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Obstacle negotiation while dual-tasking in children with Developmental Coordination Disorder (DCD): An augmented-reality approach

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ABSTRACT

Background: Children with Developmental Coordination Disorder (DCD) exhibit deficits in predictive motor control, balance, and aspects of cognitive control, which are important for safely negotiating obstacles while walking. As concurrent performance of cognitive and motor tasks (dual-tasking) may exacerbate these deficits, we examined motor and cognitive dual-tasking differences between children with DCD and their typically developing (TD) peers during obstacle negotiation.
Methods: 34 children aged 6–12 years (16 TD, 18 DCD) walked along a 12 m path, stepping over an obstacle (30 % or 50 % of leg length) at its mid-point. On dual-task trials, participants completed a simple or complex (cognitive) visual discrimination task presented via an augmented reality headset. Proportional dual-task costs (pDTCs) were measured on cognitive and gait outcomes over three phases: pre-obstacle, obstacle step-over, and post-obstacle.
Results: During the obstacle step-over phase, both groups increased their leading leg clearance when dual-tasking, while the DCD group had larger pDTC than TD for the high obstacle under simple stimulus conditions (viz simple-high combination). The complex cognitive task produced larger pDTCs than the simple one on leading leg clearance and post-obstacle gait variability.
Conclusions: In general, both DCD and TD groups showed similar pDTCs under complex conditions, while the specific deficit in DCD under the simple-high combination suggests a (default) compensatory strategy during step-over when attention is diverted to a secondary task. Competing cognitive and motor demands during obstacle negotiation present a potential safety risk for children.

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What this paper adds?

- This paper assessed locomotor obstacle negotiation under dual-task conditions, a common scenario that has safety implications for developing children and is new to dual-task research on DCD.
- The cognitive visual discrimination stimulus was presented via an AR headset which permitted natural visual gaze behaviour and precise/automated response measurement.
- The paper shows that children with DCD can successfully perform the dual-task by making subtle gait adjustments in response to task constraints. Notably, adjustments to toe clearance may reflect a motor compensation strategy for motor deficits, enabling safe obstacle negotiation.
- This paper strengthened the quantification of dual-task performance by using the pDTC metric, allowing for comparison across different performance measures.
- The (dual-task) performance compensation of children with DCD suggests clinical applications for understanding individuals with DCD and for tailored intervention.

Data Availability

Data will be made available on request.

1. Introduction

The ability to perform two independent tasks at the same time (i.e., dual-tasking) is a common aspect of everyday behaviour, supported by the progressive development of motor control and cognitive functions over childhood, adolescence and early adulthood (Adolph & Tamis-LeMonda, 2014; Anderson, 2002; Hagmann-von Arx et al., 2016; Kail, 1991). To move and function effectively, children must learn to navigate increasingly complex physical environments, composed of numerous fixed and moving objects like curbs, steps, pathways, and road or pedestrian traffic. Safely negotiating these obstacles involves complex motor planning and cognitive control, as miscalculation in foot placement or foot clearance over an obstacle or along a pathway may result in injury or a fall (Lu et al., 2006). A daily dual-task activity for children may involve walking over a curb while looking at their iPad. For children with Developmental Coordination Disorder (DCD), a common neurodevelopmental disorder (American Psychiatric Association, 2013), motor control difficulties that impact dynamic balance and postural control (Fong et al., 2011, 2016) can present a heightened risk of injury, while also impacting movement confidence. These performance issues are exacerbated further under dual-task conditions when a secondary cognitive or motor task are introduced. In the study presented here, dual-task performance during obstacle negotiation was explored in children with DCD under varying task constraints.

Poor predictive motor control and skill automaticity in DCD (aka *internal modelling deficit* (IMD) account) (Adams et al., 2014; Subara-Zukic et al., 2022; Tsai et al., 2009; Wilson et al., 2013), along with deficits in perceptual-motor coupling and executive function (cognitive control) (Wilson & McKenzie 1998; Wilson et al., 2013; 2017) all contribute to performance challenges, especially during dual-tasks. Under dual-task conditions, performance costs reflect a reduced ability to share attentional resources between two tasks, especially when they compete for a specific sensory system, response modality or visual field (Multiple Resource Theory) (MRT; Wickens, 2008). For example, walking while also making a visual discrimination judgment would compete for visual processing resources according to this framework (Wickens, 2008). Complementing this approach is the notion that the degree of interference between tasks differs according to the key factors of task novelty and complexity (viz Dual-Task Taxonomy of McIsaac et al., 2015). Task novelty is linked to the notion of automaticity (Moors & De Houwer, 2006), a central tenant of the early capacity theories (e.g., Shiffrin & Schneider, 1977). Task complexity covers factors such as speed-accuracy trade-off, variability in the level of task performance, relative task difficulty, and cognitive load (Guadagnoli & Lee, 2004; Paas et al., 2004; Wulf & Shea, 2002).

At the level of motor control, resource-sharing between tasks is afforded by efficient predictive control, a fact neglected in earlier theorising on dual-tasking. For children with DCD who have deficits in predictive control (or internal modeling deficit—IMD), there is greater reliance on slower feedback-based motor control, manifest as jerkier, less-efficient goal-directed movement and greater sway when balancing under complex task conditions (Adams et al., 2014; Verbecque et al., 2021; Wilson et al., 2013, 2017). The combination of both predictive motor control and executive function control deficits in DCD would confer particular challenges when performing locomotor-based dual-tasks, particular those involving obstacle negotiation.

A small body of research on dual-tasking in DCD over the past 15 years has revealed mixed findings (Chen et al., 2012; Chen & Tsai, 2016; Cherng et al., 2009; Kuijpers et al., 2022; Laufer et al., 2008; Schott et al., 2016; Tsai et al., 2009). Several studies have paired static balance and continuous cognitive tasks (Chen et al., 2012; Chen & Tsai, 2016; Laufer et al., 2008; Przysucha et al. 2016; Tsai et al., 2009), with some showing greater postural sway under dual-task conditions for children with DCD compared with TD (Chen et al., 2012; Chen & Tsai, 2016; Laufer et al., 2008), and others no evidence of group differences (Przysucha et al. 2016; Tsai et al., 2009).

For paradigms that pair a primary locomotor task with a secondary visuomotor task, higher dual-task costs have been reported in DCD on walking adaptability (Kuijpers et al., 2022). The complex step adaptability task of Kuijpers had children walk at a set pace on a treadmill (either stepping on targets or avoiding them) while also balancing a tennis ball on a racket. Results showed higher costs on step success rates in DCD, while no group difference was observed on this measure when a cognitive secondary task was used. Kinematic measures were not reported. Using a Trail Walking Task, others have shown higher costs in DCD on both motor outcomes (measured by walking time) and cognitive, an effect exacerbated by increases in task complexity (Schott et al., 2016). Cherng and colleagues (2009), by contrast, only showed group differences on gait cadence when a secondary motor task (i.e., carrying a tray) was imposed when walking, but not cognitive (i.e., digit span); cadence increased appreciably for the DCD group, especially when the tray was laden with marbles.

In contrast to the above, locomotor work conducted in our lab has shown that proportional dual-task costs on gait metrics do not differ appreciably between DCD and TD groups (Subara-Zukic et al., 2024). In this study, children were asked to walk along a straight path while responding to a visual discrimination task presented on an augmented reality headset. Both groups showed a performance cost under dual-task conditions, measured on step width variability and step length variability, and prioritised the cognitive task (Subara-Zukic et al., 2024). The absence of group differences may be explained by high variability on gait metrics for DCD under single-task conditions (see also Wilmut et al., 2017c) and use of a simple, highly automated walking task. Similarly, an absence of group differences under low task complexity has been identified in recent cognitive-motor dual-task research (see also Krajenbrink et al., 2023).Therefore, there is a need to examine locomotor dual-tasking in DCD under more complex conditions like obstacle avoidance. Specifically, it is important to know how obstacles are negotiated when a secondary cognitive task is presented at phases of the movement that demand high levels of predictive motor control.

Obstacle negotiation tasks reveal difficulties in the control of gait for DCD and aging populations and require the frequent use of compensatory strategies (Beurskens & Bock, 2013; Bock, 2008; Deconinck et al., 2010; Kaewkaen et al., 2021; Kim & Brunt, 2007; Parr et al., 2020; Wilmut & Barnett, 2017b, 2017a). When required to step over an obstacle, children with DCD have been shown to demonstrate well-controlled anticipatory gait adaptations during obstacle approach and crossing but have difficulties maintaining stability as obstacle height increases (Deconinck et al., 2010). When motor tasks demand accurate foot placement, greater anteroposterior error is evident in DCD compared with their TD peers (Parr et al., 2020). For example, when walking a pathway onto a step and then over a hurdle, foot placement accuracy was reduced in DCD (Parr et al., 2020). Placement errors of this type may occur as a consequence of poor predictive motor control (Wilson & McKenzie 1998; Wilson et al., 2013; 2017),. Such errors may be exacerbated under dual-task conditions. Alternately, other obstacle avoidance tasks (like walking around a gate) elicit earlier adjustments in DCD (e.g., earlier medio-lateral acceleration of the trunk during approach) and greater path deviations (Wilmut & Barnett, 2017a). Both DCD and TD groups reduced their step length and stepped away from the obstacle during the approach (Wilmut & Barnett, 2017b). In effect, children with DCD adopt larger safety margins to negotiate obstacles, likely to compensate for reduced predictive motor control.

Under dual-task conditions, obstacle negotiation poses a particular risk for children with DCD, and yet no studies to date have evaluated such performance. Developmental studies do suggest age-related differences on measures of gait variability (Gill et al., 2017). For example, during an obstacle-crossing task with a secondary manual box-carrying task, variability in box/arm position, stride length, and stride velocity is reduced with age over childhood (Gill et al., 2017). Whether children with DCD demonstrate an immature pattern of performance remains to be tested (viz neuro-maturational delay hypothesis) (Sigmundsson et al., 1999; Tallet et al., 2013). Complicating the picture, few studies control for the level of single-task complexity or fail to measure proportional costs, so dual-task effects per se remain equivocal (Saxena et al., 2017). Research on adult aging is instructive, suggesting a slower, more conservative approach to obstacle crossing under dual-task conditions in older adults (65+ years), perhaps in response to their heightened risk of falls (Kaewkaen et al., 2021; Kim & Brunt, 2007). Moreover, for more difficult dual-tasks (e.g., narrower or obstacle-laden pathway paired with a time-critical visual task) costs are exacerbated in older adults (Beurskens & Bock, 2013).

Our study aimed to examine locomotor-cognitive dual-task performance in children with and without DCD during obstacle negotiation and to evaluate whether compensatory strategies are evident. We hypothesised that dual-task costs (on both cognitive and motor metrics) would be greater for children with DCD compared with their TD peers. For the *Obstacle Step-Over Phase,* the largest costs were predicted on the motor task given the high demands on predictive motor control. As well, larger pDTCs were predicted for the complex cognitive task compared with simple, with the DCD group expected to be more impaired than their TD peers, particularly under the high obstacle condition. We also predicted a significant positive relationship between leading leg clearance pDTCs and response time pDTCs, with the DCD group demonstrating a stronger relationship than their TD peers. For the *Post-Obstacle* phase, we predicted increased gait variability for the DCD group relative to TD, exacerbated by obstacle height.

2. Material and methods

2.1. Participants & measures

There was a total of 34 participants aged 6–12 years, 18 DCD and 16 TD, also examined in another study by Subara-Zukic and colleagues (2024). All children in the DCD group were recruited from the community using online community groups and met research-equivalent criteria of DCD (Geuze et al., 2001), determined via parent report (DCD-Q), performance below the 16th percentile on the Movement ABC, and the absence of any other identifiable medical condition that may explain their motor skill difficulty. The TD group were recruited from online community groups, did not meet any DSM-IV-TR criterion for DCD, and had no major medical or psychiatric condition. An a-priori power analysis showed that the total sample ($n = 34$) was sufficient based on the desired power of 0.80 and a predicted group effect size of $d = 0.80$ (Faul et al., 2007).

2.2. Locomotor-cognitive dual-task paradigm

Overground walking with obstacle negotiation is a common everyday task that can be broken down into three distinct phases – pre-obstacle, step-over, and post-obstacle – each varying in their attentional and motor control demands (Deconinck et al., 2010; Nieto et al., 2018; Wilmut et al., 2016, 2017c). To ensure safe and efficient crossing during the step-over phase, planning and implementation of adequate toe clearance (aka endpoint control) and safe landing of the leading foot post-obstacle is critical. Forward modelling of step-over and its online control is necessary to manage this important phase of movement. The more automated this process, the better able the performer is to adjust the step-over should external perturbations occur, or a concurrent task is introduced. Indeed, we argue that presenting a secondary (visual) task stimulus at pre-obstacle foot contact will disrupt step-over and landing to the extent that the forward modeling process that controls this phase of movement is not well developed (da Silva Costa et al., 2018; Timmis & Buckley, 2012). Presenting this stimulus via an AR headset enables investigation of these dual-task effects while maintaining natural gaze behaviour while walking.

The Locomotor Obstacle Negotiation Single-Task involved walking along a 12 m walkway, crossing an obstacle at the mid-point, and walking to the end of the walkway. The middle 8 m of the walkway was fitted with the GAITRite® system; an instrumented surface comprising pressure-activated sensors that measured the spatiotemporal parameters of gait. The obstacle (1 cm in width) was standardised to two heights that represented 30 % (low) and 50 % (high) of the participant's leg length to control for developmental differences and create two levels of motor task difficulty. The participants completed a total of 8 video-recorded single-task walks - 4 at the low obstacle height and 4 at the high obstacle height. The timing of each footstep was measured via activation of the GAITRite® sensors and the relative distance between the feet was determined using the collected step pattern data (Webster et al., 2005). Participants were required to walk at their preferred speed and completed two familiarisation trials before their video-recorded trials. The spatiotemporal analysis of gait was completed in real-time using the paired GAITRite® computer application and data for each step was downloaded and exported to RStudio post-assessment for further analysis.

The Cognitive Visual Discrimination (VD) Single-Task involved the participants observing and vocally responding to a visual image of either a rabbit or fox that was displayed on the HoloLens2™ headset (Fig. 1). Eight trials of this task were completed while seated and the participants vocally identified their answer ("left" or "right") via prepotent (simple) or response inhibition (complex) responses (see Subara-Zukic et al., 2024 for further detail).

The Locomotor Obstacle-Cognitive VD Dual-Task Trials were completed after the single-task trials. The participants completed 16 video-recorded walk trials, eight with low and eight with high obstacle height, along the GAITRite® mat whilst wearing the HoloLens2™ headset (Fig. 2). Two high-speed video cameras (GoPro HERO 4) recorded the trials at 120 Hz, one positioned perpendicular to the obstacle to allow for the calculation of obstacle clearance and the other positioned diagonally to record the entire walkway along its long axis. VD stimuli (simple and complex) were presented in pseudo-random order such that two simple trials and two complex trials were presented for each obstacle height. Each VD stimulus was presented pseudo-randomly within a 0–0.4 ms window at two points, either within the first 5 steps (point 1) or at the final foot contact before the obstacle (point 2); this timing was initiated by foot contact on an inground force plate (AMTI Biomechanics Force Platform, Model OR6-6, Fz Natural Frequency 1000 Hz) situated at the mid-point under the GAITRite® mat. The point 1 stimuli presentation acted as 'catch trials' to add uncertainty and reduce the predictability of the cognitive stimulus (Abernethy, 1988; Bhojwani et al., 2022), with only the data for point 2 analysed within this paper. The participants were instructed to complete the walking and the VD tasks together and were given no advice or recommendations regarding task prioritisation. That is, participants were instructed to respond to the cognitive VD task as quickly and accurately as possible while walking over the obstacle and continuing their walk to the end of the walkway. The lead author used a visual storybook to introduce the two tasks, visual discrimination characters, and methods of completion to ensure consistency of instructions. Once the story was read to each participant, they were provided with an opportunity to ask questions to ensure they understood the task(s).

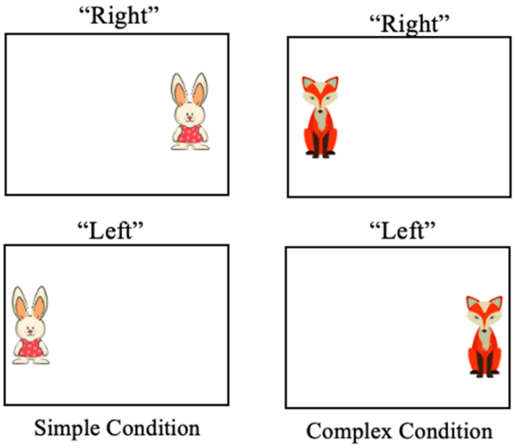

Fig. 1. An example of the visual stimuli presented in the simple (left top and bottom) and complex (right top and bottom) conditions.

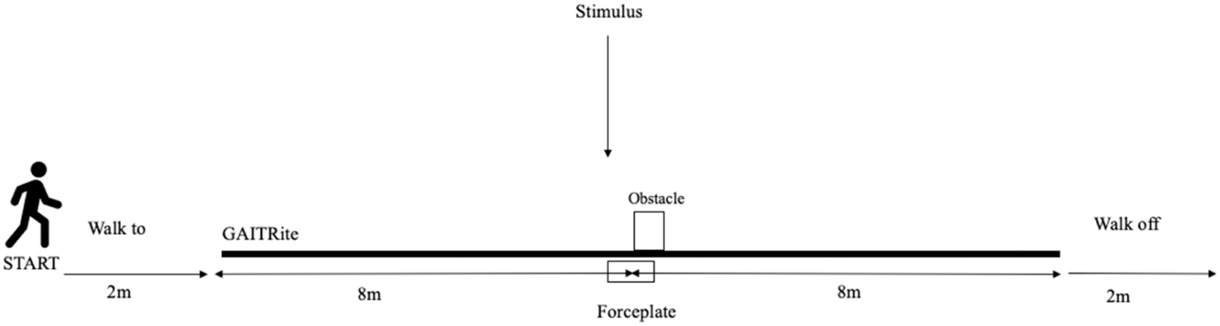

Fig. 2. An example of the experimental setup.

2.2.1. *Outcome measures*

The single-task, dual-task, and pDTC values for both the motor and cognitive tasks were used to map performance differences when dual-tasking. The cognitive outcomes were response time and response accuracy (% correct). The spatiotemporal and gait variability motor outcomes were taken from both pre-obstacle and post-obstacle time points and comprised of walk velocity (cm/s), time in double-support (s), stride length (cm), stride time (s), step length variability (cm), and step width variability (cm). Obstacle clearance motor outcomes included obstacle clearance by the leading leg (cm), obstacle clearance by the lagging leg (cm), pre-obstacle step distance (cm), and post-obstacle step distance (cm).

2.2.2. *pDTC calculation*

Proportional dual-task costs (pDTC) were calculated using the standard formula: ((dual-task score – single-task score) / single-task score) × 100, with negative values indicating a performance decrement under dual-task conditions (Pike et al., 2022). The metrics of response time (s), double support (s), step length variability averaged across both legs (cm), and step width variability averaged across both legs (cm) were multiplied by -1 so that negative values reflected a performance decrement under DT conditions. For all calculations, single-task scores were calculated as the mean performance across single-task trials, while dual-task scores were calculated as the performance score per trial. Consequently, a pDTC was calculated for each individual trial. For cognitive outcomes, mean pDTC was calculated for each combination of task complexity and obstacle height. For motor outcomes, the spatiotemporal and gait variability outcomes were divided into pre-obstacle, obstacle step-over, and post-obstacle categories. Within the categories, mean pDTC was calculated for each combination of task complexity and obstacle height.

2.3. *Procedure*

The testing sessions were completed in conjunction with the testing sessions of our previous work (Subara-Zukic et al., 2024), including the completion of a questionnaire and the Groton Maze Learning Task (GMLT;Thomas et al., 2016). The participants first completed the baseline motor and cognitive measures and completed task familiarisation. Following, the participants completed the single cognitive task, eight single-task obstacle-crossing walks (4 at low and 4 at high obstacle heights) and then completed 16 dual-task obstacle-crossing walks (8 low and 8 high, half of which were ‘catch trials’).

2.4. *Data analysis*

RStudio (R Core Team 2021) was used to analyse the data and the participant descriptive statistics were consistent with our previous work (Subara-Zukic et al., 2024). The data were examined for missing data points and outliers. Outliers were first identified and removed (±3 SD) for single and dual-task results for each outcome variable. The pDTC metrics were next calculated, and outliers were identified and removed (±3 SD) (Osborne, 2010). As the data was non-normal, non-parametric Wilcoxon rank-sum tests and linear mixed-effects model (LMM) analyses were used to test the hypotheses. Effect sizes (Wilcoxon r) were categorised into small ($r <$ 0.10), moderate ($r =$ 0.20–0.40), and large effect ($r >$ 0.50) categories based on the suggestions of Cohen (1988) and the p-value (p <0.05) was used to determine the statistical significance of the effect. We employed (LMM) to fit pDTC metrics, accounting for within-subject correlations between participant trials. The LMM analyses were performed using the *lme*4 package (Bates et al., 2014) in RStudio (R Core Team 2021). LMM use a linear regression model that assesses both fixed and random effects, including group effects and participant differences (Peat & Barton, 2008). The models aimed to identify the effect of group (DCD or TD), cognitive task difficulty (simple or complex), and motor task difficulty (low or high) on pDTCs for each cognitive and motor outcome variable and incorporating a random intercept for each subject to account for repeated measures across the trials. Predictors of executive function (GMLT Total) and leg length (cm) were also included in the models. The proportion of variance explained by the model was categorised as moderate (conditional R^2 = 0.20–0.40, marginal R^2 = 0.10–0.25) and substantial (conditional $R^2 > 0.40$, marginal $R^2 > 0.25$) (Johnson, 2014; Nakagawa & Schielzeth, 2013). This approach was chosen due to its ability to account for repeated measures within participants and handle missing data points (Bono et al., 2021; Krueger & Tian, 2004; Vagenas & Totsika, 2018). Lastly, a linear regression analysis was run using the *Hmisc* package (Frank, 2015) to evaluate the relationship between the lead leg clearance pDTC

Table 1
Descriptive statistics of participant groups.

	TD	DCD	*p*-value
n	16	18	
Age M (SD)	8.75 (2.11)	9.44 (1.61)	0.30
Age Distribution			
6–7 years	6	2	
8–9 years	4	8	
10–12 years	6	8	
Gender (M/F)	7/9	9/9	0.73
MABC Percentile M (SD)	45.38 (24.37)	6.50 (4.29)	0.00**
Physical activity days/week M (SD)	2.50 (1.09)	2.06 (2.18)	0.45
Physical activity minutes/session M (SD)	63.75 (26.55)	45.00 (47.43)	0.16
Verbal Comprehension Index M (SD)	112.00 (8.47)	110.20 (16.05)	0.69
GMLT Total M (SD)	81.25 (37.97)	81.00 (28.29)	0.98
Leg Length (cm) M (SD)	71.0 (8.95)	71.8 (7.50)	0.01**

Note. ** Indicates statistical significance at $p < 0.01$

and response time pDTC during the obstacle step-over phase and the difference between TD and DCD groups.

3. Results

Table 1 presents descriptive statistics for the TD and DCD groups. There was a significant difference between the groups on MABC percentile scores and leg length, while all other comparisons did not differ significantly.

3.1. Pre-obstacle

3.1.1. Walk velocity – pDTC

The trial velocity pDTCs before the obstacle are presented in Fig. 3A. No significant effects were revealed between groups or conditions (Supplementary Tables 2 and 3). The LMM analysis did not demonstrate significant effects on trial velocity pDTC (Supplementary Table 3).

3.1.2. Double Support - pDTC

The double support pDTCs before the obstacle are presented in Fig. 3B. A consistent pattern of negative pDTCs for both groups and motor/cognitive task conditions was revealed, however, no significant effects were noted between groups or conditions (Supplementary Tables 1 and 2). The LMM analysis did not demonstrate significant effects on double support pDTC (Supplementary Table 3).

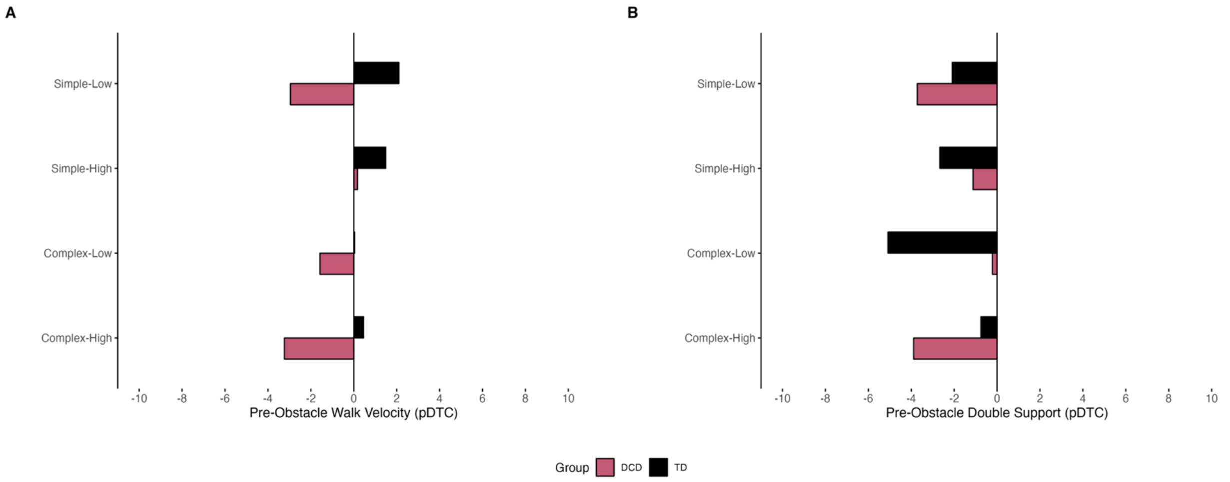

Fig. 3. Comparison of Pre-Obstacle pDTC between groups and conditions. *Note. A negative pDTC indicates a performance decrement under dual-task conditions.*

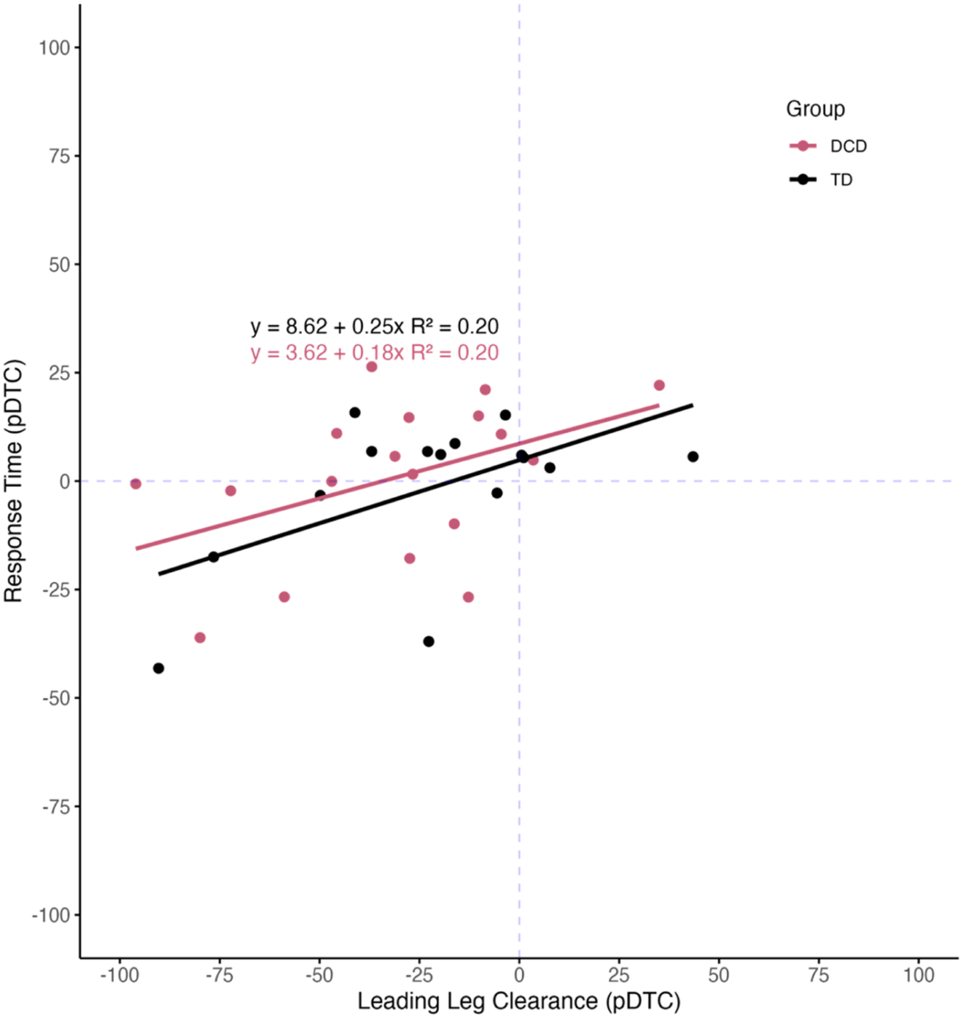

Fig. 4. Scatterplot representing the correlation between motor and cognitive pDTC at the point of obstacle crossing. *Note. A negative pDTC indicates a performance decrement under dual-task conditions.*

3.2. Obstacle step-over

3.2.1. Cognitive and motor pDTC trade-off

The comparison between cognitive and motor pDTCs between groups at the point of obstacle step-over was explored through a linear regression analysis and visually presented in Fig. 4. For both groups, a small positive association was observed between leading leg clearance pDTC and response time, however, significance was not met. This result indicated that as leading leg clearance pDTC increased, there was a non-significant tendency for response time pDTCs to increase for both groups. However, the effect size was small, with leading leg clearance pDTCs explaining only 20.10 % and 19.62 % of the variance in response time pDTC for the DCD and TD groups, respectively.

3.2.2. Cognitive - response time DTC

The response time pDTCs are presented in Fig. 5A and demonstrate a significant pattern of negative pDTCs under complex compared to simple task conditions for both groups. This is supported by the LMM analysis (Supplementary Table 4), which showed a significant effect of GMLT score (executive function) and cognitive task complexity on pDTCs, with the complex cognitive task resulting in significantly greater pDTCs on VDT response time. No significant group effects were found. Across low and high obstacle heights, mean DT scores of the DCD group were slower for complex VDT stimuli compared with simple stimuli (Supplementary Tables 7 and Table 8). No significant DT performance differences were revealed for TD children between cognitive task complexity for response time.

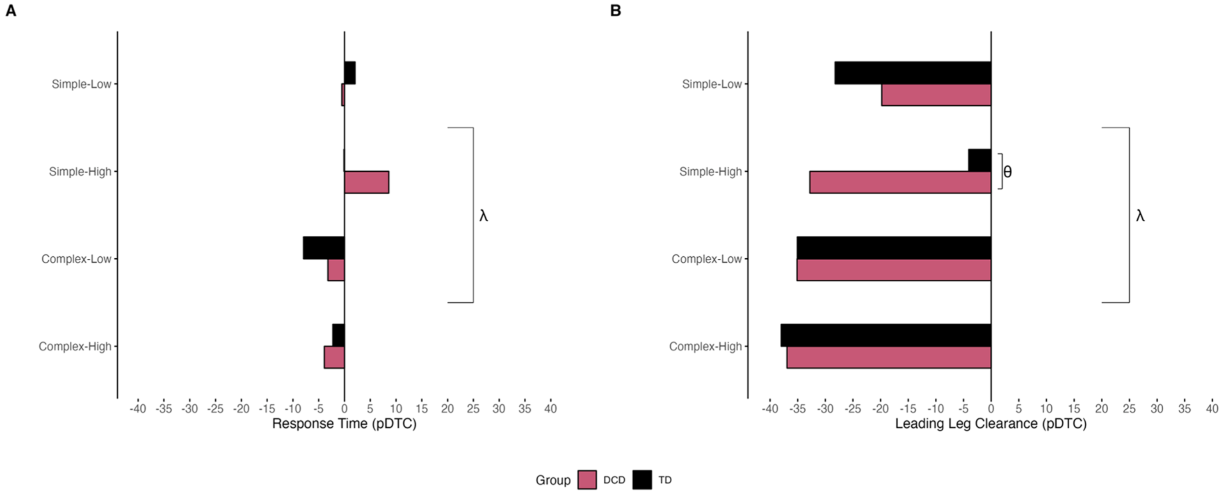

Fig. 5. Comparison of Obstacle Step-Over pDTC between groups and conditions. *Note. A negative pDTC indicates a performance decrement under dual-task conditions.* *θ* Indicates significance of the Wilcox Comparison at p <0.05. λ Indicates a significant effect of Cognitive Task Complexity from the Linear Mixed Model Analysis at p <0.001.

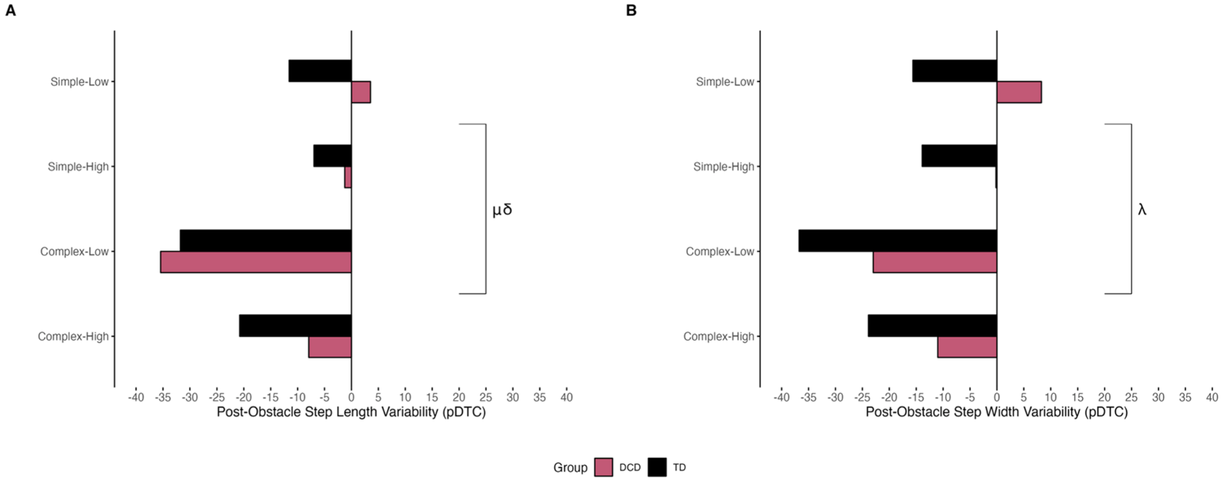

Fig. 6. Comparison of Post-Obstacle pDTC between groups and conditions. *Note. A negative pDTC indicates a performance decrement under dual-task conditions*. μ indicates a significant effect of Cognitive Task Complexity from the Linear Mixed Model Analysis at p <0.05. δ indicates a significant effect of Motor Task Complexity from the Linear Mixed Model Analysis at p <0.05. λ indicates a significant effect of Cognitive Task Complexity from the Linear Mixed Model Analysis at p <0.001.

3.2.3. Motor - leading leg clearance pDTC

The leading leg obstacle clearance pDTCs are presented in Fig. 5B and consistently demonstrated negative pDTCs for both groups during both cognitive and motor task complexity conditions. The LMM analysis supported the effect of cognitive task complexity on leading leg clearance, with complex cognitive tasks resulting in larger clearance pDTCs (Supplementary Table 4). During high obstacle tasks, a significant group difference was revealed under simple cognitive task conditions, with the DCD group demonstrating a significantly larger performance cost (negative pDTCs) than the TD group (Supplementary Table 7). No significant effects between groups or conditions for low obstacle height (Supplementary Table 8).

3.3. Post-obstacle

3.3.1. Step length variability - pDTC

The post-obstacle step length variability pDTCs are presented in Fig. 6A and this demonstrates a pattern of larger, negative pDTCs under complex compared to simple cognitive task conditions. No significant group effects were found. However, the LMM analysis supported the effect of cognitive task complexity on post-obstacle step length variability pDTCs, with complex cognitive tasks resulting in larger clearance pDTCs (Supplementary Table 9). The LMM analysis also highlighted a significant effect of motor task condition, with greater performance costs (negative, large pDTCs) during the low obstacle condition compared to the high obstacle condition.

3.3.2. Step width variability - pDTC

The post-obstacle step width variability pDTCs are presented in Fig. 6B and demonstrate a pattern of larger, negative pDTCs under complex compared to simple cognitive task conditions. No significant group effects were found. However, the significant effect of cognitive task complexity on post-obstacle step width variability pDTCs was supported by the LMM analysis (Supplementary Table 9).

3.4. Summary of results

Compared with single task conditions, the obstacle step-over and post-obstacle phases were performed differently under dual-task conditions for both groups. During the obstacle step-over phase, the complex cognitive task resulted in greater performance costs on response time and leading leg clearance (negative pDTCs). During the post-obstacle phase, the complex cognitive task saw greater step length and step width variability (negative pDTCs); intriguingly, there was a significant effect of obstacle height on step length variability with greater pDTCs shown for the low obstacle condition. Notably, for the simple-high condition, the DCD group showed significantly greater performance costs on obstacle clearance (negative pDTCs) than the TD group.

4. Discussion

Our study presented here evaluated dual-task performance during obstacle negotiation in children with DCD compared with their TD peers. In line with earlier work (Subara-Zukic et al., 2024), we presented a concurrent cognitive task at two levels of difficulty (simple and complex) using augmented reality, and the motor task at two levels of obstacle height (low and high). Under dual-task conditions, the children were asked to walk along a straight flat pathway with an obstacle at its mid-point. Visual stimuli were presented pseudo-randomly at one of two points, either before or coincident with the final foot contact before the obstacle, with a vocal response required. We predicted significant dual-task interference effects on selected gait metrics at the obstacle step-over and post-obstacle phases, with the former phase showing larger performance costs. For the **obstacle step-over phase,** results supported our hypothesis by showing a larger dual-task interference effect on leading leg clearance for each level of cognitive task complexity and obstacle height. The pattern of costs here was similar between groups; however, the one exception was under the simple-high condition for the DCD group who stepped over the obstacle with significantly larger clearance (i.e., negative pDTC) than their TD peers. For the **post-obstacle phase**, the pattern of dual-task performance costs on gait variability metrics was similar for the DCD and TD groups. In general, significant main effects of cognitive task complexity were evident on cognitive task response time and motor task leading leg clearance, post-obstacle step length variability and post-obstacle step width variability, but these did not vary between groups. The following section will discuss in detail the main dual-task effects for the obstacle step-over phase and isolated group effect, the effect of cognitive task complexity/obstacle height, and the implications of these findings for theory and further research.

4.1. Obstacle step-over phase effects

Our specific group effect on obstacle clearance demonstrates that children with DCD were most disadvantaged when performing the dual-task under only the *simple-high* task condition, relative to TD. This result is intriguing and suggests that children with DCD adjusted their internal safety margins to clear the obstacle across all conditions, whereas the TD group showed no such adjustment as a function of obstacle height (aka motor difficulty). From a kinematic perspective, clearance of an obstacle during locomotion requires several factors, including the visual perception of obstacle location and height, precise adjustment of gait parameters in the approach phase and end-point control of the swing leg to ensure the safety and efficiency of the step-over phase (Austin et al., 1999; Rietdyk & Rhea, 2006). One plausible hypothesis to explain the larger obstacle clearance by children with DCD is compensation for known motor performance difficulties, especially those that present risk during obstacle navigation. That is, the child with DCD may be aware of their motor limitations and increase safety margins, accordingly.

Motor compensation by children with DCD is also seen in other obstacle circumvention research that shows earlier gait adjustment and greater path deviation for DCD compared with TD groups (Wilmut & Barnett, 2017a). Specifically, Wilmut & Barnett's (2017a) study asked children to adjust their walk to the appearance of an unexpected closed gate obstacle that appeared in their path. Children with DCD were shown to adjust their medio-lateral velocity and acceleration to a greater extent than TD peers and began to deviate their path earlier (and further away) from the obstacle. This pattern of performance may be a consequence of known challenges with predictive motor control (IMD hypothesis) (Wilson & McKenzie 1998; Wilson et al., 2013; 2017)—a movement compensation to help reduce the risk of a collision (Wilmut & Barnett, 2017a). In our study, both groups increased their leading leg clearance (greater motor pDTCs) to enhance safety margins when crossing the obstacle while maintaining cognitive performance standards. Greater pDTCs on motor outcomes (linked to dynamic postural stability) relative to cognitive is also supported by studies of older adults (Corp et al., 2018) and clinical populations like Alzheimer's disease and stroke (Simieli et al., 2015; Smulders et al., 2012). For example, individuals with Alzheimer's disease show greater impairment by slowing their gait pattern, shortening their steps, and widening their step width compared with typical adults. This may be understood in line with the "posture first" strategy to prioritise safe completion of the motor task (Simieli et al., 2015). In sum, our findings suggest that both groups adopt a conservative approach to obstacle clearance under most task conditions. However, the safety margins adopted by the DCD group were more pronounced, in general. Whether group differences become even more noticeable under more novel or difficult conditions, such as paths with uneven terrain or under time constraints, is an important area of future investigation, particularly as such environments have associated risks for safety.

Taken together, our obstacle step-over results can be explained, in part, in terms of the IMD account of DCD (Wilson & McKenzie 1998; Wilson et al., 2013; 2017), with implications for dual-task behaviour.

Our study shows the importance of considering task-related constraints within a Dual-Task Taxonomy such as McIsaac et al. (2015), notably the differential effect of task complexity at both a motor and cognitive level. Parametric investigation of dual-tasking enables the identification of nuances in performance that can reveal both fundamental deficits in motor control but also pragmatic compensations in behaviour that enable the child to maintain safety within limits that are deemed acceptable from a safety perspective, at least.

4.2. Post-obstacle phase effects

During the post-obstacle phase, the most notable dual-task effects on gait were found under complex cognitive task conditions, while the high obstacle resulted in smaller performance costs on gait variability than the low obstacle. This effect on gait variability may reflect earlier adjustments made during the obstacle step-over phase, specifically a more deliberate and less automatic approach to step-over. It has been shown that stepping over a high obstacle enlists more cognitive resources by conscious attention to achieving a safer toe clearance and subsequent landing relative to a lower obstacle (Shin et al., 2015). Our results suggest that both DCD and TD groups adopt such a pattern, particularly under complex-high task conditions. The net effect was reduced gait variability during the post-obstacle phase. This finding and interpretation is supported by developmental research that shows younger and mid-aged children take a careful approach to obstacle crossing (Yoshimoto et al., 2023) and make task-specific anticipatory gait adjustments (i.e., to step length and toe clearance) compared with older children and adults (Virji-Babul & Brown, 2004). Gait variability should be explored further to better understand the specific constraints under which DCD/TD groups differ to ensure safe obstacle negotiation under dual-task demands.

4.3. Cognitive complexity effect

An effect of cognitive task complexity was evident for both groups on cognitive and motor metrics, both for the obstacle step-over and post-obstacle phases. It is instructive to compare our results here with an earlier study of locomotor dual-tasking performed on a clear terrain using the same cognitive task. Whereas our earlier study failed to show an effect of cognitive task complexity (Subara-Zukic et al., 2024), an effect was observed in the current study under more stringent motor task constraints (namely, obstacle avoidance, demanding high levels of predictive control and balance). We expect that continued development of the Dual-Task Taxonomy (McIsaac et al., 2015) will identify other interactive parameters that determine the nature and level of dual-task interference in populations like DCD, e.g., local vs. focal visual field, when processing a secondary visual task (Wickens, 2002, 2008).

An effect of cognitive task complexity was also evident in one other locomotor dual-task study that investigated this parameter in DCD (Schott et al., 2016). Using a Trail-Walking-Test (a locomotor version of Trail Making Test), Schott showed that the level of dual-task interference under complex cognitive conditions was greater for DCD on walk completion times. The earlier study of Schott did not collect or analyse kinematic metrics, however, making comparisons difficult. In aging populations, as well, studies of locomotor-cognitive dual-tasking have revealed complexity effects for obstacle negotiation (Kim & Brunt, 2007; Simieli et al., 2015). For example, Kim & Brunt's (2007) study assessed step initiation over an obstacle under dual-task conditions with two levels of complexity, random and predictable cognitive stimuli. The more difficult random task showed greater dual-task on toe clearance. Thus, these findings emphasise the importance of task complexity relevant to the population across both motor and cognitive task conditions and, if varied strategically, discernible patterns of dual-task cost can be observed which inform our understanding of underlying control processes.

4.4. Limitations

Our participant group was common to both our current and earlier study (Subara-Zukic et al., 2024). Hence, while sampling error is not a factor when comparing these results, replication using independent samples is recommended. Like most studies of dual-tasking in children, all completed the single tasks first, and we did not randomise the order of presentation of obstacle height. There is some chance that fatigue may have influenced performance toward the end of the test session, but anecdotally, we did not observe such effects. Indeed, we limited the number of repeated task trials to optimise attention to the task and to limit fatigue in our sample of children (see also Subara-Zukic et al., 2024). Finally, obstacle height was set to proportional leg length, consistent with previous research (Virji-Babul & Brown, 2004); moreover, the 30 % leg length was designed to equate to step heights of 150–190 mm, consistent with government building standards in Australia (Victorian Government, 2018). Due to the shorter leg length of child participants, the mean for the 50 % obstacle was 359 mm for DCD and 355 mm for TD groups. While such height is not customary in the real-world experience of children, we did aim to set a high level of challenge for both groups. Future research should also consider standardised step heights to further enhance the ecological validity of the dual-task paradigm.

5. Conclusion

Compared with single-task conditions, the obstacle step-over and post-obstacle phases were performed differently under dual-task conditions for both DCD and TD groups. However, we showed that during the critical obstacle step-over phase, children with DCD were most disadvantaged under simple-high task conditions on toe clearance, in particular, relative to their TD peers. This pattern may represent a motor compensation strategy by children with DCD who prioritise the need to reduce/avoid the risk of hitting the obstacle (under cognitive load), perhaps as a consequence of deficits in the predictive control of leading leg trajectory. These results inform our theoretical and clinical understanding of DCD and the types of pragmatic compensations that these children may employ to function safely in the world. Future work should address other parameters, some not yet embedded in dual-task taxonomies, that further clarify the performance tendencies of children with DCD as they negotiate their physical world under the demand of concurrent and sometimes competing tasks.

CRediT authorship contribution statement

A/Prof Michael Cole: Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Prof Peter H Wilson:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Dr Emily Subara-Zukic:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Investigation, Formal analysis, Data curation. **Dr Thomas B McGuckian:** Writing – review & editing, Supervision, Project administration, Methodology.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ridd.2024.104853.

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