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Cognitive and neuroimaging findings in developmental coordination disorder: new insights from a systematic review of recent research

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This article is commented on by Liégeois on page 1103 of this issue.

AIM To better understand the neural and performance factors that may underlie developmental coordination disorder (DCD), and implications for a multi-component account.

METHOD A systematic review of the experimental literature published between June 2011 and September 2016 was conducted using a modified PICOS (population, intervention, comparison, outcomes, and study type) framework. A total of 106 studies were included.

RESULTS Behavioural data from 91 studies showed a broad cluster of deficits in the anticipatory control of movement, basic processes of motor learning, and cognitive control. Importantly, however, performance issues in DCD were often shown to be moderated by task type and difficulty. As well, we saw new evidence of compensatory processes and strategies in several studies. Neuroimaging data (15 studies, including electroencephalography) showed reduced cortical thickness in the right medial orbitofrontal cortex and altered brain activation patterns across functional networks involving prefrontal, parietal, and cerebellar regions in children with DCD than those in comparison groups. Data from diffusion-weighted magnetic resonance imaging suggested reduced white matter organization involving sensorimotor structures and altered structural connectivity across the whole brain network.

INTERPRETATION Taken together, results support the hypothesis that children with DCD show differences in brain structure and function compared with typically developing children. Behaviourally, these differences may affect anticipatory planning and reduce automatization of movement skill, prompting greater reliance on slower feedback-based control and compensatory strategies. Implications for future research, theory development, and clinical practice are discussed.

Difficulties acquiring movement skills (or developmental coordination disorder (DCD)) is one of the most common issues of development, affecting around 5% to 6% of all children. These motor difficulties are evident from an early age, are not associated with a known medical condition (like cerebral palsy, muscular dystrophy, etc.), and present a risk factor for concomitant problems in psychosocial and behavioural function. Experimental studies of DCD continue to grow as we try to explain its underlying mechanisms. Several meta-analyses and systematic reviews have described the body of work, informing specific hypotheses about causal mechanisms of DCD. However, so far, no large-scale review has successfully spanned the complement of experimental work across behavioural and neuroimaging studies (including electroencephalography [EEG]), or captured the proliferation of these studies over recent years. The systematic review presented here is designed to address this gap, providing a critical synthesis of the literature and identifying unifying themes across areas of research. The review covers work conducted from cognitive neuroscience and ecological approaches to motor behaviour and motor skill. (Cognitive neuroscience is concerned with understanding the biological processes that underpin cognition and action: in broad terms, the causal relationships between brain function, cognition, and behaviour. Ecological approaches focus more on the dynamics of the interaction between the individual, a given task, and environmental workspace, which gives rise to particular movement patterns and levels of motor skill. The term ‘motor skill’
refers to a task involving physical movement that has a specific goal to achieve [e.g. free-throw shooting in basketball, walking on stepping stones, tying shoelaces, etc.]. Skills are normally refined/learned with practice.)

A meta-view of recent reviews reveals an interesting pattern of deficit in DCD, but also the need for further integration. Of the behavioural data, a meta-analysis of work conducted between 1997 and mid-2011 suggested both a generalized pattern of impairment across different aspects of motor performance and motor control,4 and areas of more pronounced deficit, most notably in internal modelling (especially predictive control), rhythmic multi-joint coordination, and executive function. (Internal modelling is an important construct in cognitive neuroscience models of motor control. So-called forward [or predictive] models use a copy of motor command signals to predict future states of the moving limb[s], a process that supports real-time control and learning. The inverse model [or controller] generates the motor output signals necessary to achieve a desired goal state.) The issue of internal modelling was also the subject of a systematic review by Adams et al.5 who covered work published up to January 2013. Their review showed that motor control deficits were evident across different effector systems ranging from oculomotor control, manual target-directed reaching, simulated action, and dynamic postural control. Unfortunately, neural data were not addressed.

In a related synopsis, Reynolds et al.6 evaluated both behavioural and neuroimaging data on aspects of the mirror neuron system (MNS). The MNS is a distributed, multimodal system that is activated when a performer observes another person performing a movement skill or when one reproduces an observed action. As such, it is critical to observational learning and motor imagery (or internally simulated/imagined action). MNS structures include parts of the inferior frontal gyrus, ventral premotor cortex, superior temporal sulcus, and inferior parietal cortex.7 These same structures (especially frontoparietal projections) overlap those associated with the ability to internally model a prospective action. Reynolds et al. identified 31 studies addressing aspects of the MNS, divided into three clusters: motor imagery, imitation, and neuroimaging. Like earlier reviews, a complex pattern of deficits was observed in motor imagery and the reproduction of gestures. Importantly, the neural data showed evidence of hypoactivation and reduced connectivity along structures linked to the MNS including regions of parietal, frontal, and temporal cortices. At that time, however, only nine neuroimaging studies were reviewed, no functional magnetic resonance imaging (fMRI) studies, no whole-brain network analysis, and no direct test of the MNS hypothesis. A related review of neuroimaging work by Brown-Lum and Zwicker8 included published literature up to the end of 2014, showing evidence of hypoactivation across structures implicated in motor control (including frontoparietal and frontocerebellar networks) and reduced white matter organization. Since 2014, however, there have been at least seven additional neuroimaging studies, using more sophisticated techniques including whole-brain network analyses based on graph theory.9 Dissecting the more recent cognitive neuroscience research will help determine how these results extend earlier trends and our understanding of motor control in DCD.

Cognitive neuroscience approaches have continued to offer important insights on the nature of motor control and learning in a wide range of areas including dynamic postural control, gait, implicit motor learning, handwriting and graphomotor control, catching dynamics, oculomotor control, and praxis. A major theme uniting these areas in recent years has been a dedicated focus on control and coordination in response to different task and environmental parameters. Another important trend has been the accumulation of evidence showing that DCD is not solely a motor problem but that cognitive factors also contribute. The current review will describe and critique these factors (especially executive function, task planning, and self-regulation).

From an ecological and dynamical systems perspective, behavioural research has addressed the broad hypothesis that DCD reflects difficulties in rhythmic coordination and perceptual–motor coupling.4 This is shown by the difficulty in developing stable modes of coordination in response to task and informational constraints, and efficient synergies within and between the limbs. For example, rhythmic coupling of limb movements to external events (like a sound beat) is difficult for these children.10 In recent years there has been a move towards constraints testing in a variety of activities from locomotor navigation11 to golf putting.12 (Constraints are the many physical or informational variables that can influence the dynamics of motor behaviour [i.e. physical attributes of the performer or workspace, and information available through light, sound, etc.].) The goal is to better understand variation in performance (both within- and between-person) in response to different task constraints, as well as to identify compensatory strategies that may enable children with DCD to find adequate solutions to motor problems. Developments in this area have not been integrated within a more unified framework for DCD, capturing both behavioural and neuroimaging evidence.

Emanating from the European Academy of Childhood Disability (EACD), this review also informed the renewal of the International Clinical Practice Guidelines for DCD.13 An international panel of experts was formed in
The overarching aim of this review is to provide a coherent synthesis of the recent experimental work on DCD and to identify implications for a theory of DCD, clarifying the more promising hypotheses and avenues for future work. The specific aims are to: (1) provide a critical evaluation the experimental research (behavioural and neuroimaging) on DCD conducted since August 2011; (2) explain the patterns of deficit within a multi-component account of DCD; and (3) identify new research questions at the forefront of theory on DCD and related neurodevelopmental disorders.

**METHOD**

**Search protocol and sample of studies**

A modified PICOS framework (population, intervention, comparison, outcomes, and study type) was used to define the search parameters for the review. The population was defined as DCD (and other accepted terms; see below); interest as motor and cognitive processes and neural correlates; comparison as DCD compared with typically developing children; study type as any study producing original data.

We searched literature for research papers published in peer-reviewed journals between August 2011 and 1 September 2016 using seven electronic databases: Scopus, MEDLINE, PubMed, CINAHL Plus, PsycINFO, Web of Science, and Embase. The search was confined to English language journals. In addition to the term ‘developmental coordination disorder’, the following were also searched: ‘minimal brain dysfunction’; ‘minor neurological dysfunction’; ‘developmental dyspraxia’; ‘perceptual–motor disorder/dysfunction’; and ‘specific developmental disorder of motor function’.

**Coding of studies**

**Test categories**

Studies were first grouped according to the dominant approaches to DCD research: (1) cognitive neuroscience or (2) ecological–dynamical systems. Under each approach, studies were grouped by consensus agreement into the various performance domains (like handwriting or catching dynamics) or core processes (like executive function or internal modelling) (Table I). (Consensus was reached among members of the authorship team using a combination of teleconference and face-to-face meetings, as well as distribution of working documents by e-mail and Google Docs.) This breakdown of test categories was informed by current trends in the cognitive neuroscience of motor control and learning, embodied accounts of cognition and goal-directed action, and current ecological accounts of motor learning.

<table>
<thead>
<tr>
<th>Performance category</th>
<th>N of contributing studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Computational approach</td>
<td>16</td>
</tr>
<tr>
<td>1.1. Internal modelling/predictive control</td>
<td>14</td>
</tr>
<tr>
<td>1.2. Postural control</td>
<td>7</td>
</tr>
<tr>
<td>1.3. Handwriting</td>
<td>6</td>
</tr>
<tr>
<td>1.4. Gait</td>
<td>5</td>
</tr>
<tr>
<td>1.5. Learning</td>
<td>5</td>
</tr>
<tr>
<td>1.6. Catching kinematics</td>
<td>3</td>
</tr>
<tr>
<td>1.7. Oculomotor control</td>
<td>2</td>
</tr>
<tr>
<td>1.8. Praxis</td>
<td>2</td>
</tr>
<tr>
<td>1.9. Executive function</td>
<td>16</td>
</tr>
<tr>
<td>1.10. Sensori-perceptual processing</td>
<td>3</td>
</tr>
<tr>
<td>1.11. Multimodal integration</td>
<td>3</td>
</tr>
<tr>
<td>1.12. Neuroimaging</td>
<td>15</td>
</tr>
<tr>
<td>2. Ecological–dynamical approach</td>
<td>10</td>
</tr>
<tr>
<td>2.1. Constraints testing</td>
<td>1</td>
</tr>
<tr>
<td>2.2. Rhythmic coordination and timing</td>
<td>1</td>
</tr>
</tbody>
</table>

*Sensori-perceptual processing includes visuospatial functioning, kinaesthetic perception, and tactile perception.

**Study attributes**

Identifying information on each study included study title, authors, year of publication, and source journal. Aspects of participant sampling included recruitment procedure for DCD (i.e. referred versus not referred), sample size, age range (minimum and maximum), screening tool (i.e. Movement Assessment Battery for Children, Bruininks-Oseretsky Test of Motor Proficiency, or other), motor cut-point for DCD inclusion (5th, 10th, or 15th centile), sex ratio, and matching variables (e.g. age and sex). Design-related attributes included quality ratings (see below), study paradigm, and design including the main variables. Study results included the main comparisons between groups, effect size estimates for key comparisons (converted to Cohen’s d where possible), and the main findings. A positive effect size value indicated a more favourable result for typically developing children. The magnitude of d was interpreted as follows: 0.30 (small effect size), 0.50 (moderate), 0.80 (large), and >1.0 (very large).

Study quality was determined using a 10-item inventory based on the Critical Appraisal Skills Programme for case–control studies (Table II). Each item was scored as confirmed (1) or not (0), giving a total score out of 10. Studies with ratings of 8 or above were regarded as high quality, 5 to 7 as moderate, and less than 5 as low. Ratings were cross-validated by two independent experts in the field of DCD. Instances of disagreement were resolved by consensus among the authorship team.

**RESULTS**

**Study selection**

There were 3085 studies identified from the initial computerized database search. Of these, 2079 did not meet the inclusion criteria, most not addressing basic processes and...
Motor imagery was investigated in seven studies, six using the hand rotation task and two the visually guided pointing task. Prospective planning of grip for end-state comfort was examined in three studies and planning for onward actions in one. Other paradigms were covert orienting of (voluntary) visuospatial attention, steering under different levels of advance information, double-step reaching, visuomotor adaptation for manual aiming movements, and coincident timing using motor imagery.

Motor imagery deficits were confirmed in all relevant studies cited above. Williams et al. showed inaccuracy on the hand rotation task in DCD and mild cerebral palsy. In the case of comorbid attention-deficit–hyperactivity disorder (ADHD), they confirmed that children with DCD alone show deficits on both the hand rotation task (i.e. accuracy) and the visually guided pointing task (i.e. poor fit between response time and item difficulty); however, deficits in children with both comorbid DCD and ADHD were specific to the hand rotation task.

Deficits in end-state comfort planning were also task specific. This aspect of motor planning involves the ability to plan a movement (comprising multiple steps) such that the final step results in a comfortable posture; this may involve adopting a starting posture that is uncomfortable. Two studies showed no group difference on a bar grasping task that required grip selection for subsequent insertion in a holder (with coloured end facing down). By comparison, selection for end-state comfort was worse in DCD for the more complex sword insertion task and an octagon task involving rotational movements of the hand. Similarly Wilmot et al. showed adequate forward planning in DCD for tasks with low precision demands in terms of final endpoint, but not for tasks requiring more precise placement. Use of motor imagery when making coincident timing judgements was also impaired, particularly when using a hand-held tool for targets moving away from the body.

Postural control. There were 14 studies in this category, 12 of high to very high quality (Table III).

Most studies examined sway in controlled stance while manipulating the availability of different sensory inputs. Experimentally controlled studies of postural control in more natural situations were less common. Both in controlled standing as well as in more functional tasks (kicking a ball and step up), children with DCD showed more postural sway, more variability on kinematics, less optimal balance strategies including more hip-than ankle-based adjustments, and more reactive postural adjustments than a comparison group. In general, poorly coordinated anticipatory adjustments in DCD were observed (e.g. Kane and Barden). Neurmuscular reactions to physical perturbation were also delayed and limits of stability from a standing position were reduced, which also correlated with the incidence of falls in DCD.

**Table II: Quality rating scheme (modified Critical Appraisal Skills Programme)**

<table>
<thead>
<tr>
<th>Item number</th>
<th>Item description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>In the study rationale, is there sufficient acknowledgement of essential aspects of theory and pivotal studies?</td>
</tr>
<tr>
<td>2</td>
<td>Did the study address a clearly focused (theory-driven) question?</td>
</tr>
<tr>
<td>3</td>
<td>Was the task paradigm well chosen to address the research question(s)?</td>
</tr>
<tr>
<td>4</td>
<td>Was sample size sufficient or justified using power calculation?</td>
</tr>
<tr>
<td>5</td>
<td>Were children with developmental coordination disorder identified/screened appropriately and thus (sufficiently) representative of the population?</td>
</tr>
<tr>
<td>6</td>
<td>Were control children representative of the population?</td>
</tr>
<tr>
<td>7</td>
<td>Were the constructs of interest clearly operationalized and measured?</td>
</tr>
<tr>
<td>8</td>
<td>Were major confounds adequately controlled?</td>
</tr>
<tr>
<td>9</td>
<td>Were the statistical methods appropriate and adequately presented?</td>
</tr>
<tr>
<td>10</td>
<td>Are the major implications of the results clearly discussed?</td>
</tr>
</tbody>
</table>

**Table III: Descriptive characteristics of the studies**

<table>
<thead>
<tr>
<th>Study descriptive</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample size (median)</td>
<td></td>
</tr>
<tr>
<td>DCD</td>
<td>20</td>
</tr>
<tr>
<td>Typically developing children</td>
<td>21</td>
</tr>
<tr>
<td>Average males in DCD groups</td>
<td>66.7%</td>
</tr>
<tr>
<td>Age range of DCD sample</td>
<td></td>
</tr>
<tr>
<td>Minimum (median)</td>
<td>7y</td>
</tr>
<tr>
<td>Maximum (median)</td>
<td>12y</td>
</tr>
<tr>
<td>Using referred children</td>
<td>67%</td>
</tr>
<tr>
<td>Motor screening</td>
<td></td>
</tr>
<tr>
<td>MABC/MABC-2</td>
<td>77%</td>
</tr>
<tr>
<td>Other motor test</td>
<td>15%</td>
</tr>
<tr>
<td>Clinical assessment</td>
<td>8%</td>
</tr>
<tr>
<td>Motor cut-offs (centile)</td>
<td></td>
</tr>
<tr>
<td>5th</td>
<td>49%</td>
</tr>
<tr>
<td>10th</td>
<td>8%</td>
</tr>
<tr>
<td>15th</td>
<td>43%</td>
</tr>
<tr>
<td>Quality rating (median)</td>
<td>7.6</td>
</tr>
</tbody>
</table>

DCD, developmental coordination disorder; MABC/MABC-2, Movement Assessment Battery for Children/2nd edition.

mechanisms in DCD, or not providing a comparison between typically developing children and those with DCD on a measure of motor control, on learning or cognition, or on neuroimaging metrics. The final number of studies included in the systematic review was 106. The characteristics of the included studies are summarized in Table III. Separate tables (Tables SI–SXIII, online supporting information) are presented for each of the main performance categories.

**Test categories**

**Cognitive neuroscience approach**

Internal modelling. There were 16 papers addressing various aspects of internal modelling, 11 of which were high quality and 5 moderate (Table SI).
Children with DCD were less able to complete a dual task while maintaining stability, even when the secondary task was cognitive. Unlike typically developing children, they failed to dampen postural sway when performing an aiming task with high accuracy demands. However, light finger touch reduced sway in DCD (like the comparison group) and improved signal detection performance.

Children with DCD also showed a deficit in multisensory integration in a postural task in which touch and visual information were systematically varied. The ability to integrate vestibular information (based on the Sensory Organization Test) was also poorly developed. In general, postural sway and sway variability were greater in children with DCD in response to various motor task manipulations, external perturbations, and the imposition of cognitive loads during balance tasks.

**Handwriting.** There were seven handwriting studies, six of high quality (Table SIV). In addition to poor production quality, children with DCD showed difficulties in performing well controlled and fluently timed movements in handwriting and in spatial organization of text on the page.

There were some contradictory results for handwriting speed as group differences varied with the type of measure. Slower stroke production in DCD was found in two studies, whereas another by Prunty et al. found no group difference. Notwithstanding this, overall time to copy was longer in DCD, explained mainly by longer pauses and more time in the air. Larger variability in DCD was seen across measures, particularly temporal. Interestingly, Rosenblum and Regev showed that handwriting metrics (both timing and production quality) correlated moderately with response timing (using the interactive metronome device). In addition, delayed short-term procedural learning was evident on a task requiring the reproduction of novel letterforms.

Finally, in native Chinese children, DCD was also associated with writing difficulties in the Chinese language (where no grapheme-to-phoneme mapping exists).

**Gait.** Six articles examined gait patterns in DCD, five of these in children and one in adults (Table SV). Two studies characterized walking patterns in DCD. Wilmut et al. showed that children with DCD had wider normalized steps and higher variability in double support time and stride time. A similar pattern was observed for adults.

Only one study focused on both kinematic and kinetic running profiles of children with DCD. Using a fixed running speed (2.44 m/s), the two groups showed similar kinematic parameters for the thorax, pelvis, hip, and ankle, but variability was greater in DCD. Trends were evident on kinetic parameters, but were not explored at different running speeds.

The oxygen cost of (treadmill) running was examined by Chia et al., who found no group differences. However, the overall metabolic cost of running was higher in DCD. A follow-up study showed longer stance time and less knee flexion in DCD.

Finally, propulsive strategies were compared during walking and running. No group differences were observed for normal and fast walking. However, when required to increase speed to jog and run, children with DCD exhibited poor use of ankle plantar flexor and compensatory hip flexor power at push off.

**Learning.** Five learning studies (three of high quality and two moderate) were reviewed (Table SVI).

Three of these focused on procedural learning, one on learning with an internal/external focus of attention, and one on learning balance control. The rate of procedural learning did not differ between groups using either a serial reaction time task, a perceptual-motor procedural learning task, or a sequential finger tapping task.

On a more complex balance control task using the Wii Fit slalom game, overall performance and the rate of learning was slower in DCD both for duration and gates missed. Jarus et al. used a continuous computer (joystick) tracking task and showed that poorer implicit learning in DCD, which was not affected greatly by attentional focus. In general, learning on the more complex tasks was slower in children with DCD than those who were typically developing, while simple procedural learning was relatively intact.

**Catching dynamics.** Five descriptive studies investigated intra- and/or interlimb coordination patterns when catching a ball, with two of high quality and three of moderate quality (Table SVII). For single-handed catching, coordination patterns were more variable and differed from typically developing children on interaction torques and cross-joint coupling.

For two-handed catching, intralimb coordination was greater in typically developing children, as was mean interlimb temporal coordination, especially for fast ball movement. The two limbs were also more asymmetric in DCD.

**Oculomotor control.** There were three studies on oculomotor control (Table SVIII), two of high quality and one moderate. Studies examined the incidence of ophthalmic abnormalities, poor ocular accommodation and its relationship to lower levels of motor skill performance, and impaired vertical and horizontal smooth pursuit eye movements.

On standard clinical measures, children with DCD showed more ocular abnormalities, poorer accommodation metrics, and worse vertical (but not horizontal) pursuit gain.

**Praxis.** Two studies examined praxis in DCD, one of high quality and one low (Table SIX). Giofrè et al. showed that children with DCD had difficulty reproducing modelled gestures accurately, and had associated visuospatial memory deficits on the Corsi Blocks Test. Chang and Yu showed difficulties both in action imagery and in aspects of gesture production performed to verbal command or by imitation. No difficulty recognizing the conventional use of various objects was shown.

**Executive function.** There were 16 papers on executive function (Table SX) covering a range of measures and of varying quality (five high quality and 11 moderate).
These studies covered both conventional themes like cold executive function and new themes: executive function under different task constraints, hot executive function (which concerns the implementation of cognitive control in the context of tasks with a salient reward/motivational component), everyday executive function, self-regulation during motor learning, motor inhibition, and cognition in young adults with DCD. Asanitou et al. used a battery approach to investigate executive function in younger children (aged 5–6y) and showed moderate correlations between domains of executive function and movement skill. In a later cluster analysis of the same children, there were six subgroups with a combination of cognitive and motor issues. Zhu et al. confirmed earlier work showing reduced cognitive flexibility in DCD using the Wisconsin card sorting task. Functional aspects of memory that are applied in daily life (i.e. everyday memory) was examined in younger children by Chen et al. using the RBMT-C; here everyday memory issues were mediated by Verbal IQ. Bernardi et al. also showed slower verbal inhibition in DCD when repeating an alternative word, but not motor inhibition when copying an alternate hand gesture (pointed finger versus fist).

By comparison, other work showed that inhibitory control issues in DCD were modulated by task complexity and motor load. Pratt et al. showed poor inhibition in children with DCD (aged 6–14y) on more difficult tasks. Similarly, Leonard et al. showed that school-aged children with DCD were most disadvantaged by executive function tasks with a motor or visuospatial load. Using both behavioural and physiological measures, Chen et al. showed reduced modulation of heart rate in response to changing task difficulty in DCD.

For the first time, we see studies of hot executive function in DCD. Using both go/no-go and hungry donkey paradigms (a child-friendly version of the Iowa gambling task), Rahimi-Golkhandan et al. presented data (albeit on the same group of children) suggesting a reduced ability in DCD to modulate responses to stimuli of high immediate reward.

Finally, we now see studies of executive function in young adults with DCD. A large sample of adults aged 19 to 25 years were assessed on behavioural rating scales for executive function and an executive strategies questionnaire for everyday tasks. While mindful of questionnaire-based screening, results did show persistent executive function deficits (of moderate effect size), even for those with borderline DCD.

Sensory–perceptual factors. Three articles reported findings on sensory factors (one of high quality and two moderate), using both experimental and norm-referenced tasks (Table SXI). Kinaesthetic sensitivity was measured using passive motion apparatus in one study, a tactile perception battery including single- and two-point discrimination, and haptic perception tasks, and a visuoperceptual battery. Li et al. showed a similar pattern of performance between older children with DCD (aged 11y) and younger typically developing children (7y). Cox et al. showed poor tactile perception in DCD and a relationship with reduced upper-limb function. Similarly, Cheng et al. confirmed a significant correlation between visual–perceptual abilities and motor skill on the Movement Assessment Battery for Children (2nd edition).

Multimodal integration. There were three studies under this category using very different paradigms, two of good quality (Table SXII): bimodal stimuli (i.e. object location specified by visual and auditory cuing) was shown to improve motor planning of aiming movements in DCD but not controls; another study showed a negligible relationship between sensory integration ability and everyday functional skills; the third showed that children with DCD were capable of making multisensory visual-to-motor adaptations in response to a visual feedback rotation.

Neuroimaging. There have been 15 published papers since 2011 using neuroimaging techniques (seven of high quality, seven moderate, and one low), most with small numbers of participants (7–14 with DCD) (Table SXIII). Studies by Debrabant et al. used the same sample of children, however. The types of study included structural MRI, functional MRI, EEG, and functional transcranial ultrasound in an adult study.

Structural MRI studies using T1-weighted anatomical scans showed cortical thinning in the right medial orbitofrontal cortex in children with DCD and correlations with motor function tests including the Mc Carron Assessment of Neuromuscular Development and the Beery-Buktenica Developmental Test of Visual Motor Integration. Several functional MRI or EEG studies – using a variety of motor tasks such as predictive motor timing, finger sequencing, and visuomotor drawing tasks – showed underactivation in cerebellar, parietal, and prefrontal networks in DCD relative to same-age peers, which overlap a couple of key structures within the MNS and internal modelling regions. Reynolds et al. provided more direct evidence of reduced activation in MNS-related regions in DCD when they observed action, including precentral gyrus, inferior frontal gyrus, and cingulate, as well as lower activation in the pars opercularis during imitation. However, there is also evidence of reduced activation outside MNS/internal modelling deficit (IMD) regions. For example, Licari et al. showed reduced activation in the left superior frontal gyrus in DCD, as well as increased activation in the right postcentral gyrus. It is also worth bearing in mind that there remains conjecture over the detail of the MNS in humans, particularly how clearly observed actions can be mapped to the goals of the performer (see Hickok). As well, structural differences between DCD and comparison groups do not always map to the architecture of the MNS/IMD systems, as currently understood.

Structural diffusion MRI studies have demonstrated alterations of white matter microstructural organization, particularly in sensorimotor tracts that include the corticospinal tract, posterior thalamic radiation, and parietal...
Subregion of the corpus callosum. However, there is also evidence of activation outside motor areas associated with internal modelling and the MNS. Langevin et al. found reduced cortical thickness in the right anterior temporal pole in children with DCD compared with controls. While for those with both comorbid DCD and ADHD, a more or less generalized reduction in cortical thickness was evident across all cortical regions. Note that some overlap in sampling with the earlier study by the same authors is likely. In two studies, significant correlations between diffusion MRI metrics and motor function (e.g. Beery-Buktenica Developmental Test of Visual Motor Integration) in DCD were identified. Positive correlations were found between fraction anisotropy and axial diffusivity in specific brain regions and scores on motor assessments. Results of studies using cognitive evoked potentials suggest that neuroanatomical mechanisms of motor dysfunction in children with DCD are related to deficits in low-level visuoperceptual functions and auditory attention. Finally, the graph theoretical approach has emerged as a useful tool for characterizing brain network (connectome) changes in developmental disorders. In DCD, weaker segregation and integration of the structural network and a significant relationship between these graph metrics and visuomotor deficits have been demonstrated.

Methodologically, these studies had very small sample sizes with limited behavioural (motor, cognitive) or missing data from the fMRI sessions, did not correct for multiple comparisons or global brain metrics (such as whole brain volume), did not utilize parametric designs, and did not control for the confounding effects of demographic variables (e.g. sex, age), clinical variables (e.g. IQ), or related disorders of development (e.g. ADHD). In short, the neuroimaging studies published so far have presented several methodological flaws that hinder a formal conclusion about the neural basis of DCD. Continued work will hopefully see neuroimaging used as a biomarker to help guide the treatment of individual children.

**Ecological–dynamical approach**

Twelve papers from an ecological–dynamical systems perspective were reviewed, with all but one of high or very high quality (Table SII). The studies reviewed used a range of paradigms (and task constraints), with little overlap, making generalizations difficult: coordination of jump and clap movements under different task conditions; length estimation using tools; golf putting under varying task conditions; virtual driving; movement patterns in active video games; manual rod length estimation; perception of optimal sitting height; navigating through apertures; finger torque control; and visual-motor aiming using different interfaces or controllers. In general, studies showed poorer performance in DCD, while higher variability over trials was also a key finding in three of these studies. Notably, in three studies, group differences were evident only when environmental or task circumstances changed or were made more difficult.

**DISCUSSION**

The 106 studies reviewed here show a continued evolution of work in the field of DCD. First, a summary of study characteristics shows more careful attention to methodological detail than earlier work. Second, we see several discernible changes in tack in the method and topic of research over recent years. Most notably, there were further developments in work on motor control (e.g. internal modelling and MNS), constraints testing from an ecological perspective, postural control under different constraints, executive function, and neuroimaging approaches. In the sections that follow, we readdress the main themes identified in the Introduction in light of the body of work since 2011. We endeavour to highlight the most important trends in work over the past 5 years, their implications for a theory of DCD and clinical practice, as well as critical questions for future work.

**Motor control: action representation, internal modelling, and MNS**

The IMD account has undergone continued investigation and attracted conditional support across several studies, with some evidence suggesting a developmental delay. However, there are important caveats to this account. Foremost, task factors alter the pattern and magnitude of the control issues that are observed. Performance varies as a function of task type/complexity, the availability of vision and target speed, and the required precision of end-point control. Indeed, on some paradigms and conditions used to test the IMD hypothesis, children with DCD can perform similarly to typically developing children. Group differences are less apparent on some endstate planning tasks (mainly of low complexity), performance time trade-offs on mental limb rotation tasks, and online control of manual steering. In some cases, the severity of DCD may explain these null findings, but additional work is needed to untangle the causes.

In general, however, performance deficits are evident across effector systems (see also Adams et al.) Control of manual actions is impaired on more complex planning tasks, accuracy reduced for judgements of limb position made using motor imagery, and online adjustments are slower in response to unexpected target jumps. In the case of posture and gait, difficulty using predictive control is amplified during performance of concurrent (or dual) tasks. In general, we see more reliance on slower feedback-based control and reduced automatization of muscle synergies that support postural control.

Conditional support for the IMD hypothesis has some implications for how motor training/practice is scheduled and for the use of feedback. Results suggest that children with DCD need more extended periods of practice, especially when learning novel or more complex skills, and that augmented feedback might be particularly useful (see Li...
and Bo). Novel technologies like virtual reality can enhance the provision of augmented feedback and benefit skill development in cerebral palsy, for example.

Poor predictive control may induce the development of compensatory movement patterns in DCD. For instance, underestimating the extent of a prospective reach may create a safety margin, compensating for a poorly developed position sense. In a similar vein, when navigating through gaps, earlier initiation of shoulder/body rotation may compensate for poor forward planning and execution or perhaps issues in visuospatial perception.

Longitudinal studies are needed to understand the development of motor control more fully. Using growth curve modelling, Ruddock et al. recently showed that children with DCD require a more extended period of development than typically developing children to refine online motor control and to couple this effectively with inhibitory control (as when completing anti-reach movements).

Finally, there is intriguing new evidence that children with DCD and mild cerebral palsy share similar deficits in motor imagery and planning. This is also a topic for longitudinal investigation.

**Mirror neuron system**

The MNS serves a variety of motor functions, including the ability to predict the intended goal and endpoint trajectory of an action. While there is debate about how this is achieved, a process of internal simulation is thought to be involved. Both imagery and action observation activate overlapping structures within the MNS network and are part of a broader motor system that underpins the ability to perceive (action) goal intentions and internal modelling.

Recent work shows impaired motor imagery and action observation/ reproduction in DCD, but also aspects of performance that are age appropriate, primarily for simple tasks.

**Ecological–dynamical perspective on task constraints**

From an ecological perspective, difficulties perceiving environmental affordances are often cited when explaining group differences (Affordances are the perceptual qualities/features of the environment that provide opportunities for action: e.g. a rigid, flat surface can afford sitting.) For example, on a (virtual) road crossing task, children with DCD were less adept at judging the relative approach rate of a vehicle. Interestingly, they used compensatory ‘strategies’ to negotiate these different constraints in a safe manner: that is, allowing more time than necessary to cross a road.

Studies of motor learning also show the effect of task constraints/complexity. In early studies of procedural learning, children with DCD performed worse; however, earlier tasks were complicated by a spatial separation of the stimulus display and the response device (e.g. keyboard). Learning was preserved in DCD when a more intuitive response involving a touchscreen was used, or when simple sequential finger tapping was required. Consolidation of learning was also demonstrated by Biotteau et al. under dual-task conditions supporting ‘true’ learning effects (not mere practice effects). On a more complex continuous tracking task (using a joystick), implicit learning was compromised in DCD. Whether these children are able to ‘catch up’ after more extensive practice is an issue for future work, as is the effect of training procedures that better encourage children to adopt an external focus of attention.

The gradual integration of ecological and cognitive neuroscience perspectives is evident in recent task-oriented approaches to intervention, including neurormotor task training, as well as the use of tangible computing in rehabilitation of DCD and cerebral palsy. In the case of neurormotor task training, client-centred practices are combined with careful attention to task scheduling and varied constraints to facilitate motor learning.

The concept of variability in DCD is still in need of systematic investigation. There are now several excellent papers and books on this topic in mainstream motor learning. Indeed, variability can be conceptualized and modelled in several ways: (1) movement consistency—that is, refining the movement by reducing variability; (2) movement adaptability—that is, being more flexible in response to changing environmental constraints, thereby showing higher variability; (3) performance variability from one day to the next, with age, and on different tasks; (4) so-called good and bad variability (i.e. differentiating stochastic variability that allows flexibility in performance from signal noise that serves no goal-related or control function).

Taken together, studies from an ecological perspective suggest that affordances for action are not as readily perceived (or learned) by children with DCD and perception–action couplings are not well refined over time (or with experience). Importantly, the perception–action deficiency occurs across sensory modalities, for example visual–motor mapping when navigating, somatic position sense when wielding objects, and entraining body sway to the size of visual targets.

There are still relatively few experimental studies on perception–action from an ecological perspective and very few on motor learning. No study has yet tracked what are a critical triad of components at the same time: parametric changes in task constraints, coordination dynamics, and real-time functional brain activity (e.g. mobile EEG or near-infrared spectroscopy techniques). This type of study, especially when conducted longitudinally, will advance knowledge of causal processes in DCD and have very specific implications for intervention.

**Cognitive control (also called executive function)**

Recent work shows that executive function deficits are wide ranging, extending across basic functions measured experimentally (like working memory, inhibition, and executive attention), to aspects of hot cognition, and ‘everyday cognition’ assessed using questionnaires and ecological task
analysis. As well, results show that deficits remain a persistent feature of DCD into adolescence and early adulthood in most people (around two-thirds), and have adverse consequences for planning and organizing activities in everyday life. A confounding issue here is the presence of comorbid ADHD, which has been shown to be associated with inhibitory control issues; of the 16 studies that examined executive function, only half stated explicitly that children with ADHD were excluded.

The pervasive and persistent nature of executive function deficits suggests a heightened focus on this issue in future research. In the mainstream literature, corticocerebellar dysfunction has been linked to a pattern of deficits in timing, predictive control, fine-motor coordination, and basic cognitive functions.\(^{147,148}\) Whether subgroups of children with DCD are identified (with and without executive function issues) remains an empirical question.

**Neuroimaging**

In recent neuroimaging work (15 studies since August 2011), multiple brain regions (across association cortex, and primary, paralimbic, and subcortical regions) have been associated with DCD, while data on the broader neural network is only just emerging. Structural MRI shows reduced cortical thickness of the orbitofrontal cortex in DCD.\(^{101}\) Diffusion MRI shows alterations of white matter networks, especially in sensorimotor tracts including corticospinal tract, posterior thalamic radiation, and the parietal subregion of the corpus callosum.\(^{102,103,105}\) In addition, connectome mapping using graph theoretical analyses shows weaker segregation and integration of the structural connectome in DCD.\(^{9,102}\) This pattern is consistent with a ‘disconnection syndrome’ to the extent that the (integrated) activity of a distributed processing system is compromised. However, additional data are needed to support this argument.

Task-related functional MRI and EEG/event-related potentials provide evidence (on a variety of simple perceptual–motor tasks) for regional underactivation in DCD compared with typically developing children across cerebellar, parietal, and prefrontal cortices,\(^{101,107,110,112}\) areas that are also involved in internal modelling (see also Kashiwagi et al.\(^{149}\)). Recent data also show reduced activity in MNS-related structures during action observation including precentral gyrus, inferior frontal gyrus, precuneus, and posterior cingulate.\(^{109}\) However, there is also evidence of underactivation in structures outside the MNS/IMD networks (including the left superior frontal gyrus), as well as studies showing enhanced activations in DCD (e.g. in the right postcentral gyrus). Taken together, although there is some evidence for altered activation patterns in MNS/IMD networks, the data do not converge in a manner sufficient to fully support either hypothesis. Additional work is needed, particularly using more sophisticated functional connectivity analyses.

Interestingly, the patterns of connectivity and neural recruitment in DCD are similar to those seen in mild cerebral palsy and children born preterm, including evidence of cortical thinning.\(^{150}\) Whether biomarkers for DCD can be identified remains an issue for further examination. This quest can be difficult using functional neuroimaging owing to movement artefacts, use of non-parametric techniques, and so on. As well, not all studies show MRI abnormalities in DCD when stringent statistical thresholds are used, or strong relationships between neural changes and behavioural deficits.

We cannot yet determine the extent to which brain differences in DCD are the product of reduced physical activity (or participation). In other groups like those with acquired brain injury, motor and cognitive training studies demonstrate how intensive activity can affect structural connectivity at the level of white matter networks and functional connectivity between different regions of the cortex.\(^{151}\) Apart from one preliminary study by Zwicker et al.,\(^{110}\) no MRI study has yet evaluated brain connectivity changes in children with DCD before and after training, nor has EEG been used to show neurophysiological markers.\(^{152}\)

While it is premature to make firm conclusions about the source of brain alterations in DCD, in our opinion those alterations of structural and functional neural connectivity may reflect immature (or delayed) development of brain connectivity (that is, ‘developmental miswiring’) or a developmental disorder of neural connectivity within the brain network as a whole (Di Martino et al.\(^{153}\)). Other categories of abnormal developmental trajectories are also possible.\(^{154}\) Future longitudinal MRI studies are necessary to build a brain-behaviour model of DCD that captures the most likely trajectories. Such knowledge will inform the design of training programmes.

**Implications for a theory of DCD and directions for future research**

The high quality of experimental work on DCD over recent years provides an opportunity to better compare results across studies and to consider how findings might be integrated to inform theoretical accounts of DCD.

In general, we are seeing more evidence that motor control deficits in DCD depend on the nature of the task at hand. Deficits are especially apparent for dual tasks, and tasks that demand more precision (both spatial and temporal), more advanced planning, or that stress the system in a way that requires some adaptation/adjustment at a perceptual–motor level to maintain stability. As well, associated executive function issues (e.g. response inhibition) may constrain the ability to implement motor control\(^{153}\) and to automate skill without the need for extended periods of practice. However, sampling overlap suggests some caution when interpreting executive function results; the two studies of Tal-Saban et al.\(^{93,94}\) and two by Rahimi-Golkhandan et al.\(^{37,88}\) each used the same sample of participants. In general, motor issues that suggest poor predictive control and reduced automatization are likely to heighten reliance on slower feedback-based control and use of compensatory
strategies to maintain ‘safety’. It is unclear whether motor control issues of this type are due to delays in the development of sensorimotor networks that underpin internal modelling and observational learning (i.e. the MNS or disruptions to these and/or other brain systems. The net impact of these issues may be to force the developing system into a mode of control that is more reliant on external feedback. However, we still know little of the specific mechanisms that explain these issues in motor control, especially in the context of development with age. Indeed, the issue of delay versus deviance is still unresolved. As well, cross-cultural studies are needed to verify the impact of executive function on daily organization and planning in adolescents and young adults with DCD.

Clinical implications

This review has several important clinical implications. The first relates to the co-occurrence of cognitive issues in DCD. The imperative is to assess broadly across motor and cognitive functions, taking aspects of task organization and self-regulation into account also, not only in childhood but through adolescence and into early adulthood.

In addition, tempering assessment and treatment is the issue of heterogeneity in the presentation of DCD and in severity, which is evident across studies. For instance, a child may be functionally impaired and yet perform within the normal range for motor control and cognition, or the reverse may apply (normal function but impaired control). Similarly, current data do not allow us to say whether a child with mild, moderate, or severe DCD will present with a particular cluster of motor and cognitive issues. In the absence of further evidence, it remains doubly prudent for clinicians to assess comprehensively across motor and cognitive functions.

That motor control and executive function deficits are expressed variously as a function of task type and difficulty suggests a very measured approach to assessment and intervention. Clinicians are encouraged to assess movement skill in different domains by varying systematically task and environmental constraints. Identifying those specific aspects of the task that present difficulty will directly inform approaches to training, especially the scaling of difficulty.

Finally, the strong suggestion of neurocognitive issues in DCD (as in ADHD and other neurodevelopmental disorders) suggests that clumsiness in children should not be ignored clinically, and that it be given due consideration on its own.

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SUPPORTING INFORMATION

The following additional material may be found online:

Table SI: Study results for the internal modelling task category
Table SII: Results for the ecological–dynamical category
Table SIII: Study results for the postural control task category
Table SIV: Study results for the handwriting task category
Table SV: Study results for the gait task category
Table SVI: Study results for the motor learning task category
Table SVII: Study results for the catching dynamics task category
Table SVIII: Study results for the oculomotor task category
Table SIX: Study results for the praxis task category
Table SX: Study results for the executive function task category
Table SXI: Study results for the sensory–perceptual factors task category
Table SXII: Study results for the multimodal integration task category
Table SXIII: Study results for the neuroimaging category

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