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Reduced motor imagery efficiency is associated with online control difficulties in children with probable developmental coordination disorder

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ABSTRACT

Recent evidence indicates that the ability to correct reaching movements in response to unexpected target changes (i.e., online control) is reduced in children with developmental coordination disorder (DCD). Recent computational modeling of human reaching suggests that these inefficiencies may result from difficulties generating and/or monitoring internal representations of movement. This study was the first to test this putative relationship empirically. We did so by investigating the degree to which the capacity to correct reaching mid-flight could be predicted by motor imagery (MI) proficiency in a sample of children with probable DCD (pDCD). Thirty-four children aged 8 to 12 years (17 children with pDCD and 17 age-matched controls) completed the hand rotation task, a well-validated measure of MI, and a double-step reaching task (DSRT), a protocol commonly adopted to infer one's capacity for correcting reaching online. As per previous research, children with pDCD demonstrated inefficiencies in their ability to generate internal action representations and correct their reaching online, demonstrated by inefficient hand rotation performance and slower correction to the reach trajectory following unexpected target perturbation during the DSRT compared to age-matched controls. Critically, hierarchical moderating regression demonstrated that even after general reaching ability was controlled for, MI efficiency was a significant predictor of reaching correction efficiency, a relationship that was constant across groups. Ours is the first study to provide direct pilot evidence in support of the view that a decreased capacity for online control of reaching typical of DCD may be associated with inefficiencies generating and/or using internal representations of action.

1. Introduction

Developmental coordination disorder (DCD) is a neuro-developmental condition characterised by impaired motor competence in the absence of neurological or intellectual deficit (Geuze, Jongmans, Schoemaker, & Smits-Engelsman, 2001). Heterogeneous in nature, atypical motor skill affects around 6% of school-aged children (APA, 2013; Blank, Smits-Engelsman, Polatajko, & Wilson, 2012) significantly impacting on a child's capacity to undertake many motor related day-to-day

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activities including those required for self-care (i.e., tooth brushing, hair brushing etc.), using utensils, and dressing (e.g., tying shoelaces; Miller, Missiuna, Macnab, & Malloy-Miler, 2001; Missiuna, Moll, King, King, & Law, 2007; Summers, Larking, Dewey, 2008; Wang, Tseng, Wilson, & Hu, 2009). Importantly, the impact of DCD extends beyond the motor domain, with sufferers presenting with an increased risk for developing psychological (Kristensen & Torgersen, 2008; Campbell, Missiuna, Vaillancourt, 2012; Missiuna et al., 2014) social (Mandich, Polatajko, & Rodger, 2003) and academic difficulties (Cantell, Smyth, & Ahonen, 2003; Dewey, Kaplan, Crawford, & Wilson, 2002). Additionally, the physical health of those affected appears to be reduced relative to healthy age-matched controls as indicated by an increased incidence of obesity and poorer aerobic fitness (Cairney & Veldhuizen, 2013; Joshi, Missiuna, Hanna, Hay, Faught, & Cairney, 2015).

While the underlying cause/s of DCD are the subject of considerable debate (see Wilson, Ruddock, Smits-Engelsman, Polatajko, & Blank, 2013 for a review), a number of research groups, including our own, have proposed that deficits in the ability to represent movement at an internal 'neural' level may contribute to some of the more critical motor skill difficulties documented in children with DCD (see Wilson et al., 2013; Adams, Lust, Wilson, & Steenbergen, 2014 for reviews)—this includes the ability to adapt reaching movements seamlessly and efficiently in-flight (*viz* online control; Hyde & Wilson, 2011a,b, 2013). Briefly, a series of recent studies have shown that children with DCD are slower and less accurate when correcting their reach movements mid-flight following unexpected target perturbation (Hyde & Wilson, 2011a,b; Hyde & Wilson, 2013; Wilmut, Wann, & Brown, 2006). Based on recent models of human reaching which propose that the efficiency of these types of corrective actions is predicated on one's ability to generate an accurate action representation for an impending movement and integrate it seamlessly with in-coming sensory signals (Izawa & Shadmehr, 2011; Shadmehr & Krakauer, 2008; Wolpert, Diedrichsen, & Flanagan, 2011), it has been proposed that the reduced capacity for online control to reaching shown by children with DCD may reflect, at least in part, difficulties monitoring and/or using internal action representations. Critically however, as detailed below, no available investigation of online control in DCD has simultaneously measured the same sample of children's capacity to engage the internal action representation. Accordingly, while theoretically justified, the purported role of the internal action representation in the inefficient online control previously documented in children with DCD has yet to be challenged experimentally, and thus remains speculative.

1.1. The role of action representation in online manual responses to unexpected environmental changes

So-called 'online control' of reaching is central to one's capacity to interact effectively with an unpredictable and fluid environment (Wilson and Hyde, 2013). One's capacity to engage this system appropriately is dependent on the proficiency with which the nervous system can generate an estimate of sensory in-flow for an impending motor command and, when actual sensory signals become available at movement onset, compare the two in real-time (Desmurget & Grafton, 2000; Izawa & Shadmehr, 2011; Shadmehr & Krakauer, 2008; Wolpert et al., 2011). Specifically, to circumvent delays associated with processing basic sensory feedback, the central nervous system uses a copy of the impending motor command (known as an *efference copy*) to predict the sensory consequences of an action should the movement unfold according to the motor command. Once movement commences, this is compared to actual visual, tactile and proprioceptive sensory in-flow in real-time. Should incongruence between the expected and actual sensory consequences of movement arise (e.g., following unexpected target perturbation), an error signal is generated with minimal delay. This error signal is then sent to, and integrated with, the un-folding motor command to facilitate limb re-direction (Desmurget & Grafton, 2000; Izawa & Shadmehr, 2011; Wolpert et al., 2011). Corrections of this type have been shown to occur within 100 ms, too quickly for cortico-sensory feedback to be accommodated (Castiello, Paulignan, & Jeannerod, 1991; Farnè et al., 2003; Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991). Indeed, were the latter the only feedback mechanism available, neural processing delays would render correction of movement in response to unexpected environmental changes slow and, subsequently, often inaccurate (Desmurget & Grafton, 2000). Accordingly, the action representation and its associated control systems (often collectively referred to as an internal modelling system; Wilson et al., 2013) are fundamental to the fluent and stable correction of action online. This computational account of human reaching is supported by a number of lines of empirical evidence including recent experimental work demonstrating that the ability of healthy young adults to generate and use internal representation of action is a significant predictor of the efficiency with which they are able to correct their reaching mid-flight (Hyde, Wilmut, Fuelscher, & Williams, 2013).

1.2. Impaired online control of reaching in children with DCD: Insights from double-step reaching performance

The ability to fluently correct movement in-flight following unexpected target perturbation is central to one's capacity to act and respond in a highly unpredictable environment. Interestingly, while typical maturation of neuro-motor systems generally sees individuals' do so with increasing efficiency, these systems appear to be well developed by late childhood. Indeed, in typically developing children, evidence from double-step reaching task (DSRT) performance indicates that online correction of reaching follows a non-linear development through the primary school years, where subsequent incremental improvements are observed into adulthood. The DSRT, a well validated measure of online control of reaching informed by computational models of motor control (Castiello, Bennet, Bonfiglioli, Lim, & Peppard, 1999; Desmurget & Grafton, 2000; Gréa et al., 2002; Farnè et al., 2003; Sarlegna, Gauthier, Bourdin, Vercher, & Blouin, 2006), requires participants to reach and touch a target in peripersonal space that randomly changes location at movement onset for a small percentage of trials (i.e., jump trials) but remains stationary for the remainder of trials. A key performance indictor of one's capacity to engage in