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Dissecting online control in Developmental Coordination Disorder: A kinematic analysis of double-step reaching

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ABSTRACT

In a recent study, children with movement clumsiness (or Developmental Coordination Disorder—DCD) were shown to have difficulties making rapid online corrections when reaching, demonstrated by slower and less accurate movements to double-step targets (Hyde & Wilson, 2011). These results suggest that children with DCD have difficulty using predictive estimates of limb position when making rapid adjustments to movement, in-flight. However, chronometric data alone does not provide strong evidence for this hypothesis: it remains unclear whether early (and rapid) control parameters or post-correction stages of the movement trajectory are affected. Thus, the overarching aim of this study was to conduct a kinematic analysis of double-step reaching in order to isolate the different control parameters that might explain the slower and less accurate double-step reaching performance of children with DCD. Participants were a new sample of 13 children with DCD aged between 8–12 years and 13 age-matched controls. Children were required to reach and touch one of three possible targets presented at the coordinates −20°, 0° and 20° on a 17 in. LCD touch-screen. For most trials (80%) the target remained stationary for the duration of movement (non-jump trials), while for the remainder (20%), the target jumped randomly to one of two peripheral locations at movement onset (jump trials). Consistent with earlier work, children with DCD were slower to initiate reaching compared to controls and showed longer MT and more errors on jump trials. Kinematic data showed that while the two groups did not differ on time to peak velocity or acceleration, children with DCD were slower to correct reach trajectory on jump trials. No group differences were observed on late kinematic markers, e.g., post-correction time. The pattern of results support and extend earlier work showing deficits in ROC in DCD. From a computational perspective, delayed corrections to the reach trajectory suggests some difficulty integrating information about the target perturbation with a predictive (or forward) estimate of limb position relative to the initial target. These conclusions are discussed, along with directions for future research.

1. Introduction

The development of online motor control is thought to be crucial to the smooth and flexible control of action. In typically developing children, the nature of online control alters with the changing constraints of maturation and experience (Hyde & Wilson, 2011). Important among these changes is the capacity of the nervous system to make rapid changes in trajectory, in-flight, should movement be perturbed in some way or should something in the environment change. This form of rapid online control (ROC) is thought to be viable to the extent that the nervous system can predict the future location of the moving limb using a *forward internal model* (Desmurget & Grafton, 2003; Jeannerod, 2006; Wolpert, 1997).[1] This forward estimate of limb position provides a means of rapidly integrating efferent and afferent signals – sometimes referred to as an *internal feedback loop* – thereby speeding responses to any changes in the environment during the course of movement (Desmurget & Grafton, 2003). This type of control is illustrated clearly in cases where the goal of a task changes as the movement is being performed; e.g., reaching for a pen as it rolls away. Experimentally, this scenario can be simulated using a double-step perturbation procedure whereby the movement target shifts to another location at movement onset. From a computational perspective, the initial state of the limb is defined by visual and proprioceptive coordinates and the target by visual coordinates. As the movement is generated, a corollary discharge encodes a copy of the movement commands (via efference copy) which is used to

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[1] Internal models are conceived as being of two types: So-called *forward models* use a copy of the motor command (viz efference copy) to predict the future state of the moving limb(s). By comparison, the *inverse model* (or controller) generates the motor commands necessary to achieve a desired goal state. In computational terms, forward estimates are compared with actual sensory feedback as a way of training both motor prediction and the accuracy of inverse modeling.

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predict how the limb will move in response to the motor command; the predicted consequences are specified in an (internal) forward model (Shadmehr, Smith, & Krakauer, 2010). In neural terms, a functional loop between parietal cortex and the cerebellum is thought to monitor these forward estimates of limb position and correct ongoing motor commands online should the action deviate from expectations (Blakemore & Sirigu, 2003; Shadmehr & Krakauer, 2008).

In the case of visual perturbations, a forward model of limb position relative to the target is generated and compared with sensory afference which signals actual target location. Any mismatch is thought to generate an error signal that is used to update limb trajectory. More precisely, computational modeling suggests that rapid online corrections are organized by ''superimposing'' a dynamic error signal onto the outgoing feedforward motor command (Gritsenko, Yakovenko, & Kalaska, 2009). These online adjustments are tuned to the dynamic inertial properties of the moving limb and circumvent the processing delays associated with sensorimotor feedback loops (Flanagan, Vetter, Johansson, & Wolpert, 2003). Indeed, this form of predictive control is vitally important because the position of the moving limb has changed appreciably by the time sensory feedback alone can be used to alter motor commands. Importantly, a number of studies show that smooth online corrections are disrupted when the involvement of posterior parietal cortex (PPC) is disturbed by lesion (Gréa et al., 2002) or through TMS (Desmurget et al., 1999). Parietal regions are thought to be crucial in updating forward estimates of limb position, particularly when vision of the moving hand itself is not available. In a similar vein, rapid online adjustments are also necessary during the early stages of movement or when the moving limb itself undergoes some external perturbation which forces it, momentary, off course. Ascending cerebellar pathways are thought to monitor somatic perturbations of this type, detecting with minimal time lag the discrepancy between the predicted dynamic properties of the limb in response to the motor command and its actual behavior. Indeed, the cerebellum has been referred to as a ''somatic event detector'' to highlight its vital role in motor control (Miall & King, 2008).

In general, healthy young adults have little difficulty adjusting their movement in-flight in response to visual and mechanical perturbation, suggesting seamless use of predictive control. Indeed, the development of predictive control is regarded as one of the most significant achievements in motor control during childhood and over the course of adolescence where biomechanical constraints are changing rapidly as a result of maturation (Choudhury, Charman, Bird, & Blakemore, 2006). The significance of prediction in development is highlighted by the fact that children with movement difficulties (or Developmental Coordination Disorder—DCD) show poor coupling of hand and eye movements during target-directed reaching (Wilmut, Wann, & Brown, 2006) and impaired online adjustments to visual perturbation (Hyde & Wilson, 2011). Briefly, DCD is characterized by a deficit in fundamental motor skill in the absence of neurological or physical impairment, a feature which distinguishes it from common developmental disorders of movement such as Cerebral Palsy (Pearsall-Jones, Piek & Levy, 2010). Until recently, the evidence on the nature of ROC in DCD was mixed.

Work by Wilmut et al. (2006) demonstrated that children with DCD were equally as efficient when reaching to a single target but were slower and less accurate when reaching sequentially from one target to another. The DCD group spent more time foveating targets presented sequentially before initiating hand movements, which led to an increase in error. This pattern suggested difficulties in feedforward control, but did not examine ROC directly in response to target perturbation. More recently, Plumb and Colleagues (2008) suggested that ROC in reaching was preserved in DCD. They found that the effect of target perturbation on movement time was similar for both DCD and non-DCD groups. However, Plumb also acknowledged that there were methodological limitations in this study; group comparisons were compromised by the fact that DCD and control groups performed different versions of the same task (i.e., children with DCD were seated and used a large pointing stylus, while control children stood and used a smaller stylus).

To address these conflicting accounts of online control in DCD, we recently examined double-step reaching while controlling all task parameters (Hyde & Wilson, 2011). A chronometric analysis showed that children with DCD were more disadvantaged by target jumps, manifest as slower and more error-ridden performance on jump trials compared with typically developing children. We explained this pattern of performance from a neuro-computational perspective. Here ROC is thought to be implemented by integrating predictive (or feedforward) and feedback based mechanisms efficiently. This argument accounts for recent evidence showing that feedback based mechanisms are used continuously throughout the movement cycle (Saunders & Knill, 2003, 2005), rather than simply towards the end of movement vis-à-vis the old dual-component model of reaching (for a review see Elliott, Helsen, & Chua, 2001). We argued that slower and less accurate double-step reaching in DCD may reflect a difficulty using predictive (or forward) models to rapidly update movement plans; this has been expressed previously under the *internal modeling deficit* (IMD) hypothesis (Williams, Thomas, Maruff, Butson, & Wilson, 2006; Williams, Thomas, Maruff, & Wilson, 2008; Wilson et al., 2004).

A major limitation of chronometric analysis alone is that it does not allow one to dissect the subtle transitions in motor control that occur at different time points in the movement cycle—i.e., the question of whether control parameters are affected early or late in the movement trajectory. For jump trials, due to time delays associated with processing non-visual and visual sensory feedback, reaching is thought to rely heavily on predictive control during the early phase of movement, up to the point when early kinematic markers are expressed (i.e. time to peak acceleration and velocity: tPA and tPV). These early markers together with the first detectable change in movement trajectory are thought to reflect the integration of real-time sensory feedback with the ongoing motor command. More precisely, to circumvent processing delays, sensory signals are thought to be compared with forward estimates of limb position (relative to the initial target) allowing discrepancies to be detected rapidly in real-time, and corrective signals generated to adjust the movement trajectory. Though online control is exerted over the entire movement cycle, demands on this system are maximal during the early phase of double-step reaching when the larger scale changes in trajectory are implemented in response to target perturbation, and reduced during the later (post-correction) phase of reaching which serves mainly to brake the limb as it captures the target at its new, fixed location (see Wolpert & Flanagan, 2001).

Other work using the double-step task has revealed distinct patterns of deficit based on early kinematic markers. In patients with optic ataxia, for instance, corrections to the reach trajectory after target perturbation occur significantly later than in healthy adults suggesting difficulties using internal feedback control to update the motor command (Gréa et al., 2002). Desmurget and Grafton argue that the posterior parietal cortex and its reciprocal connections to the cerebellum may support these early corrections. For visually-guided reaching, predictive models for limb position are thought to be generated and/or monitored at the level of PPC (see Desmurget & Sirigu, 2009). These forward estimates enable the system to respond rapidly if self-to-target relations change during the course of a movement, as when targets shift their location. The PPC is one site where comparison between the expected location of the limb (with respect to the target) and that indicated