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Coupling of online control and inhibitory systems in children with atypical motor development: A growth curve modelling study

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ABSTRACT

Introduction: Previous research indicates that children with Developmental Coordination Disorder (DCD) show deficits performing online corrections, an issue exacerbated by adding inhibitory constraints; however, cross-sectional data suggests that these deficits may reduce with age. Using a longitudinal design, the aim of the study presented here was to model the coupling that occurs between inhibitory systems and (predictive) online control in typically developing children (TDC) and in those with Developmental Coordination Disorder (DCD) over an extended period of time, using a framework of *interactive specialization*. We predicted that TDC would show a non-linear growth pattern, consistent with re-organisation in the coupling during the middle childhood period, while DCD would display a developmental lag.
Method: A group of 196 children (111 girls and 85 boys) aged between 6 and 12 years participated in the study. Children were classified as DCD according to research criteria. Using a cohort sequential design, both TDC and DCD groups were divided into age cohorts. Predictive (online) control was defined operationally by performance on a Double-Jump Reaching Task (DJRT), which was assessed at 6-month intervals over two years (5 time points in total). Inhibitory control was examined using an anti-jump condition of the DJRT paradigm whereby children were instructed to touch a target location in the hemispace opposite a cued location.
Results: For the TDC group, model comparison using growth curve analysis revealed that a quadratic trend was the most appropriate fit with evidence of rapid improvement in anti-reach performance up until middle childhood (around 8–9 years of age), followed by a more gradual rate of improvement into late childhood and early adolescence. This pattern was evident on both chronometric and kinematic measures. In contrast, for children with DCD, a linear function provided the best to fit on the key metrics, with a slower rate of improvement than controls.
Conclusion: We conclude that children with DCD require a more extended period of development to effectively couple online motor control and executive systems when completing anti-reach movements, whereas TDC show rapid improvement in early and middle childhood. These group differences in growth curves are likely to reflect a maturational lag in the development of motor-cognitive networks in children with DCD.

1. Introduction

Everyday tasks such as selecting a book from a shelf, dressing, or simply walking through a busy room are acquired easily by most children but certainly not all. Typically developing children (TDC) acquire motor skills quite seamlessly over the course of development, mainly by a process of visual modelling but also through verbal instruction and hands-on manipulation by a skilled adult or caregiver (Wilson, Ruddock, Smits-Engelsman, Polatajko, & Blank, 2013). Changes in performance are shown by greater synergy between joints and muscle activations, and enhanced perceptual-motor coupling, measured on kinematic and kinetic markers. In general, there is a gradual transition from initial freezing of degrees

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of freedom to a more unconstrained exploration of movement space (Asmussen, Przysucha, & Dounskaia, 2014). Emerging through this transition, the child's sense of body position in space (or body schema) and ability to scale movements in relation to targets and obstacles is refined. Indeed, impairments in multimodal integration (underpinning body schema) have been linked to atypical development of movement skill (aka DCD, Wilson et al., 2013). In typical development, body sense and motor prediction (aka forward internal modelling) might be considered two sides of the same coin in that the former is a necessary but perhaps not sufficient condition for the latter (Shadmehr, Smith, & Krakauer, 2010). With the development of motor prediction there emerges an ability to adapt movements to complexity or flux in the environment.

The capacity to adapt to a dynamic environment and quickly update movement plans in the face of sudden, or unexpected consequences, occurs via online control (Shadmehr et al., 2010). Neuro-computational models of human reaching posit that online motor control is critical for fluent and efficient movement. Underpinning online control are fast *internal feedback loops* which utilise predictive (or forward) estimates of limb position based on the expected sensory consequences of self-motion (Desmurget & Grafton, 2003). Once (actual) visual and proprioceptive signals become available to the nervous system at movement onset, these signals are compared with those predicted by a 'forward' model in real-time. Where discrepancies arise, error signals are generated and relayed back to the controller to be integrated with the unfolding motor command, allowing for rapid adjustments to limb dynamics should they be necessary (Desmurget & Grafton, 2000). Impressively, these corrections can occur within 100 ms (Castiello, Paulignan, & Jeannerod, 1991) and support the stability of the motor system with minimal processing delay.

While the nature of rapid online control during reaching and its neurocognitive bases have been well studied in adult populations (e.g. Gaveau et al., 2014; Pisella et al., 2000), only recently has it been addressed in children. While this work is in its formative stage, it is becoming clear that mechanisms linked to fast corrective processes undergo considerable changes between the ages of 6 and 12 years (Bard, Hay, & Fleury, 1990; Van Braeckel, Butcher, Geuze, Stremmelaar, & Bouma, 2007; Wilson & Hyde, 2013). By 7 years of age, children are able to generate fast and accurate ballistic movements but are slower to integrate online feedback than older children, resulting in some inefficiency for more complex movements. At around 8–9 years of age, children are able to make 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 a steep improvement in their capacity to implement corrective actions. By 9–12 years, the nervous system is able to integrate predictive and sensory systems smoothly, resulting in an adult-like ability to correct simple movements online (e.g. see Wilson & Hyde, 2013) while movement skills continue to develop into adolescence.

Research on the development of brain morphology provides important insights into the timescales over which perceptual-motor systems unfold. At a neural level, studies in healthy adults have implicated the posterior parietal cortices (PPC) in corrective hand movement during the course of goal-directed action (Gréa et al., 2002; Reichenbach, Bresciani, Peer, Bulthoff, & Thielscher, 2011; Reichenbach, Thielscher, Peer, Bülthoff, & Bresciani, 2014). In typically developing children, improvement in online control appears to coincide with patterns of neural maturation that include synaptogenesis, myelination, and formation of white matter networks (WMNs) (for reviews see Casey, Tottenham, Liston, & Durston, 2005; Chen, Liu, Gross, & Beaulieu, 2013; Collin & Van Den Heuvel, 2013; Spreng, Sepulcre, Turner, Stevens, & Schacter, 2013; Sripada, Kessler, & Angstadt, 2014; Vértes & Bullmore, 2014). Of the various cortical and sub-cortical networks, peak periods of myelination and synaptic pruning are observed to occur last in frontal and parietal zones, shaped by both external (i.e., experiential learning) and internal/maturational growth factors (Casey, Getz, & Galvan, 2008). Similarly, development of dorsal attention and fronto-parietal WMNs is maximal during older childhood (10–13 years of age) (Sripada et al., 2014). This same fronto-parietal circuitry is critical to the control of goal-directed and target-directed motion (Gréa et al., 2002; Reichenbach, Thielscher, Peer, Bülthoff, & Bresciani, 2014). The dorsal visuomotor network comprises the posterior parietal cortex (PPC) and its reciprocal connections to frontal and cerebellar cortices (Shadmehr et al., 2010). PPC is a prime site for processing forward internal models; these neurons are capable of re-mapping their receptive fields in anticipation of the sensory effects of an impending eye movement or goal-directed reach, for example.

Traditional accounts of brain-behaviour (e.g., modular models in clinical neuropsychology) posit a number of separable brain systems that support a narrow range of behaviours, each unfolding under specific maturational timelines. In the case of motor control, for instance, this implies that specific processes/behaviours develop according to localised neural regions. However, neural networks are far more dynamic in their interaction than this model would suggest. A more parsimonious account is that separate systems (with individual growth trajectories) can impact the development of each system through a process of *interactive specialization* (Johnson, 2005, 2011, 2013).

Recent behavioural and neurophysiological evidence indicates that the emergence of new or more refined behaviour is often the result of several brain regions/networks whose growth trajectories may differ, but yet support each other (Johnson, 2011). This theory has been applied quite persuasively in describing the development of behaviours as varied as linguistic processing, social cognition, and face perception (Johnson, 2011). We argue that co-development of online motor control and executive function (EF) is another important case in point.

In typically developing children (TDC), we have shown that the expression of rapid online control – supported by dorsal stream and parieto-cerebellar networks – appears to be constrained by concurrent demands on frontal executive systems (i.e. Ruddock et al., 2014). For relatively simple movements to visual perturbation (without an executive load), the capacity to enlist online control improves rapidly between 6 and 9 years of age, followed by steady but more modest growth into older childhood (Wilson & Hyde, 2013). Importantly, online control is based on predictive estimates of limb position. As such, predictive control for simple movements is a landmark achievement of development over early and middle childhood, an ability subserved by posterior visuomotor networks including posterior parietal cortex (Shadmehr et al., 2010). In contrast, the pattern of development differs when online corrections must be implemented under an executive (inhibitory) load. For anti-reach movements, the performance of mid-age children deteriorates relative to that of older children aged 10–12 years (Ruddock et al., 2014) and was more similar to the performance of younger children (aged 6–7 years).

The importance of EF to motor control is further supported by evidence that children with atypical motor development (i.e. Developmental Coordination Disorder; DCD) show deficits on tasks that involve the joint action of frontal executive and (dorsal) visuomotor systems. For example, in the case of the online control of reaching, recent research has shown that older children with DCD are able to reach to stationary targets as efficiently as age-matched peers, but they take longer to correct arm reaching following unexpected target displacement mid-movement (Hyde & Wilson, 2011a). From a neuro-computational perspective, corrections of this type are predicated by the integrity of predictive