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Combined action observation and motor imagery: An intervention to combat the neural and behavioural deficits associated with developmental coordination disorder

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1. Introduction

Developmental coordination disorder (DCD) is a neurodevelopmental disorder prevalent in up to 5-6% of children (American Psychiatric Association, 2013). A primary consequence of DCD is the impairment of both fine and gross motor coordination, resulting in the disruption of daily routines and the execution of activities of daily living (ADLs; Summers et al., 2008). Secondary consequences are that children with DCD are reported to have poorer physical and mental health (Cermak et al., 2015; Lingam et al., 2012), and are more prone to social withdrawal (Sylvestre et al., 2013). According to the Diagnostic and Statistical Manual of Mental Health Disorders, Fifth Edition (DSM-5; American Psychiatric Association, 2013), for a child to meet the criteria for a DCD diagnosis they must exhibit substandard motor ability appropriate to their chronological age (not attributable to other neurological or sensory conditions), which has been present since early development (i.e., delays in early motor milestones). Motor ability is typically assessed using the Movement Assessment Battery for Children – Second Edition (MABC-2; Henderson et al., 2007). Those who perform ≤ 16th percentile are assumed to have borderline DCD, whereas those who score ≤ 5th percentile are more likely to have the disorder (Blank et al., 2019). The substandard motor abilities must also impair the child's ability to execute ADLs successfully and interrupt academic productivity (Blank et al., 2019). Furthermore, the movement difficulties must not be attributable to any intellectual disabilities (American Psychiatric Association, 2013).

While the aetiology of DCD is not fully understood, neuroscience research is beginning to explain the movement difficulties associated with DCD through the disruption of neural structures and networks, and their functions. Children with DCD have been reported to have a reduced cortical thickness of fronto-parietal regions compared to their typically developing (TD) counterparts (Reynolds et al., 2017a). This reduction in grey matter is assumed to contribute to deficiencies in motor planning, attention, and executive functioning. Variations in white matter connectivity of the sensorimotor tracts (i.e., the corticospinal tract) and within the posterior thalamic radiation are also evident in children and adults with DCD (Williams et al., 2017; Zwicker et al., 2012). This disruption is strongly associated with motor impairments in other neurodevelopmental disorders (e.g., cerebral palsy; Gordon, 2016), and may, therefore, contribute to the motor difficulties associated with DCD. Abnormality in the parietal sub-region of corpus callosum has also been reported in children with DCD (Langevin et al., 2014). Given corpus callosum's role in inter-hemispheric coordination and the transfer of sensorimotor information between hemispheres (Tallet & Wilson, 2020), this may explain some of the documented difficulties in bimanual coordination (Gheysen et al., 2011). Suppression of the function of the putative human mirror neuron system (hMNS) - comprising the inferior frontal gyrus (IFG), ventral premotor cortex (PMv), and the inferior parietal lobule (IPL; Molenberghs et al., 2012) - has also been reported in DCD populations (Reynolds et al., 2015a). This fronto-parietal network contains neurons that are active during the performance of an action, as well as during the observation of that same action. As a result, this network is proposed to mediate imitation and play a role in visuomotor learning (Vogt & Thomaschke, 2007). Reduced functional connectivity between mirror regions, bilateral IFG, precentral gyrus and motor cortex may contribute to this impairment (Mcleod et al., 2014). Disruptions to cerebellar functioning have also been reported in DCD (Debrabant et al., 2013; Zwicker et al., 2011) with the role of the cerebellum implicated in internal modelling; specifically the forward model (de Xivry & Ethier, 2008). The internal model deficit (IMD) hypothesis suggests that impairment in the generation of forward models disrupts the comparison of predicted and actual sensory feedback in DCD, thus impeding the learning and performance of motor actions (see Adams et al., 2014 for a review).

Due to uncertainty regarding the cause of DCD, 'treatments' vary but typically emphasise repetitive physical practice as the primary strategy to improve motor skills (for a review, see Smits-Engelsman et al., 2018). There is evidence, however, that physical practice alone is insufficient to overcome the motor impairments associated with the condition (Brown-Lum & Zwicker, 2017). For example, Zwicker et al. (2011) reported that children with DCD showed no improvement in the performance of a fine motor tracing task after physical practice alone. Several brain regions associated with motor learning (i.e., the right dorsolateral prefrontal cortex, IPL and cerebellum) were also found to be suppressed during the tracing task in this study. Based on this evidence, Brown-Lum and Zwicker (2017) proposed that cognitive strategies and explicit feedback that help target impaired brain regions are required in addition to physical practice to support the acquisition of motor skills in children with DCD. Two cognitive training strategies often recommended to improve performance in sport and rehabilitation settings have been action observation (AO) and motor imagery (MI). These two strategies are referred to here as examples of *motor simulation*.

2. Motor simulation

AO is the deliberate and structured observation of human movement, often to support imitation (Neuman & Gray, 2013), whereas MI involves generating, maintaining, and transforming visual and kinaesthetic perceptual representations of movement (Kosslyn et al., 2010). Jeannerod's (2001; 2006) simulation theory proposed AO and MI to be 'functionally equivalent' to motor execution, that is, they all activate some common regions of the brain (Grèzes & Decety, 2001). In addition, it was assumed that continual activation of these overlapping regions through covert simulation would translate into improved physical performance of the simulated actions in a similar manner to Hebbian learning (Holmes & Calmels, 2008). The covert activation of motor regions via AO and MI stimulate central and, in some cases, peripheral neural pathways (Fadiga et al., 1995; Fadiga et al., 1998). By doing so, it has been suggested that functional connectivity and various types of neural plasticity may occur within the brain (Ray et al., 2013; Yoxon & Welsh, 2020), and a greater recruitment and synchronisation of motor units may occur within the peripheral nervous system (Lebon et al., 2010). It is by this process that physical performance could, in part, be enhanced through motor simulation techniques. Both AO and MI separately have been shown to have beneficial effects for performance in healthy individuals (Kim et al., 2017; Simonsmeier et al., 2020; Toth et al., 2020), and in rehabilitation settings (Buccino et al., 2014; Caligiore et al., 2017). These two motor simulation processes, integrated into and delivered through mental training strategies, may have the potential to provide additional cognitive skills training which are thought necessary for improved skill acquisition in DCD populations (Brown-Lum & Zwicker, 2017).

2.1. Action observation research in DCD

In recent years, there have been reports of neurological deficits during AO and imitation tasks for children with DCD. While the research discussed in this review referred to the hMNS in the context of observation and imitation, the current review will refer to this fronto-parietal circuit as the action observation network (AON). The AON encompasses the putative hMNS and a wider set of regions which contribute to visuomotor learning (Cross et al., 2009). Reynolds et al. (2015b) reported the first direct evidence for a potential disruption of the AON during AO and imitation for this population. Participants observed and imitated a finger sequencing task inside an fMRI scanner. Results indicated significantly reduced BOLD activity in the precentral gyrus, right IFG, middle temporal gyrus, posterior cingulate and precuneus for children with DCD during AO, compared to their TD counterparts (Reynolds et al., 2015b). Region of interest analysis revealed significantly reduced activity in the pars opercularis of the right IFG for children with DCD when imitating, compared to TD participants. Reynolds et al. (2019) were unable to replicate these findings. While the imitation task used by Reynolds et al. (2019) was the same hand sequencing task (sequenced finger-thumb contact of the digits) used by Reynolds et al. (2015b), the observation task differed in their replication study, using a simpler index finger adduction/abduction task. Reynolds et al. (2019) found small group differences between children with and without DCD during imitation in regions associated with motor planning and motor attention, namely the thalamus, caudate, posterior cingulate cortex and the precuneus. A recent investigation of the AON in children with DCD by Kilroy et al. (2020) found only significantly reduced activity within the pons during AO, but found significantly reduced activations during imitation tasks within the right IFG (pars opercularis), right superior frontal gyrus and the supplementary motor area. Using fMRI, Licari et al. (2015) reported the left IFG to have reduced activation for children with DCD during an imitation task. While this study did not aim to directly investigate the AON, it was suggested that the reduced activation of the left IFG reflected a supressed AON due to the corresponding task performed (i.e., the imitation of pictures of hand actions). Lust et al. (2019) provided further evidence for AON disruption in children with DCD. Their EEG findings showed mu rhythm suppression during observational learning. Collectively, the impairment of these motor regions could result in difficulties in learning new actions, or planning, preparing, and executing movement (Sakreida et al., 2018; Vogt et al., 2007).

Additional evidence for the disruption of the AON in DCD can be found through behavioural research (i.e., imitation). Literature largely suggests an impairment in imitation of familiar gestures for children with DCD (Sinani et al., 2011; Zoia et al., 2002), although there are some exceptions (Dewey et al., 2007). Furthermore, this population experience difficulties when imitating unfamiliar gestures (Reynolds et al., 2017b) suggesting that the memorial structures required to repeat a movement may need to be part of an individual's physical performance repertoire when consciously required to imitate the movement. These studies assessed imitation via gestures using a subjective rating scale. Scott et al. (2020) therefore assessed imitative ability through more objective assessments of the kinematics of familiar rhythmical actions. They found that the DCD group's imitation was significantly less accurate than those without DCD. It is notable, however, that no significant differences have been reported in unintentional imitation (automatic imitation) between these groups (see Scott et al., 2019). This may be due to the involvement of more complex neural systems supporting intentional imitation, which may be impaired in DCD populations (Scott et al., 2020).

Although, strictly speaking, there are no AO training studies in DCD populations, research involving quiet eye training for throwing and catching tasks shows promise for action observation-based training methods in children with DCD (Miles et al., 2014; 2015; Slowinski et al., 2019; Wood et al., 2017). Wood et al. (2017) provided interventions that instructed participants to direct their visual attention differently during observation of a throwing and catching video. Instructions for the quiet eye training group required participants to focus on the flight path of the ball, whilst viewing a video showing the gaze strategy of the expert model. In the technical training group participants were required to attend to the appropriate technique for throwing and catching whilst viewing the movement of the model in the video (i.e., an AO intervention). Significant improvements from baseline for throwing and catching performance were reported in both groups across both retention tests. Although the largest improvement was reported in the quiet eye training group, improvements were also found following the technical training, which resembled AO. Similar findings have also been reported in previous quiet eye training studies in DCD populations (Miles et al., 2014; 2015). The interventions provided for the technical training groups in these studies represent the closest approximation to an AO intervention in children with DCD to date, and would seem to support the efficacy of AO-based interventions within this population.

2.2. Motor imagery research in DCD

The earliest study investigating electrophysiological activity in children with DCD during MI was by Lust et al. (2006) using electroencephalography (EEG). The amplitude of the rotation-related negativity, an event-related potential related to mental rotation tasks, was recorded across parietal regions. The findings revealed no difference in amplitudes between children with and without DCD during MI. It is noteworthy, however, that no group differences were detected on the MI task either (i.e., the mental hand rotation task). This task requires the use of MI in order to differentiate between images of left and right hands that are rotated to varying degrees (Barhoun et al., 2019; Wilson et al., 2004). Complexity of the hand rotation task differs depending on various factors, including the orientation of the hand, whether the hand is pronated or supinated, the occlusion of the participant's own hand, and the addition or omission of MI instructions (i.e., explicit and implicit MI, respectively; Reynolds et al., 2015a). When MI instructions are omitted, the implicit use of MI is required as the individual has to rotate the presented limb mentally to determine which hand is displayed. Despite being frequently adopted in DCD research to assess MI characteristics, the mental hand rotation task may not access cortical motor areas in the same way as, for example, MI of complex movements of hands and limbs (Hétu et al., 2013). This may, therefore, explain the null effects reported in by Lust et al. (2006). Reynolds et al. (2019) studied the neural correlates of MI in children with and without DCD through functional magnetic resonance imaging (fMRI) measuring blood oxygen level dependent (BOLD) activity. Although differences in performance of the mental hand rotation task were revealed prior to scanning, whole brain analysis revealed there to be no measurable neurological differences between the two groups when imagining themselves performing a finger-tapping task. Furthermore, the region of interest analysis focusing on areas associated with motor planning and action execution (i.e., the IFG, supplementary motor area (SMA), premotor area, IPL and superior temporal sulcus (STS)) revealed no group differences during MI use. Future neurophysiological research investigating MI in children with DCD would benefit from more standardised MI protocols across studies to help determine any potential deficits; for example, the inclusion of explicit MI instructions and the consistent use of more complex assessments of MI.

Neurophysiological differences have, however, been reported between adults with and without DCD (Hyde et al., 2018; Kashuk et al., 2017). Using fMRI Kashuk et al. (2017) revealed significantly reduced activations across the middle frontal gyrus, the left superior parietal lobule and cerebellum during mental hand rotation task where MI was explicitly instructed for adults with possible DCD. Hyde et al. (2018) conducted a similar investigation using transcranial magnetic stimulation (TMS). When the primary motor cortex (PMC) was stimulated during a mental hand rotation task, corticospinal excitability was reduced in those with DCD, compared to healthy adults. As self-reported kinaesthetic imagery ability is correlated positively with corticospinal excitability during MI (Williams et al., 2012), this finding suggests a possible reduced motor simulation capability for adults with DCD when transforming images using MI. These different neurological findings for children and adults with DCD during MI may be due to developmental changes that occur between childhood and adulthood. For example, a greater overlap between brain areas activated during motor simulations and action execution could occur in adults compared to children (Morales et al., 2019). This increased overlap in adults with DCD may have revealed a MI deficit when motor regions associated with action execution were directly stimulated with TMS during MI (Hyde et al., 2018).

Despite the equivocal findings for neurophysiological deficits reported during MI in individuals with DCD, differences in cognitive ‘measures’ of MI are more consistently reported in children with DCD. One of the paradigms used most frequently to assess MI ability is the mental hand rotation task. To date, deficits have been reported in children with DCD on this task both when implicit MI is used (Barhoun et al., 2019; Wilson et al., 2004), and when explicit imagery instructions are provided (Williams et al., 2006; 2008). When explicit MI was instructed, Williams et al. (2008) reported that children at or below the 5th percentile on the MABC-2 performed significantly worse than both TD children and children between the 6th and 15th percentile. Similar findings were also reported for a whole-body mental rotation task (Williams et al., 2006; 2008). Finally, using questionnaire measures Fuchs and Caçola (2018) reported that children with DCD had a reduced ability to spatially manipulate objects using MI compared to TD children, whilst Scott et al. (2020) reported differences in self-reported kinaesthetic image generation ability. Collectively, cognitive measures of MI indicate a sub-optimal ability for image generation and transformation in children with DCD, which may hinder the experience of kinaesthesis during MI of more complex movements (Holmes & Calmels, 2008).

Behavioural measures are commonly used to assess the mental chronometry of MI in individuals with DCD. For example, children with DCD have a temporal incongruency between imagined and performed actions on the visually-guided point task (Ferguson et al., 2015; Maruff et al., 1999; Williams et al., 2013). This difference has been suggested to be due to imagined actions not conforming to Fitts's Law (i.e., the speed accuracy trade off; Fitts, 1954). Deficits in the maintenance of MI have also been reported in the imagination and subsequent performance of rhythmical actions (Scott et al., 2020). This was proposed to reflect temporal difficulties during MI causing inaccurate imitation of the actions. While functional equivalence of imagined and executed actions has been proposed (Jeannerod 2001; 2006), findings through behavioural measures of MI (i.e., the temporal incongruency between imagined and executed actions) may suggest variance in the supporting motor networks for these two processes in children with DCD. When considering MI as a training tool to facilitate movement for children with DCD, a potential difference in the underling mechanisms between MI and physical execution may limit its potential (see Holmes & Collins, 2001).

The discrepant findings across neurological, cognitive, and behavioural dimensions indicate that while there are no conclusive neurological differences between individuals with DCD, cognitive and behavioural differences may exist in children. Despite the possible MI deficits seen in DCD populations, MI training appears to have beneficial effects on planning and executing movement (Blank et al., 2019). The earliest account of MI training in children with low motor ability was by Wilson et al. (2002). In this study, imagery was developed systematically through the use of independent visual imagery, first- and third-person visual perspective action observation, and first- and third-person perspective MI, which was followed by physical practice. Although this study did not include a strict DCD sample (≤ 49th percentile criteria), significant improvements in physical performance (i.e., balance, hand-eye coordination, and catching and throwing) were shown after a five-week intervention involving AO, MI and physical practice. This finding was later replicated by Wilson et al. (2016) using the same protocol but with a stricter inclusion criteria for DCD ($\leq$ 10th percentile criteria). In a recent feasibility study, Adams et al. (2017) examined the efficacy of MI for enhancing movement outcomes in children with DCD. The participants followed a nine-week intervention involving AO, MI and physical practice of participant-selected tasks. These tasks ranged from catching and throwing, cutlery use, and gross movements (i.e., badminton, running, or jumping a rope). The authors reported improvements in MABC-2 scores for all children in the MI group. Further support for MI training in a DCD population was reported by Bhoyroo et al. (2019). They found that acute MI instructions significantly improved movement planning and end state comfort for children with DCD.

In line with the IMD hypothesis, it is believed that MI training may improve forward modelling in children with DCD and the prediction of the sensory consequences of their actions (Miall & Woplert, 1996; Wilson et al., 2013). This may explain the moderate to large effect size attained by Wilson et al. (2016) for their MI group and the findings of Bhoyroo et al. (2019). Furthermore, across the studies of both Wilson et al. (2016) and Adams et al. (2017) 14 out of 16 children improved performance following treatments involving MI, 10 of which performed above the standard error of measurement for their respective study. While MI interventions in DCD are sparse, the evidence suggests there to be favourable outcomes for motor skill learning interventions incorporating MI in this population.

3. Combined action observation and motor imagery (AOMI)

Although the independent use of AO and MI interventions have been shown to be effective for improving motor performance in children with DCD, several problems exist with these techniques. For example, an inherent problem with MI interventions is the lack of control associated with asking any individual to imagine a motor action, as there is currently no way to confirm that the individual is imagining the action exactly as prescribed. Whilst imagery scripts are often developed to provide content and cues for imagery, the step-by-step nature in which imagery scripts describe the process of imagining movement execution could arguably serve to promote the cognitive control of the movement more characteristic of novice performance. Whilst some researchers have used AO techniques to provide a guide prior to MI (Adams et al., 2017; Wilson et al., 2002; 2016), it remains the case that the MI processes of children with DCD have temporal incongruency with the performed actions (Ferguson et al., 2015; Williams et al., 2013; Wilson et al., 2002). When considering these issues, together with the discussed compromised imagery ability characteristics in DCD populations (Reynolds et al., 2015a), it is conceivable that progress obtained through AO or MI training may be slower than that of a TD individual.

Within the past decade it has been proposed that AO and MI may have greater benefits when combined and used concurrently (i.e., AOMI, see Eaves et al., 2016a; Vogt et al., 2013). Vogt et al. (2013) proposed a spectrum of AOMI states, whereby MI content during AO can vary according to the level of congruence between the observed and imagined action. What Vogt et al. termed congruent AOMI involves instructing the user to observe an action on video, whilst imagining *simultaneously* the kinaesthetic feelings and sensations associated with executing the observed action. Whilst it is now acknowledged that this process cannot be truly described as ‘congruent’ given the different visual and kinaesthetic modalities prioritised during the respective components (Frank et al., 2020), there are promising neurophysiological and behavioural findings in the research exploring this AOMI process to date (see Eaves et al., 2016a). Before continuing, an important distinction needs to be made between this combined use of AOMI and the previously discussed protocols in DCD interventions that have used AO as a primer *before* MI (e.g., Adams et al., 2017; Wilson et al., 2002; 2016). While AO followed by MI does activate motor regions of the brain and can be beneficial for subsequent movement execution, this approach does not constitute AOMI as described in the recent literature where the AO and MI components must occur simultaneously (e.g., Eaves et al., 2016a; Taube et al., 2015; Vogt et al., 2013).

The earliest neurophysiological account of AOMI was by Sakamoto et al. (2009). Using TMS, they demonstrated that corticospinal excitability was facilitated to a greater extent when adult participants engaged in AOMI, compared to when they engaged in either AO or MI alone. This finding has since been replicated in numerous TMS studies exhibiting greater MEP amplitudes during AOMI than either or both AO and MI alone (e.g., Bruton et al., 2020; Meers et al., 2020; Mouthon et al., 2015; Ohno et al., 2011; Tsukazaki et al., 2012; Wright et al., 2014; 2016; 2018). Based on these findings, the use of AOMI could be more advantageous than independent AO or MI for activating a potentially compromised corticospinal tract in children with DCD. The reliability of these TMS findings have been further confirmed through research using other techniques, including fMRI (Macuga & Frey, 2012; Nedelko et al., 2012; Taube et al., 2015; Villiger et al., 2013) and EEG (Berends et al., 2013; Eaves et al., 2016b; Sun et al., 2016).

The research using fMRI provides an indication of the different activations in the motor system during AOMI, compared to independent AO and MI. Nedelko et al. (2012) reported greater activations for AOMI than AO in the IFG, inferior parietal cortex, the caudate nucleus, and the SMA. Increased activity in similar regions was reported by Villiger et al. (2013) when comparing AOMI and AO instructions. In this study, AOMI was also found to activate the PMv and left insula more so than AO. Taube et al. (2015) also compared the neural activation during AOMI with that found during both independent AO and MI. Results showed that AOMI facilitated greater activity in the bilateral PMC, bilateral cerebellum, and precuneus, compared to MI. Contrasts between AOMI and AO revealed a greater activation of the left PMC, the left superior and right inferior frontal gyrus, the IPL, the SMA, basal ganglia, and cerebellum for AOMI. Taken together, consistent TMS and fMRI findings indicate increased activity in the motor system during AOMI, compared to either or both independent AO and MI. Reinforcing activity in these brain regions associated with motor planning and execution regularly over the course of an AOMI intervention may have the potential to contribute to improvements in motor function through Hebbian plasticity mechanisms (Wright et al., 2018). This, however, remains to be established.

Behavioural research in healthy adults has reported greater effects for AOMI on automatic imitation (Eaves et al., 2014; 2016b), and intentional imitation (Bek et al., 2016) than either or both AO and MI. The simultaneous use of these instructions has also been shown to be beneficial for improving performance outcomes. When compared to both AO and MI separately, AOMI interventions have been shown to significantly improve the performance and kinematics of aiming tasks (Romano-Smith et al., 2018; 2019). Significant improvements have also been reported for motor learning both before (Kawasaki et al., 2018) and after inducing a training plateau (Aoyama et al., 2020), rehabilitation (Marusic et al., 2018), and eye-hand coordination tasks (Marshall et al., 2020a), when compared to a control group. The benefits of AOMI for clinical adult populations is also becoming apparent. Sun et al. (2016) reported significantly greater improvements in pinch-grip strength and dexterity for stroke patients following an AOMI intervention, compared to an alternating AO *then* MI intervention. In addition, more pronounced event-related desynchronization was reported in the alpha frequency band over the left motor cortex for the AOMI group. The authors interpreted this electrophysical activation following AOMI training to reflect improved neuroplasticity, which translated to improved function of the right hemiplegic limb (Sun et al., 2016). Enhanced imitation when using AOMI has also been reported when compared to independent AO for individuals with Parkinson's disease AOMI (Bek et al., 2019). A recent pilot intervention assessing the feasibility and acceptability of AOMI suggests that it could be beneficial for training ADLs in those with Parkinson's disease (Bek et al., 2020). These findings provide promising evidence for the efficacy of AOMI training in populations with motor impairments, and for the potential of AOMI as a home-based intervention. As children with DCD struggle with manual dexterity and the performance of ADLs (Blank et al., 2019), the results of Sun et al. (2016) and Bek et al. (2020) may provide additional evidence for the suitability of AOMI in this population.

3.1. AOMI in children with DCD

Scott et al. (2019) investigated the behavioural correlates of the AON in this population through an automatic imitation paradigm. Automatic imitation is a type of stimulus-response compatibility effect, whereby observing a task-irrelevant action can facilitate execution of similar actions, or impede execution of different actions (Heyes, 2011). Scott et al. (2019) instructed the children in the AOMI condition to imagine, simultaneously, the feeling and sensations associated with executing the everyday rhythmical actions (e.g., face washing) they watched during videos. The AOMI instruction significantly enhanced the automatic imitation effect compared to both independent AO and MI for those with DCD.

Recently, Scott et al. (2020) explored the effects of AOMI on intentional imitation in children with DCD through the kinematics of familiar rhythmical actions. Children were instructed to watch videos of the actions prior to imitating them as closely as possible. The instruction to use AOMI before imitating significantly improved imitation for the DCD group, compared to the AO followed by MI condition. Although demonstrated on simple unilateral actions, this provides preliminary evidence that AOMI may be superior to the systematic use of AO then MI (e.g., Adams et al., 2017; Wilson et al., 2016) for promoting the temporal congruency of imagined actions and improving movement for children with DCD.

Marshall et al. (2020b) studied the effects of AOMI training on eye-hand coordination during visuomotor adaption in children with DCD. While both groups had the same amount of physical practice, the AOMI training group were provided with videos in which they observed a performer complete the same task from a first-person visual perspective while they simultaneously imagined the kinaesthetic sensations associated with executing that task. A control group received videos showing no human motor content. After training, the AOMI group showed faster task completion times, significantly smoother movement kinematics, and more effective eye-hand coordination. The improvements in performance and gaze behaviour were interpreted as improved internal modelling as a result of AOMI.

Although there are currently no studies investigating the neurophysiological effects of AOMI in DCD, if AO and MI alone can target suppressed motor regions in those with DCD then AOMI may do this to a greater extent. Furthermore, this would align with the recent call by Brown-Lum & Zwicker (2017) for mental training interventions to target supressed brain regions in children with DCD. Two AON regions reported to be impaired in this population are the precentral gyrus and pars opercularis of the IFG (Kilroy et al., 2020; Reynolds et al., 2015b). While the evidence for the suppression of these motor regions has only been obtained through AO and imitation in DCD (Reynolds et al., 2015b; 2015a), these regions also play a role in MI and action execution in adults

(Hardwick et al., 2018) and children (Reynolds et al., 2015b). Greater activation of the precentral gyrus has been reported during AOMI compared to AO and MI separately in adults (Taube et al., 2015). As the precentral gyrus has been found to be impaired in children with DCD (Mcleod et al., 2014; Reynolds et al., 2015a), using AOMI may have the potential to increase activity within this area to that of a TD individual (Taube et al., 2015).

Reduced BOLD activity has also been reported in both the left (Licari et al., 2015; Zwicker et al. 2010) and right IFG (Debrabant et al., 2013; Kilroy et al., 2020; Reynolds et al., 2015b) in children with DCD. Bilaterally, the IFG is involved during MI, AO and action execution (Hardwick et al., 2018). Within the IFG is the pars opercularis, a structure associated with imitation (Kilner et al., 2009; Molnar-Szakacs et al., 2005), MI generation and maintenance (Hétu et al., 2013), and AO (Molnar-Szakacs et al., 2005; Vogt et al., 2007). Region of interest analyses by Kilroy et al. (2020) and Reynolds et al. (2015b) revealed the pars opercularis of the right IFG to be activated less during imitation in this population. Studies by Nedelko et al. (2012) and Taube et al. (2015) found greater activations in the left and right IFG, respectively. If AO and MI can co-exist and coalesce during AOMI (Bruton et al., 2020; Eaves et al., 2016a; Vogt et al., 2013), activity in the bilateral IFG could be enhanced (Nedelko et al., 2012; Taube et al., 2015). This process could explain the enhanced imitation for DCD children reported by Scott et al. (2019; 2020) following AOMI.

Additional regions reported to be impaired in children with DCD are the precuneus (Reynolds et al., 2015b; Reynolds et al., 2019; Zwicker et al., 2011) and the cerebellum (Debrabant et al., 2013; Zwicker at al., 2011). Greater activity in both of these regions has been reported during AOMI than either or both AO and MI (Nedelko et al., 2012; Taube et al., 2015). Independent MI can facilitate activity to regions of the cerebellum (Hardwick et al., 2018). Although cerebellar activity has been associated with the suppression of physical movement (Decety, 1996), the enhancement of activity in this region could also explain the improvements for motor skills via MI interventions in DCD (Adams et al., 2017; Bhoyroo et al., 2019; Wilson et al., 2016). The cerebellum has been proposed to generate forward models to predict the sensory consequences of movement (de Xivry & Ethier, 2008), which are thought to be impaired in DCD (Adams et al., 2014). Accordingly, and in alignment with the IMD hypothesis, it is conceivable that AOMI could facilitate the generation of more accurate forward models in children with DCD, to a greater extent than AO and MI alone. By this process, AOMI could further enhance predictive motor control for children with DCD, as found by Marshall et al. (2020).

The synthesis of evidence above suggests that AOMI may be a superior motor simulation technique for increasing the activation of motor regions and producing better behavioural outcomes for children with DCD (Marshall et al., 2020b; Scott et al., 2019; 2020), compared to either AO or MI alone. So why does AOMI provide such benefits? While MI interventions require an individual to use both visual and kinaesthetic imagery, there is an inherent assumption that they have the abilities to support both modalities of motor simulation. A principal characteristic of AOMI is the presence of a visual guide *during* MI. The visual guide provided during AOMI may allow greater cognitive resources to focus on the kinaesthetic aspect of the imagery rather than the generation of a visual component. Earlier it was highlighted that there is a temporal incongruence for the MI processes of children with DCD, which could potentially distort the content of prior AO. Indeed, this incongruence would still exist during AOMI, at least during early training; however, this incongruence may be offset with continual training and the additional structure provided for the MI by the AO content. This should provide the user with opportunities to refine their MI through simultaneous and consistent feedback from a congruent observed action. This could be particularly beneficial for those of a sub 5th percentile MABC-2 score who have been reported to have difficulty utilising explicit MI instructions (Williams et al., 2008). In addition, providing a proficient model to observe *during* MI provides appropriate action content with which the user can synchronise their MI, potentially improving sequencing and timing of action execution (Wright et al., 2018). This could be advantageous for children with DCD in particular, as the MI for these individuals is temporally incongruent with their physical actions when the visual component of the MI has to be generated alongside the kinaesthetic (Ferguson et al., 2015; Wilson et al., 2002; Williams et al., 2013).

4. Future directions

There are currently no neurological studies on AOMI in children with or without DCD. The above section, however, has evidenced the relationship between the potential neurophysiological deficits in

DCD and the neural correlates of AOMI. Preliminary investigations of AOMI in children with DCD suggest behavioural benefits when using AOMI compared to independent AO and MI (Scott et al., 2019; 2020); research should now investigate the neurological activations in children with and without DCD during AOMI. In accordance with adult AOMI literature (Eaves et al., 2016; Taube et al., 2015; Wright et al., 2014), it could be hypothesised that the activations of AOMI would be greater than AO and MI separately. The overlap between motor simulations, however, might not occur to the same degree in children (Morales et al., 2019) and the increased activity associated with AOMI might be reduced in children compared to adults.

While AOMI interventions benefit adult populations with and without motor impairments (Bek et al., 2020; Scott et al., 2017; Sun et al., 2016; Taube et al., 2014), future research should investigate the efficacy of longitudinal AOMI training in children with DCD. To date, only acute AOMI training benefits have been shown for children with DCD (Marshall et al., 2020b; Scott et al., 2019; 2020). Furthermore, research by Marshall et al. (2020b) and Scott et al. (2019; 2020) demonstrated the benefits of AOMI on abstract tasks (a visuomotor rotation task and rhythmical actions, respectively). As AO followed by MI has been shown to be beneficial for this population over interventions of five (Wilson et al., 2016) and nine (Adams et al., 2017) week durations, a comparison of AOMI with the aforementioned AO and MI protocols could allow the progression and optimisation of motor simulation treatments in DCD. The addition of meaningful tasks such as ADLs, which are problematic within the DCD population (Summers et al., 2007), would also improve the ecological validity of this research. Such work would offer the opportunity for the development of more cost-effective, home-based AOMI interventions delivered using mobile devices (e.g., Bek et al., 2020).

An assumption in AOMI research focusing on adults is that greater motor activity facilitates skilled movement. Indeed, greater activity during AO and MI separately is indicative of expert level capability in performing a simulated movement; however, neural activity during actual physical performance in experts is reduced – a neural efficiency effect (Mizuguchi & Kanosue, 2017). Although the benefits of the increased neurophysiological activity induced by AOMI across motor learning stages is yet to be established in adults, promoting activity across deficient motor areas in

DCD may accelerate learning to that of a TD individual. To examine such effects in children with DCD, utilising neuroimaging techniques (e.g., fMRI and EEG) across AOMI interventions would provide a welcome insight to changes in neurological markers. AON related regions (i.e., the PMC, IPL, superior parietal lobule) may show decreased (early training) or increased activity (later training) during AO and MI separately (Mizuguchi & Kanosue, 2017), this however is dictated by the level of learning achieved which will likely be slower in DCD children. Similar trends may be observed for AOMI across these motor related regions after training phases and could act as an indicator of motor learning through fMRI. Alternatively, greater event-related desynchronization of alpha and lower beta frequency bands during EEG can be an indicator of mastery of an observed movement (Orgs et al., 2008). While it remains to be determined whether children with DCD can achieve the level of expertise assessed within these neuroimaging studies, these trends in activities may provide indicators of motor learning throughout AOMI interventions. Once the long term behavioural and neurophysiological effects of AOMI are better understood, there may be greater confidence in the delivery and optimisation of this instruction.

To date beneficial behavioural effects have been reported following AOMI interventions in children with DCD when the action observation content has been recorded from both first- (Marshall et al., 2020b) and third-person (Scott et al., 2019; 2020) visual perspectives. Research should now determine the best perspective for training movement skills in DCD, and how this may vary across different tasks. A first-person perspective is associated with greater corticomotor excitability (Maeda et al., 2002) and greater activity in the sensorimotor cortex (Jackson et al., 2006). In line with MI literature, however, it could be hypothesised that third-person perspective would be advantageous for training gross motor skills where movement form is important (Hardy & Callow, 1999), and accordingly, first-person perspective would be preferable for fine motor tasks where movement form is less important. A comparison of these individual perspectives and their combination would allow the further development of AOMI interventions for children with DCD. Furthermore, the studies of Marshall et al. (2020) and Scott et al. (2019; 2020) used observations of others. Recent research has investigated the benefits of self-modelled AOMI in adults (McNeill et al., 2021), showing benefits for refining well-learned motor skills. Research should now investigate the benefits of self vs. other modelling in AOMI contexts for children with DCD. Although the observation of a skilled other has provided benefits for children with DCD (Marshall et al., 2020b), self-observation may allow a greater experience of agency for this population (Holmes & Calmels, 2008), and improvements in self-efficacy (Ste-Marie et al., 2020). Showing a skilled other performing a task could be counterproductive for a child with DCD, as the gap in motor ability, may reduce self-efficacy and engagement in the task. Therefore, comparisons of self vs. other models could provide a welcome insight to the physical and psychological benefits of AOMI in individuals with movement impairments. An alternative use of self-modelling that has received attention in sport populations is feed-forward self-modelling. This involves compiling and splicing recorded videos of the individual performing movements to create a complete movement sequence beyond the individual's current ability (Vertes & Ste-Marie, 2013). Should self-observations be helpful for children with DCD, feed-forward self-modelling could provide a fruitful avenue for future research.

In the case of co-occurring DCD and ADHD, using AOMI could prove to be difficult. Using AOMI requires attentional focus principally on the internal MI content while observing external AO content. This may prove to be troublesome for individuals with attentional difficulties. Alternatively, Adams et al. (2017) outlined a participant inclusion criterion in their feasibility study where they included those with co-occurring ADHD if the occupational therapists confirmed they had the attentional capacity to maintain MI. The use of a video display showing the same action they are required to imagine (AOMI) may provide cues to help them maintain their MI and may allow the inclusion of these children. Further research should, therefore, seek to identify the capacity of individuals with ADHD or other attentional deficits to engage with AOMI in order to verify the efficacy of this technique in these populations. The use of eye tracking techniques may provide an effective modality to assess the benefits of the accompanying visual display during MI in populations with attentional difficulties. Children with ADHD typically make more saccades and have poor fixation capabilities (Levantini et al., 2020). Meanwhile, gaze strategies of TD individuals during MI share similar patterns to actual movement execution (Heremans et al., 2008). Children with ADHD would presumably exhibit more frequent saccades during MI; however, the presence of a video showing actions in meaningful environments, combined with kinaesthetic imagery (AOMI), may help improve the attention of gaze to the relevant stimuli during AOMI and actual performance. Determining these effects may help to broaden the inclusion criteria for future DCD interventions instructing MI.

5. Conclusion

There is growing evidence for the efficacy of MI training and some promising evidence for AO training in children with DCD. Based on the recent findings of Marshall et al. (2020b) and Scott et al. (2019; 2020), further exploration of the combined use of these motor simulations (i.e., AOMI) in children with DCD is warranted. Future investigations should focus on identifying the neural correlates of AOMI in children with DCD and the benefits of manipulating perspective and agency during its use. Research should also focus on the development of more complex interventions assessing the efficacy and effectiveness of the AOMI approach, in a similar manner to previous MI research with DCD (Wilson et al., 2016; Adams et al., 2017). Despite further research required to fully understand the underlying mechanisms of DCD, AOMI may provide a promising training tool to alleviate neuromotor deficits reported for children with DCD.

Declaration of interest

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