Research in Developmental Disabilities 36 (2015) 244–255

Contents lists available at ScienceDirect

Research in Developmental Disabilities

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

Scott Ruddock[a], Jan Piek[b], David Sugden[c], Sue Morris[b], Christian Hyde[d], Karen Caeyenberghs[a], Peter Wilson[a,*]

[a] Australian Catholic University, Melbourne, Australia
[b] Curtin University, Perth, Australia
[c] University of Leeds, United Kingdom
[d] Deakin University, Melbourne, Australia

ARTICLE INFO

*Article history:*
Received 3 September 2014
Accepted 10 October 2014
Available online

*Keywords:*
Developmental Coordination Disorder (DCD)
Motor control
Motor learning
Predictive modelling
Inhibitory control
Executive function
Motor development

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 are needed to clarify this intriguing finding. The theoretical and applied implications of these results are discussed.



## 1. 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

* Corresponding author. Tel.: +61 399533445.
*E-mail address:* peterh.wilson@acu.edu.au (P. Wilson).

http://dx.doi.org/10.1016/j.ridd.2014.10.013

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 research (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). To address this issue in relation to the neurocognitive underpinnings of DCD, we enlisted 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, Bulthoff, & 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. Ruddock 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).

### *1.1. 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, & Roebers, 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