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Neural underpinnings of impaired predictive motor timing in children with Developmental Coordination Disorder

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ABSTRACT

A dysfunction in predictive motor timing is put forward to underlie DCD-related motor problems. Predictive timing allows for the pre-selection of motor programmes (except 'program' in computers) in order to decrease processing load and facilitate reactions. Using functional magnetic resonance imaging (fMRI), this study investigated the neural correlates of motor timing in DCD ($n = 17$) and typically developing children ($n = 17$). The task involved motor responses to sequences of visual stimuli with predictive or unpredictive interstimulus intervals (ISIs). DCD children responded with a smaller reaction time (RT) advantage to predictive ISIs compared to typically developing children. Typically developing children exhibited higher activation in the right dorsolateral prefrontal cortex (DLPFC) and right inferior frontal gyrus (IFG) for responses at unpredictive as opposed to predictive ISIs, whereas activations in DCD children were non-differentiable. Moreover, DCD children showed less activation than typically developing children in the right DLPFC, the left posterior cerebellum (crus I) and the right temporo-parietal junction (TPJ) for this contrast. Notably, activation in the right temporo-parietal junction (TPJ) positively correlated with RT as an indicator of processing load in both groups. These data indicate that motor performance in DCD children requires extra processing demands due to impaired predictive encoding.

1. Introduction

Developmental Coordination Disorder (DCD) is a condition that is characterized by impaired performance in daily activities that require motor coordination (DSM-IV-TR, American Psychiatric Association, 2000). A recent prevalence study reports that almost 2% of all 7-year-old children meet the diagnostic criteria of this condition (Lingam, Hunt, Golding, Jongmans, & Emond, 2009). The motor performance of children diagnosed with DCD is often described as clumsy in activities like writing, dancing and sports. Their clinical picture shows clear interindividual differences in terms of the severity and diversity of the experienced motor problems, as well as in the co-occurrence of other developmental disorders including attention deficit hyperactivity disorder (ADHD), autism spectrum disorders, or dyslexia (Visser, 2003). DCD is not associated with a specific pathogenetic cause and is therefore considered to be a clinical label that refers to children with an impaired

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motor development (Wilson, 2005). In the present study, we focus on the ability of effective motor response timing as one of the underlying difficulties of voluntary motor behaviour in children with DCD (Wilson, Ruddock, Smits-Engelsman, Polatajko, & Blank, 2013).

When motor responses are elicited by an incoming visual stimulus, different sequential processes occur such as stimulus perception, motor programme (except 'program' in computers) selection, motor preparation, and correctly timed movement initiation (Lloyd, Shore, Spence, & Calvert, 2003). Efficient motor responding, which appears problematic in DCD, is enabled by neural systems that attempt to decrease the processing load through predictive coding (Kilner, Friston, & Frith, 2007; Summerfield et al., 2006). This Bayesian predictive coding principle is increasingly supported by recent experimental and clinical findings, and can be illustrated by means of the following example from Körding and Wolpert (2004). When acquiring a motor skill, for instance playing tennis, the perceptual system first provides an imperfect prediction of the ball's velocity in order to be able to hit the ball at the right time. Over the course of practice, a more accurate probability distribution of velocities is set which reduces the error in this estimate. Because the perceptual input can be compared only against the expectations or prior distribution rather than being analyzed from scratch, this predictive model entails a substantial reduction in processing load. However, in children with DCD, the level of motor skill proficiency often endures at the initial practice level. In the example involving ball skills, DCD children continue to fail at effectively catching and/or returning the ball (Astill & Utley, 2006; Utley, Steenbergen, & Astill, 2007; Van Waelvelde, De Weerdt, De Cock, Smits-Engelsman, & Peersman, 2004). DCD children do not seem to learn to assimilate the prior distribution of perceptual timing feedback as compared to their typically developing peers. Consequently, processing loads may not reduce despite extensive practice. Moreover, impaired predictive motor responding in DCD not only hampers ball skills, but also accounts in part for deficits in fine motor skills and postural control (Bo, Bastian, Kagerer, Contreras-Vidal, & Clark, 2008; Gheysen, Van Waelvelde, & Fias, 2011; Johnston, Burns, Brauer, & Richardson, 2002; Van Waelvelde et al., 2006). Previous studies have assessed predictive motor timing using synchronization paradigms where children were asked to execute finger movements to a rhythmic auditory or visual pacing stimulus (de Castelnau, Albaret, Chaix, & Zanone, 2007; de Castelnau, Albaret, Chaix, & Zanone, 2008; Lundyekman, Ivry, Keele, & Woollacott, 1991; Volman & Geuze, 1998; Whitall et al., 2008; Williams, Woollacott, & Ivry, 1992). The key finding of these studies is that children with DCD show increased temporal variability compared with typically developing children (Whitall et al., 2008).

However, neuroimaging research in DCD remains scarce. To date, only four fMRI studies have been published, which focused on visuomotor tracking (Kashiwagi, Iwaki, Narumi, Tamai, & Suzuki, 2009), executive functions (Querne et al., 2008), and trail-tracing (Zwicker, Missiuna, Harris, & Boyd, 2010; Zwicker, Missiuna, Harris, & Boyd, 2011). Results from these studies suggest that children with DCD exhibit differences in neural network activity and connectivity as compared with typically developing children. Kashiwagi et al. (2009) reported that children with DCD demonstrated lower activation in the left posterior parietal cortex and postcentral gyrus, whereas Querne et al. (2008) showed both increased and decreased functional connectivity in DCD children's executive network including the middle frontal cortex (MFC), anterior cingulate cortex (ACC), inferior parietal cortex (IPC), and striatal components. Zwicker et al. (2010, 2011) on the other hand, described under-activation in the cerebellar-parietal and cerebellar-prefrontal networks. To the best of our knowledge, no paediatric imaging studies have been performed on predictive motor timing so far.

The present study attempts to fill this gap in three ways. The first aim is to delineate the neural correlates of predictive motor timing abilities in typically developing children. To this end, we used a visuomotor reaction time (RT) task. In this task, the degree of temporal predictability of the visual stimuli was manipulated by alternating blocks of predictive (regular) and unpredictive (irregular) interstimulus intervals (ISIs). Stimuli with predictive ISIs enable the encoding of temporal information. The temporal error is expected to be small in this condition, which leads to efficient motor reactions (RT advantage). At fully predictable ISIs, the structure of the prior stimulus timing is reinforced. In case of stimuli with unpredictive ISIs, no precise temporal information can be encoded, hence leading to higher prediction errors and less efficient motor responding (no RT advantage). As a result, the prior stimulus timing will be continuously updated as an attempt to better align further temporal predictions.

In this visuomotor RT task, children were asked to make a fast response to a stimulus appearing at an expected time (rather than explicit timing judgements). Timing mechanisms are thus engaged automatically (implicitly) rather than deliberately (explicitly) (Coull & Nobre, 2008). Paradigms that investigate explicit timing demand an estimate of a certain stimulus duration (Coull, Vidal, Nazarian, & Macar, 2004). Neural systems associated with explicit timing involve the dorsal striatum of the basal ganglia (BG) with task-dependent co-activation of the supplementary motor area (SMA), cerebellum, and prefrontal cortex (for a review, see Coull, Cheng, & Meck, 2011).

In adults, neural correlates of predictive motor timing have been assessed using similar visuomotor RT tasks (Dreher, Koechlin, Ali, & Grafman, 2002; Jakobs et al., 2009; Sakai et al., 2000). When contrasting unpredictive and predictive visual pacing conditions (unpredictive > predictive), these studies have reported an increased activation in the dorsolateral prefrontal cortex (DLPFC), the right inferior frontal gyrus (IFG), the posterior cerebellar lobe, and the temporo-parietal junction (TPJ). The relative activation increase in these regions has been related to additional processing and/or updating of priors at unpredictive stimulus pacing. Conversely, well-encoded predictive intervals require less processing as the prior stimulus structure only needs reinforcement. In a previous study, we demonstrated that children's predictive motor timing abilities progress through middle and late childhood (Debrabant, Gheysen, Vingerhoets, & Van Waelvelde, 2012). Therefore, similar activations were expected in the DLPFC, right IFG, posterior cerebellar lobe, and right TPJ for responding to unpredictive versus predictive visual pacing.