

NOTICE: this is the author's version of a work that was accepted for publication in the Journal Research in Developmental Disabilities. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in the Journal Research in Developmental Disabilities, Vol.36, (2014). DOI: [10.1016/j.ridd.2014.10.013](https://doi.org/10.1016/j.ridd.2014.10.013)

Title

Coupling online control and inhibitory systems in children with Developmental Coordination Disorder: Goal-directed reaching

Scott Ruddock¹, Jan Piek², David Sugden³, Sue Morris², Christian Hyde⁴, Karen Caeyenberghs¹, & Peter Wilson¹

¹*Australian Catholic University, Melbourne, Australia*

²*Curtin University, Perth, Australia*

³*University of Leeds, United Kingdom*

⁴*Deakin University, Melbourne, Australia*

Abstract

For children with Developmental Coordination Disorder (DCD), the real-time coupling between frontal executive function and online motor control has not been explored despite reported deficits in each domain. The aim of the present study was to investigate how children with DCD enlist online control under task constraints that compel the need for inhibitory control. A total of 129 school children were sampled from mainstream primary schools. Forty two children who met research criteria for DCD were compared with 87 typically developing controls on a modified double-jump reaching task. Children within each skill group were divided into three age bands: younger (6-7 years), mid-aged (8-9), and older (10-12). Online control was compared between groups as a function of trial type (non-jump, jump, anti-jump). Overall, results showed that while movement times were similar between skill groups under simple task constraints (non-jump), on perturbation (or jump) trials the DCD group were significantly slower than controls and corrected trajectories later. Critically, the DCD group was further disadvantaged by anti-jump trials where inhibitory control was required; however, this effect reduced with age. While coupling online control and executive systems is not well developed in younger and mid-aged children, there is evidence of age-appropriate coupling in older children. Longitudinal data is needed to clarify this intriguing finding. The theoretical and applied implications of these results are discussed.

Highlights

- Previous research has found that online control is compromised in children with DCD on a double-step task
- Deficits in executive control (e.g. inhibition) are also commonly observed in this group.
- Superimposing an inhibitory constraint on a modified rapid reaching task exacerbates deficits in online control among children with DCD; however, this deficit appears to dissipate with age.
- Longitudinal data is needed to clarify the nature of the coupling between frontal executive and motor control systems.
- The interaction between motor control and executive function should be considered when planning interventions for DCD.

Keywords

- Developmental Coordination Disorder
- Online control
- Predictive modelling
- Inhibition
- Executive Function

Introduction

Deficits in motor prediction have been implicated as one possible cause of motor clumsiness in children with Developmental Coordination Disorder (Hyde & Wilson, 2013). A recent meta-analysis has shown deficits in studies as varied as target-directed reaching, grip force control, dynamic balance, and eye-movement control (Wilson, Ruddock, Smits-Engelsman, Polatajko, & Blank, 2013). Also seen as part of the constellation of processing problems in DCD is poor executive control, evident across tasks of selection attention, working memory, and response inhibition. Of some importance in developmental terms is how predictive (online) control and executive function (EF) are coupled in the service of goal-directed action. This issue has also emerged as a focus in recent developmental studies (Gonzalez et al., 2014) with data showing that motor control and EF emerge along similar timelines and share overlapping neural networks (Pangelinan et al., 2011). We addressed here in relation to the neurocognitive underpinnings of DCD, enlisting a double-jump paradigm performed with and without inhibitory constraints.

The ability to correct one's movement in response to unexpected target or environmental changes (viz online control) is a critical part of efficient, goal-directed action. Recent neuro-cognitive models of human reaching propose that online control occurs by the action of *internal feedback loops* that generate forward estimates of the dynamics of limb position and egocentric location - a process referred to variously as (forward) internal modelling or predictive control (Ruddock et al., 2014). This system of rapid control is critical for movement stability because of processing delays associated with sensory feedback loops and general impedance of the motor plant (Wolpert & Flanagan, 2001). For visually-guided movements, adult studies have shown recruitment of reciprocal loops between premotor cortex, posterior parietal cortices (PPC), and cerebellum, with strong PPC-cerebellar activation under target perturbation (Gréa et al., 2002; Reichenbach, Bresciani, Peer,

Bülthoff, & Thielscher, 2011; Reichenbach, Thielscher, Peer, Bülthoff, & Bresciani, 2014). Only recently has the nature of online control in children with and without motor difficulties been studied with renewed focus.

Available data suggest that mechanisms linked to fast corrective processes undergo considerable change between 6 and 12 years of age (Bard, Hay, & Fleury, 1990; Van Braeckel, Butcher, Geuze, Stremmelaar, & Bouma, 2007; Wilson & Hyde, 2013). Younger children (5-7 years of age) are able to generate fast, ballistic movements but are slower to integrate online feedback when correcting their reaching mid-flight, resulting in reduced endpoint accuracy and/or inefficient timing. During middle childhood (around 8-9 years) there is earlier and greater use of sensory feedback (e.g. Chicoine, Lassonde, & Proteau, 1992) as both feedforward and feedback (predictive) control become better integrated, resulting in better online error correction. By 9-12 years, the system of predictive control is well developed, approaching adult levels (e.g. see Wilson & Hyde, 2013).

It is no coincidence that the developmental timescale over which online control unfolds coincides with periods of increased myelination and structural connectivity along fronto-parieto pathways (Casey, Tottenham, Liston, & Durston, 2005; Lebel, Walker, Leemans, Phillips, & Beaulieu, 2008). Predictive control in particular is underpinned by maturation of reciprocal connections between frontal, parietal and cerebellar cortices, pathways that are sculpted by experience (Gaveau et al., 2014) In short, an interplay between external (i.e., experiential) and internal (e.g. neural myelination and synaptic pruning) factors support the fidelity of predictive control with development (Casey, Getz, & Galvan, 2008).

A unifying hypothesis in cognitive neuroscience that can shed light on the development of function in DCD is the notion of *interactive specialization* (Johnson, 2011). Here it is posited that behavioural competencies unfold through the interaction of several brain regions whose individual growth trajectories may differ in developmental time. For

example, (automatic) online control is supported by fast dorsal motor systems (Pisella et al., 2000) that forge reciprocal connections with frontal executive systems over the course of childhood, bestowing a degree of flexibility in action (i.e. Ruddle et al., 2014). However, this coupling between motor and executive systems is not well refined until later childhood. Using a target perturbation paradigm, we found that under an inhibitory load (or anti-reach condition), the ability to adjust movement trajectory was reduced in mid-aged children (8-9 years) relative to older children (10-12 years), despite the fact that online control per se was well developed by 9 years of age (Wilson & Hyde, 2013). We observed that the time taken to correct reach trajectories (in this case to the hemi-space opposite the target jump) increased in mid-aged children to an extent similar to that seen in younger children (6-7 years). We argued that while frontal systems are unfolding rapidly during the middle childhood period, there is lag in the coupling of these systems to more posterior perceptual-motor systems. Only by later childhood do we see evidence of more seamless integration of fronto-parietal systems, manifest as smooth and efficient reach trajectories and greater endpoint accuracy under not only double jump constraints but also anti-reach conditions (Wilson & Hyde, 2013).

The link between Executive Function and Online Control in Children with Developmental Coordination Disorder

Importantly, deficits in both executive and motor control systems are widely reported in children (Livesey, Keen, Rouse, & White, 2006; Michel, Roethlisberger, Neuenschwander, & Roebbers, 2011; Piek, Dyck, Francis, & Conwell, 2007) and adolescents (Rigoli, Piek, Kane, & Oosterlaan, 2012) with atypical motor development (or DCD), suggesting that the process of coupling between systems may be particularly problematic with development. Recent studies of goal-directed reaching have shown that children with DCD aged 8-12 years are disadvantaged by target perturbation, taking longer to correct movements on jump trials (Hyde & Wilson, 2011a). This pattern of performance is thought to reflect an underlying

difficulty using predictive models of action. Additionally, Hyde and Wilson (2013) showed that the performance of children with DCD aged 8-12 years was not qualitatively different to younger typically developing children suggesting a neurodevelopmental delay in structures that underpin predictive control, particularly fronto-parietal and parieto-cerebellar loops. Other work using fMRI suggests possible disruption of top-down (or anterior) modulation of posterior networks for tasks requiring inhibition (Querne et al., 2008). Converging evidence of reduced executive function in DCD (Piek et al., 2007; Wilson et al., 2013) suggest a more generalised level of delay in these children.

Problems of inhibitory control are particularly common in DCD (Livesey et al., 2006; Michel et al., 2011). On the Simon Task, for example, children with DCD show difficulty inhibiting a manual response to a visual stimulus relative to controls (Mandich, Buckolz, & Polatajko, 2002). On tasks of *voluntary* visuospatial attention, poor inhibitory control has also been identified (Mandich, Buckolz, & Polatajko, 2003; Tsai, Yu, Chen, & Wu, 2009; Wilson & Maruff, 1999; Wilson, 1997), inferred from a reduced ability to disengage visual attention from invalidly-cued locations (Mandich et al., 2003). This raises the possibility that children with DCD may be particularly disadvantaged when called to enlist inhibitory control in the context of a motor task requiring motor prediction.

Our main hypothesis here is that impaired coupling between frontal executive and more posterior visuo-motor regions associated with predictive control (and spatial updating) may be an important factor in DCD. Hence, the broad aim of our study was to examine whether poor online control in DCD is exacerbated when tasks demand higher levels of executive control, specifically response inhibition. Addressing this issue will also clarify the often cited observation that motor skill deficits in DCD are more pronounced under conditions of high cognitive load (Wilson et al., 2013). Specifically, we assessed children's ability to implement rapid online corrections on a double-jump perturbation paradigm under

three task conditions: non-jump, jump, and anti-jump. In line with earlier studies of online control (Hyde & Wilson, 2011a, 2011b, 2013) we predicted that, overall, children with DCD would be slower to correct their reach trajectory mid-flight following an unexpected target shift than typically developing children. Moreover, we also predicted that their performance would be further compromised by the addition of an inhibitory load (viz anti-reach condition), manifest as slower movement time and delayed time to correction, but that the deficit would be less pronounced in older children in lieu of the developmental delay suggested by earlier work (Hyde & Wilson, 2013).

Method

Participants

The sample was drawn from a large longitudinal project and consisted of 129 children: 42 in the DCD group and 87 in the control group (refer to Table 1 for descriptive data). Group selection involved a two-step process: (a) parents completed a medical and developmental history questionnaire and (b) children's motor proficiency was tested using the McCarron Assessment of Neuromuscular Development (MAND; McCarron, 1997). On the MAND, children who scored less than 15th percentile (Noten, Wilson, Ruddock, & Steenbergen, 2014; Piek, Baynam, & Barrett, 2006) (Criterion A), whose difficulty learning motor skills was deemed to interfere with daily activities (Criterion B), and whose movement difficulties were evident by school age (Criterion C), were included in the DCD group. Children scoring above 20th percentile were placed into the control group (Hyde & Wilson, 2011a). Additionally, selection for the DCD group adhered to research criteria specified from the Diagnostic and Statistical Manual 5 (American Psychiatric Association, 2013). Children were excluded from the study if they reported a developmental, neurological and/or physical condition (Criterion D), which was confirmed by the child's school health officer. As children were recruited from mainstream primary schools and attending standard classes,

intelligence was assumed to be within the normal range (Gueze, Jongmans, Schoemaker, & Smits-Engelsman, 2001).

All children and parents gave their informed consent to participate in the study which was approved by institutional and government research ethics committees.

Instrumentation

A modified version of the Double-Jump Reaching Task (DJRT) was used to assess online motor control. VIRTTOOLS Software Package (3DVIA, 2010) was presented on a black Samsung 40-inch touchscreen. The touchscreen was in portrait orientation on a table and elevated at 10° from horizontal. The background of the display was black to match the bezel of the TV, reducing contrast interference. The computerised display consisted of a circular 'home base', 2.5cm in diameter, positioned centrally 5cm from the near edge of the bezel. Three yellow targets were positioned above the home base, located at -20° , 0° , 20° from a vertical line extending upward from the home base. All target distances were scaled according to three age groups: young children, 25cm; mid-age children, 28cm; and older children, 30cm (Gerver, Drayer, & Schaafsma, 1989). Arm movement was recorded using the Zebris CMS10 (Noraxon, 2010) system for 3D-motion analysis with 200Hz sample rate. The motion tracking system was secured to the table and positioned at a height of 1 m above the centre of the screen. A 7mm ultrasonic sensor/marker was attached by adhesive pad to the child's dominant index finger tip and tethered with adhesive tape along the arm and then to the Zebris receiver.

Procedure

Hand preference was assessed by asking each child which hand children he/she wrote with, and then observing them as they wrote their name. The DJRT was performed in a quiet classroom under low lighting conditions to prevent visual feedback from the hand (Farnè et al., 2003) and the imposition of environmental distractors. At the beginning of the DJRT, the

nature of the task was explained and the child was then directed to stand in front of the screen while the kinematic sensor was attached to the index finger of their dominant hand.

Testing was conducted in two blocks, with the order of conditions randomised: a typical 'jump' DJRT and modified 'anti-jump' DJRT. For the jump condition, children were instructed to place their index finger on the green home base at the beginning of each trial. The three possible target locations were indicated at the start of each trial, while individual targets per se were triggered on a trial-by-trial basis by a doubling in luminance. The finger was held stationary until the home base was extinguished and the middle yellow target doubled in luminance at the same time and a random delay of 500-1500ms was programmed across trials to ensure participants did not anticipate the change in target illumination. Children were instructed to *follow the target* and touch its centre as *quickly and accurately as possible*. A successful trial resulted in the newly acquired target light being extinguished while an auditory tone was emitted to reinforce to children that the trial was complete. On 80% of trials the middle target remained lit until touched (*non-jump* trial) while on 20% of trials the location of the target jumped at movement onset either to the left or right position (*jump* trial). At the end of each trial, children repositioned their finger back on home base in readiness for the next trial. The anti-jump condition was administered using the same procedure described for the jump condition. However, children were instructed to reach and touch the opposite side (*anti-jump* trial) when the target shifted to a peripheral location (refer to Figure 1).

At the commencement of the first condition, the researcher modelled the action necessary for *non-jump*, *jump*, and *anti-jump* trials. Children were then given 10 practice trials to familiarise themselves with the nature of the task and permitted additional practice trials if task requirements were not met. Children performed two blocks within each condition; each block was of 40 trials (32 *non-jump* and 8 *jump/anti-jump*) which were

interspersed pseudo-randomly across left and right target locations. At the end of the first condition, children were permitted a 2 minute rest before commencing the second condition. Total administration time of the task was 15 minutes.

Data Analysis

For each child, reaction time (RT) and movement time (MT) of the DJRT was recorded. Only successfully completed trials were included and outliers for all chromomeric and kinematic variables were excluded from analysis; outliers were defined as values $> +/- 2.5 SDs$ from the mean (Ruddock et al., 2014). An average of 20 (14%) non-jump trials and 4 (25%) jump/anti-jump trials were removed from the DCD group, and 18 (13%) and 3 (19%) respectively from the control group. *Jump-* and *anti-reach* trials were aggregated over left and right target locations and eight successful *jump/anti-jump* trials per block was a minimum requirement for valid data inclusion (Ruddock et al., 2014). MT was compared between groups using 3-way repeated measures ANOVA (3 [Age] x 2 [Skill Group] x 3 [Trial: non-jump, jump & anti-jump]). RT was compared between groups using 2-way repeated measures ANOVA (3 [Age] x 2 [Skill Group]). We measured the impact of the inhibitory load on online control by calculating the difference in MT between anti-jump and jump trials ($AJMT_{diff}$). Specifically, using a 2-way ANOVA, we tested whether the effect of inhibitory load (as measured by $AJMT_{diff}$) varied as a function of the interaction between group and age.

Kinematic variables were time of correction (ToC) and time of correction 2 (ToC2; for anti-reach trials only which was the interval between movement onset and the point at which spatial trajectory changed toward the location opposite that of the target), and were filtered post-task using a fourth order Butterworth filter with a cut off of 10Hz. For jump trials, time of correction (ToC) was defined as the point at which the hand initiated a change in direction away from the centre target toward the left or right peripheral target (Hyde &

Wilson, 2011b) . On anti-jump trials, the critical deviation in trajectory occurs after an initial deviation toward the cued location (Cameron, Cressman, Franks, & Chua, 2009); this second correction (ToC2) reflects the implementation of inhibitory control as part of the corrected movement plan toward the location opposite the cued side. All participants demonstrated a tendency for the hand to be drawn first toward the illuminated target before (purposefully) redirecting movement to the opposite target location (Cameron et al., 2009). Finally, post correction time for anti-jump trials (PCT-AJ) was defined as the time taken after TOC2 to touch the location contralateral to the cue.

Movement trajectories were plotted on a 2D Cartesian plane using MATLAB (Mathworks, 2010) computer software and ToC and ToC2 values were determined by two independent raters (Ruddock et al., 2014). Time of correction was analysed using 2-way repeated measures ANOVA (2 [Age] x 2 [Skill Group]).

Error responses were also recorded on the DJRT. A touch down error (TDE) occurred when a participant touched outside of the yellow target boundary. Anticipation error (AE) was recorded when finger lift-off from 'home base' occurred before the yellow central target illuminated. Logically, this cannot vary as a function of cue type as there is no probability information available to predict this with any certainty. Centre touch error (CTE) was defined as a touch to the centre target instead of a peripheral target during a *jump/anti-jump* trial. Finally, an *anti-jump* error (AJE) occurred when the incorrect (i.e., cued target) was touched on anti-jump trials.

Initial analyses showed that both gender and site locations were not systematically related to performance on any measure. Partial η^2 was used to interpret the magnitude of the effect size.

Results

Table 2 displays the values for each variable across skill group and age.

Reaction Time

As there were no significant effects involving trial type, mean RT was averaged over this factor. Two-way ANOVA showed a significant main effect for age, $F(2, 127) = 33.58, p < .001$, partial $\eta^2 = .35$, with younger children (607ms) slower than mid-aged (499ms) who were in turn slower than older (442ms), $p < .05$. The main effect of group was also significant with controls (498ms) faster than DCD (540ms), $F(1, 127) = 10.39, p = .002$, partial $\eta^2 = .08$. The interaction between age and group was not significant, $F(2, 127) = 2.40, p = .10$, partial $\eta^2 = .04$.

Movement time

Mean MT (+/- SE) for age groups within DCD and control group are displayed in Figure 2. 3-way ANOVA on MT showed significant main effects for age, $F(2,123) = 54.63, p < .001$, partial $\eta^2 = .47$, skill group, $F(1,123) = 14.42, p < .001$, partial $\eta^2 = .11$, and trial, Wilks' $\Lambda = .08, F(2,122) = 754.88, p < .001$, partial $\eta^2 = .93$. The higher order 3-way interaction between these factors was also significant, Wilks' $\Lambda = .91, F(4,244) = 2.92, p = .022$, partial $\eta^2 = .05$. Simple interaction effects were therefore explored within each skill group.

For the control group, there was a significant simple interaction between age group and trial, $F(4,166) = 12.80, p < .001$, partial $\eta^2 = .24$. Follow-up tests of the simple effect of age revealed the following: for non-jump trials, there was no significant difference between mid-aged and younger children, whereas both these groups were slower than the older children. For jump trials, younger children were slower than mid-aged who, in turn, were slower than older children (by around 105ms). For anti-jump trials, younger children were slower than mid-aged (by ~ 230ms) who, in turn, were slower than older children (by around 150ms).

For the DCD group, the simple interaction between age and trial type was also significant, $F(4,76) = 8.67, p < .001$, partial $\eta^2 = .31$. For non-jump trials, mid-aged and older children with DCD were not shown to differ, unlike controls; both these groups were, in turn, faster than younger children. For jump and anti-jump trials, the pattern of differences between age groups was similar to that shown for controls; however, the mean difference between mid-aged and older children on anti-jump trials was very large at around 245ms. Importantly, for older children on anti-jump trials there was no significant difference between skill groups whereas the same comparisons for mid-aged and younger children showed faster performance in controls.

We also examined the magnitude of group differences within each trial condition. For non-jump trials, the effect of group varied with age: there was no difference between mid-aged DCD and control children (partial $\eta^2 = .00$), and between older DCD and controls (0.05). However, younger children with DCD (630ms) were significantly slower than younger controls (501ms), partial $\eta^2 = .27$. For jump trials, the significant difference between DCD and controls (partial $\eta^2 = .05$) did not vary as a function of age: the simple interaction of group by age was not significant, $F(2, 132) < 1$. Finally, for anti-jump trials, the difference between DCD and control groups varied as a function of age: for younger children, partial $\eta^2 = .20$, for mid-age (0.17), and for older children (0.04).

Anti-Jump Movement Time difference

The mean AJMT_{diff} for DCD and control group is displayed in Figure 3. Three outliers (2 older controls and one mid-aged DCD) were removed from the 2-way ANOVA as values were greater than 2.5 SDs from the mean. Results showed a significant main effect for age group, $F(2,120) = 24.47, p < .001$, partial $\eta^2 = .29$, with values for younger children (395ms) higher than that for both the mid-aged (280ms) and older children (209ms). The difference between mid-aged and older children was also significant. Overall, the DCD group (334ms)

were significantly higher than controls (269ms), however the main effects were moderated by a significant interaction between age and group, $F(2,120) = 3.40, p = .037$, partial $\eta^2 = .05$. The simple effect for skill group was significant for younger children, $F(1, 35) = 6.89, p = .013$, partial $\eta^2 = .17$, mid-aged children, $F(1, 54) = 11.69, p = .001$, partial $\eta^2 = .18$, but not older, $F(1, 41) < 1$, partial $\eta^2 = .00$.

Time of Correction

TOC for jump trials. The average ToC (+/- SE) for DCD and control group is displayed in Figure 4. 2-way ANOVA on mean ToC showed no significant interaction between skill group and age, $F(2,127) = 1.21$, partial $\eta^2 = .02$. There was a main effect for age group, $F(2,127) = 32.27, p < .001$, partial $\eta^2 = .34$ and skill group, $F(1,127) = 28.85, p < .001$, partial $\eta^2 = .19$. Younger children (321ms) were slower to correct trajectory than mid-aged (283ms), who in turn were slower than older (253ms). Overall, children with DCD (307ms) were slower than controls (274ms).

TOC2 for anti-jump trials. For ToC2 on anti-jump trials, 2-way ANOVA showed no significant interaction between age and skill group, $F(2,124) < 1$, partial $\eta^2 = .01$. There was a main effect for age group, $F(2,124) = 53.51, p < .001$, partial $\eta^2 = .46$, and skill group, $F(1,124) = 9.31, p = .003$, partial $\eta^2 = .07$. Younger children (644ms) were slower to make the second correction on anti-jump trials than mid-aged (519ms), who in turn were slower than older (431ms). Overall, children with DCD (550ms) were slower than controls (516ms).

Post Correction Time for Anti-Jump Trials

2-way ANOVA revealed a significant effect for group, $F(1,129) = 19.64, p < .001$, partial $\eta^2 = .13$, and age, $F(2,129) = 50.42, p < .001$, partial $\eta^2 = .44$, while the interaction was not significant, $p = .18$. Older children (432ms) had faster PCTs than mid-aged (514), who were in turn faster than younger (628). Children with DCD (555ms) were slower to finish the post-correction phase than controls (502ms).

Response Errors

Initial analyses on TDEs and AEs showed no effects involving trial type; hence, error variables were examined as a function of age and group.

Touch down errors. 2-way ANOVA showed no significant interaction between age and skill group, $F(2,124) < 1$, partial $\eta^2 = .006$. A main effect for age was significant, $F(2,124) = 3.92$, $p = .022$, partial $\eta^2 = .06$; younger children (3.44) made significantly more TDE than older children (2.31) but not mid-age (3.15). There was no difference between mid-age and older children. There was no effect for group as DCD and control groups made 2.98 errors respectively, $F(1,124) < 1$, partial $\eta^2 = .001$.

Anticipation errors. 2-way ANOVA revealed no interaction between age and group, $F(2,124) < 1$, partial $\eta^2 = .01$. There was a main effect for age, $F(2,124) = 5.23$, $p = .005$, partial $\eta^2 = .08$, and skill group, $F(1,124) = 5.33$, $p = .023$, partial $\eta^2 = .04$. On average, younger children (1.19) made significantly more AE than mid-age (0.65) and older children (0.59). There was no difference between mid-age and older children. The DCD group (1.02) made significantly more errors than controls (0.67).

Centre touch errors. For CTE, there was no 2-way interaction between age and group, $F(2,125) < 1$, partial $\eta^2 = .02$. There was no main effect for age, $F(2,125) < 1$, partial $\eta^2 = .01$: younger (0.42), mid-age (0.44) and older (0.23) children; and no effect for group: DCD (0.33) and controls (0.29), $F(2,125) < 1$, partial $\eta^2 = .001$.

Anti-jump errors. On AJE, there was no interaction between age and skill groups, $F(2,125) < 1$, partial $\eta^2 = .01$. There was a main effect for age, $F(2,125) = 3.04$, $p = .05$, partial $\eta^2 = .05$; younger children (mean of 0.97 out of 8 anti-jump trials) had significantly more AJE than older children (0.45) but not mid-age (0.95). The difference between mid-age and older children was also significant. There was no significant difference between DCD (0.88) and controls (0.76), $F(2,125) < 1$, partial $\eta^2 = .003$.

Discussion

The aim of the study presented here was to examine the ability of children with DCD to implement online control when inhibitory constraints are superimposed on a reaching task. Using a double-jump paradigm, we confirmed that these children were significantly slower than non-DCD to adjust their arm reaching movement on jump trials, evident by longer movement time and delayed time to initiate a corrective movement. Importantly, on anti-jump trials, children with DCD were further disadvantaged relative to controls, evident by larger $AJMT_{diff}$ scores and longer duration to implement a second corrective movement (i.e. ToC2) after their hand was first drawn to the cued location. However, this effect was moderated by age such that the anti-reach performance of older children with DCD approached that of their age-matched peers. These results support the hypothesis that children with DCD have particular difficulty coupling executive control (i.e., response inhibition) to online control during goal-directed action, particularly during younger and middle childhood. This deficit might explain the particular difficulty these children have with more complex tasks, both cognitively and from a motor control perspective. The implications of these findings are discussed below.

Chronometric Performance Measures

For reaction time, the non-significant effect for trial type (non-jump vs jump vs anti-jump) and its interactions were expected since the stimulus display up to the point of finger lift-off was identical for each condition. The DCD group was slower to initiate reaching than controls which is in line with recent studies of online control (Hyde & Wilson, 2011a, 2013) and accords with a recent meta-analysis (Wilson et al., 2013) that shows longer latencies when responding to externally cued stimuli. Reduced neural transmission times when responding to external events may underlie this issue.

For non-jump trials, only the younger children with DCD differed from their age-matched controls. This accords with earlier research showing that mid-aged and older children with DCD can complete simple goal-directed reaching within a comparable timeframe as typically developing children of the same age, at least where the need for online adjustments is minimal (Wilmot, Wann, & Brown, 2006; Wilson & Hyde, 2013). What our data suggests is that younger children with DCD may be slower to implement even simple movements within peripersonal space.

For both DCD and control groups, movement time increased significantly from non-jump to jump trials. This accords with previous work (Castiello, Bennett, & Chambers, 1998; Hyde & Wilson, 2011a) and reflects the added computation and implementation time involved when modulating movements in-flight to perceptible changes in target location. In a recent review of online control, Gaveau and colleagues (2014) have commented that increased MT is generally observed when target jumps are of sufficient extent to enlist more voluntary aspects of online control. By comparison, under conditions of saccadic suppression, fast online corrections to relatively small target jumps are performed automatically, without conscious awareness, and with no significant increase in MT relative to non-jump trials. In line with previous studies (Querne et al., 2008; Rigoli et al., 2012) performance deficits were manifest by longer response times while group differences were not found on touch down, centre touch or anti-jump errors. The added (temporal) costs associated with using feedback-based control are likely to explain this effect, perhaps a function of reduced efficiency in processing visual information through fast dorsal stream channels (Wilson et al., 2013).

Overall, children with DCD were slower to correct movements in response to jump trials (TOC). Indeed, this effect was not moderated by age suggesting some residual deficit in online control per se over childhood. What is intriguing, however, is the differential effect between groups of the added inhibitory load, measured both chronometrically and

kinematically. This finding is described in detail below and is the central focus for the remainder of the discussion.

Deficits in the online control of reaching are exacerbated with increased inhibitory demands

Movement times increased between jump- and anti-jump trials for both groups. For anti-jump trials, we saw two corrective movements in response to the (perceptible) shift in target location which account for the increase in MT over what is a longer trajectory length. The first correction occurs toward the compelling lateral cue and the second inhibiting movement away from the cued location and toward the contralateral target, equidistance from the midline. This bi-phasic correction has also been noted in studies of healthy adults (Pisella et al., 2000) and in our recent developmental work assessing children aged 7 to 12 years (Ruddock et al., 2014). The first correction is considered automatic in that the initial deviation is very difficult to withhold under task instructions that emphasise both speed and accuracy (Gaveau et al., 2014). The second correction is voluntary for what is an unfamiliar task.

Results for $AJMT_{diff}$ suggest a specific impairment in younger children with DCD that may subside with age. Overall, the $AJMT_{diff}$ score (i.e., between jump and anti-jump trials) was larger for the DCD group compared with controls, but importantly its magnitude varied as a function of age. Only for younger and mid-aged children was the comparison between skill groups significant. This suggests a reduced capacity in DCD over this age period to integrate inhibitory and online control during the brief time course of goal-directed reaching. However, by older childhood this capacity in DCD may approach levels of typically developing children. Interestingly, while TOC and TOC2 were delayed in DCD as a whole, there was no moderation of this effect with age. Measures of MT appear to be more sensitive than kinematic measures to change with age and as a function of motor skill.

Finally, children with DCD as a whole were also slower to complete the post-correction phase on anti-jump trials. However, this effect did not decline as a function of age. This suggests two possibilities: first, it could be taken as evidence that the early stages of online control (up to TOC) are not fully developed in younger and mid-aged children with DCD, or second, it may suggest that the process of implementing trajectory changes remains problematic in DCD over childhood. In lieu of the compelling results for $AJMT_{diff}$, we suggest that the former hypothesis is more likely.

Taken together, our results suggest that the online motor control difficulties of children with DCD are exacerbated when an inhibitory load is superimposed on a dynamic reaching task. Importantly, however, our cross-sectional data shows that by older childhood the level of efficiency in controlling anti-reach movements approaches that seen in typically developing children. We argue that in younger and mid-aged children with DCD, their slower anti-reach performance reflects an immature coupling between frontal and posterior control systems (likely PPC), delaying the voluntary adjustment of movement trajectories in real time. Evidence for improved coupling in older children can be attributed to a combination of neural maturation and experience-dependent plasticity in these same networks (Casey et al., 2008; Johnson, 2005). For example, Balsters, Whelan, Robertson, and Ramnani (2013) found that cerebellum Crus I and II are strongly connected with the prefrontal cortex (PFC) which may support the cognitive control of action systems. What remains to be seen is how particular forms of practice or intervention can alter these couplings over short and long timescales.

From a neural perspective, changes to EF appear to be mirrored by an increase in (sub)cortical structures tied closely to the PFC (Durstun et al., 2006). When emerging networks come ‘online’ there is often a period of adjustment as new skills are adopted and refined (Johnson, 2011). With regards to performance on step-perturbation tasks, non-linear

changes (i.e. more variability in performance) become apparent as the child learns to hone their motor skills in the pursuit of goal-directed action. The problems the older DCD group showed, in particular, when making online adjustments under an inhibitory load might be either the result of executive systems further containing an already impaired ability to redirect movement, or problems coupling multiple systems to more demanding action. Certainly, neuroimaging studies could help clarify the specific structures and regions at play here and shed light on how the two proposed systems interact.

Implications and Limitations

Comparison of the results from the current study to previous online control research may be limited due to several reasons. First, it may be difficult to directly assess data from mid-age children as the age groups defined here (i.e., 6-7, 8-9, and 10-12) are different from the criteria used in the study from Hyde and Wilson (2013) where younger children were grouped between 5-7 years. In addition, we used the 15th percentile as a cut point to define the DCD group compared with the 10th percentile used by Hyde and Wilson. The online deficit on jump trials was somewhat more pronounced in the earlier study, underlining the issue of severity in causal accounts of DCD. Finally, to provide a stronger test of the hypothesis that children with DCD have difficulty coupling online control and executive systems we suggest use of a longitudinal design (c.f. the cross-sectional data presented here). This would provide a clearer window into the developmental trajectory of these control systems, and their pattern of interaction over childhood.

Conclusion

Overall, results extend earlier work by showing that children with DCD have difficulty performing online adjustments and that this is compounded when inhibitory constraints are imposed on a reaching task. Importantly, however, the latter effect was reduced as a function of age. Whereas younger and mid-aged children with DCD were

disadvantaged by anti-jump trials – as shown by MT and AJMT_{diff} scores – older children were not relative to age-matched controls. This intriguing finding suggests that whatever is driving the poor motor skill performance of older children with DCD, it is not the ability to couple inhibitory function with online control. Before this age, however, immature coupling may compound the performance issues in DCD, particularly when motor tasks make demands on executive function. Put another way, the coupling between these systems may require a more protracted period of development in DCD before being functionally integrated. Longitudinal data is needed to unravel the changing pattern of interaction between these systems with age and their relationship to other aspects of executive function.

Acknowledgments

We express our thanks to Ray Duckman for his technical expertise in programming the double-jump paradigm and to Justin Doward for developing code to screen data. For their helpful and enthusiastic assistance during data collection, our sincere gratitude also extends to the staff and students of Belle Vue Primary School, Beverley Hills Primary School, St. Augustine's Primary School, New Life Christian College, John Septimus Roe Anglican Community College, and St. Andrews Grammar.

Funding

We thank the Australian Research Council (ARC) for funding this project under the Discovery Grants Scheme (DP1094535).

Table 1

Descriptive Statistics of Developmental Coordination Disorder Group and Control Group

Groups for the Double Jump Reaching Task

	Control					DCD				
	<i>n</i>	Sex		Age (years)		<i>n</i>	Sex		Age (years)	
		Girls	Boys	<i>M</i>	<i>SD</i>		Girls	Boys	<i>M</i>	<i>SD</i>
6-7	26	17	9	7.20	0.46	10	5	5	7.27	0.69
8-9	38	23	15	8.92	0.63	16	5	11	8.87	0.63
10-12	23	13	10	10.74	0.49	16	10	6	11.07	0.38

Note. *N* = 129

Table 2

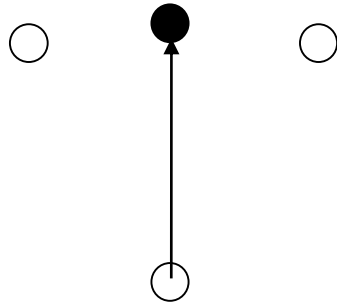
Descriptive Statistics of Variables on the Double Jump Reaching Task

Skill	Age	Trial	MT (ms)		AJMTdiff (ms)		ToC (ms)		ToC2 (ms)		PCT-AJ (ms)		TDE		AE		CTE		AJE	
			M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Control	6-7	N-J	504	88									7.96	7.28	3.58	2.73				
		J	855	157			307	51					5.32	3.19	1.08	1.26	2.73	2.97		
		A-J	1220	215	352	170	304	41	625	115	594	115	3.31	2.15	1.00	1.20	0.38	1.02	0.96	1.40
	8-9	N-J	497	93									5.00	5.16	1.66	1.73				
		J	733	95			286	36					3.26	2.67	0.76	1.60	1.55	2.29		
		A-J	989	140	248	102	272	40	497	81	488	75	3.08	2.16	0.53	0.65	0.53	0.95	0.79	1.23
	10-12	N-J	445	68									3.43	3.38	1.35	1.53				
		J	630	67			252	36					1.78	2.07	0.48	0.66	0.29	0.55		
		A-J	840	116	210	91	242	27	421	70	417	53	2.43	1.56	0.52	0.79	0.17	0.48	0.50	1.17
DCD	6-7	N-J	620	140									11.00	8.31	4.30	3.74				
		J	894	114			375	70					4.60	3.10	1.60	1.51	1.10	1.73		
		A-J	1393	139	499	166	361	38	691	94	707	117	3.80	2.10	1.70	1.16	0.50	0.85	1.00	1.49
	8-9	N-J	482	80									7.06	5.97	5.00	5.37				
		J	792	141			320	51					4.50	2.83	0.81	0.66	2.06	3.70		
		A-J	1135	175	359	128	309	53	566	87	564	108	3.25	1.65	0.88	1.03	0.24	0.44	1.29	1.40
	10-12	N-J	468	91									3.31	2.91	2.00	2.00				
		J	685	114			272	39					1.94	1.95	0.56	0.89	0.25	0.68		
		A-J	892	134	207	99	269	40	442	70	450	74	2.13	1.86	0.69	1.20	0.31	0.48	0.38	0.89

Note. MT = Movement Time, AJMTdiff = Movement Time Difference between Anti-jump and Jump Trials, ToC = Time of Correction (jump trials), ToC2 = Time of Correction for Anti-Jump Trials, PCT-AJ = Post Correction Time Anti-Jump Trials, TDE = Touch Down Error, AE = Anticipation Error, CTE = Centre Touch Error, AJE = Anti-Jump Error, N-J = Non jump, J = Jump, A-J = Anti-Jump

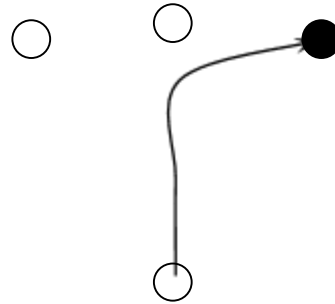
Block A

Non-jump trial



The central target remains lit until touchdown.

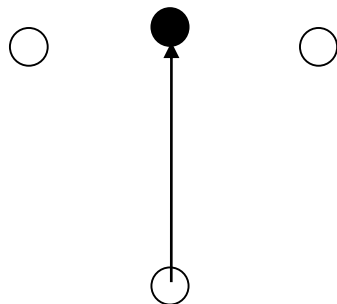
Jump trial



The central target jumps either left or right at finger lift off.

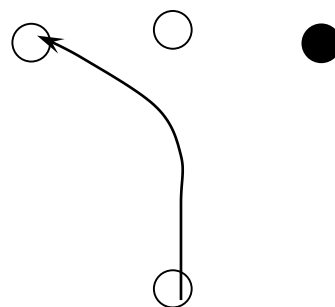
Block B

Non-jump trial



The central target remains lit until touchdown.

Anti-jump trial



The central cue jumps either left or right at lift off, while the child is instructed to reach and touch the opposite locations.

Figure 1. Experimental set-up for the double jump reaching task showing trial types over two blocks of trials.

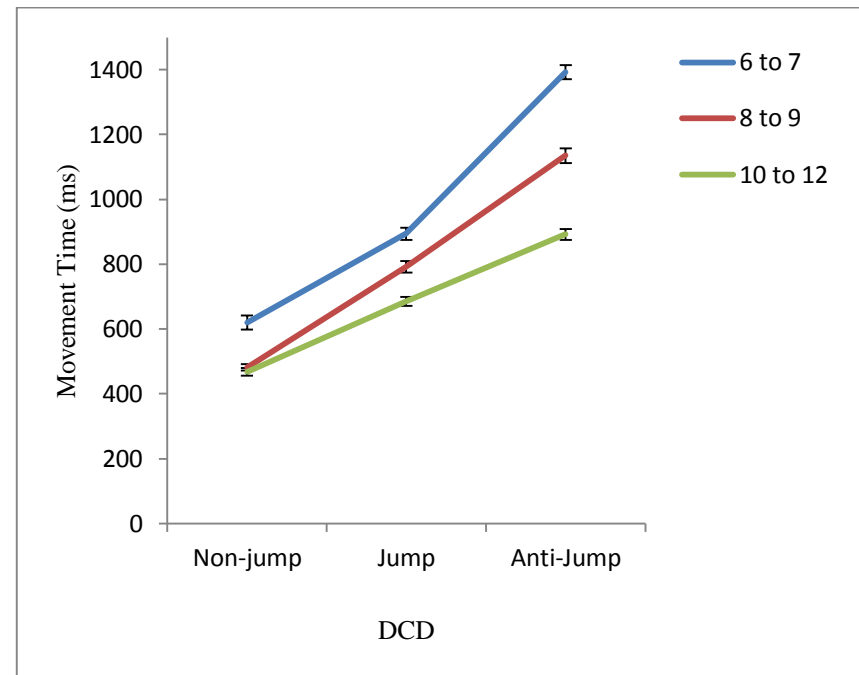
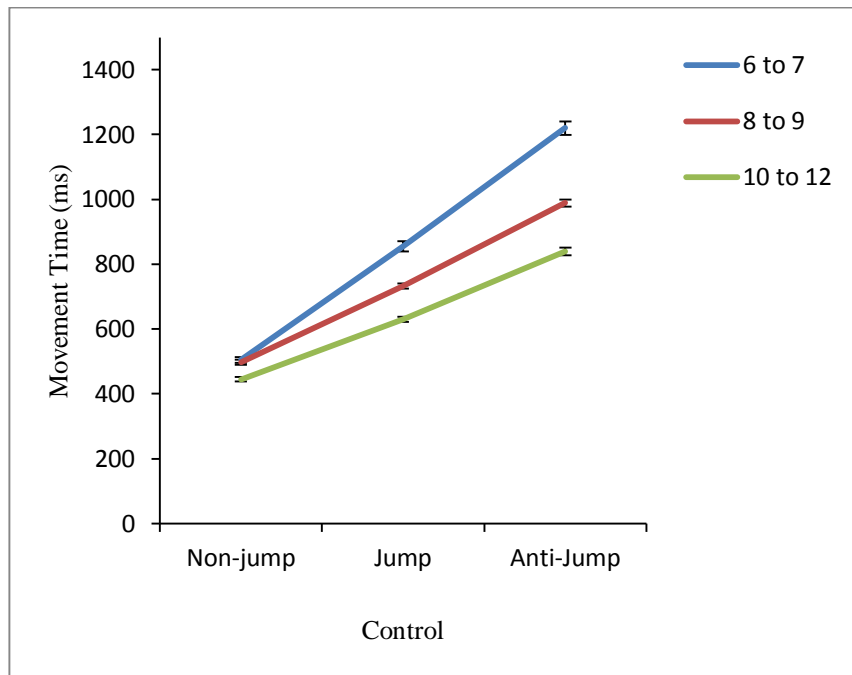


Figure 2. Mean movement time (MT +/- SE) values of young (6-7), mid-age (8-9) and older (10-12) children for DCD and control groups on the double-jump reaching task

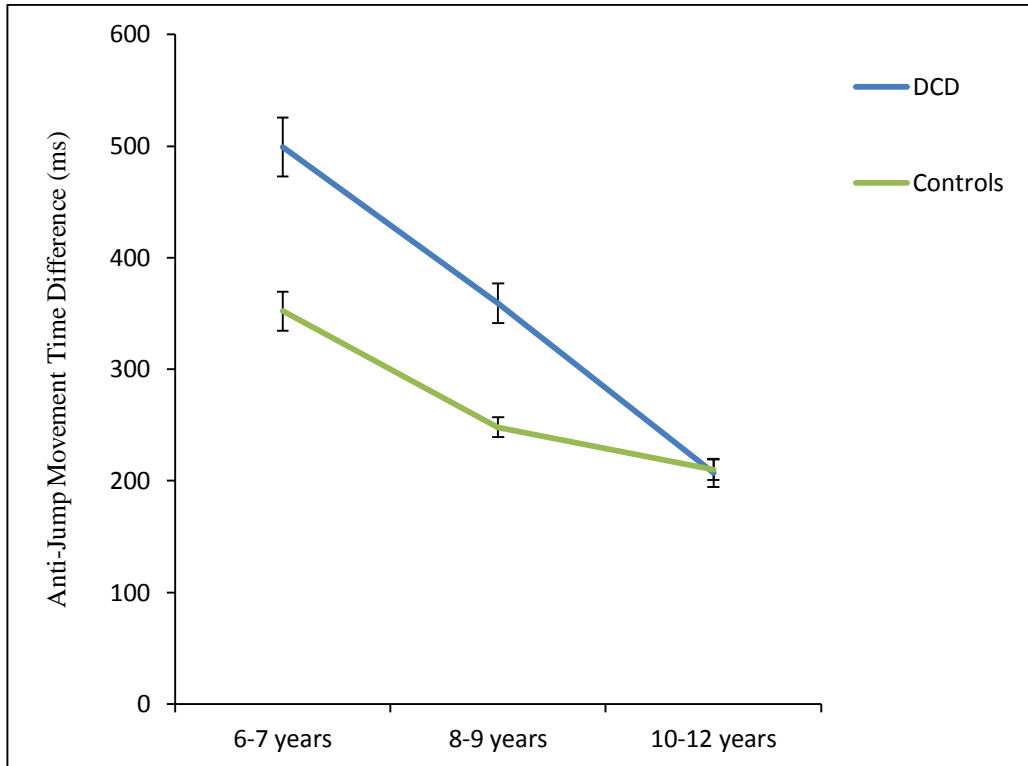


Figure 3. Mean anti-jump movement time difference ($AJMT_{diff} \pm SE$) values of young (6-7), mid-age (8-9) and older (10-12) children for DCD and control groups on the double-jump reaching task

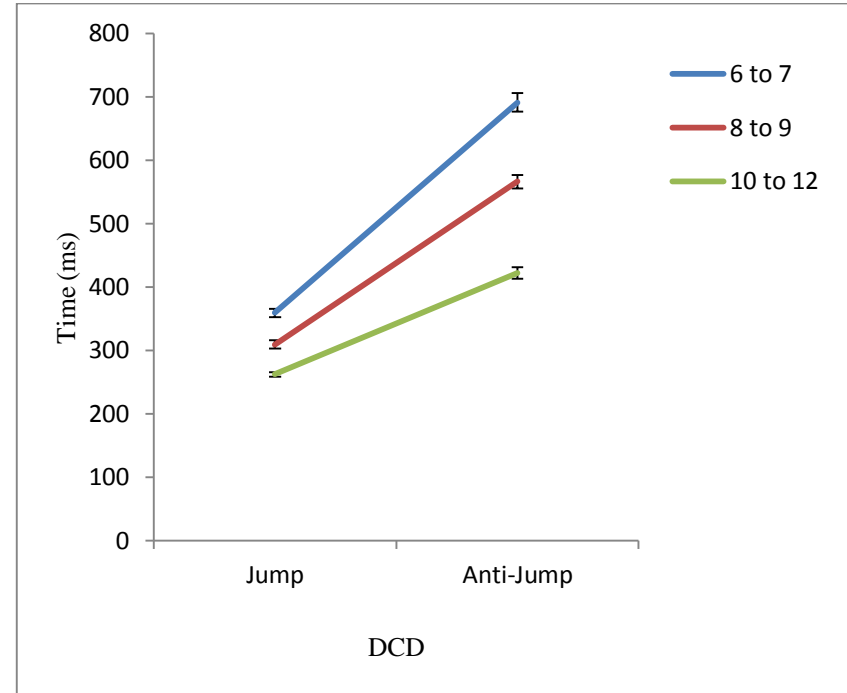
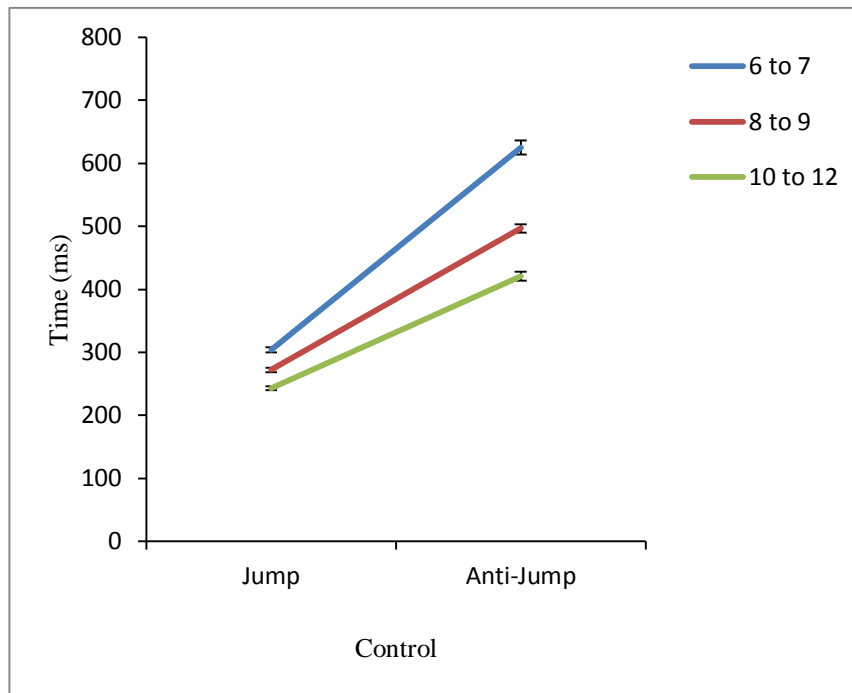


Figure 4. Mean time of correction (+/- SE) showing initial correction (ToC) and second correction (ToC2) on anti-jump trials for DCD and control group on the double-jump reaching task

References

- 3DVIA. (2010). Virtools [Computer Software]. France: Dassault Systemes.
- American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders: DSM-5*. Arlington, VA: American Psychiatric Publishing, Inc.
- Balsters, J. H., Whelan, C. D., Robertson, I. H., & Ramnani, N. (2013). Cerebellum and cognition: Evidence for the encoding of higher order rules. *Cerebral Cortex*, *23*(6), 1433-1443. doi: 10.1093/cercor/bhs127
- Bard, C., Hay, L., & Fleury, M. (1990). Timing and accuracy of visually directed movements in children: Control of direction and amplitude components. *Journal of Experimental Child Psychology*, *50*(1), 102-118.
- Cameron, B. D., Cressman, E. K., Franks, I. M., & Chua, R. (2009). Cognitive constraint on the 'automatic pilot' for the hand: Movement intention influences the hand's susceptibility to involuntary online corrections. *Consciousness and Cognition*, *18*(3), 646-652. doi: 10.1016/j.concog.2009.04.008
- Casey, B. J., Getz, S., & Galvan, A. (2008). The adolescent brain. *Developmental Review*, *28*, 62-77. doi: 10.1016/j.dr.2007.08.003
- Casey, B. J., Tottenham, N., Liston, C., & Durston, S. (2005). Imaging the developing brain: what have we learned about cognitive development? *Trends in Cognitive Sciences*, *9*(3), 104-110. doi: 10.1016/j.tics.2005.01.011
- Castiello, U., Bennett, K., & Chambers, H. (1998). Reach to grasp: The response to a simultaneous perturbation of object position and size. *Experimental Brain Research*, *120*(1), 31-40. doi: 10.1007/s002210050375
- Chicoine, A., Lassonde, M., & Proteau, L. (1992). Developmental aspects of sensorimotor integration. *Developmental Neuropsychology*, *8*(4), 381-394.

- Durston, S., Davidson, M. C., Tottenham, N., Galvan, A., Spicer, J., Fossella, J. A., & Casey, B. J. (2006). A shift from diffuse to focal cortical activity with development. *Developmental Science*, 9(1), 1-8. doi: 10.1111/j.1467-7687.2005.00454.x
- Farnè, A., Roy, A. C., Paulignan, Y., Rode, G., Rossetti, Y., Boisson, D., & Jeannerod, M. (2003). Visuo-motor control of the ipsilateral hand: Evidence from right brain-damaged patients. *Neuropsychologia*, 41(6), 739-757.
- Gaveau, V., Pisella, L., Priot, A. E., Fukui, T., Rossetti, Y., Pelisson, D., & Prablanc, C. (2014). Automatic online control of motor adjustments in reaching and grasping. *Neuropsychologia*, 55, 25-40. doi: 10.1016/j.neuropsychologia.2013.12.005
- Gerver, W. J. M., Drayer, N. M., & Schaafsma, W. (1989). Reference values of anthropometric measurements in Dutch children: The Oosterwolde study. *Acta Paediatrica Scandinavica*, 78(2), 307-313. doi: 10.1111/j.1651-2227.1989.tb11075.x
- Gonzalez, C. L. R., Mills, K. J., Genee, I., Li, F., Piquette, N., Rosen, N., & Gibb, R. (2014). Getting the right grasp on executive function. *Frontiers in Psychology*, 5(APR). doi: 10.3389/fpsyg.2014.00285
- Gréa, H., Pisella, L., Rossetti, Y., Desmurget, M., Tilikete, C., Grafton, S., . . . Vighetto, A. (2002). A lesion of the posterior parietal cortex disrupts on-line adjustments during aiming movements. *Neuropsychologia*, 40(13), 2471-2480.
- Gueze, R. H., Jongmans, M. J., Schoemaker, M. M., & Smits-Engelsman, B. C. (2001). Clinical and research diagnostic criteria for developmental coordination disorder: a review and discussion. *Hum Mov Sci*, 20(1-2), 7-47.
- Hyde, C., & Wilson, P. H. (2011a). Online motor control in children with developmental coordination disorder: Chronometric analysis of double-step reaching performance. *Child: Care, Health and Development*, 37(1), 111-122. doi: 10.1111/j.1365-2214.2010.01131.x

- Hyde, C., & Wilson, P. H. (2011b). Dissecting online control in Developmental Coordination Disorder: a kinematic analysis of double-step reaching. *Brain Cognition*, *75*(3), 232-241. doi: 10.1016/j.bandc.2010.12.004
- Hyde, C., & Wilson, P. H. (2013). Impaired online control in children with developmental coordination disorder reflects developmental immaturity. *Developmental Neuropsychology*, *38*(2), 81-97. doi: 10.1080/87565641.2012.718820
- Johnson, M. H. (2005). *Developmental Cognitive Neuroscience* (2nd ed.). Oxford: Wiley-Blackwell.
- Johnson, M. H. (2011). Interactive Specialization: A domain-general framework for human functional brain development? *Developmental Cognitive Neuroscience*, *1*(1), 7-21. doi: 10.1016/j.dcn.2010.07.003
- Lebel, C., Walker, L., Leemans, A., Phillips, L., & Beaulieu, C. (2008). Microstructural maturation of the human brain from childhood to adulthood. *Neuroimage*, *40*(3), 1044-1055. doi: 10.1016/j.neuroimage.2007.12.053
- Livesey, D., Keen, J., Rouse, J., & White, F. (2006). The relationship between measures of executive function, motor performance and externalising behaviour in 5- and 6-year-old children. *Hum Mov Sci*, *25*(1), 50-64. doi: S0167-9457(05)00085-0 [pii]
10.1016/j.humov.2005.10.008
- Mandich, A., Buckolz, E., & Polatajko, H. (2002). On the ability of children with developmental coordination disorder (DCD) to inhibit response initiation: The simon effect. *Brain and Cognition*, *50*(1), 150-162.
- Mandich, A., Buckolz, E., & Polatajko, H. (2003). Children with developmental coordination disorder (DCD) and their ability to disengage ongoing attentional focus: more on inhibitory function. *Brain and Cognition*, *51*(3), 346-356. doi: S0278262603000393

- Mathworks. (2010). MATLAB (Version 7.11) [Computer software]. Natick, Massachusetts, USA.
- McCarron, L. T. (1997). *McCarron Assessment of Neuromuscular: Development: Fine and Gross Motor Abilities*. Dallas, TX, USA: Common Market Press.
- Michel, E., Roethlisberger, M., Neuenschwander, R., & Roebbers, C. M. (2011). Development of cognitive skills in children with motor coordination impairments at 12-month follow-up. *Child Neuropsychology*, *17*(2), 151-172. doi: 10.1080/09297049.2010.525501
- Noraxon. (2010). ZEBRIS CMS10 [Hardware]. USA: Noraxon.
- Noten, M., Wilson, P., Ruddock, S., & Steenbergen, B. (2014). Mild impairments of motor imagery skills in children with DCD. *Research in Developmental Disabilities*, *35*(5), 1152-1159. doi: 10.1016/j.ridd.2014.01.026
- Pangelinan, M. M., Zhang, G., VanMeter, J. W., Clark, J. E., Hatfield, B. D., & Haufler, A. J. (2011). Beyond age and gender: Relationships between cortical and subcortical brain volume and cognitive-motor abilities in school-age children. *Neuroimage*, *54*(4), 3093-3100. doi: 10.1016/j.neuroimage.2010.11.021
- Piek, J. P., Baynam, G. B., & Barrett, N. C. (2006). The relationship between fine and gross motor ability, self-perceptions and self-worth in children and adolescents. *Human Movement Science*, *25*(1), 65-75. doi: 10.1016/j.humov.2005.10.011
- Piek, J. P., Dyck, M. J., Francis, M., & Conwell, A. (2007). Working memory, processing speed, and set-shifting in children with developmental coordination disorder and attention-deficit-hyperactivity disorder. *Developmental Medicine & Child Neurology*, *49*(9), 678-683. doi: 10.1111/j.1469-8749.2007.00678.x

- Pisella, L., Gréa, H., Tilikete, C., Vighetto, A., Desmurget, M., Rode, G., . . . Rossetti, Y. (2000). An 'automatic pilot' for the hand in human posterior parietal cortex: Toward reinterpreting optic ataxia. *Nature Neuroscience*, *3*(7), 729-736. doi: 10.1038/76694
- Querne, L., Berquina, P., Vernier-Hauvettea, M., Fall, S., Deltour, L., Meyer, M., & de Marco, G. (2008). Dysfunction of the attentional brain network in children with Developmental Coordination Disorder: A fMRI study. *Brain Research*, *1244*, 89-102. doi: 10.1016/j.brainres.2008.07.066
- Reichenbach, A., Bresciani, J.-P., Peer, A., Bulthoff, H. H., & Thielscher, A. (2011). Contributions of the PPC to online control of visually guided reaching movements assessed with fMRI-guided TMS. *Cerebral Cortex*, *21*(7), 1602-1612. doi: 10.1093/cercor/bhq225
- Reichenbach, A., Thielscher, A., Peer, A., Bühlhoff, H. H., & Bresciani, J. P. (2014). A key region in the human parietal cortex for processing proprioceptive hand feedback during reaching movements. *Neuroimage*, *84*, 615-625. doi: 10.1016/j.neuroimage.2013.09.024
- Rigoli, D., Piek, J. P., Kane, R., & Oosterlaan, J. (2012). Motor coordination, working memory, and academic achievement in a normative adolescent sample: Testing a mediation model. *Archives of Clinical Neuropsychology*, *27*(7), 766-780. doi: 10.1093/arclin/acs061
- Ruddock, S., Hyde, C., Piek, J., Sugden, D., Morris, S., & Wilson, P. (2014). Executive systems constrain the flexibility of online control in children during goal-directed reaching. *Developmental Neuropsychology*, *39*(1), 51-68. doi: 10.1080/87565641.2013.855215
- Tsai, C. L., Yu, Y. K., Chen, Y. J., & Wu, S. K. (2009). Inhibitory response capacities of bilateral lower and upper extremities in children with developmental coordination

- disorder in endogenous and exogenous orienting modes. *Brain and Cognition*, 69(2), 236-244. doi: <http://dx.doi.org/10.1016/j.bandc.2008.07.012>
- Van Braeckel, K., Butcher, P. R., Geuze, R. H., Stremmelaar, E. F., & Bouma, A. (2007). Movement adaptations in 7- to 10-year-old typically developing children: Evidence for a transition in feedback-based motor control. *Human Movement Science*, 26(6), 927-942. doi: doi:10.1016/j.humov.2007.07.010
- Wilmot, K., Wann, J. P., & Brown, J. K. (2006). Problems in the coupling of eye and hand in the sequential movements of children with Developmental Coordination Disorder. *Child Care Health and Development*, 32(6), 665-678. doi: 10.1111/j.1365-2214.2006.00678.x
- Wilson, P. H., & Hyde, C. (2013). The development of rapid online control in children aged 6-12 years: Reaching performance. *Human Movement Science*, 32(5), 1138-1150. doi: 10.1016/j.humov.2013.02.008
- Wilson, P. H., & Maruff, P. (1999). Deficits in the endogenous control of covert visuospatial attention in children with developmental coordination disorder. *Human Movement Science*, 18(2), 421-442.
- Wilson, P. H., Maruff, P., & McKenzie, B. E. (1997). Covert orienting of visuospatial attention in children with developmental coordination disorder. *Developmental Medicine & Child Neurology*, 39(11), 736-745.
- Wilson, P. H., Ruddock, S., Smits-Engelsman, B., Polatajko, H., & Blank, R. (2013). Understanding performance deficits in developmental coordination disorder: a meta-analysis of recent research. *Developmental Medicine and Child Neurology*, 55(3), 217-228.
- Wolpert, D. M., & Flanagan, J. R. (2001). Motor prediction. *Current Biology*, 11(18), R729-R732.

