



Review

Compromised motor control in children with DCD: A deficit in the internal model?—A systematic review

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ABSTRACT

A viable hypothesis to explain the compromised motor ability of children with Developmental Coordination Disorder (DCD) suggests a fundamental deficit in their ability to utilize internal models for motor control. Dysfunction in this mode of control is thought to compromise their motor learning capabilities. The aim of this systematic review is to examine the available evidence for the *internal modeling deficit* (IMD) hypothesis. A systematic review using five databases identified 48 relevant articles. These studies were categorized according to the effector system involved in the evaluation of motor control and were evaluated for methodological quality. In most papers, DSM-IV-TR criteria for the classification of DCD were not completely fulfilled and possible attentional problems not accounted for. Results showed compromised control of overt and covert eye movements, dynamic postural control, manual control for tasks that vary in complexity, and for motor imagery of manual and whole-body postures. Importantly, this review shows support for general hypothesis that deficits of predictive control manifest in DCD across effector systems.

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1. Introduction

Children with Developmental Coordination Disorder (DCD) show an impaired ability to learn age-appropriate motor skills in the absence of any general medical condition, pervasive developmental disorder, or low IQ (American Psychiatric Association, 2000).¹ A prevalence rate of about 6% in children aged 5–6 years (Mandich and Polatajko, 2003) attests to the significance of the disorder. Indeed, longitudinal data show that children with motor deficits also commonly experience social problems, emotional difficulties and learning problems at school which can persist into adolescence (Hellgren et al., 1993; Rasmussen and Gillberg, 2000).

The etiology of DCD is still largely unknown. DCD was first described as a form of 'minimal brain dysfunction' (MBD). This term was used to describe a collection of symptoms reflecting learning, attention, and motor coordination deficits (Clements and Peters, 1962). MBD was later replaced by complex 'minimal neurological dysfunction' (MND), described as 'a distinct form of perinatally acquired brain dysfunction which is likely associated with a structural deficit of the brain' (Hadders-Algra, 2002, p. 568); pre-term birth was believed to be one factor that commonly contributes to the expression of MND (Davis et al., 2007; Goyen and Lui, 2009; Holsti et al., 2002; Missluna et al., 2008). Over the past 15–20 years, the DSM has formalized the diagnostic categorization of poor motor skill in children as Developmental Coordination Disorder (DSM-IV; American Psychiatric Association, 1994). This has undergone minor modification since this time, right up to the current version, DSM-V (American Psychiatric Association, 2013).

Several hypotheses about the etiology of DCD have been postulated in earlier research. One suggests that DCD is the result of diffuse brain dysfunction, rather than abnormality of specific areas of the brain. Gilger and Kaplan (2001) have proposed that symptoms of DCD, reading disability and ADHD all reflect the same underlying brain deficit labeled as 'atypical brain development' (ABD) (Gilger and Kaplan, 2001; Kaplan et al., 1998). According to Kaplan et al. (1998), ABD may express itself in a variety of behavioral symptoms and deficits depending on the timing, location, and severity of the disruption in brain growth and development. However, testing of and evidence in support of this hypothesis has been difficult to garner (Wilson et al., 2013).

Other researchers attempt to find the cause of DCD by isolating the motor control systems that might be compromised in DCD and, thus, explain their skill learning difficulties (Hill and Wing, 1999). Earlier work pointed to a variety of sensori-perceptual deficits in DCD, particularly in the visual modality. This was summarized in the meta-analysis of Wilson and McKenzie (1998). In other work

since then, there has been some converging evidence of motor programming and timing deficits in DCD with cerebellar involvement likely. Cerebellar involvement has been proposed in several studies: (i) deficits in grip force control and coordination at early and late stages of movement (Hill and Wing, 1999); (ii) difficulty in the temporal coordination of eye and hand movements (Hill and Wing, 1999); and (iii) less accurate and more variable performance of cyclical movements (Bo et al., 2008; Sugden and Chambers, 2006).

A general reduction in the ability to automate motor skills is also consistent with impaired cerebellar function and is shown by over-reliance on external forms of feedback when controlling movements (e.g., Nicolson et al., 2001). Nicolson and colleagues formulated this as the 'automatization deficit hypothesis' in relation to dyslexia and argued that any deficit in this automatization process will appear if conscious monitoring of the motor skill is difficult, either by stress or by some other task requiring attentional resources.

1.1. Internal modeling in DCD

Another prominent hypothesis on the basis of motor control deficits in DCD concerns the internal modeling of movements. According to the *internal modeling deficit* (IMD) hypothesis, children with DCD have a reduced ability to utilize predictive motor control (Wilson and Butson, 2007; Wilson et al., 2013). Internal models provide stability to the motor system by predicting the outcome of movements before slow, sensori-motor feedback becomes available (Wolpert, 1997), providing a means of rapid online correction (Hyde and Wilson, 2011a,b). Dysfunction to this mode of control would severely impact the motor learning capabilities of a child, consistent with the profile of performance we see in children with DCD. These children are characterized by slow, effortful, and inaccurate movements, and are regarded as being overly dependent on visual feedback (Wilson et al., 2013). Delay or disruption to the parieto-cerebellar axis may explain this pattern of performance. This network is involved specifically in the generation of forward (or predictive) models and the process of comparing forward estimates of limb position with actual sensory feedback (Desmurget and Grafton, 2003). Errors of prediction are detected rapidly, with error signals (sent by both the cerebellum and posterior parietal cortex) used to modulate output signals as well as modifying internal models for action as part of the motor learning process (Kawato, 1999). Wilson and Butson (2007) noted that the response pattern of children with DCD showed marked similarities to that seen in patients with a unilateral lesion in the parietal lobe when performing a motor imagery task.

In a recent review on DCD the main motor control and cognitive deficits associated with DCD were described (Wilson et al., 2013). Among the categories of deficit was internal modeling (i.e., predictive control), together with rhythmic coordination and timing, executive function, dynamic control of posture and gait, and interceptive action (catching and manual interception). The IMD

¹ In the recently released DSM-V (American Psychiatric Association, 2013), a pervasive developmental disorder is no longer an exclusion criterion for DCD. We refer to the DSM-IV-TR criteria because all of the included studies in this current review utilize DSM-IV-TR (American Psychiatric Association, 2000).

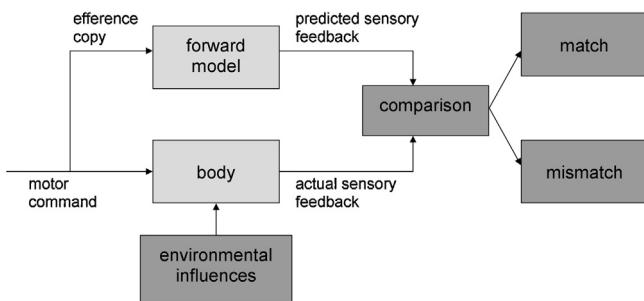


Fig. 1. Forward model of motor control (adapted from Bubic et al., 2010).

hypothesis is supported by a number of studies showing deficits of predictive control in manual action, eye movements, and posture and gait. While comprehensive, the review of Wilson and colleagues did not include an evaluation of research quality for each study in the sample. As well, the body of work has continued to grow significantly since mid-2011. Therefore, the present paper presents an up to date systematic review and a critical evaluation of the available empirical evidence for a deficit in the internal modeling of movements in DCD.

The process of forward internal modeling is depicted schematically in Fig. 1 and shows the importance of prediction in the control of action (Grush, 2004). According to Kawato (1999), internal models are mechanisms that simulate the input or output functions of the motor apparatus. When a motor plan is generated, a motor command is generated by the motor cortex and relayed to the body via descending corticospinal tracts (Tresilian, 2012). At the same time, an efference copy of this motor command is generated as a corollary discharge and relayed to parietal-cerebellar cortices (Wolpert, 1997). The predicted and actual sensory feedback is then compared, with somatic events processed at the level of the cerebellum and visuospatial integration in parietal association cortex. When mismatch occurs between predictive estimates of limb position and position indicated by sensory feedback, error signals are generated in order to correct/modulate the unfolding motor output commands in real time. Online correction is needed when the initial movement plan is not specified accurately either because the initial model was incorrect or because of environmental changes (or perturbations). Again, the ability to make these (rapid) online corrections is thought to be related to how well the nervous system can predict the future location of moving limbs using a forward internal model (Desmurget and Grafton, 2003; Jeannerod, 2006; Shadmehr et al., 2010; Wolpert, 1997). A functional loop between parietal cortex and the cerebellum is thought to monitor forward estimates of limb position, the basis for online correction (Blakemore and Sirigu, 2003; Shadmehr et al., 2010). Importantly, error signals also act as a training signal for refining the accuracy of predictive models; this iterative process is thought to be fundamental for motor learning (Davidson and Wolpert, 2005). Internal models of movements are constructed in order to provide expectations of the sensory feedback and to enhance the processing of sensory information. In the case of motor imagery, these models can also be run off-line. Motor imagery can, thus, also help to evaluate motor representations and to train predictive control (Grush, 2004).

The development of internal models tends to be specific to the effector system involved (Kawato, 1999; Wolpert and Miall, 1996) but is flexible enough for some degree of generalization across related types of movement. For instance, a forward model system has been proposed for oculomotor control, located in brain stem circuits, and others for target-directed, manual action. Indeed, separable but overlapping systems support the forward modeling of eye movements, reaching movements, grip force control, and dynamic postural control (Davidson and Wolpert, 2005). At the same time, multiple internal models can be learned and combined

adaptively with repeated practice (Wolpert and Kawato, 1998; Wolpert et al., 1998; Ahmed and Wolpert, 2009). In short, internal models can be regarded as motor primitives—the building blocks used to construct motor behaviors and motor learning (Wolpert and Kawato, 1998). Whether putative deficits to the internal modeling system (that is predictive control—Wilson et al., 2013) are generalized to different effector systems or are more confined to specific systems (or forms of body mapping) is an important issue of debate. The results of the study of Ahmed and Wolpert (2009) support the existence of separate mappings for posture and movement. These two mappings encode similar dynamics but can be adapted independently. The present systematic review will help to clarify whether deficits in the internal modeling system in DCD are generalized or more confined to specific systems.

The IMD hypothesis has now been tested using a converging set of paradigms including covert orienting of visuospatial attention (e.g., Tsai et al., 2009b; Wilmut et al., 2007; Wilson and Maruff, 1999; Wilson et al., 1997), imagined or simulated pointing (e.g., Lewis et al., 2008; Maruff et al., 1999), mental rotation of limb-versus object-based stimuli (e.g., Williams et al., 2006, 2008, 2012), predictive control of eye movements (e.g., Katschmarsky et al., 2001; Langaas et al., 1998), grip force and anticipatory postural adjustments (e.g., Jover et al., 2010; Jucaite et al., 2003; Pereira et al., 2001), and studies on the rapid online control of reaching movements (e.g., Hyde and Wilson, 2011a,b). The results of these studies converge on the argument that children with DCD have difficulty representing a predictive model of a prospective action, whether based on visuospatial or somatic information. Critically, each paradigm used in these studies requires that the performer uses forward estimates of limb/body dynamics or perceptual experience in order to maintain movement control, the main distinctions being the effector system involved and the type of information that is modeled—for example, oculomotor plans in the case of visuospatial attention; endpoint coordinates that specify limb trajectory in the case of manual response, and manual force in the case of grasping and lifting (Geuze, 2007).

Taken together, there is good support for the hypothesis that predictive control (forward internal modeling) is impaired in DCD (Wilson et al., 2013). However, a systematic review is needed to equate the quality of evidence, to include studies up until the beginning of 2013, and evaluate studies according to the effector system involved. The specific objectives of this systematic review were to: (i) conduct a systematic review of the DCD literature focused on the IMD hypothesis; (ii) examine the methodological quality of the relevant studies, (iii) describe whether the support for an internal modeling deficit is convincing enough to conclude it exists in children with DCD and (iv) make informed recommendations for future research.

2. Methods

2.1. Search strategy

A literature search was conducted using 5 electronic databases: PsycINFO, Web of Science, PubMed, Embase and the Cochrane Library. These databases were selected as they represent a broad spectrum of disciplines that perform research related to DCD. The final search was performed on the 22nd of January 2013. There was no restriction to the year of publication—all articles present in the databases at this time point were searched. The search was conducted in English and limited to the English language publications. For all databases, except the Cochrane Library, it was possible to directly limit our search to the English language. Because the term DCD was only introduced rather recently (American Psychiatric Association, 1987) and other terms to describe children with motor coordination problems are widely used in the literature,

Table 1

Search terms used for selection of scientific articles.

#1 DCD	#2 Visuospatial attention	#3 Motor imagery	#4 Motor planning	#5 Online control
'Developmental coordination disorder' DCD 'Motor skills disorder' ^{**} Clumsiness 'Clumsy child syndrome' 'Clumsy child' Clumsy	'Visuospatial attention' 'attention disengagement'	'Motor imagery' 'Mental rotation' 'Internal imagery' 'Mental simulation' 'Action representation' 'Mental representation'	'Motor planning' 'Feedforward modeling' 'Feedforward modeling' 'End state comfort' 'End-state comfort' 'Planning action'	'Online control' 'Online feedback' 'Rapid online control' 'Online motor control' 'Error feedback' 'Inhibitory control' 'inhibitory response capability' 'Response inhibition' 'Motor adaptation' 'Predictive control' 'Predictive information' 'Online correction' 'Online corrections'
Incoordination Dyscoordination			'Action planning' 'Movement prediction'	
'Minimal brain dysfunction' 'Minor neurological dysfunction' 'Minor neurological disorder' 'Motor delay' 'Perceptual motor deficit' 'Perceptual motor difficulty' 'Perceptual motor dysfunction' 'Perceptual motor impairment' 'Developmental dyspraxia' Dyspraxia ^{***} Dysgraphia 'Developmental right hemisphere syndrome' 'Movement disorder' 'Motor impairment' 'Motor coordination difficulty' 'Motor coordination problem' 'Motor learning difficulty' 'Motor learning problem' 'Mild motor problem' 'Non verbal learning disability' 'Non verbal learning disorder' 'Non verbal learning dysfunction' 'Physical awkwardness' 'Physically awkward' 'Psychomotor disorder' 'Deficits in attention motor control and perception'				
DAMP Apraxia 'Motor delay' 'Motor learning disability' 'Developmental apraxia' 'Sensorimotor difficulties' 'Sensory integration dysfunction 'Dyspraxia-dysgnosia' 'Poorly coordinated children'	#6 IMD 'Internal modeling deficit hypothesis' IMD 'Efference copy' 'Forward model' 'Forward modeling' 'Predictive modeling' 'Predictive modeling' 'Inverse model' 'Feedforward control' 'Feedforward mode of control' 'Internal model' 'Internal modeling' 'Internal modeling' 'Perceptual-motor interaction' 'Perceptual motor interaction'	#7 Parietal function 'Parietal function' 'Parietal dysfunction'	#8 Cerebellar function 'Cerebellar function' 'Cerebellar dysfunction'	#9 Frontal function 'Frontal function' 'Frontal dysfunction'

^{*} Used as Thesaurus term in Embase with the 'explode function'.^{**} Used as MESH term in Pubmed with the 'explode' function.^{***} Used as Thesaurus term in Psychinfo and Embase with the 'explode function'.

we searched a broad spectrum of synonyms for DCD (see Table 1). To maximize inclusion of studies relevant to the IMD hypothesis we combined the term DCD and its synonyms (1) with the following key terms: (2) visuospatial attention, (3) motor planning, (4) motor imagery, (5) online control, (6) IMD, (7) parietal function, (8) cerebellar function and (9) frontal function. Various synonyms of these key terms were also searched (see Table 1) and in some cases combined with the ‘explode’ feature to search narrower related terms in the hierarchical list. If applicable, synonyms were searched in singular and plural and with and without dash sign between words. In Psychinfo and Embase, Thesarus terms were used if possible, and in Pubmed search terms were also used as MESH terms, if available. The key terms were combined as follows: 1 AND (2 OR 3 OR 4 OR 5 OR 6 OR 7 OR 8 OR 9). In addition, hand searches were made of the reference lists of relevant reviews and included articles. Finally, a minor search in Google Scholar was conducted with only the key terms (1–9) to check whether any additional research reports appeared.

2.2. Inclusion and exclusion criteria

The inclusion criteria for the systematic review were studies that (1) presented experimental data that bore directly on the integrity of (forward) internal modeling in DCD; (2) were published in peer reviewed journals; (3) provided a comparison between children meeting a minimum definition of DCD and a typically developing control group; and (4) utilized a standardized assessment of motor skill to achieve a research “diagnosis” of DCD (including Movement Assessment Battery for Children (MABC

Henderson and Sugden, 1992), McCarron Assessment of Neuromuscular Development (MAND McCarron, 1997) or Bruininks Test of Motor Proficiency-2 (BOT-2 Bruininks and Bruininks, 2005). In addition, only studies written in English were included in this systematic review. Exclusion criteria were (1) studies that focused on a medical intervention (paramedical studies were included); (2) studies that were qualitative in nature; (3) case studies; and (4) studies with participant groups that violated DSM-IV-TR criteria for DCD, such as children with an identifiable neurological disorder, an IQ score outside the normal range or children with any (gross) physical or sensory impairment.

2.3. Identification

The database search identified a total of 1421 records. After removing duplicates, a total of 998 records were identified. On the basis of abstract, title, and in- and exclusion criteria, 76 potentially relevant articles were identified and screened for retrieval. Based on full-text, 40 of these 76 were selected for this systematic review and were supplemented with 7 articles found in the reference lists (of the 40 selected research reports and relevant narrative reviews) and 1 article from Google Scholar. This resulted in a total of 48 articles in this review. All the included studies were case control studies. We did not find relevant cohort or controlled intervention studies. We categorized the included studies according to the effector system that was involved: (i) visuospatial attention and oculomotor control (13 studies), (ii) control of manual action (33 studies) and (iii) dynamic postural control (2 studies). Details can be found in Fig. 2.

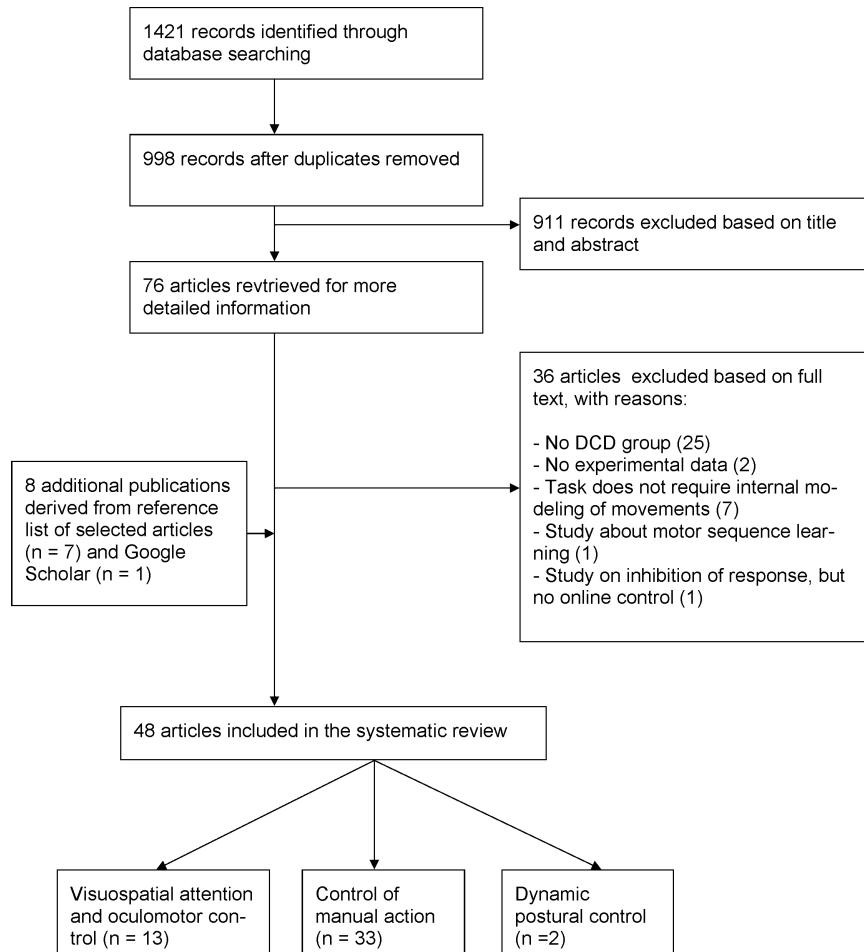


Fig. 2. Flow chart of the included and excluded studies.

In the first category (visuospatial attention and oculomotor control) there were four studies on overt oculomotor control and nine on covert oculomotor control. Overt oculomotor control was examined using a double step saccade task and pursuit eye tracking. Covert oculomotor control was measured mainly using the covert orienting of attention task (COVAT); here central cues are used to elicit voluntary shifts of attention (endogenous mode) and peripheral cues elicit automatic shifts (exogenous control).

The second category (control of manual action) comprised 22 studies on (overt) manual control and 11 studies on covert simulation of manual control. The former was examined using either target-directed movements (reach and grasp, pointing, or tracing) or load lifting tasks. Target-directed movements were included only if a significant element of predictive control was required as when correcting an ongoing movement (e.g., double-step reaching), simulating a prospective action (e.g., planning manual action that afford end-state comfort; Rosenbaum et al., 1996), or adapting movements over trials to altered task constraints (e.g., reaching under altered visual feedback). In the case of double step reaching, rapid online corrections are necessary, which presupposes a system of feedforward prediction (Wilson et al., 2013). The load lifting tasks mainly required adjustments to altered surface properties or inertial load. Effective adaptation to these perturbations is based on detection of somatic events that are not necessarily predicted as part of the forward modeling process. Indeed, Blakemore and colleagues (Blakemore et al., 2001) refer to this as "somatic event detection", mediated largely by cerebellar circuits. Covert simulation of manual action is required for mental (limb) rotation tasks and the visually guided pointing task (VGPT); these covert (or imagined) actions are based on an internal representation of limb dynamics and prospective changes in limb orientation.

The third category (dynamic postural control) contained two studies that were concerned with anticipatory postural adjustments made during a lifting task.

Overall, the studies included in the review covered a broad range of tasks that tested different aspects of the internal modeling of movement across effector systems in DCD.

2.4. Methodological quality

All included publications in this systematic review were fully read by the first and second author (I.A, J.L) and were assessed using the Critical Appraisal Skills Programme (CASP) for case control studies (CASP, 2010a). The CASP questionnaire has sections that assess study validity: methodological quality, presentation of results and external validity. Question 6a relating to confounds was rephrased as, 'Have the authors identified all important confounding factors?', in accordance with the CASP for cohort studies (CASP, 2010b). Furthermore, we scored whether precise statistical results were presented with 'yes', 'can't tell', or 'no', using the answers to questions 7 and 8 of the case control list. Question 9, addressing whether the results were interpreted appropriately, was answered in the same way as question 10 of the cohort list ('yes', 'can't tell', or 'no'). Question 10, relating to the generalizability of results was rephrased as, 'Can the results be applied to the general population?'. To evaluate the inclusion of cases more thoroughly, question 3 was expanded with four additional questions (3a to 3d) that reflected whether DSM-IV-TR criteria for DCD were fulfilled (American Psychiatric Association, 2000). The DSM-IV criteria were used because most of the included studies were published before the new DSM-V criteria for DCD were released in 2013 (American Psychiatric Association, 2013). The first and second author both read and scored the articles according to CASP independently. Then the CASP scores were discussed until consensus was achieved (Table 2). Cohen's kappa was calculated as a measure of initial inter-observer agreement.

3. Results

The results of the included studies are presented in Table 3 which also provides an overview of study characteristics: first author, year of publication, sample size, inclusion criteria, age range, tests used and main results. Only statistically significant results are displayed in this table. In Section 3.1, the initial inter-rater agreement is reported. Results are then discussed per effector system in Sections 3.2 to 3.4: visuospatial attention and oculomotor control (Section 3.2), control of manual action (Section 3.3) and dynamic postural control (Section 3.4). Sections 3.2 and 3.3 are divided into two main categories, overt and covert actions. For each category, the study characteristics, methods and methodological quality, and results are discussed. Primary conclusions are formulated according to the effector system.

3.1. Methodological quality

Initial interrater agreement on all studies was moderate (Cohen's Kappa = 0.491; (Landis and Koch, 1977). After the results were discussed in three separate sessions 100% consensus was reached. The scores for methodological quality according to CASP can be found in Table 2.

3.2. Visuospatial attention and oculomotor control

Both overt and covert attentional shifts require the generation of a forward internal model. Covert shifts of visuospatial attention enlist the same motor preparatory and forward modeling processes as overt shifts (which involve eye movements). These shifts of attention are designed to improve the processing of sensory information in specific parts of the visual field, and help set coordinates for prospective actions into that space (Ariff et al., 2002). According to Rizzolatti et al. (1987, 1994), spatial attention derives from a weak activation of frontal-parietal circuits that directs motor behavior toward specific spatial locations. Receptive fields in frontal eye fields (FEF), supplementary eye fields (SEF), and parietal lobes are updated before a saccade is initiated (Rizzolatti et al., 1994). In short, a forward model of saccade direction appears to provide a spatial (or egocentric) frame for planning limb movements (Ariff et al., 2002). First the results of the studies on overt oculomotor control will be presented, followed by the studies on covert oculomotor control

3.2.1. Overt visuospatial attention and eye movement control

3.2.1.1. Study characteristics. Four studies tested overt eye movements: Katschmarsky et al. (2001) used a double-step saccade task; Langaas et al. (1998) had children visually track a moving stimulus, and Wilmut et al. (2007) and Wilmut and Wann (2008) studied the allocation of visual attention during a motor task. Inclusion criteria for the DCD group varied across studies: Katschmarsky et al. (2001) used a mABC score \leq 15th percentile, while Wilmut et al. (2007) and Wilmut and Wann (2008) both used $<$ 10th percentile, and Langaas et al. (1998) \leq 5th. These four studies included children from 5 to 12 years in their DCD group. Additionally, in the study of Wilmut and Wann (2008) there was also an older DCD group with participants aged 13–23 years.

3.2.1.2. Methods and methodological quality. Double-step saccade tasks (DSST) have been used to assess the integrity of internal modeling in DCD. The DSST is a rapid successive tracking task where two target lights are flashed sequentially and then disappear. In Katschmarsky et al. (2001), the first target appeared for 140 ms and the second for 100 ms. Because the second target is extinguished before the first saccade has landed, children are required here to make a motor plan for their second saccade based on a predictive

Table 2

Methodological quality of included studies scored with the CASP list for case control studies.

	Screening		Methodological quality								Presentation of results		External validity		
	1	2	3	3A	3B	3C	3D	4	5	6A	6B	7+8	9	10	11
1. Visuospatial attention and oculomotor control															
1.1. Overt visuospatial attention and oculomotor control															
Katschmarsky et al. (2001)	y	y	y	y	n	c	y	y	y	n	c	y	c	y	y
Langaas et al. (1998)	y	y	y	y	y	n	y	n	y	n	y	n	c	c	y
Wilmut et al. (2007)	y	y	y	y	n	n	y	y	y	n	y	n	c	y	y
Wilmut and Wann (2008)	y	y	y	y	c	y	y	y	y	c	n	y	c	y	y
1.2. Covert visuospatial attention and eye movement preparation															
Endogenous mode															
Chen et al. (2012)	y	y	c	y	c	y	y	y	y	c	n	y	c	y	y
Tsai et al. (2009b)	y	y	y	y	n	c	y	y	y	y	y	y	y	y	y
Tsai (2009)	y	y	y	y	y	y	y	y	y	c	y	y	y	y	y
Mandich and Polatajko (2003)	y	y	y	y	y	c	y	y	y	n	y	y	c	c	y
Exogenous mode															
Tsai et al. (2010)	y	y	y	y	y	y	y	y	y	y	y	y	y	y	n
Tsai et al. (2012)	y	y	y	y	y	y	y	y	y	y	y	y	y	y	c
Endogenous and exogenous mode															
Tsai et al. (2009a)	y	y	y	y	n	c	y	y	y	y	y	y	y	y	y
Wilson et al. (1997)	y	y	y	y	y	c	y	y	y	n	y	y	y	y	y
Wilson and Maruff (1999)	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
2. Control of manual action															
2.1. Overt manual control															
2.1.1. Reach-to-grasp tasks with alternated vision															
Brookes et al. (2007)	y	y	y	c	c	n	y	n	y	n	n	n	c	c	y
Biancotto et al. (2011)	y	y	y	y	n	y	y	y	y	n	n	n	c	y	y
Cantin et al. (2007)	y	y	y	c	y	c	c	c	y	n	y	n	c	c	n
Kagerer et al. (2004)	y	y	y	y	n	y	y	y	y	n	y	n	c	y	y
Kagerer et al. (2006)	y	y	y	y	n	y	y	c	y	n	y	n	c	y	y
King et al. (2011)	y	y	y	y	n	y	y	c	y	n	y	n	c	y	y
Smyth et al. (2001)	y	y	c	y	c	n	c	c	y	n	y	n	c	c	y
Zoia et al. (2005)	y	y	y	y	y	y	y	y	y	n	y	n	c	y	y
2.1.2. Reach-to-grasp tasks under normal vision															
Johnson and Wade (2009)	y	y	y	y	c	n	y	y	y	n	c	y	c	y	y
Smyth and Mason (1997)	y	y	y	y	c	n	y	y	y	n	y	n	c	y	n
Van Swieten et al. (2010)	y	y	y	y	c	y	y	n	y	n	n	n	c	y	n
Wilmut et al. (2013)	y	y	y	y	y	y	y	y	y	n	c	y	c	y	c
2.1.3. Double step pointing task															
Wilmut et al. (2006)	y	y	y	y	n	n	y	y	y	n	y	n	c	y	y
2.1.4. Tracing tasks															
De Oliveira and Wann (2010)	y	y	c	y	y	y	y	c	y	n	y	n	y	c	y
Kashiwagi et al. (2009)	y	y	c	y	y	y	y	c	y	n	y	n	c	c	y
Zwicker et al. (2010)	y	y	y	y	y	y	y	y	y	n	y	n	y	y	c
2.1.5. Rapid online adjustments to visual perturbations															
Hyde and Wilson (2011a)	y	y	y	y	y	c	y	y	y	y	y	y	y	y	y
Hyde and Wilson (2011b)	y	y	y	y	y	c	y	y	y	y	y	y	y	y	y
Plumb et al. (2008)	y	y	y	y	c	n	y	n	c	c	n	n	c	c	c
2.1.6. Load lifting tasks															
Law et al. (2011)	y	y	y	y	c	c	y	n	y	n	y	n	n	c	c
Mak (2010)	y	y	c	y	c	c	c	n	y	n	y	n	c	c	y
Pereira et al., 2001	y	y	y	c	n	n	y	c	y	n	y	y	c	n	y
2.2. Covert manual action/motor imagery															
Mental rotation															
Deconinck et al. (2009)	y	y	c	y	c	y	c	c	y	y	y	y	y	c	y
Lust et al. (2006)	y	y	y	y	c	c	y	y	y	n	y	n	c	y	n
Williams et al. (2006)	y	y	y	y	n	c	y	y	y	n	y	y	c	y	c
Williams et al. (2008)	y	y	y	y	n	c	y	y	y	n	y	n	c	y	y
Williams et al. (2011)	y	y	y	y	y	c	y	y	y	n	y	y	c	y	y
Wilson et al. (2002)	y	y	y	c	y	y	y	y	y	n	y	y	c	y	y
Wilson et al. (2004)	y	y	y	y	c	c	y	y	y	n	y	y	c	y	y
Mental chronometry															
Lewis et al. (2008)	y	y	y	y	c	y	y	y	y	c	c	n	c	y	y
Maruff et al. (1999)	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
Wilson et al. (2004)	y	y	y	y	c	c	y	y	y	n	y	y	c	y	y
Mental rotation + chronometry															
Williams et al. (2012)	y	y	y	y	y	y	y	y	y	n	y	y	y	y	y
3. Dynamic postural control: anticipatory adjustments															
Jover et al. (2010)	y	y	y	y	c	c	c	n	y	n	c	n	c	y	y
Jucaite et al. (2003)	y	y	y	y	c	c	y	c	y	n	y	c	c	y	y

Table 3

Overview of the characteristics of the included studies.

Study	Participants	Inclusion criteria DCD*	Age DCD (mean (sd/range))	Paradigms used	Results
1. Visuospatial attention and oculomotor control					
1.1. Overt visuospatial attention and eye movement control					
Katschmarsky et al. (2001)	10 DCD, 10 TD	mABC ≤15th, impaired MI	9.5 (1.1)	Double step saccade task	DCD: less able to plan second saccade
Langaas et al. (1998)	8 DCD, 32 TD, 8 adults	mABC ≤5th	5–7 years	Pursuit eye movements	DCD: less able to temporally synchronize eye movements; reduced gain
Wilmut et al. (2007)	7 DCD, 46 TD	mABC <10th	7.4 (7.0–8.5)	Automatic orienting of attention during an aiming task	DCD: deficit to disengage attention in look + hit condition, but not in look condition
Wilmut and Wann (2008)	23 DCD, 23 TD	mABC ≤10th	6–12 years (9.5), 13–23 years (16.4)	Grasping with and without central and peripheral precues	DCD: relied on slower strategy (first fixate and then move) and only effectively used unambiguous precues
1.2. Covert visuospatial attention and eye movement preparation					
Endogenous mode					
Chen et al. (2012)	24 sDCD, 51 mDCD, 38 TD	sDCD: mABC <1st, mABC >1–<5th	9–10 years	COVAT—endogenous	At short SOA (350 ms) invalid cue effect size same as controls; at longer SOA (850 ms) deficit in endogenous mode of attention
Mandich and Polatajko (2003)	18 DCD, 18 TD	mABC <15th	9.9 (1.5)	COVAT—endogenous mode	At SOA 500 ms, deficit in endogenous mode of attention both manual and attentionally
Tsai et al. (2009b)	29 DCD, 29 TD	mABC <5th and BOT-M ≤10th	9.9 (0.5)	COVAT—endogenous	At SOA 350 ms, deficit in endogenous mode of attention.
Tsai (2009)	28 DCD, 29 TD	mABC <5th	DCD-training: 9.5 (0.4), DCD-non-training: 9.5 (0.3)	COVAT—endogenous before and after table tennis training	At SOA 350 ms, deficit in endogenous mode of attention. Exercise intervention improves inhibitory control and motor performance
Exogenous mode					
Tsai et al. (2010)	30 DCD, 30 TD	mABC <5th	9.5 (0.33)	COVAT—exogenous mode—central-eye gazed cues	At SOA 500 ms, deficit in exogenous mode of attention
Tsai et al. (2012)	30 DCD (16 training, 14 non-training, 21 TD)	mABC <5th	DCD-training: 9.7 (0.5), DCD-non-training: 9.5 (0.3)	COVAT—exogenous mode—central eye-gazed cues. Tested before and after soccer training	At SOA 500 ms, deficit in exogenous mode of attention. Soccer training improved ERP and task performance indices in DCD group
Endogenous and exogenous mode					
Tsai et al. (2009a)	36 DCD-Les, 36 TD	mABC ≤5th, total balance score ≤10th	9.9 (0.5)	COVAT—endogenous and exogenous mode	At SOA 150 and 850, deficit in attention disengagement only in endogenous mode
Wilson et al. (1997)	20 DCD, 20 TD	mABC ≤15th	9–10 years	COVAT—endogenous and exogenous mode	At SOA 150 and 350, deficit in attention disengagement only in endogenous mode
Wilson and Maruff (1999)	20 DCD, 20 TD	mABC ≤15th	10.3 (9.5–12.0)	COVAT—endogenous and exogenous mode	At SOA 150 and 850, deficit in attention disengagement only in endogenous mode
2. Control of manual action					
2.1. Overt manual control					
2.1.1. Reach-to-grasp tasks with alternated vision					
Biancotto et al. (2011)	9 DCD, 27 TD	mABC ≤5th, manual dext. ≤5th	7–9 years	Reach-to-grasp with and without vision—kinematics	DCD: grasping action slower; more dependent on vision and more variable

Table 3 (Continued)

Study	Participants	Inclusion criteria DCD ^a	Age DCD (mean (sd/range))	Paradigms used	Results
Brookes et al. (2007)	8 DCD, 6 DCD + dyslexia, 12 TD	Poor coordination based on combination WISC-III, VMI and mABC mABC ≤ 5th	12.5 (2.8)	Prism adaptation	DCD: impaired rate of adaptation
Cantin et al. (2007)	9 DCD, 11 TD	mABC ≤ 5th	6–11 years	Prism adaptation	DCD: comparable adaptation, but DCD more variable and less accurate
Kagerer et al. (2004)	7 DCD, 7 TD	mABC ≤ 15th	7.5 (0.5)	Prism adaptation	DCD: impaired rate of adaptation
Kagerer et al. (2006)	10 DCD, 10 TD	mABC ≤ 5th	8.2 (1.5)	Prism adaptation	DCD: adaptation after abrupt, but not gradual perturbation
King et al. (2011)	6 DCD, 10 TD	mABC < 5th	9–11	Reaching to visual and acoustic targets with prism adaptation	DCD: similar visuomotor adaptation; similar influence on auditory-motor performance as controls
Smyth et al. (2001)	8 DCD, 8 TD	mABC < 15th	9.7 (8.7–10.8)	Reach-to-grasp with and without vision	DCD: impaired adaptation; less accurate and less use of visual information
Zoia et al. (2005)	26 DCD, 26 TD	mABC < 10th	7–8 years: 7.8 (0.6), 9–10 years: 9.7 (0.6)	Prism adaptation	DCD: longer and more curved trajectories than controls. Impaired rate of adaptation
2.1.2. Reach-to-grasp tasks under normal vision					
Johnson and Wade (2009)	12 DCD, 12 TD	mABC ≤ 15th	11.5 (0.6)	Judgement of maximal hand reach	DCD: only right adjustment in one of the three perturbations
Smyth and Mason (1997)	95 DCD, 91 TD	mABC < 15th	4–8 years	Grip selection task	DCD: planning of grip selection same as controls
Van Swieten et al. (2010)	27 DCD, 70 TD, 40 adults	mABC < 5th	6–13 years	Grip selection task	DCD: less end state comfort
Wilmut et al. (2013)	18 DCD adults, 24 DCD children, 18 TD adults, 24 TD children	Adults: mABC < 15th and BOT-M < 15th. Children: mABC < 5th	Adults: 18–29 years (24.9), children 8–11 (9.1).	Reaching to throw vs. reaching to place	DCD: able to plan movements in relation to onward intentions, but not fully developed
2.1.3. Double step pointing task					
Wilmut et al. (2006)	7 DCD, 10 TD	mABC < 10th	7.4	Double step pointing task	DCD: look-then-move strategy suggesting impaired feedforward mode of control
2.1.4. Tracing tasks					
De Oliveira and Wann (2010)	20 DCD (diagnosis at age 10.3 (sd = 3)), 20 TD	mABC ≤ 15th	15–27 years	Steering task—steer smoothly on virtual winding course	DCD: slower and more variable, and could not use advance information effectively
Kashiwagi et al. (2009)	12 DCD, 12 TD	mABC < 15th	10.8 (1.0)	Tracking horizontally moving target with joystick	DCD: less accurate in tracing a target plus a dysfunction in the parietal lobe
Zwicker et al. (2010)	9 DCD, 9 TD	mABC < 20th	10.8 (1.5)	Flower-shaped trail-tracing task	DCD: no difference in performing trail-tracing, but regions for visuospatial processing are activated instead of regions for spatial processing and motor control
2.1.5. Rapid online adjustments to visual perturbations					
Hyde and Wilson (2011a)	17 DCD, 27 TD	MAND < 10th	9.68 (1.7)	Double step reaching	DCD: longer MT and more errors on jump-trials
Hyde and Wilson (2011b)	13 DCD, 13 TD	MAND < 10th	10.5 (1.7)	Double step reaching	DCD: longer MT and more errors on jump-trials; slower to correct reach trajectory

Table 3 (Continued)

Study	Participants	Inclusion criteria DCD [*]	Age DCD (mean (sd/range))	Paradigms used	Results
Plumb et al. (2008)	13 DCD, 13 TD	mABC <1st	9.8 (7–13)	Double step reaching	DCD: poor performance in jump and no-jump trials. No specific deficit in online control
2.1.6. Load lifting tasks					
Law et al. (2011)	21 DCD, 17 TD	mABC ≤15th	6–12 years	Grip force (GF) control	DCD: could adapt GF, but slower rate of GF generation and lower GF peak
Mak 2010	16 DCD, 11 TD	mABC <15th	8.1 (0.6)	Grasp a toy sliding down a slope	DCD: modified MT and GF same as controls, but slower generation and larger force
Pereira et al. (2001)	11 DAMP, 9 DCD, 12 TD	Motor perception dysfunction	DAMP: 10.6 (0.5), DCD: 10.6 (0.5)	Precision grip lifts	DCD and DAMP: could adapt grip force, but higher grip forces and safety margins
2.2. Covert manual action/motor imagery					
Mental rotation (MR)					
Deconinck et al. (2009)	13 DCD, 13 TD	mABC ≤15th	9 (0.7)	MR—hands and letters	Comprised MI (slower and less accurate)
Lust et al. (2006)	10 DCD, 7 TD, 14 adults	mABC <15th	10.4 (9–11)	MR—hands	MI same as in controls
Williams et al. (2006)	18 DCD, 18 TD	mABC <15th	9.7 (0.7)	MR—hands (± MI instr.), letters, whole-body	DCD did use MI, but did not benefit from MI instructions
Williams et al. (2008)	21 sDCD, 21 mDCD, 21 TD	sDCD mABC <5th, mDCD 6–14th	sDCD 9.4 (0.7) mDCD 9.2 (1.4)	MR—hands (± MI instr.), whole-body (+ MI instr.)	Comprised MI (according to level of motor impairment)
Williams et al. (2011)	21 DCD, 21 TD	mABC <5th	9.4 (0.7)	MR—hands (+ MI instr.), whole-body (+ MI instr.)	Comprised MI (accuracy ↓ hand, whole-body); atypical RT whole-body
Wilson et al. (2002)	54 DCD (18 MI training, 18 PM training, 18 wait-list)	mABC <50th, 11 children <15th in each group	7–12 years	MI training	MI training as effective as PM training
Wilson et al. (2004)	16 DCD, 18 TD	mABC ≤15th	10.3 (1.6)	MR—hands	Comprised MI (moderate trade-off RT vs. angle of rotation)
Mental chronometry					
Lewis et al. (2008)	15 DCD, 14 ADHD + DCD, 15 TD	mABC ≤15th	8–12 years	VGPT	DCD: only real movements conformed to Fitts' law. ADHD + DCD: both real and imagined movements according to Fitts' law
Maruff et al. (1999)	24 DCD, 20 TD	mABC <15th	9.8 (9.0–10.8)	VGPT	DCD: only real movements conformed to Fitts' law
Wilson et al. (2001)	20 DCD, 20 TD	mABC ≤15th	10.0 (8.1–11.5)	VGPT	DCD: only real movements conformed to Fitts' law
Mental rotation + chronometry					
Williams et al. (2012)	10 DCD, 16 ADHD + DCD, 18 TD	mABC ≤15th	DCD: 8.45 (1.25) ADHD + DCD: 9.07 (1.65)	VGPT + MR—hands	DCD: only real movements conformed to Fitts' law. MR—hands: DCD and ADHD + DCD less accurate
3. Dynamic postural control: anticipatory adjustments					
Jover et al. (2010)	16 DCD, 16 TD	mABC <5th	9.0 (2.0)	Bimanual load lifting—APA	APA's less efficient in DCD
Jucaite et al. (2003)	12 DCD, 13 ADHD + DCD, 15 age-matched TD, 11 younger TD	mABC <15th	9.0 (0.6)	Lifting of different weights—APA	DCD: deficiencies in coordination of fingertip forces and APA's.

APA = anticipatory postural adjustment; BOT-M = Bruininks–Oseretsky test of motor proficiency; DAMP = deficits in attention, motor control and perception; DCD-Les = DCD in lower extremities; ERP = evoked related potentials; GF = grip force; MAND = McCarron Assessment of Neuromuscular Development; mDCD = mild DCD; MI = motor imagery; MI instr. = motor imagery instruction; MR = mental rotation; MT = movement time; PM = perceptual motor (training); RT = reaction time; sDCD = severe DCD; SOA = stimulus-onset asynchrony; VGPT = visually guided pointing task; VMI = developmental test of visuo-motor integration; WISC-III = Wechsler intelligence scale for children (3rd ed.).

* mABC total percentile score is indicated as not otherwise stated.

estimate of the first (Katschmarsky et al., 2001). To track or trace a certain stimulus smoothly with your eyes also requires a high degree of predictive control (Langaas et al., 1998). In this case, the smooth pursuit system must anticipate the continued trajectory of the target; critically, tracking with a lag of under 100 ms requires eye motion that is based in part on a forward model and not retinal error signals (Langaas et al., 1998). In relation to the allocation of overt attention, Wilmut et al. (2007) examined attentional shifts in tasks that did or did not require arm movements. In one condition, children were instructed to visually capture and touch visual targets that appeared (look+hit condition), while in another they only had to look at the visual target (look only condition). Saccade and hand movement latencies were measured on two different trial types: gap trials (gap between fixation offset and target onset) and overlap trials (fixation offset and target onset overlapped). In a subsequent study by Wilmut and Wann (2008), a motor task was presented using (static) cues presented centrally and peripherally. The methodological quality of the studies above was moderate: not all DSM-IV-TR criteria for DCD were met, control of confounding variables (age, gender, ADHD and learning problems) was incomplete, and precise statistical results were lacking in the studies of Langaas et al. (1998) and Wilmut et al. (2007) (see Table 2).

3.2.1.3. Results. The studies on overt oculomotor control showed that children with DCD were less accurate in terms of final eye position on second saccades (Katschmarsky et al., 2001) and that they were less able to temporally synchronize their tracking response to the stimulus (Langaas et al., 1998). In the study of Wilmut et al. (2007) it was shown that children with DCD were only slower to disengage attention in the look+hit condition but not in the look-only condition. This prolonged disengagement time was also observed in younger children. In a subsequent study, Wilmut and Wann (2008) showed that the DCD group relied on a slower strategy by first fixating the target and then starting to move and that they were only able to use unambiguous precues effectively.

3.2.2. Covert visuospatial attention and eye movement preparation

3.2.2.1. Study characteristics. Nine studies were included which focused on covert attention in children with DCD. All studies in this category have used the covert orienting of visuospatial attention task (COVAT), modeled on the work of Posner (1980, 1988). Two different modes of covert orienting are conceptualized: the endogenous and exogenous mode. Four of the sampled studies examined just the endogenous mode of covert orienting in DCD (Chen et al., 2012; Mandich and Polatajko, 2003; Tsai et al., 2009b; Tsai, 2009), two studies the exogenous mode alone (Tsai et al., 2010, 2012), and three studies both modes (Tsai et al., 2009a; Wilson and Maruff, 1999; Wilson et al., 1997).

In the majority of studies children in the 7–12 year-old range were tested. The inclusion criteria for the DCD group varied over studies: three studies used a mABC score below or at the 15th percentile as an inclusion criteria for the DCD group (Mandich and Polatajko, 2003; Wilson and Maruff, 1999; Wilson et al., 1997), and all studies by Tsai and colleagues used <5th percentile. The study of Chen et al. (2012) compared mild (mABC >1–5th percentile) and severe (mABC <1st percentile) DCD on the endogenous Posner paradigm. All five studies of Tsai et al. and the studies of Wilson et al. (1997) and Wilson and Maruff (1999) excluded children with ADHD.

3.2.2.2. Methods and methodological quality. The COVAT is a spatial precueing paradigm whereby the nature of attentional shifts can be evaluated by varying the type of precue, its probability, and the stimulus-onset asynchrony (SOA—the time interval between cue and target). Valid precues facilitate attentional shifts to the target

location and reduce response time. By comparison, invalid precues have a processing cost by misdirecting attention to a spatial location in the hemispace opposite to the visual target. The difference in response time between valid and invalid trials is termed the invalid cue effect (ICE) and measures attentional disengagement time (Tsai et al., 2009b; Tsai, 2009; Wilson and Maruff, 1999; Wilson et al., 1997). Using Posner's classic paradigm, the endogenous (or voluntary) mode of covert orienting was tested using symbolic cues presented centrally, with the percentage of valid trials set generally at around 80%. In contrast, exogenous (or automatic) orienting refers to attentional shifts elicited involuntarily by external events (Joindees, 1981), most commonly by peripheral spatial cues at the location of potential targets (Wilson and Maruff, 1999; Wilson et al., 1997). In the case of Tsai et al. (2010, 2012), however, it was argued that central cues can still elicit automatic control if presented to the immediate left or right of central fixation. Notably, in two studies of Tsai et al. (2009a, 2010) children had to respond by pressing pedals with their feet, instead of a button press using fingers. The authors reasoned that the correlation between general motor skill and lower limb function is higher than the correlation with the upper limbs (Kauranen and Vanharanta, 2001). This is explained by the fact that the upper extremities involve more lateralized activity than the lower (Kapreli et al., 2006), and a tighter correlation between the level of ipsilateral motor and premotor activity (Ciccarelli et al., 2005). In general, the stimulus-onset asynchrony (SOA) varied between 150 and 800 ms. Larger SOAs tend to elicit more voluntary control.

The methodological quality of studies of eye movement control was moderate. In particular, inclusion criteria for DCD did not conform to criteria B and C of the DSM-IV-TR (i.e., interference with daily life, and medical conditions that excludes a diagnosis DCD) and confounding factors were not described or controlled (see also Table 2). Only one study scored positively on all DSM-IV-TR and CASP criteria (Wilson and Maruff, 1999).

3.2.2.3. Results. The four studies that examined only the endogenous mode of attention found that children with DCD exhibited a deficit of inhibitory control (Chen et al., 2012; Mandich and Polatajko, 2003; Tsai et al., 2009b; Tsai, 2009). Chen et al. (2012) found that this deficit was only present at a SOA of 800 ms and not 350 ms. Interestingly, the results of this study showed that this deficit of endogenous control did not vary according to the severity of DCD. At short SOAs, both TD and DCD children needed a comparable amount of time to shift attention from invalidly cued locations to the correct one. For longer SOAs, children with severe and moderate DCD were more disadvantaged by the invalid cue. By comparison, the two studies of Tsai only used a SOA of 350 ms and found no deficit of inhibitory control in the endogenous mode. The two studies of Tsai and colleagues (Tsai et al., 2010, 2012) showed that children with DCD were disadvantaged by cues presented near central fixation, and suggested that this reflected a deficit of inhibitory control in the context of automatic orienting. The studies that examined both the endogenous and exogenous control of attention (Tsai et al., 2009a; Wilson and Maruff, 1999; Wilson et al., 1997) showed that children with DCD were only more disadvantaged by invalid cues compared to controls in the endogenous mode, regardless of the SOA. In the exogenous mode the reaction times of the DCD groups did not differ from the control groups. Finally, the training studies of Tsai (2009), Tsai et al. (2012) showed that exercise intervention (table tennis training or soccer training, respectively) can improve the inhibitory control of children with DCD.

3.2.3. Primary conclusions

The results suggest that children with DCD have problems with the predictive control of overt eye movements. They were less able

to plan an eye movement based on a forward estimate of a prior eye movement (Katschmarsky et al., 2001) and less able to temporally synchronize their eye tracking to a (predictable) moving stimulus (Langaas et al., 1998). In the studies of Wilmut et al. (2007) and Wilmut and Wann (2008), children with DCD were slower to disengage attention and used a slower and less efficient strategy than controls by first fixating the target and then starting to move. The results of these studies should, however, be interpreted with a degree of caution because not all DSM-IV-TR criteria for a diagnosis of DCD were fulfilled and correction for confounds was incomplete. Results of studies on covert attention were rather consistent. All included studies that examined endogenous control of attention showed a deficit in the voluntary disengagement of attention in DCD. This was shown by larger invalid cue effect sizes in DCD compared with controls. Two studies by Tsai et al. (2010, 2012) argued that the exogenous mode of attention was also impaired in DCD. However, because it can be questioned whether central cues truly enlist the exogenous mode of attention (Wilson and Maruff, 1999), these results should be interpreted with caution. Studies that assessed both the endogenous and exogenous mode of attention consistently found that only the endogenous mode of control was impaired in DCD. Exclusion of children with ADHD (Tsai et al., 2009a,b, 2010, 2012; Tsai, 2009; Wilson et al., 1997; Wilson and Maruff, 1999) suggested that these deficits are specific to DCD and do not arise as a consequence of attentional symptoms of ADHD. Results of the included studies on covert oculomotor control should be interpreted with a degree of caution because most studies did not control for confounds and did not indicate whether all DSM-IV-TR criteria for DCD were fulfilled. However, since the results are rather consistent, there is sufficient evidence to conclude that children with DCD have a deficit in the endogenous control of attention; reduced inhibitory control may explain this effect.

3.3. Control of manual action

Thirty-three of the included studies focused on the control of manual action (including tasks of motor planning). These studies can be divided into overt manual control (Section 3.3.1) and covert manual control/motor imagery (Section 3.3.2). The studies on overt manual control are divided in six categories: (a) reach-to-grasp tasks with alternated vision, (b) Reach-to-grasp tasks without alternated vision, (c) double step pointing tasks, (d) tracing tasks, (e) rapid online control and, (f) load lifting tasks.

3.3.1. Overt manual control

3.3.1.1. Reach-to-grasp tasks with alternated vision.

3.3.1.1.1. Study characteristics. Eight studies manipulated vision during a reach-to-grasp task. Most of these studies used a prism-adaptation test, and included children aged 7–15 years. Two studies used a mABC score <15th percentile as an inclusion criteria for DCD (Smyth et al., 2001; Kagerer et al., 2004), while the other studies used <10th percentile (Zoia et al., 2005) or ≤5th (Biancotto et al., 2011; Cantin et al., 2007; Kagerer et al., 2006; King et al., 2011). Brookes et al. (2007) used a diagnosis of poor coordination by occupational therapists on the basis of one or a combination of instruments including the WISC-III (Wechsler, 1992), the VMI (Beery, 1998) and the mABC (Henderson and Sugden, 1992). In the article of Biancotto et al. (2011), signs of ADHD were examined in the DCD group. However, in the analysis of the results there was no correction for ADHD. The other studies did not report on signs of ADHD. All studies had a DCD group of 10 or even less participants, except Zoia et al. (2005).

3.3.1.1.2. Methods and methodological quality. Aspects of internal modeling are also involved in tasks that have been used traditionally to assess motor planning. Unlike executive planning—an aspect of executive function (Van Swieten et al.,

2010), motor planning (Cohen and Rosenbaum, 2004; Rosenbaum et al., 1996) involves behavior that depends on learned movement skills; a prime example are grip selection tasks. However, there are other tests thought to examine motor planning like prism adaptation tasks. These tests also require that participants are able to update their forward model of an action to altered task constraints. In fact, a number of DCD studies have directly tested this capacity by examining accuracy and movement time before and after visual perturbation. The methodological quality of the included studies was not considered high as there was only one study (Biancotto et al., 2011) that described all confounding variables. However, the correction for these confounds was incomplete. Precise statistical results were often not presented. Many studies did not report on all DSM-IV-TR criteria for DCD (especially criteria B and C were not reported), except for the study of Zoia et al. (2005) (see Table 2).

3.3.1.1.3. Results. The tests of adaptation after a visuomotor perturbation all reported accuracy and/or movement time. The studies that used a prism adaptation test all reported that the children with DCD were less able to update their forward model in response to a visuomotor perturbation which was reflected by higher variability, lower accuracy and/or longer movement times after perturbation in the DCD group compared to controls (Brookes et al., 2007; Cantin et al., 2007; Kagerer et al., 2004, 2006; Zoia et al., 2005). In addition, in two studies the after-effect in the DCD group was also decreased (Cantin et al., 2007; Kagerer et al., 2004). To examine the multisensory characteristics of spatial-to-motor transformations for reaching movements, King et al. (2011) compared the performance of a DCD and control group during discrete arm movements to visual and acoustic targets prior to and following exposure to an abrupt visual feedback rotation (prism adaptation). In contrast to the other prism adaptation studies, the visual after effects were equivalent in the DCD and control group and the influence of visuomotor adaptation on auditory-motor performance was also similar in the two groups. The studies of Biancotto et al. (2011) and Smyth et al. (2001) used an alternative adaptation test and examined grasping movements in conditions with, and without vision. Smyth et al. (2001) showed that the DCD group was less accurate and showed less adaptation to removal of vision. In addition, Biancotto et al. (2011) showed the DCD group to have great difficulties when vision was removed: they always had a wider grasping aperture, especially in the no-vision condition, and their performance was slower and more variable than controls.

3.3.1.2. Reach-to-grasp tasks under normal vision.

3.3.1.2.1. Study characteristics. Of the four studies in this category, two looked at planning for end state comfort (Smyth and Mason, 1997; Van Swieten et al., 2010), one examined the planning of reaching (Wilmut et al., 2013), and another judgments of the limits of reach extent (Johnson and Wade, 2009). Children in these four studies were aged 4–13 years. In the study of Wilmut et al. (2013), the DCD and control group were divided into two age bands (8–11 and 18–29 years). A mABC cut-off of <15th percentile was used in three studies (Smyth and Mason, 1997; Johnson and Wade, 2009; adult group in Wilmut et al., 2013), and two used a cut-off of <5th percentile (Van Swieten et al., 2010; child group in Wilmut et al., 2013). In the article of Wilmut et al. (2013), signs of ADHD were examined in the DCD group but not factored out in the analysis. Sample sizes varied greatly, ranging from 12 children with DCD in Johnson and Wade (2009) to 95 children with DCD in Smyth and Mason (1997).

3.3.1.2.2. Methods and methodological quality. Grip selection tasks are a prime example of traditional motor planning tasks (Cohen and Rosenbaum, 2004; Rosenbaum et al., 1996). Several studies showed that participants prefer to end an action with a ‘comfortable end posture’ and sacrifice comfort of the initial posture in order to attain this goal (e.g., Rosenbaum et al., 1992). This

so called 'end-state-comfort effect' was studied in DCD by [Smyth and Mason \(1997\)](#) and [Van Swieten et al. \(2010\)](#). [Wilmut et al. \(2013\)](#) studied planning of reaching in relation to onward intentions (i.e., place an object on a target, throw the object, or lift the object vertically). In the study of [Johnson and Wade \(2009\)](#), children judged the limit of their horizontal reach under different task constraints (namely, one-hand versus two-hand reach, standard versus short effective foot-length, and rigid versus compliant support surface). The methodological quality of the four studies in this category was moderate; only the study of [Wilmut et al. \(2013\)](#) reported all DSM-IV-TR inclusion criteria for DCD, correction for confounds was often incomplete, and precise statistical results were not always presented (see [Table 2](#)).

3.3.1.2.3. Results. Studies that examined the end-state-comfort effect showed conflicting results. [Smyth and Mason \(1997\)](#) showed that there was no difference in grip selection between the DCD and control groups. By comparison, [Van Swieten et al. \(2010\)](#) showed that children with DCD were biased toward selecting the simplest initial movement, indicating reduced forward planning. The study of [Wilmut et al. \(2013\)](#) showed that both adults and children with DCD were able to plan movements in relation to the movement goal that was required subsequently. However, this skill was not fully refined in typically developing children. Finally, in a variant of a reach task, [Johnson and Wade \(2009\)](#) showed that children with DCD were less able to judge whether targets could be reached under different task constraints (namely, one-hand versus two-hand reach, standard versus short effective foot-length, and rigid versus compliant support surface).

3.3.1.3. Double step pointing task.

3.3.1.3.1. Study characteristics. A double step pointing task has been used to examine the control of manual action and the coupling of the eye and hand ([Wilmut et al., 2006](#)). Children in this study were aged 7–8 years, and had a mABC score <10th percentile. This study did not report on signs of ADHD. The sample size in this study was small with only 7 in the DCD group.

3.3.1.3.2. Methods and methodological quality. During the double-step pointing task children are required to make a pointing movement to two sequential targets that appear on a computer screen (and in some trials that subsequently disappear), while eye and hand movement are recorded simultaneously ([Wilmut et al., 2006](#)). Movement time and accuracy of the first and second movement are recorded to examine the ability to make a second movement based on a forward model of the first. The inclusion criteria for the DCD group in this study did not conform to criteria B and C of the DSM-IV-TR and not all confounding factors were taken into account (see [Table 2](#)).

3.3.1.3.3. Results. The results of the study of [Wilmut et al. \(2006\)](#) showed that children in both DCD and control groups preferred to foveate the target prior to initiating a hand movement if time allowed. However, if necessary, the control children were better able to reduce the foveation period and shift toward a feed-forward mode of control for hand movements. Children with DCD, on the other hand, maintained a look-then-move strategy which led to greater error.

3.3.1.4. Tracing tasks.

3.3.1.4.1. Study characteristics. Tracing tasks have been used to examine whether children with DCD are able to track a stimulus with their hand accurately and efficiently, in time and space ([De Oliveira and Wann, 2010](#); [Kashiwagi et al., 2009](#); [Zwicker et al., 2010](#)). Children in the studies of [Kashiwagi et al. \(2009\)](#) and [Zwicker et al. \(2010\)](#) were aged 8–12 years. The steering task of [De Oliveira and Wann \(2010\)](#) was performed only by adults (15–27 years), and these participants were classified as having DCD when they were

10 years of age. [Kashiwagi et al. \(2009\)](#) and [De Oliveira and Wann \(2010\)](#) used a mABC score <15th and ≤15 percentile respectively as an inclusion criteria for DCD, while [Zwicker et al. \(2010\)](#) used <20th percentile. Sample size in these three studies varied from 9 to 20 in the DCD group. Only the study of [Zwicker et al. \(2010\)](#) excluded children with ADHD, while the other two studies did not report on signs of ADHD.

3.3.1.4.2. Methods and methodological quality. Continuous tracing tasks were conceptualized as involving the ability to adapt forward models over time in response to a predictable but moving target; forward planning of the movement is required to anticipate the trajectory of the target that moves at a given speed. The methodological quality of the three studies was moderate: correction for confounders was incomplete and precise statistical results were not always presented (see [Table 2](#)). However, [Kashiwagi et al. \(2009\)](#) and [Zwicker et al. \(2010\)](#) both conformed to all DSM-IV-TR criteria for DCD.

3.3.1.4.3. Results. The steering task of [De Oliveira and Wann \(2010\)](#) showed that children with DCD were slower and more variable and could not use advance information effectively. Similarly, [Kashiwagi et al. \(2009\)](#) showed that children with DCD were less accurate in tracing a moving target with their hands (manipulating a joystick). By contrast, [Zwicker et al. \(2010\)](#) showed similar trail tracing performance between a DCD and a control group. But, different brain regions were activated in children with DCD during this task, namely left inferior parietal lobule, right middle frontal gyrus, right supramarginal gyrus, right precentral gyrus, right superior temporal gyrus and right cerebellar lobule VI, suggesting (according to Zwicker) that the DCD group relied on visuospatial processing to complete the task. The control group had significantly more activation than the DCD in left precuneus, left superior frontal gyrus, right superior temporal gyrus, left inferior frontal gyrus and left postcentral gyrus; these regions have been associated with spatial processing, motor control and learning and error processing ([Zwicker et al., 2010](#)).

3.3.1.5. Rapid online adjustments to visual perturbations.

3.3.1.5.1. Study characteristics. Three studies were identified that reported on rapid online control ([Hyde and Wilson, 2011a,b](#); [Plumb et al., 2008](#)). The study of [Hyde and Wilson \(2011b\)](#) was an extension of the first study, using both chronometric and kinematic analysis of double step reaching movements. The children with DCD in the three studies were aged 7–13 years. The studies of Hyde and Wilson used a MAND score <10th percentile ([McCarron, 1997](#)) as an inclusion criterion for DCD, while [Plumb et al. \(2008\)](#) used a mABC score <1st percentile. [Hyde and Wilson \(2011a,b\)](#) excluded children with ADHD. While [Plumb et al. \(2008\)](#) did identify that 4 of the 13 children with DCD had an ADHD score outside the normal range, they did not correct for ADHD in their analysis. The sample sizes of the studies could be considered rather small at around 15 children with DCD, although power analyses showed this to be sufficient in anticipation of moderate to high effect sizes.

3.3.1.5.2. Methods and methodological quality. Rapid online adjustments were tested with a double step reaching paradigm, requiring a target-directed reach and touch (or grasp) movement to one of several possible targets. For the majority of trials, the target remained the same for the duration of the movement, while for a small number of trials, the target changed (or 'jumped') unexpectedly at, or shortly after, movement onset. Hence, the children had to adjust their movements 'on the fly' ([Hyde and Wilson, 2011a,b](#)). It is important to note that in the study of [Plumb et al. \(2008\)](#), the task was modified for children with DCD because they had difficulty managing a hand-held stylus and performing the task from a standing position; these children were seated, unlike controls, and used a much thicker stylus. It has been observed repeatedly that children with DCD have particular difficulty completing complex

movements (e.g., Wilmut et al., 2006; Wilson and McKenzie, 1998). Simplifying the task, while appropriate for the DCD group, does compromise the experimental comparison between groups.

3.3.1.5.3. Results. Both studies of Hyde and Wilson (2011a,b) showed that children with DCD were slower to initiate reaching compared to controls. Notably, children with DCD made more errors and had a longer movement time on jump trials than controls. Kinematic data from the second study 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. In the study of Plumb et al. (2008) there was a non-significant trend showing longer movement times in DCD for both the perturbation and non-perturbation conditions.

3.3.1.6. Load lifting tasks.

3.3.1.6.1. Study characteristics. Manual control in children with DCD was also examined using lifting tasks. Children in these studies were aged 6–12 years. The studies of Law et al. (2011) and Mak (2010) used a mABC score \leq and <15th percentile respectively as an inclusion criteria for DCD, while Pereira et al. (2001) studied children with DCD and children with Deficit of Attention, Motor Control and Perception (DAMP). Law et al. (2011) excluded children with ADHD while Mak (2010) did not report on signs of ADHD. Sample size ranged from 11 to 21 participants in the DCD group.

3.3.1.6.2. Methods and methodological quality. Lifting tasks were used in combination with adaptation to different frictional properties (Pereira et al., 2001), different speed of a moving target (Mak, 2010) or a combination of different weights (water in a cup) and frictional properties (Law et al., 2011). These tasks also enlist the ability to update internal (working) models of the action according to altered task constraints. The methodological quality of these three studies was low as they did not fulfill all DSM-IV-TR criteria for DCD, nor did they correct for all major confounds (see Table 2).

3.3.1.6.3. Results. In the study of Pereira et al. (2001) and Law et al. (2011) it was shown that children with DCD (and children with DAMP in the study of Pereira et al., 2001) are able to adapt the force output in response to the friction properties of the object. Furthermore, Law et al. (2011) showed that children with DCD were able to modulate grip appropriately when a cup was filled with water. Using a moving target, Mak (2010) showed that children with DCD were able to modify movement time and grip force according to the velocity of the target. However, Law et al. (2011) and Mak (2010) detected a slower rate of grip force generation and longer movement times in DCD compared with controls. Notably, higher peak grip force was found in DCD by Pereira et al. (2001) and Mak (2010), while Law et al. (2011) found it to be lower.

3.3.2. Covert manual action/motor imagery

3.3.2.1. Study characteristics. The representation of (manual) actions can be tested using motor imagery paradigms. Six studies used a mental rotation paradigm (Deconinck et al., 2009; Lust et al., 2006; Williams et al., 2006, 2008, 2011; Wilson et al., 2004), three used a mental chronometry paradigm (Lewis et al., 2008; Maruff et al., 1999; Wilson et al., 2001), and one reported performance on both a mental rotation task and a mental chronometry task (Williams et al., 2012). In addition, the effects of motor imagery training was examined in a study by Wilson et al. (2002). The sampled children in these 11 studies were all 7–12 years of age. In the motor imagery training study by Wilson et al. (2002) a mABC score <50th percentile was used as an inclusion criteria for the DCD group, while in two studies of Williams et al. (2008, 2011) a more strict inclusion criteria <5th percentile was used. All other studies in this category used a mABC score <15th percentile as an inclusion criteria. Two of the studies also included a group of children with ADHD

and a group with ADHD and combined DCD (ADHD + DCD) (Lewis et al., 2008; Williams et al., 2012). In four studies ADHD was defined as an exclusion criterion (Deconinck et al., 2009; Maruff et al., 1999; Wilson et al., 2001, 2002), while the remaining five studies did not report on signs of ADHD. The study groups that were compared had between 10 and 25 children per group.

3.3.2.2. Methods and methodological quality. Motor imagery involves the mental rehearsal or simulation of a motor task in the absence of overt movement (Decety, 1996; Sirigu et al., 1995). It exhibits many of the properties of represented action and is considered a valid means of describing the content of internal models for action (Decety and Grezes, 1999; Wilson et al., 2001). The included studies on motor imagery in DCD used two different motor imagery paradigms: mental rotation and mental chronometry. In the mental rotation paradigm, children make judgments on the laterality or identity of stimuli (i.e., hands, whole-body, letter stimuli) displayed at different angles of rotation, and sometimes in different viewpoints as well (i.e., palm and back view for hands). Two outcome measures are generally analyzed: response accuracy and reaction time. Use of mental rotation is inferred when an increase in reaction time occurs with increases in rotation angle of the stimuli. Use of motor imagery is suggested when the biomechanical constraints of the simulated movement are reflected in the response time or error pattern (i.e., prolonged reaction time or decreased accuracy for biomechanically more awkward orientations). Studies that used a mental rotation paradigm enlisted either hand-stimuli (Lust et al., 2006; Williams et al., 2012; Wilson et al., 2004), hand and letter stimuli (Deconinck et al., 2009), hand and whole body stimuli (Williams et al., 2008, 2011) or a combination of hand, whole-body and letter stimuli (Williams et al., 2006). In the studies of Williams et al. (2006, 2008, 2011) the hand rotation and whole-body task was performed with and without explicit motor imagery instruction. With respect to the mental chronometry paradigm, the relation between the duration of real and imagined movements was studied using the visual guided pointing task (VGPT) in four papers (Lewis et al., 2008; Maruff et al., 1999; Williams et al., 2012; Wilson et al., 2001). This task is based on the underlying assumption that the duration of the pointing movements is dependent on the width and the distance of the target, expressed as an index of difficulty (ID) under Fitts' law (Fitts, 1954). When motor imagery is used, the relation between duration and ID should also be evident when participants imagine pointing to the target. In the motor imagery training study of Wilson et al. (2002), children were asked to first observe video's and then imagine the performance of a selection of fundamental motor skills: catching a tennis ball, throwing a tennis ball, striking a softball, jumping to a target using a two-leg take-off, balancing a ball on a bat while walking, and placing objects on a formboard. The methodological quality of the studies on motor imagery was moderate. Only Maruff et al. (1999) and Williams et al. (2012) conformed to all DSM-IV-TR criteria for DCD. In addition, correction for confounds was often incomplete (see Table 2).

3.3.2.3. Results. Results of the mental rotation tasks will be discussed first, followed by results on the mental chronometry task. The studies on mental rotation all had accuracy and response time (RT) as outcome measures. However, only four of the studies that used mental rotation of hands also compared the RTs of lateral versus medial rotations to confirm that motor imagery had been used (Deconinck et al., 2009; Lust et al., 2006; Williams et al., 2011, 2012). Rotating a hand outwards in the lateral direction is biomechanically more challenging than rotating it inwards (or medially); if motor imagery is indeed used, lateral rotations see increased response time and/or reduced accuracy. The other three studies

(Williams et al., 2006, 2008; Wilson et al., 2004) did not compare RTs of lateral versus medial rotations, and therefore, use of visual imagery or other forms of imagery cannot be ruled out. Two studies found that children with DCD were able to perform motor imagery, although slower and less accurate than controls (Deconinck et al., 2009; Williams et al., 2008). The study of Williams et al. (2011) showed that children with DCD performed motor imagery as fast as controls, but less accurately. Three studies demonstrated a weaker tradeoff in DCD between RTs and rotation angle in a similar task (Williams et al., 2006, 2012; Wilson et al., 2004). In the study of Williams et al. (2008) it was found that children with severe DCD ($mABC \leq 5$ th percentile) did not benefit from specific motor imagery instructions, while children with mild DCD ($mABC 6\text{--}15$ th percentile) did. The study of Lust et al. (2006) is the only study reporting that children with DCD performed the hand rotation task as fast and as accurately as controls. In the articles of Williams et al. (2006, 2008, 2011) a whole-body rotation task was also used. The studies of 2008 and 2011 showed an atypical response pattern in DCD, and all three showed reduced accuracy, barely above chance. In addition, Deconinck et al. (2009) and Williams et al. (2006) showed that the DCD groups performed the alphanumeric task as fast and accurately as controls, suggesting preserved visual imagery. The studies on mental chronometry all showed that only for real movements performance did conform to Fitts' law in DCD, while both real and imagined movements did for controls (Lewis et al., 2008; Maruff et al., 1999; Williams et al., 2012; Wilson et al., 2001). Finally, in the training study of Wilson et al. (2002) the imagery protocol was found to be equally effective to perceptual-motor training in facilitating the development of motor skill. It has to be noted that children in this study were classified as motor impaired; not all met the standard research criterion for DCD as a $mABC$ cut-off of the 50th percentile was used.

3.3.3. Primary conclusions

Presented first are conclusions for overt manual control, followed by those for covert manual control. The overt control of manual action has been examined with various tasks. Most of the studies that used visuomotor adaptation (Section 3.3.1.1) suggest that children with DCD are less able to update their internal models for action online. Results on reach-to-grasp in relation to end-state-comfort and subsequent actions (Section 3.3.1.2) were mixed, as were those for lifting tasks (Section 3.3.1.6), although there was the suggestion of difficulties adjusting manual forces to altered constraints. The results on double step pointing task (Section 3.3.1.3) and also the results of the tracing tasks (Section 3.3.1.4) were more straightforward; most studies showed reduced feed-forward planning in the DCD group indicated by slower and less accurate performance. The more controlled studies on rapid online control (Hyde and Wilson, 2011a,b) show that children with DCD have deficits in rapid correction of ongoing movements. Investigation of online control under varying cognitive load will clarify the extent of these difficulties and their implications for function. It was unclear whether explicit exclusion of children with ADHD had any direct impact on results as the results from some studies that did take this measure showed reasonable ability in DCD for forward planning (Law et al., 2011; Zwicker et al., 2010) while others did not (Hyde and Wilson, 2011a,b; Pereira et al., 2001). While behavioral data reported by Zwicker et al. (2010) showed preserved forward planning in DCD during tracing, atypical brain activation patterns were recorded in DCD during performance. Zwicker argued that these patterns show that children with DCD rely more on visuospatial processing to complete the task than the control group. As such it is hard to conclude whether the motor planning deficits that are observed in DCD are not in some way related to symptoms of ADHD. Small sample sizes in many of these studies is contentious; however, effect sizes in many instances are high enough to instill some

confidence about the pattern of performance differences between groups. The lack of control around some confounds does, however, warrant caution. Taken together, studies on manual control showed that children with DCD are impaired on different aspects of forward planning and the online control of hand movements, but that variation does exist within the DCD population, perhaps partly attributable to differing co-morbid conditions, or merely natural heterogeneity within the DCD population. Studies that examined covert movements of the hand (Section 3.3.2) yielded diverse results. Some studies showed that children with DCD are able to use motor imagery, but more slowly and less accurately than controls. Other studies using mental rotation tasks showed a weaker tradeoff between response time and rotation angle, which probably indicates that children with DCD relied more on visual imagery (Wilson et al., 2004). Furthermore, children with DCD were less able to benefit from MI instructions. Only one study showed that the DCD group performed the mental (hand) rotation task in a manner similar to controls (Lust et al., 2006). Results using the visual guided pointing task were consistent in showing that imagined movements in DCD did not conform to Fitt's law. The four studies that excluded children with ADHD all found that motor imagery was impaired in the DCD group (Deconinck et al., 2009; Wilson et al., 2001, 2002; Maruff et al., 1999). Moreover, both Lewis et al. (2008) and Williams et al. (2012) showed that children with ADHD + DCD performed the visual guided pointing task in the same way as controls; Williams et al. (2012) also showed reduced motor imagery capacity only in the DCD group and not in the ADHD + DCD group on the hand rotation task. In sum, these results indicate that motor imagery deficits can be attributed to DCD and that the effect of ADHD is minor. Since the methodological quality of studies on covert manual action was moderate, mainly because DSM-IV-TR criteria were not followed strictly, results should be interpreted with care. In addition, not all studies of mental rotation examined whether performance varied according to biomechanical or postural constraints.

3.4. Dynamic postural control: Anticipatory adjustments

3.4.1. Study characteristics

Dynamic postural control was addressed in two studies that examined anticipatory postural adjustments during load lifting. Children in these two studies were aged 5–13 years (Jover et al., 2010) and 8–11 years (Jucaite et al., 2003). Jover and colleagues used an inclusion criterion, $mABC$ score <5 th percentile, while Jucaite and colleagues used <15 th percentile. The study of Jucaite examined the adaptation to different loads during a lifting task in children with DCD, ADHD, ADHD + DCD and controls. The DCD group in these studies consisted of 12 (Jucaite et al., 2003) and 16 children, respectively (Jover et al., 2010).

3.4.2. Methods and methodological quality

Jover et al. (2010) investigated anticipatory postural adjustments (APAs) using a bimanual load-lifting task. Using a hand-held weight (either 300 or 450 g), the task consisted of the unloading of the forearm by the voluntary movement of the child's other arm. This task requires feedforward control in that smooth performance presupposes both accurate representation of the load and coordination between limbs as a function of the changing forces that result through loading and unloading. Only with an accurate prediction of the changing biomechanics of the limbs is it possible to minimize the disruption of forearm position at the point of unloading. By comparison, a deficit of predictive control would result in imprecise and variable APAs, as observed. In the study of Jucaite et al. (2003) APAs were investigated by means of a unimanual load-lifting task using four different weights, 300, 700, 500 and 1000 g. The methodological quality of these two studies was moderate: description of DSM-IV-TR criteria for the DCD group and control of confounds was

incomplete and statistical results were not precisely presented (see Table 2).

3.4.3. Results

[Jover et al. \(2010\)](#) showed that although children with DCD could compensate for the consequences of unloading, there APAs were less efficient than controls. In addition, [Jucaite et al. \(2003\)](#) showed that the children with DCD and ADHD did not scale manual and postural forces appropriately in amplitude and showed delayed timing of postural adjustments.

3.4.4. Primary conclusions

Both studies showed poor stabilization of manual and postural forces demonstrating poor predictive modeling in DCD. However, it should be kept in mind that the methodological quality of the studies was moderate, and only two studies addressed dynamic postural control in DCD.

4. Discussion

The internal modeling deficit (IMD) hypothesis states that children with DCD have difficulties generating or implementing predictive models of action ([Wilson and Butson, 2007](#)). A difficulty of this type would severely hamper motor control and learning because internal models are thought to provide stability to the motor system by utilizing (fast) internal feedback loops before slow sensorimotor feedback becomes available ([Wolpert, 1997](#)). The IMD hypothesis was examined thoroughly in the review presented here. As development of internal models is specific to the effector system involved ([Kawato, 1999; Wolpert and Miall, 1996](#)), we discuss our principle findings according to the effector system involved: oculomotor control and attention (Section 4.1), control of manual action (Section 4.2) or dynamic postural control (Section 4.3).

4.1. Visuospatial attention and oculomotor control

Studies of overt and covert orienting of visuospatial attention were included in this systematic review. The results of studies on overt orienting showed that children with DCD have problems with the forward planning of eye movements. More specifically, they were less able to plan double-step saccades when reliant on forward estimates of eye position/fixation ([Katschmarsky et al., 2001](#)) and less able to temporally synchronize their eye tracking to the stimulus ([Langgaas et al., 1998](#)). In the studies of [Wilmut et al. \(2007\)](#) and [Wilmut and Wann \(2008\)](#) children with DCD were slower to disengage attention and used an inefficient control strategy by first fixating the target before starting the limb movement. Generalization of the results of these four studies is difficult, however, because not all DSM-IV-TR criteria for a diagnosis DCD were fulfilled and correction for confounds (age, gender, ADHD, learning problems) was incomplete. Studies of covert orienting tested the endogenous mode of attention, the exogenous mode, or both. Covert attentional shifts are tightly coupled to the process of programming saccadic eye movements to the location of visual cues ([Maruff et al., 1999](#)). Covert orienting mirrors the process of setting the spatial coordinates for an intended action in 3-D space. Delayed disengagement of attention from invalid (or non-informative) cues will impair this aspect of predictive control ([Geuze, 2007](#)). Importantly, all studies that examined the endogenous mode of control showed performance deficits in DCD, interpreted mainly as a problem of attentional disengagement. [Tsai et al. \(2010, 2012\)](#) also reported that children with DCD were disadvantaged by cues presented near central fixation, and suggested, first, that this reflected a deficit of inhibitory control and, second, that the used mode of control during this task was largely automatic. This hypothesis remains open to

debate. When combined with information about the probability of valid cues, a more likely hypothesis is that children with DCD have problems with the voluntary re-orienting of visuospatial attention (i.e., endogenous mode). Nonetheless, because a number of studies on visuospatial attention did not fulfill criteria B and/or C of the DSM-IV-TR and did not correct for all confounding factors, care should be taken when interpreting the results. Conclusions about the influence of the high comorbidity of ADHD are given in Section 4.5.

4.2. Control of manual action

Aspects of internal modeling are also involved in tasks that have been used traditionally to assess motor planning. Motor planning can be defined as the formulation of a strategy of action taking into account the future demands associated with the goal of the action ([Gentilucci et al., 1997; Johnson-Frey et al., 2004](#)). Motor planning appeared to be impaired in DCD on most but not all tasks. Tests of visuomotor adaptation showed that children with DCD are less able to adapt their movement to different task constraints. This was shown by a higher variability, lower accuracy and/or longer movement durations. Additionally, two studies showed that the after-effect of visuomotor perturbation was reduced in DCD ([Cantini et al., 2007; Kagerer et al., 2004](#)). For end-state-comfort planning results were conflicting. Other work showed a consistent pattern of impairment in DCD. The study on double step pointing showed that children with DCD were less able to enlist a feedforward mode of control ([Wilmut et al., 2006](#)). Most tracking tasks also showed a reduced ability to predict the forward motion of a moving target by tracing ([De Oliveira and Wann, 2010; Kashiwagi et al., 2009](#)). Results for load-lifting tasks were mixed: two studies ([Pereira et al., 2001; Law et al., 2011](#)) showed an ability in DCD to adapt the force output to different frictional properties, but Law et al. showed a lower rate of grip force generation, perhaps linked to a reduced sensitivity to dynamic tactile information. Whether manual force generation issues are linked specifically to predictive control or are a function of more basic sensory processing issues, or both, remains an issue of debate. Deficits of online control have been shown in DCD in two studies using double-step reaching paradigms ([Hyde and Wilson, 2011a,b](#)). While [Plumb et al. \(2008\)](#) failed to detect a deficit in online control in DCD, the methodological quality of this study was low since task constraints differed for DCD and control groups. Motor imagery (that is covert action) was tested using two classes of paradigm: mental rotation and mental chronometry. It is important to note that the extent to which motor imagery is enlisted is not an 'all-or-nothing' phenomenon. Results suggest that motor imagery is accessible to children with DCD, but less refined/developed compared with healthy controls. This was certainly evident in the results of our review. Most studies found that children with DCD were able to perform motor imagery, but with the rate of mental transformation slower and less accurate than controls ([Deconinck et al., 2009; Williams et al., 2006, 2008, 2012; Wilson et al., 2004](#)). Overall, it seems that children with DCD can enlist motor imagery adequately for simple tasks, but it may be used less consistently than in children without DCD. As such, like motor planning tasks, it is important to vary systematically the complexity of motor imagery tasks in order to assess the particular capabilities of the child with DCD. Studies that used the visual guided pointing task all showed problems of explicit motor imagery in DCD as the pattern of response did not conform to Fitts' Law. Interestingly, deficits of this type have been interpreted to reflect a problem of body schema and, associated with this, the ability to model prospective changes in the egocentric representation of space ([Schwoebel et al., 2001](#)). The body schema is a multimodal construct derived from the correlated forms of sensory input – including visual, tactile, kinesthetic and vestibular – as

well as outflow from muscle afferents that also signal prospective changes in body orientation. Indeed, it would be more correct to say that dynamic body schema can only be derived when sensory inputs and the anticipated sensory consequences of self-motion can be integrated in a veridical and harmonious fashion (Miall and Wolpert, 1996; Grush, 2004). It is possible, however, that the mere disruption of multimodal integration could have profound implications for the development and the learning of prospective control and skill. This suggestion warrants an interesting hypothesis for future study. Motor imagery is also proposed to be a backdoor mechanism that emulates the motor system (Grush, 2004; Sharma et al., 2006). As such, motor imagery can be enlisted voluntarily to reinforce the relationship between (simulated) motor output signals and the resultant behavior of the physical system. Supporting this view, the translation of motor imagery training into improved skill and function is pervasive in both the motor learning and rehabilitation literature. In the case of DCD, this was confirmed by the motor imagery training study of Wilson et al. (2002) who showed training effects comparable to conventional physical therapy. We argue that the mechanism of change has to do with the training of predictive models of action with repeated mental simulation. Taken together, those studies that addressed motor imagery showed deficits in children with DCD. In future research it is important to also consider whether tasks were executed according to biomechanical and postural constraints to confirm the use of motor imagery. The CASP scores showed that correction for confounds was limited in most studies on manual control, criteria B and C for DCD in DSM-IV-TR were often not described, and precise statistical results not always presented. Replication studies using tighter experimental control and screening is suggested and much needed in future work. Notwithstanding this, deficits of predictive control on a range of manual tasks suggest sufficient evidence in favor of the IMD account, although the magnitude of this deficit appears to vary with task complexity. In the backdrop of pediatric neurology, DCD remains a relatively mild motor disorder, one best revealed by use of complex manual tasks, preferably with a requirement for sequential or multi-step actions, or under high spatiotemporal constraints. For example, two of the three studies on reach-to-grasp under different visual conditions showed difficulties in adapting action to different task constraints (Biancotto et al., 2011; Smyth et al., 2001). In both studies children had to grasp and lift an object of varying size over a range of distances. By comparison, using a relatively simple, discrete aiming task involving sensorimotor adaptation, King et al. (2011) failed to show impairment in DCD using linear modeling; however, deficits were revealed using more sophisticated multi-level modeling. These examples highlight two important points: first, the importance of task selection and task complexity in identifying motor control problems, and second, the choice of statistical analysis, with those offering resolution at both group and individual levels preferable.

4.3. Dynamic postural control

Two studies measured anticipatory postural adjustments (APAs) (Jover et al., 2010; Jucaite et al., 2003). Both studies showed that although children with DCD could compensate for the consequences of unloading, that their APAs were less efficient than controls. Children with DCD also showed delayed timing of postural adjustments. These results suggest difficulties with the forward modeling of postural adjustments. However, they should be interpreted with caution because only two studies on dynamic postural control were found and the methodological quality of these two studies was low. Repetition of these experiments, observing full DSM-IV-TR criteria for DCD, correction for confounds, and presentation of precise statistical results is warranted.

4.4. Internal models for different effector systems

Overall, it appears that the process of internal modeling when using different effector systems (oculomotor, manual and postural control) is impaired in children with DCD. In addition, control of not only the overt movement of the eyes and hand is impaired, but also covert movement (orienting of visuospatial attention and motor imagery). Upon reviewing all the studies sampled, it is suggested that the internal modeling deficit observed in children with DCD is more a central deficit rather than one specific to a certain effector system. Several authors (see Hill, 2005, for a review) have also promoted the idea that the deficit in timekeeper processes observed in DCD is also a more central problem rather than a defect in motor output implementation at a peripheral level.

4.5. Additional remarks on the included studies

It is well possible that impaired visuomotor integration may be an epiphenomenon that affected the results in all tasks. The earlier meta-analysis of Wilson and McKenzie (1998) showed that the most frequently observed deficit in DCD involved the processing of visual information. In most tasks, target location and/or the visual perturbation must be processed before the final set of motor commands can be implemented in order to achieve the desired end-state. Whether the processing issue is more a question of purely mapping the motor commands from perceptual input, or predicting perceptual outcomes based on a given set of motor commands, or both, remains an important question for future work that may be advanced by neuroimaging methods. Most of the studies included had a sample size of 20 or less per group. Those on manual control tended to have smaller samples (sometimes <10 participants per group). The expected effect sizes for some were sufficient to warrant this, but for others statistical power was low. By comparison, studies on the covert orienting of attention had rather large sample sizes, often with 25 or more children per group. Generalization of the results was constrained somewhat by variation in the use of inclusion and exclusion criteria for the DCD group. Twenty-two studies used a mABC score at or below the 15th percentile to indicate motor impairment, while 14 used a <or ≤5th percentile. In particular, it was not indicated whether DCD groups conformed to criteria B and C of the DSM-IV-TR which relate to the motor impairment interfering with daily activities or academic achievement and to the exclusion of medical conditions. Only five studies excluded children on the basis of a formal examination that identified medical and neurological conditions (Chen et al., 2012; Deconinck et al., 2009; King et al., 2011; Van Swieten et al., 2010; Wilmut and Wann, 2008). Other studies that fulfilled criteria C did so by using questionnaires or interviews. Notably, the more recent studies adhered more tightly to DSM-IV-TR criteria for DCD. Fifteen studies included in this review used ADHD as exclusion criteria for the DCD group. Twelve of these showed that the DCD group had problems with the forward modeling of movements. Four studies included in this review had a separate DCD and ADHD+DCD group (Jucaite et al., 2003; Lewis et al., 2008; Pereira et al., 2001; Williams et al., 2012). All four studies showed that the DCD group was impaired in the forward modeling of movements. However, it was intriguing to note that the ADHD+DCD group showed better performance than the DCD group in three studies. In sum, there is good evidence that the difficulties that are observed with the predictive control of movements in children with DCD are directly associated with the motor skill learning problem itself and not with issues associated with comorbid ADHD.

4.6. Recommendations for the future

The present systematic review reveals that children with DCD have problems with the predictive control of movement across

effector systems, supporting the IMD hypothesis. This systematic review also highlighted a number of pointers and avenues that are important for future research to clarify the IMD hypothesis further. First, task complexity should be varied systematically. Low complexity in terms of stimulus-response mapping for example, may be insufficient to identify problems of predictive control; variation of tasks in terms of their dual-task or attentional load, as well as the number and combination of effector units involved or subtasks to be fulfilled, would help disentangle the extent of underlying motor control issue. Put another way, this variation in task presentation would help define whether children with DCD have a broad-based control issue across tasks and response modalities (e.g., eye movement control, manual control or postural control) or whether a milder form of deficit exists, only becoming evident for complex tasks. This will also inform therapy and training for these children. Second, there is a distinct need to investigate the development of predictive control over time using sophisticated longitudinal designs; this would afford use of growth curve modeling and similar procedures that better account for individual variability and accommodate missing data. Third, assessment of predictive control in the context of activities of daily living would prove insightful. Fourth, cross-validation using a variation of paradigms would provide strong evidence for the IMD account; e.g., use of implicit and explicit measures of motor imagery, together with (simulated) estimates of reach extent. Fifth, at the level of group composition and recruitment, we recommend power analysis for more speculative hypothesis testing, exclusion of comorbid ADHD, more consistent use of inclusion criteria for the DCD, and more standardized screening tools (Leeds Consensus Statement; Sugden et al., 2006), enabling better inter-study comparison.

4.7. General conclusions

This is the first systematic review to examine specifically studies on the internal modeling of movements (i.e., predictive control) in children with DCD. Even conservatively, there is moderate support for deficits of predictive control in DCD which manifest across effector systems. The evidence for a deficit in the overt and covert control of eye movements, as well as covert manual action (motor imagery) was consistent and quite compelling. Results for overt manual control tasks, while more variable, showed deficits under more complex task constraints, and those for dynamic postural control, while limited to two studies, showed sufficient evidence for abnormalities of predictive control. In general, the effects observed tended to be greater for tasks that required more top-down or explicit control. Methodological differences between studies were shown to limit comparisons in a number of cases. Overall, the generalized pattern of deficit in predictive control that was found, together with moderating factors, provide very specific and informed avenues for future research.

References

- Ahmed, A.A., Wolpert, D.M., 2009. Transfer of dynamic learning across postures. *J. Neurophysiol.* 102, 2816–2824.
- American Psychiatric Association, 1987. *Diagnostic and Statistical Manual of Mental Disorders, third ed., revised*. American Psychiatric Association, Washington, DC.
- American Psychiatric Association, 1994. *Diagnostic and Statistical Manual of Mental Disorders, fourth ed.* American Psychiatric Association, Washington, DC.
- American Psychiatric Association, 2000. *Diagnostic and Statistical Manual of Mental Disorders, fourth ed., text revision*. American Psychiatric Association, Washington, DC.
- American Psychiatric Association, 2013. *Diagnostic and Statistical Manual of Mental Disorders, fifth ed.* American Psychiatric Association, Washington, DC.
- Ariff, G., Donchin, O., Nanyakatura, T., Shadmehr, R., 2002. A real-time state predictor in motor control study of saccadic eye movements during unseen reaching movements. *J. Neurosci.* 22, 7721–7729.
- Beery, K.E. (Ed.), 1998. *The VMI Developmental Test of Visuo-motor Integration. Modern Curriculum Press*, Cleveland.
- Biancotto, M., Skabar, A., Bulgheroni, M., Carrozza, M., Zoia, S., 2011. Neuromotor deficits in developmental coordination disorder: evidence from a reach-to-grasp task. *Res. Dev. Disabil.* 32 (4), 1293–1300, <http://dx.doi.org/10.1016/j.ridd.2011.02.007>.
- Blakemore, S.J., Sirigu, A., 2003. Action prediction in the cerebellum and in the parietal lobe. *Exp. Brain Res.* 153 (2), 239–245, <http://dx.doi.org/10.1007/s00221-003-1597-z>.
- Blakemore, S.J., Frith, C.D., Wolpert, D.M., 2001. The cerebellum is involved in predicting the sensory consequences of action. *NeuroReport* 12 (9), 1879–1884.
- Bo, J., Bastian, A.J., Kagerer, F.A., Contreras-Vidal, J.L., Clark, J.E., 2008. Temporal variability in continuous versus discontinuous drawing for children with Developmental Coordination Disorder. *Neurosci. Lett.* 431 (3), 215–220, DOI S0304-3940(07)01240-2.
- Brookes, R.L., Nicolson, R.I., Fawcett, A.J., 2007. Prisms throw light on developmental disorders. *Neuropsychologia* 45 (8), 1921–1930, DOI S0028-3932(06)00455-6.
- Bruininks, R.H., Bruininks, D.D., 2005. *Bruininks–Oseretsky Test of Motor Proficiency (Second Edition (BOT-2) Brief Form)*. Pearson, MN, USA.
- Bubic, A., von Cramon, D.Y., Schubotz, R.I., 2010. Prediction, cognition and the brain. *Front. Hum. Neurosci.* 4, 25, <http://dx.doi.org/10.3389/fnhum.2010.00025>.
- Cantin, N., Polatajko, H.J., Thach, W.T., Jaglal, S., 2007. Developmental coordination disorder: exploration of a cerebellar hypothesis. *Hum. Mov. Sci.* 26 (3), 491–509, DOI S0167-9457(07)00025-5.
- CASP, 2010a. Critical Appraisal Skills Programme – Making Sense of Evidence About Clinical Effectiveness – Case-control Studies. CASP, From (http://www.casp-uk.net/wp-content/uploads/2011/11/CASP.Case-Control_Appraisal_Checklist_14Oct10.pdf).
- CASP, 2010b. Critical Appraisal Skills Programme – Making Sense of Evidence About Clinical Effectiveness – Cohort Study. CASP, From (http://www.casp-uk.net/wp-content/uploads/2011/11/CASP.Cohort_Appraisal_Checklist_14Oct10.pdf).
- Chen, W.Y., Wilson, P.H., Wu, S.K., 2012. Deficits in the covert orienting of attention in children with Developmental Coordination Disorder: does severity of DCD count? *Res. Dev. Disabil.* 33 (5), 1516–1522, <http://dx.doi.org/10.1016/j.ridd.2012.03.005>.
- Ciccarelli, O., Toosy, A.T., Marsden, J.F., Wheeler-Kingshott, C.M., Sahayoun, C., Matthews, P.M., et al., 2005. Identifying brain regions for integrative sensorimotor processing with ankle movements. *Exp. Brain Res.* 166, 31–42, DOI S0891-4222(12)00060-1.
- Clements, S.D., Peters, J.E., 1962. Minimal brain dysfunctions in the school-age child. *Diagnosis and treatment. Arch. Gen. Psychiatry* 6, 185–197.
- Cohen, R.G., Rosenbaum, D.A., 2004. Where grasps are made reveals how grasps are planned: generation and recall of motor plans. *Exp. Brain Res.* 157, 486–495, <http://dx.doi.org/10.1007/s00221-004-1862-9>.
- Davis, N.M., Ford, G.W., Anderson, P.J., Doyle, L.W., 2007. Developmental coordination disorder at 8 years of age in a regional cohort of extremely-low-birthweight or very preterm infants. *Dev. Med. Child Neurol.* 49 (5), 325–330, DOI DMCN325.
- Davidson, P.R., Wolpert, D.M., 2005. Widespread access to predictive models in the motor system: a short review. *J. Neural Eng.* 2 (3), S313–S319.
- De Oliveira, R.F., Wann, J.P., 2010. Integration of dynamic information for visuomotor control in young adults with developmental coordination disorder. *Exp. Brain Res.* 205 (3), 387–394, <http://dx.doi.org/10.1007/s00221-010-2373-5>.
- Decety, J., 1996. The neurophysiological basis of motor imagery. *Behav. Brain Res.* 77 (1–2), 45–52.
- Decety, J., Grezes, J., 1999. Neural mechanisms subserving the perception of human actions. *Trends Cogn. Sci.* 3 (5), 172–178, DOI S1364-6613(99)01312-1.
- Deconinck, F.J., Spitaels, L., Fias, W., Lemoir, M., 2009. Is developmental coordination disorder a motor imagery deficit? *J. Clin. Exp. Neuropsychol.* 31 (6), 720–730, <http://dx.doi.org/10.1080/13803390802484805906196401>.
- Desmurget, M., Grafton, S., 2003. Feedback or feedforward control: end of a dichotomy. In: Johson-Frey, S.H.E. (Ed.), *Taking Action: Cognitive Neuroscience Perspectives on Intentional Acts*. MIT Press, Cambridge, MA, pp. 289–338.
- Fitts, P.M., 1954. The information capacity of the human motor system in controlling the amplitude of movement. *J. Exp. Psychol.* 47 (6), 381–391.
- Gentilucci, M., Negrotti, A., Gangitano, M., 1997. Planning an action. *Exp. Brain Res.* 115 (1), 116–128.
- Geuze, R.H. (Ed.), 2007. *Developmental Coordination Disorder: A Review of Current Approaches*. Solal Editeurs, Marseille.
- Gilger, J.W., Kaplan, B.J., 2001. Atypical brain development: a conceptual framework for understanding developmental learning disabilities. *Dev. Neuropsychol.* 20 (2), 465–481, http://dx.doi.org/10.1207/S15326942DN2002_2.
- Goyen, T.A., Lui, K., 2009. Developmental coordination disorder in “apparently normal” schoolchildren born extremely preterm. *Arch. Dis. Child.* 94 (4), 298–302, <http://dx.doi.org/10.1136/adc.2007.134692>.
- Grush, R., 2004. The emulation theory of representation: motor control, imagery and perception. *Behav. Brain Sci.* 27 (3), 377–396.
- Hadders-Algra, M., 2002. Two distinct forms of minor neurological dysfunction: perspectives emerging from a review of data of the Groningen Perinatal Project. *Dev. Med. Child Neurol.* 44 (8), 561–571.
- Hellgren, L., Gillberg, C., Gillberg, I.C., Enerskog, I., 1993. Children with deficits in attention motor control and perception (DAMP) almost grown up—general health at 16 years. *Dev. Med. Child Neurol.* 35 (10), 881–892.
- Henderson, S.E., Sugden, D.A. (Eds.), 1992. *Movement Assessment Battery for Children. The Psychological Cooperation*, Sidcup, UK.
- Hill, E.L., 2005. The planning and organisation of action and activities of daily living in developmental coordination disorder. In: Sugden, D., Chambers, M. (Eds.), *Children with Developmental Coordination Disorder*. Whurr Publishers, London, pp. 47–51.

- Hill, E.L., Wing, A.M., 1999. Coordination of grip force and load force in developmental coordination disorder: a case study. *Neurocase* 5 (6), 537–544, DOI 10.1080/13554799008402749.
- Holsti, L., Grunau, R.V., Whitfield, M.F., 2002. Developmental coordination disorder in extremely low birth weight children at nine years. *J. Dev. Behav. Pediatr.* 23 (1), 9–15.
- Hyde, C., Wilson, P., 2011a. Online motor control in children with developmental coordination disorder: chronometric analysis of double-step reaching performance. *Child Care Health Dev.* 37 (1), 111–122, <http://dx.doi.org/10.1111/j.1365-2214.2010.01131.x>.
- Hyde, C., Wilson, P.H., 2011b. Dissecting online control in Developmental Coordination Disorder: a kinematic analysis of double-step reaching. *Brain Cogn.* 75 (3), 232–241, <http://dx.doi.org/10.1016/j.bandc.2010.12.004>.
- Jeannerod, M., 2006. *Motor Cognition What Actions Tell the Self*. Oxford University Press, Oxford.
- Johnson-Frey, S.H., McCarty, M.E., Keen, R., 2004. Reaching beyond spatial perception: effects of intended future actions on visually guided prehension. *Vis. Cogn.* 11 (2–3), 371–399, <http://dx.doi.org/10.1080/13506280344000329>.
- Johnson, D.C., Wade, M.G., 2009. Children at risk for developmental coordination disorder: judgement of changes in action capabilities. *Dev. Med. Child Neurol.* 51 (5), 397–403, <http://dx.doi.org/10.1111/j.1469-8749.2008.03174.x>.
- Joinides, J., 1981. Voluntary versus automatic control over the mind's eye's movement. In: Long, J.B., Baddeley, A.D. (Eds.), *Attention and Performance*, Vol. IX. Lawrence Erlbaum, Hillsdale, NJ, pp. 187–203.
- Jover, M., Schmitz, C., Centelles, L., Chabrol, B., Assaiaante, C., 2010. Anticipatory postural adjustments in a bimanual load-lifting task in children with developmental coordination disorder. *Dev. Med. Child Neurol.* 52 (9), 850–855, <http://dx.doi.org/10.1111/j.1469-8749.2009.03611.x>.
- Jucaite, A., Fernald, E., Forssberg, H., Hadders-Algra, M., 2003. Deficient coordination of associated postural adjustments during a lifting task in children with neurodevelopmental disorders. *Dev. Med. Child Neurol.* 45 (11), 731–742.
- Kagerer, F.A., Bo, J., Contreras-Vidal, J.L., Clark, J.E., 2004. Visuomotor adaptation in children with developmental coordination disorder. *Motor Control* 8 (4), 450–460.
- Kagerer, F.A., Contreras-Vidal, J.L., Bo, J., Clark, J.E., 2006. Abrupt, but not gradual visuomotor distortion facilitates adaptation in children with developmental coordination disorder. *Hum. Mov. Sci.* 25 (4–5), 622–633, DOI S0167-9457(06)00055-8.
- Kaplan, B.J., Wilson, B.N., Dewey, D., Crawford, S.G., 1998. DCD may not be a discrete disorder. *Hum. Mov. Sci.* 17 (4–5), 471–490, [http://dx.doi.org/10.1016/S0167-9457\(98\)00010-4](http://dx.doi.org/10.1016/S0167-9457(98)00010-4).
- Kapreli, E., Athanasopoulos, S., Papathanasiou, M., Van Hecke, P., Strimpakos, N., Gouliamos, A., et al., 2006. Lateralization of brain activity during lower limb joints movement. An fMRI study. *NeuroImage* 32, 1709–1721.
- Kashiwagi, M., Iwaki, S., Narumi, Y., Tamai, H., Suzuki, S., 2009. Parietal dysfunction in developmental coordination disorder: a functional MRI study. *NeuroReport* 20 (15), 1319–1324, <http://dx.doi.org/10.1097/WNR.0b013e32832f4d87>.
- Katschmarsky, S., Cairney, S., Maruff, P., Wilson, P.H., Currie, J., 2001. The ability to execute saccades on the basis of efference copy: impairments in double-step saccade performance in children with developmental co-ordination disorder. *Exp. Brain Res.* 136 (1), 73–78.
- Kauranen, K.J., Vanharanta, H.V., 2001. Relationship between extremities in motor performance. *Percept. Mot. Skills* 92, 11–18.
- Kawato, M., 1999. Internal models for motor control and trajectory planning. *Curr. Opin. Neurobiol.* 9 (6), 718–727, DOI S0959-4388(99)00028-8.
- King, B.R., Kagerer, F.A., Harring, J.R., Contreras-Vidal, J.L., Clark, J.E., 2011. Multisensory adaptation of spatial-to-motor transformations in children with developmental coordination disorder. *Exp. Brain Res.* 212 (2), 257–265, <http://dx.doi.org/10.1007/s00221-011-2722-z>.
- Landis, J.R., Koch, G.G., 1977. The measurement of observer agreement for categorical data. *Biometrics* 33 (1), 159–174.
- Langaas, T., Mon-Williams, M., Wann, J.P., Pascal, E., Thompson, C., 1998. Eye movements, prematurity and developmental co-ordination disorder. *Vision Res.* 38 (12), 1817–1826, DOI S0042698997003994.
- Law, S.H., Lo, S.K., Chow, S., Cheung, G.L., 2011. Grip force control is dependent on task constraints in children with and without developmental coordination disorder. *Int. J. Rehabil. Res.* 34 (2), 93–99, <http://dx.doi.org/10.1097/MRR.0b013e32833f0519>.
- Lewis, M., Vance, A., Maruff, P., Wilson, P., Cairney, S., 2008. Differences in motor imagery between children with developmental coordination disorder with and without the combined type of ADHD. *Dev. Med. Child Neurol.* 50 (8), 608–612, <http://dx.doi.org/10.1111/j.1469-8749.2008.03030.x>.
- Lust, J.M., Geuze, R.H., Wijers, A.A., Wilson, P.H., 2006. An EEG study of mental rotation-related negativity in children with Developmental Coordination Disorder. *Child Care Health Dev.* 32 (6), 649–663, DOI CCH683 10.1111/j.1365-2214.2006.00683.x.
- Mak, M.K., 2010. Reaching and grasping a moving target is impaired in children with developmental coordination disorder. *Pediatr. Phys. Ther.* 22 (4), 384–391, DOI 10.1097/PEP.0b013e3181f9d88500001577-201022040-00007.
- Mandich, A., Polatajko, H.J., 2003. Developmental coordination disorder: mechanisms, measurement and management. *Hum. Mov. Sci.* 22 (4–5), 407–411, DOI S0167945703000630.
- Maruff, P., Wilson, P., Trebilcock, M., Currie, J., 1999. Abnormalities of imaged motor sequences in children with developmental coordination disorder. *Neuropsychologia* 37 (11), 1317–1324, DOI S0028393299000160.
- McCarron, L.T., 1997. *MAND McCarron Assessment of Neuromuscular Development: Fine and Gross Motor Abilities*. Common Market Press, Dallas, TX.
- Miall, R.C., Wolpert, M., 1996. Forward models for physiological motor control. *Neural Netw.* 9 (8), 1265–1279.
- Missiuna, C., Gaines, R., McLean, J., DeLaat, D., Egan, M., Soucie, H., 2008. Description of children identified by physicians as having developmental coordination disorder. *Dev. Med. Child Neurol.* 50 (11), 839–844, <http://dx.doi.org/10.1111/j.1469-8749.2008.03140.x>.
- Nicolson, R.I., Fawcett, A.J., Dean, P., 2001. Developmental dyslexia: the cerebellar deficit hypothesis. *Trends Neurosci.* 24 (9), 508–511, DOI S0166-2236(00)01896-8.
- Pereira, H.S., Landgren, M., Gillberg, C., Forssberg, H., 2001. Parametric control of fingertip forces during precision grip lifts in children with DCD (developmental coordination disorder) and DAMP (deficits in attention motor control and perception). *Neuropsychologia* 39 (5), 478–488, DOI S0028-3932(00)00132-9.
- Plumb, M.S., Wilson, A.D., Mulrouse, A., Brockman, A., Williams, J.H., Mon-Williams, M., 2008. Online corrections in children with and without DCD. *Hum. Mov. Sci.* 27 (5), 695–704, <http://dx.doi.org/10.1016/j.humov.2007.11.004>.
- Posner, M.I., 1980. Orienting of attention. *Q. J. Exp. Psychol.* 32 (1), 3–25.
- Posner, M.I., 1988. Structures and function of selective attention. In: Boll, T., Bryant, D.K. (Eds.), *Clinical Neuropsychology and Brain Function: Research, Assessment and Practice*. American Psychological Association, Washington, DC, pp. 173–202.
- Rasmussen, P., Gillberg, C., 2000. Natural outcome of ADHD with developmental coordination disorder at age 22 years: a controlled, longitudinal, community-based study. *J. Am. Acad. Child Adolesc. Psychiatry* 39 (11), 1424–1431, DOI S0890-8567(00)60192-1.
- Rizzolatti, G., Riggio, L., Dascola, I., Umiltà, C., 1987. Reorienting attention across the horizontal and vertical meridians: evidence in favor of a premotor theory of attention. *Neuropsychologia* 25, 31–40.
- Rizzolatti, G., Riggio, L., Sheliga, B.M., 1994. Space and selective attention. In: Umiltà, C., Moscovitch, M. (Eds.), *Attention and Performance XV*. MIT Press, Cambridge, MA, pp. 231–265.
- Rosenbaum, D.A., Vaughan, J., Barnes, H.J., Jorgensen, M.J., 1992. Time course of movement planning: selection of hand grips for object manipulation. *J. Exp. Psychol.: Learn. Mem. Cogn.* 15, 1058–1073.
- Rosenbaum, D.A., van Heugten, C.M., Caldwell, G.E., 1996. From cognition to biomechanics and back: the end-state comfort effect and the middle-is-faster effect. *Acta Psychol.* 94, 59–85.
- Schwoebel, J., Friedman, R., Duda, N., Coslett, H.B., 2001. Pain and the body schema—evidence for peripheral effect on mental presentation of movement. *Brain* 124, 2098–2104.
- Shadmehr, R., Smith, M.A., Krakauer, J.W., 2010. Error correction, sensory prediction, and adaptation in motor control. *Annu. Rev. Neurosci.* 33, 89–108, DOI 10.1146/annurev-neuro-060909-153135.
- Sharma, N., Pomery, V.M., Baron, J.C., 2006. Motor imagery: a backdoor to the motor system after stroke? *Stroke* 37 (7), 1941–1952, DOI 01 STR. 0000226902.43357.fc.
- Sirigu, A., Cohen, L., Duhamel, J.R., Pillon, B., Dubois, B., Agid, Y., Pierrot-Deseilligny, C., 1995. Congruent unilateral impairments for real and imagined hand movements. *NeuroReport* 6 (7), 997–1001.
- Smyth, M.M., Anderson, H.I., Churchill, A.C., 2001. Visual information and the control of reaching in children: a comparison between children with and without developmental coordination disorder. *J. Mot. Behav.* 33 (3), 306–320, <http://dx.doi.org/10.1080/00222890109601916>.
- Smyth, M.M., Mason, U.C., 1997. Planning and execution of action in children with and without developmental coordination disorder. *J. Child Psychol. Psychiatry* 38 (8), 1023–1037.
- Sugden, D., Chambers, M., Utley, A., 2006. *Developmental Coordination Disorder as a Specific Learning Difficulty*. ESRC Seminar Series, Swindon, UK.
- Sugden, D.A., Chambers, M.E., 2006. Stability and change in children with developmental coordination disorder. *Child Care Health Dev.* 33, 520–528.
- Tresilian, J., 2012. *Sensorimotor Control & Learning. An introduction to the Behavioral Neuroscience of Action*. Palgrave MacMillan, Hampshire, UK.
- Tsai, C.L., 2009. The effectiveness of exercise intervention on inhibitory control in children with developmental coordination disorder: using a visuospatial attention paradigm as a model. *Res. Dev. Disabil.* 30 (6), 1268–1280, <http://dx.doi.org/10.1016/j.ridd.2009.05.001>.
- Tsai, C.L., Pan, C.Y., Chang, Y.K., Wang, C.H., Tseng, K.D., 2010. Deficits of visuospatial attention with reflexive orienting induced by eye-gazed cues in children with developmental coordination disorder in the lower extremities: an event-related potential study. *Res. Dev. Disabil.* 31 (3), 642–655, <http://dx.doi.org/10.1016/j.ridd.2010.01.003>.
- Tsai, C., Pan, C., Chering, R., Hsu, Y., Chiu, H., 2009b. Mechanisms of deficit of visuospatial attention shift in children with developmental coordination disorder: a neurophysiological measure of the endogenous Posner paradigm. *Brain Cogn.* 71, 246–258.
- Tsai, C.L., Yu, Y.K., Chen, Y.J., Wu, S.K., 2009a. Inhibitory response capacities of bilateral lower and upper extremities in children with developmental coordination disorder in endogenous and exogenous orienting modes. *Brain Cogn.* 69 (2), 236–244, <http://dx.doi.org/10.1016/j.bandc.2008.07.012>.
- Tsai, C.L., Wang, C.H., Tseng, Y.T., 2012. Effects of exercise intervention on event-related potential and task performance indices of attention networks in children with developmental coordination disorder. *Brain Cogn.* 79 (1), 12–22, <http://dx.doi.org/10.1016/j.bandc.2012.02.004>.
- Van Swieten, L.M., van Bergen, E., Williams, J.H., Wilson, A.D., Plumb, M.S., Kent, S.W., Mon-Williams, M.A., 2010. A test of motor (not executive) planning in

- developmental coordination disorder and autism. *J. Exp. Psychol. Hum. Percept. Perform.* 36 (2), 493–499, <http://dx.doi.org/10.1037/a0017177>.
- Wechsler, D. (Ed.), 1992. *Wechsler intelligence scale for children*, , third ed. The Psychological Corporation, Sidcup, Kent, UK.
- Williams, J., Anderson, V., Reddihough, D.S., Reid, S.M., Vijayakumar, N., Wilson, P.H., 2011. A comparison of motor imagery performance in children with spastic hemiplegia and developmental coordination disorder. *J. Clin. Exp. Neuropsychol.* 33 (3), 273–282, <http://dx.doi.org/10.1080/13803395.2010.509714>.
- Williams, J., Omizzolo, C., Galea, M.P., Vance, A., 2012. Motor imagery skills of children with Attention Deficit Hyperactivity Disorder and Developmental Coordination Disorder. *Hum. Mov. Sci.*, DOI S0167-9457(12)00106-6.
- Williams, J., Thomas, P.R., Maruff, P., Butson, M., Wilson, P.H., 2006. Motor, visual and egocentric transformations in children with Developmental Coordination Disorder. *Child Care Health Dev.* 32 (6), 633–647.
- Williams, J., Thomas, P.R., Maruff, P., Wilson, P.H., 2008. The link between motor impairment level and motor imagery ability in children with developmental coordination disorder. *Hum. Mov. Sci.* 27 (2), 270–285, <http://dx.doi.org/10.1016/j.humov.2008.02.008>.
- Wilmut, K., Brown, J.H., Wann, J.P., 2007. Attention disengagement in children with Developmental Coordination Disorder. *Disabil. Rehabil.* 29 (1), 47–55, <http://dx.doi.org/10.1080/09638280600947765>.
- Wilmut, K., Byrne, M., Barnett, A.L., 2013. Reaching to throw compared to reaching to place: a comparison across individuals with and without Developmental Coordination Disorder. *Res. Dev. Disabil.* 34 (1), 174–182, <http://dx.doi.org/10.1016/j.ridd.2012.07.020>.
- Wilmut, K., Wann, J., 2008. The use of predictive information is impaired in the actions of children and young adults with Developmental Coordination Disorder. *Exp. Brain Res.* 191 (4), 403–418, <http://dx.doi.org/10.1007/s00221-008-1532-4>.
- Wilmut, K., Wann, J.P., Brown, J.H., 2006. Problems in the coupling of eye and hand in the sequential movements of children with Developmental Coordination Disorder. *Child Care Health Dev.* 32 (6), 665–678.
- Wilson, P.H., Butson, M., 2007. Deficits underlying DCD. In: Geuze, R.H. (Ed.), *Developmental Coordination Disorder: A Review of Current Approaches*. Solal Editeurs, Marseille, pp. 115–119 (Chapter 4).
- Wilson, P.H., Maruff, P., 1999. Deficits in the endogenous control of covert visuospatial attention in children with developmental coordination disorder. *Hum. Mov. Sci.* 18 (2–3), 421–442, [http://dx.doi.org/10.1016/S0167-9457\(99\)00017-2](http://dx.doi.org/10.1016/S0167-9457(99)00017-2).
- Wilson, P.H., Maruff, P., Butson, M., Williams, J., Lum, J., Thomas, P.R., 2004. Internal representation of movement in children with developmental coordination disorder: a mental rotation task. *Dev. Med. Child Neurol.* 46 (1), 754–759.
- Wilson, P.H., Maruff, P., Ives, S., Currie, J., 2001. Abnormalities of motor and praxis imagery in children with DCD. *Hum. Mov. Sci.* 20 (1–2), 135–159.
- Wilson, P.H., Maruff, P., McKenzie, B.E., 1997. Covert orienting of visuospatial attention in children with developmental coordination disorder. *Dev. Med. Child Neurol.* 39 (11), 736–745.
- Wilson, P.H., McKenzie, B.E., 1998. Information processing deficits associated with developmental coordination disorder: a meta-analysis of research findings. *J. Child Psychol. Psychiatry* 39 (6), 829–840.
- Wilson, P.H., Ruddock, S., Smits-Engelsman, B., Polatajko, H., Blank, R., 2013. Understanding performance deficits in developmental coordination disorder: a meta-analysis of recent research. *Dev. Med. Child Neurol.* 55 (3), 217–228, <http://dx.doi.org/10.1111/j.1469-8749.2012.04436.x>.
- Wilson, P.H., Thomas, P.R., Maruff, P., 2002. Motor imagery training ameliorates motor clumsiness in children. *J. Child Neurol.* 17 (7), 491–498.
- Wolpert, D.M., 1997. Computational approaches to motor control. *Trends Cogn. Sci.* 1 (6), 209–216, [http://dx.doi.org/10.1016/S1364-6613\(97\)01070-X](http://dx.doi.org/10.1016/S1364-6613(97)01070-X).
- Wolpert, D.M., Kawato, M., 1998. Multiple paired forward and inverse models for motor control. *Neural Netw.* 11 (7–8), 1317–1329, DOI S0893-6080(98)00066-5.
- Wolpert, D.M., Miall, R.C., 1996. Forward models for physiological motor control. *Neural Netw.* 9 (8), 1265–1279, DOI S0893608096000354.
- Wolpert, D.M., Miall, R.C., Kawato, M., 1998. Internal models in the cerebellum. *Trends Cogn. Sci.* 2 (9), 338–347, DOI S1364-6613(98)01221-2.
- Zoia, S., Castiello, U., Blason, L., Scabar, A., 2005. Reaching in children with and without developmental coordination disorder under normal and perturbed vision. *Dev. Neuropsychol.* 27 (2), 257–273, http://dx.doi.org/10.1207/s15326942dn2702_4.
- Zwicker, J.G., Missiuna, C., Harris, S.R., Boyd, L.A., 2010. Brain activation of children with developmental coordination disorder is different than peers. *Pediatrics* 126 (3), e678–e686, <http://dx.doi.org/10.1542/peds.2010-0059>.