group compared to the TD group. It is *possible* that the mediating factor between these two events is a poorly chosen foot placement strategy. Lack of anticipation prevents a foot placement strategy which would maximise balance control during circumvention and so we see a foot placement strategy which results in higher medio-lateral velocity. If this is the case, then re-weighting these criteria and focusing solely on stability for alternative foot placement (while a typically developing individual may also account for efficiency and maintenance of forward progression) may result in a more controlled trunk movement during obstacle avoidance. Broadly this explanation posits that alternative foot placement may not be optimal for the individuals with DCD given their level of motor control and individual constraints on movement. Future research is needed to consider this more fully, for example one could determine whether a pattern of alternative foot placement tailored to stability (e.g. a greater decreased in step length etc) would result in a greater control over medio-lateral velocity in individuals with DCD. Although appealing, this explanation needs to be treated with some caution given it is based on null group differences. However, given our sample size and careful selection of participants we believe we have sufficiently controlled for type II error and that this explanation needs careful consideration in terms of locomotive control and how individual ability constrains movement.

Our main ain of this study was to measure obstacle circumvention in as naturalistic environment as possible. This meant making no one trial exactly the same as another and allowing the participant to respond as they wished in terms of start foot, type of strategy etc. This does provide us with an understanding of how individuals with DCD and typically developing individuals walk around an obstacle which appears unexpectedly. However, it does mean that this study has some limitations. We were unable to compare circumvention strategies when the obstacle appeared on the right as compared to the left (as these were randomly presented and not all participants had three trials of each); we were unable to account for which foot the participant started the movement on; and we varied start position to avoid a predictable movement. All of these factors will have influenced exactly how a participant chooses to circumvent the obstacle, i.e. whether they chose an opening or crossing step, whether they shortened or lengthened their steps etc. Therefore, more research is needed in order to provide a fuller understanding of exactly how these factors influence circumvention in children and adults with DCD as compared to typically developing individuals.

In conclusion, we have described the nature of alternative foot placement in individuals with and without DCD during an obstacle circumvention task. We have demonstrated significant changes in age in terms of the timing of adjustments to foot placement and in terms of the choice of foot placement strategy. Interestingly, we saw only very small differences between the typically developing population and the population with DCD. It may be that the choice of foot placement strategy in individuals with DCD, although in line with their peers, is not optimal for their level of motor ability.

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