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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 $\leq 16^{th}$ percentile are assumed to have borderline DCD, whereas those who score $\leq 5^{th}$ 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

49 palsy; Gordon, 2016), and may, therefore, contribute to the motor difficulties associated with DCD.

50 Abnormality in the parietal sub-region of corpus callosum has also been reported in children with

51 DCD (Langevin et al., 2014). Given corpus callosum's role in inter-hemispheric coordination and the

52 transfer of sensorimotor information between hemispheres (Tallet & Wilson, 2020), this may explain

53 some of the documented difficulties in bimanual coordination (Gheysen et al., 2011). Suppression of

54 the function of the putative human mirror neuron system (hMNS) - comprising the inferior frontal

55 gyrus (IFG), ventral premotor cortex (PMv), and the inferior parietal lobule (IPL; Molenberghs et al.,

56 2012) - has also been reported in DCD populations (Reynolds et al., 2015a). This fronto-parietal

57 network contains neurons that are active during the performance of an action, as well as during the

58 observation of that same action. As a result, this network is proposed to mediate imitation and play a

59 role in visuomotor learning (Vogt & Thomaschke, 2007). Reduced functional connectivity between

60 mirror regions, bilateral IFG, precentral gyrus and motor cortex may contribute to this impairment

61 (Mcleod et al., 2014). Disruptions to cerebellar functioning have also been reported in DCD

62 (Debrabant et al., 2013; Zwicker et al., 2011) with the role of the cerebellum implicated in internal

63 modelling; specifically the forward model (de Xivry & Ethier, 2008). The internal model deficit

64 (IMD) hypothesis suggests that impairment in the generation of forward models disrupts the

65 comparison of predicted and actual sensory feedback in DCD, thus impeding the learning and

66 performance of motor actions (see Adams et al., 2014 for a review).

67 Due to uncertainty regarding the cause of DCD, 'treatments' vary but typically emphasise

68 repetitive physical practice as the primary strategy to improve motor skills (for a review, see Smits-

69 Engelsman et al., 2018). There is evidence, however, that physical practice alone is insufficient to

70 overcome the motor impairments associated with the condition (Brown-Lum & Zwicker, 2017). For

71 example, Zwicker et al. (2011) reported that children with DCD showed no improvement in the

72 performance of a fine motor tracing task after physical practice alone. Several brain regions associated

73 with motor learning (i.e., the right dorsolateral prefrontal cortex, IPL and cerebellum) were also found

74 to be suppressed during the tracing task in this study. Based on this evidence, Brown-Lum and

75 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

101   In recent years, there have been reports of neurological deficits during AO and imitation tasks for

102   children with DCD. While the research discussed in this review referred to the hMNS in the context

103   of observation and imitation, the current review will refer to this fronto-parietal circuit as the action

104   observation network (AON). The AON encompasses the putative hMNS and a wider set of regions

105   which contribute to visuomotor learning (Cross et al., 2009). Reynolds et al. (2015b) reported the first

106   direct evidence for a potential disruption of the AON during AO and imitation for this population.

107   Participants observed and imitated a finger sequencing task inside an fMRI scanner. Results indicated

108   significantly reduced BOLD activity in the precentral gyrus, right IFG, middle temporal gyrus,

109   posterior cingulate and precuneus for children with DCD during AO, compared to their TD

110   counterparts (Reynolds et al., 2015b). Region of interest analysis revealed significantly reduced

111   activity in the pars opercularis of the right IFG for children with DCD when imitating, compared to

112   TD participants. Reynolds et al. (2019) were unable to replicate these findings. While the imitation

113   task used by Reynolds et al. (2019) was the same hand sequencing task (sequenced finger-thumb

114   contact of the digits) used by Reynolds et al. (2015b), the observation task differed in their replication

115   study, using a simpler index finger adduction/abduction task. Reynolds et al. (2019) found small

116   group differences between children with and without DCD during imitation in regions associated with

117   motor planning and motor attention, namely the thalamus, caudate, posterior cingulate cortex and the

118   precuneus. A recent investigation of the AON in children with DCD by Kilroy et al. (2020) found

119   only significantly reduced activity within the pons during AO, but found significantly reduced

120   activations during imitation tasks within the right IFG (pars opercularis), right superior frontal gyrus

121   and the supplementary motor area. Using fMRI, Licari et al. (2015) reported the left IFG to have

122   reduced activation for children with DCD during an imitation task. While this study did not aim to

123   directly investigate the AON, it was suggested that the reduced activation of the left IFG reflected a

124   supressed AON due to the corresponding task performed (i.e., the imitation of pictures of hand

125   actions). Lust et al. (2019) provided further evidence for AON disruption in children with DCD. Their

126   EEG findings showed mu rhythm suppression during observational learning. Collectively, the

127   impairment of these motor regions could result in difficulties in learning new actions, or planning,

128   preparing, and executing movement (Sakreida et al., 2018; Vogt et al., 2007).

129   Additional evidence for the disruption of the AON in DCD can be found through behavioural

130   research (i.e., imitation). Literature largely suggests an impairment in imitation of familiar gestures

131   for children with DCD (Sinani et al., 2011; Zoia et al., 2002), although there are some exceptions

132   (Dewey et al., 2007). Furthermore, this population experience difficulties when imitating unfamiliar

133   gestures (Reynolds et al., 2017b) suggesting that the memorial structures required to repeat a

134   movement may need to be part of an individual's physical performance repertoire when consciously

135   required to imitate the movement. These studies assessed imitation via gestures using a subjective

136   rating scale. Scott et al. (2020) therefore assessed imitative ability through more objective assessments

137   of the kinematics of familiar rhythmical actions. They found that the DCD group's imitation was

138   significantly less accurate than those without DCD. It is notable, however, that no significant

139   differences have been reported in unintentional imitation (automatic imitation) between these groups

140   (see Scott et al., 2019). This may be due to the involvement of more complex neural systems

141   supporting intentional imitation, which may be impaired in DCD populations (Scott et al., 2020).

142   Although, strictly speaking, there are no AO training studies in DCD populations, research

143   involving quiet eye training for throwing and catching tasks shows promise for action observation-

144   based training methods in children with DCD (Miles et al., 2014; 2015; Slowinski et al., 2019; Wood

145   et al., 2017). Wood et al. (2017) provided interventions that instructed participants to direct their

146   visual attention differently during observation of a throwing and catching video. Instructions for the

147   quiet eye training group required participants to focus on the flight path of the ball, whilst viewing a

148   video showing the gaze strategy of the expert model. In the technical training group participants were

149   required to attend to the appropriate technique for throwing and catching whilst viewing the

150   movement of the model in the video (i.e., an AO intervention). Significant improvements from

151   baseline for throwing and catching performance were reported in both groups across both retention

152   tests. Although the largest improvement was reported in the quiet eye training group, improvements

153   were also found following the technical training, which resembled AO. Similar findings have also

154   been reported in previous quiet eye training studies in DCD populations (Miles et al., 2014; 2015).

155   The interventions provided for the technical training groups in these studies represent the closest

156   approximation to an AO intervention in children with DCD to date, and would seem to support the

157   efficacy of AO-based interventions within this population.

158   2.2.   Motor imagery research in DCD

159   The earliest study investigating electrophysiological activity in children with DCD during MI was by

160   Lust et al. (2006) using electroencephalography (EEG). The amplitude of the rotation-related

161   negativity, an event-related potential related to mental rotation tasks, was recorded across parietal

162   regions. The findings revealed no difference in amplitudes between children with and without DCD

163   during MI. It is noteworthy, however, that no group differences were detected on the MI task either

164   (i.e., the mental hand rotation task). This task requires the use of MI in order to differentiate between

165   images of left and right hands that are rotated to varying degrees (Barhoun et al., 2019; Wilson et al.,

166   2004). Complexity of the hand rotation task differs depending on various factors, including the

167   orientation of the hand, whether the hand is pronated or supinated, the occlusion of the participant's

168   own hand, and the addition or omission of MI instructions (i.e., explicit and implicit MI, respectively;

169   Reynolds et al., 2015a). When MI instructions are omitted, the implicit use of MI is required as the

170   individual has to rotate the presented limb mentally to determine which hand is displayed. Despite

171   being frequently adopted in DCD research to assess MI characteristics, the mental hand rotation task

172   may not access cortical motor areas in the same way as, for example, MI of complex movements of

173   hands and limbs (Hétu et al., 2013). This may, therefore, explain the null effects reported in by Lust et

174   al. (2006). Reynolds et al. (2019) studied the neural correlates of MI in children with and without

175   DCD through functional magnetic resonance imaging (fMRI) measuring blood oxygen level

176   dependent (BOLD) activity. Although differences in performance of the mental hand rotation task

177   were revealed prior to scanning, whole brain analysis revealed there to be no measurable neurological

178   differences between the two groups when imagining themselves performing a finger-tapping task.

179   Furthermore, the region of interest analysis focusing on areas associated with motor planning and

180   action execution (i.e., the IFG, supplementary motor area (SMA), premotor area, IPL and superior

181   temporal sulcus (STS)) revealed no group differences during MI use. Future neurophysiological

182   research investigating MI in children with DCD would benefit from more standardised MI protocols

183   across studies to help determine any potential deficits; for example, the inclusion of explicit MI

184   instructions and the consistent use of more complex assessments of MI.

185   Neurophysiological differences have, however, been reported between adults with and

186   without DCD (Hyde et al., 2018; Kashuk et al., 2017). Using fMRI Kashuk et al. (2017) revealed

187   significantly reduced activations across the middle frontal gyrus, the left superior parietal lobule and

188   cerebellum during mental hand rotation task where MI was explicitly instructed for adults with

189   possible DCD. Hyde et al. (2018) conducted a similar investigation using transcranial magnetic

190   stimulation (TMS). When the primary motor cortex (PMC) was stimulated during a mental hand

191   rotation task, corticospinal excitability was reduced in those with DCD, compared to healthy adults.

192   As self-reported kinaesthetic imagery ability is correlated positively with corticospinal excitability

193   during MI (Williams et al., 2012), this finding suggests a possible reduced motor simulation capability

194   for adults with DCD when transforming images using MI. These different neurological findings for

195   children and adults with DCD during MI may be due to developmental changes that occur between

196   childhood and adulthood. For example, a greater overlap between brain areas activated during motor

197   simulations and action execution could occur in adults compared to children (Morales et al., 2019).

198   This increased overlap in adults with DCD may have revealed a MI deficit when motor regions

199   associated with action execution were directly stimulated with TMS during MI (Hyde et al., 2018).

200   Despite the equivocal findings for neurophysiological deficits reported during MI in

201   individuals with DCD, differences in cognitive 'measures' of MI are more consistently reported in

202   children with DCD. One of the paradigms used most frequently to assess MI ability is the mental hand

203   rotation task. To date, deficits have been reported in children with DCD on this task both when

204   implicit MI is used (Barhoun et al., 2019; Wilson et al., 2004), and when explicit imagery instructions

205   are provided (Williams et al., 2006; 2008). When explicit MI was instructed, Williams et al. (2008)

206   reported that children at or below the 5th percentile on the MABC-2 performed significantly worse

207   than both TD children and children between the 6th and 15th percentile. Similar findings were also

208   reported for a whole-body mental rotation task (Williams et al., 2006; 2008). Finally, using

209   questionnaire measures Fuchs and Caçola (2018) reported that children with DCD had a reduced

210 ability to spatially manipulate objects using MI compared to TD children, whilst Scott et al. (2020)

211 reported differences in self-reported kinaesthetic image generation ability. Collectively, cognitive

212 measures of MI indicate a sub-optimal ability for image generation and transformation in children

213 with DCD, which may hinder the experience of kinaesthesis during MI of more complex movements

214 (Holmes & Calmels, 2008).

215 Behavioural measures are commonly used to assess the mental chronometry of MI in

216 individuals with DCD. For example, children with DCD have a temporal incongruency between

217 imagined and performed actions on the visually-guided point task (Ferguson et al., 2015; Maruff et

218 al., 1999; Williams et al., 2013). This difference has been suggested to be due to imagined actions not

219 conforming to Fitts's Law (i.e., the speed accuracy trade off; Fitts, 1954). Deficits in the maintenance

220 of MI have also been reported in the imagination and subsequent performance of rhythmical actions

221 (Scott et al., 2020). This was proposed to reflect temporal difficulties during MI causing inaccurate

222 imitation of the actions. While functional equivalence of imagined and executed actions has been

223 proposed (Jeannerod 2001; 2006), findings through behavioural measures of MI (i.e., the temporal

224 incongruency between imagined and executed actions) may suggest variance in the supporting motor

225 networks for these two processes in children with DCD. When considering MI as a training tool to

226 facilitate movement for children with DCD, a potential difference in the underling mechanisms

227 between MI and physical execution may limit its potential (see Holmes & Collins, 2001).

228 The discrepant findings across neurological, cognitive, and behavioural dimensions indicate

229 that while there are no conclusive neurological differences between individuals with DCD, cognitive

230 and behavioural differences may exist in children. Despite the possible MI deficits seen in DCD

231 populations, MI training appears to have beneficial effects on planning and executing movement

232 (Blank et al., 2019). The earliest account of MI training in children with low motor ability was by

233 Wilson et al. (2002). In this study, imagery was developed systematically through the use of

234 independent visual imagery, first- and third-person visual perspective action observation, and first-

235 and third-person perspective MI, which was followed by physical practice. Although this study did

236 not include a strict DCD sample ($\leq 49^{th}$ percentile criteria), significant improvements in physical

237 performance (i.e., balance, hand-eye coordination, and catching and throwing) were shown after a

238 five-week intervention involving AO, MI and physical practice. This finding was later replicated by

239 Wilson et al. (2016) using the same protocol but with a stricter inclusion criteria for DCD ($\leq 10^{th}$

240 percentile criteria). In a recent feasibility study, Adams et al. (2017) examined the efficacy of MI for

241 enhancing movement outcomes in children with DCD. The participants followed a nine-week

242 intervention involving AO, MI and physical practice of participant-selected tasks. These tasks ranged

243 from catching and throwing, cutlery use, and gross movements (i.e., badminton, running, or jumping a

244 rope). The authors reported improvements in MABC-2 scores for all children in the MI group. Further

245 support for MI training in a DCD population was reported by Bhoyroo et al. (2019). They found that

246 acute MI instructions significantly improved movement planning and end state comfort for children

247 with DCD.

248 In line with the IMD hypothesis, it is believed that MI training may improve forward

249 modelling in children with DCD and the prediction of the sensory consequences of their actions

250 (Miall & Woplert, 1996; Wilson et al., 2013). This may explain the moderate to large effect size

251 attained by Wilson et al. (2016) for their MI group and the findings of Bhoyroo et al. (2019).

252 Furthermore, across the studies of both Wilson et al. (2016) and Adams et al. (2017) 14 out of 16

253 children improved performance following treatments involving MI, 10 of which performed above the

254 standard error of measurement for their respective study. While MI interventions in DCD are sparse,

255 the evidence suggests there to be favourable outcomes for motor skill learning interventions

256 incorporating MI in this population.

257 ### 3. Combined action observation and motor imagery (AOMI)

258 Although the independent use of AO and MI interventions have been shown to be effective for

259 improving motor performance in children with DCD, several problems exist with these techniques.

260 For example, an inherent problem with MI interventions is the lack of control associated with asking

261 any individual to imagine a motor action, as there is currently no way to confirm that the individual is

262 imagining the action exactly as prescribed. Whilst imagery scripts are often developed to provide

263 content and cues for imagery, the step-by-step nature in which imagery scripts describe the process of

264 imagining movement execution could arguably serve to promote the cognitive control of the

265 movement more characteristic of novice performance. Whilst some researchers have used AO

266 techniques to provide a guide prior to MI (Adams et al., 2017; Wilson et al., 2002; 2016), it remains

267 the case that the MI processes of children with DCD have temporal incongruency with the performed

268 actions (Ferguson et al., 2015; Williams et al., 2013; Wilson et al., 2002). When considering these

269 issues, together with the discussed compromised imagery ability characteristics in DCD populations

270 (Reynolds et al., 2015a), it is conceivable that progress obtained through AO or MI training may be

271 slower than that of a TD individual.

272 Within the past decade it has been proposed that AO and MI may have greater benefits when

273 combined and used concurrently (i.e., AOMI, see Eaves et al., 2016a; Vogt et al., 2013). Vogt et al.

274 (2013) proposed a spectrum of AOMI states, whereby MI content during AO can vary according to

275 the level of congruence between the observed and imagined action. What Vogt et al. termed congruent

276 AOMI involves instructing the user to observe an action on video, whilst imagining *simultaneously*

277 the kinaesthetic feelings and sensations associated with executing the observed action. Whilst it is

278 now acknowledged that this process cannot be truly described as 'congruent' given the different

279 visual and kinaesthetic modalities prioritised during the respective components (Frank et al., 2020),

280 there are promising neurophysiological and behavioural findings in the research exploring this AOMI

281 process to date (see Eaves et al., 2016a). Before continuing, an important distinction needs to be made

282 between this combined use of AOMI and the previously discussed protocols in DCD interventions

283 that have used AO as a primer *before* MI (e.g., Adams et al., 2017; Wilson et al., 2002; 2016). While

284 AO followed by MI does activate motor regions of the brain and can be beneficial for subsequent

285 movement execution, this approach does not constitute AOMI as described in the recent literature

286 where the AO and MI components must occur simultaneously (e.g., Eaves et al., 2016a; Taube et al.,

287 2015; Vogt et al., 2013).

288 The earliest neurophysiological account of AOMI was by Sakamoto et al. (2009). Using

289 TMS, they demonstrated that corticospinal excitability was facilitated to a greater extent when adult

290 participants engaged in AOMI, compared to when they engaged in either AO or MI alone. This

291 finding has since been replicated in numerous TMS studies exhibiting greater MEP amplitudes during

292 AOMI than either or both AO and MI alone (e.g., Bruton et al., 2020; Meers et al., 2020; Mouthon et

293 al., 2015; Ohno et al., 2011; Tsukazaki et al., 2012; Wright et al., 2014; 2016; 2018). Based on these

294 findings, the use of AOMI could be more advantageous than independent AO or MI for activating a

295 potentially compromised corticospinal tract in children with DCD. The reliability of these TMS

296 findings have been further confirmed through research using other techniques, including fMRI

297 (Macuga & Frey, 2012; Nedelko et al., 2012; Taube et al., 2015; Villiger et al., 2013) and EEG

298 (Berends et al., 2013; Eaves et al., 2016b; Sun et al., 2016).

299   The research using fMRI provides an indication of the different activations in the motor

300 system during AOMI, compared to independent AO and MI. Nedelko et al. (2012) reported greater

301 activations for AOMI than AO in the IFG, inferior parietal cortex, the caudate nucleus, and the SMA.

302 Increased activity in similar regions was reported by Villiger et al. (2013) when comparing AOMI and

303 AO instructions. In this study, AOMI was also found to activate the PMv and left insula more so than

304 AO. Taube et al. (2015) also compared the neural activation during AOMI with that found during

305 both independent AO and MI. Results showed that AOMI facilitated greater activity in the bilateral

306 PMC, bilateral cerebellum, and precuneus, compared to MI. Contrasts between AOMI and AO

307 revealed a greater activation of the left PMC, the left superior and right inferior frontal gyrus, the IPL,

308 the SMA, basal ganglia, and cerebellum for AOMI. Taken together, consistent TMS and fMRI

309 findings indicate increased activity in the motor system during AOMI, compared to either or both

310 independent AO and MI. Reinforcing activity in these brain regions associated with motor planning

311 and execution regularly over the course of an AOMI intervention may have the potential to contribute

312 to improvements in motor function through Hebbian plasticity mechanisms (Wright et al., 2018).

313 This, however, remains to be established.

314   Behavioural research in healthy adults has reported greater effects for AOMI on automatic

315 imitation (Eaves et al., 2014; 2016b), and intentional imitation (Bek et al., 2016) than either or both

316 AO and MI. The simultaneous use of these instructions has also been shown to be beneficial for

317 improving performance outcomes. When compared to both AO and MI separately, AOMI

318 interventions have been shown to significantly improve the performance and kinematics of aiming

319 tasks (Romano-Smith et al., 2018; 2019). Significant improvements have also been reported for motor

320 learning both before (Kawasaki et al., 2018) and after inducing a training plateau (Aoyama et al.,

321 2020), rehabilitation (Marusic et al., 2018), and eye-hand coordination tasks (Marshall et al., 2020a),

322 when compared to a control group. The benefits of AOMI for clinical adult populations is also

323 becoming apparent. Sun et al. (2016) reported significantly greater improvements in pinch-grip

324 strength and dexterity for stroke patients following an AOMI intervention, compared to an alternating

325 AO *then* MI intervention. In addition, more pronounced event-related desynchronization was reported

326 in the alpha frequency band over the left motor cortex for the AOMI group. The authors interpreted

327 this electrophysical activation following AOMI training to reflect improved neuroplasticity, which

328 translated to improved function of the right hemiplegic limb (Sun et al., 2016). Enhanced imitation

329 when using AOMI has also been reported when compared to independent AO for individuals with

330 Parkinson's disease AOMI (Bek et al., 2019). A recent pilot intervention assessing the feasibility and

331 acceptability of AOMI suggests that it could be beneficial for training ADLs in those with Parkinson's

332 disease (Bek et al., 2020). These findings provide promising evidence for the efficacy of AOMI

333 training in populations with motor impairments, and for the potential of AOMI as a home-based

334 intervention. As children with DCD struggle with manual dexterity and the performance of ADLs

335 (Blank et al., 2019), the results of Sun et al. (2016) and Bek et al. (2020) may provide additional

336 evidence for the suitability of AOMI in this population.

337   3.1.   AOMI in children with DCD

338 Scott et al. (2019) investigated the behavioural correlates of the AON in this population through an

339 automatic imitation paradigm. Automatic imitation is a type of stimulus-response compatibility effect,

340 whereby observing a task-irrelevant action can facilitate execution of similar actions, or impede

341 execution of different actions (Heyes, 2011). Scott et al. (2019) instructed the children in the AOMI

342 condition to imagine, simultaneously, the feeling and sensations associated with executing the

343 everyday rhythmical actions (e.g., face washing) they watched during videos. The AOMI instruction

344 significantly enhanced the automatic imitation effect compared to both independent AO and MI for

345 those with DCD.

346   Recently, Scott et al. (2020) explored the effects of AOMI on intentional imitation in children

347 with DCD through the kinematics of familiar rhythmical actions. Children were instructed to watch

348 videos of the actions prior to imitating them as closely as possible. The instruction to use AOMI

349 before imitating significantly improved imitation for the DCD group, compared to the AO followed

350 by MI condition. Although demonstrated on simple unilateral actions, this provides preliminary

351 evidence that AOMI may be superior to the systematic use of AO then MI (e.g., Adams et al., 2017;

352 Wilson et al., 2016) for promoting the temporal congruency of imagined actions and improving

353 movement for children with DCD.

354   Marshall et al. (2020b) studied the effects of AOMI training on eye-hand coordination during

355 visuomotor adaption in children with DCD. While both groups had the same amount of physical

356 practice, the AOMI training group were provided with videos in which they observed a performer

357 complete the same task from a first-person visual perspective while they simultaneously imagined the

358 kinaesthetic sensations associated with executing that task. A control group received videos showing

359 no human motor content. After training, the AOMI group showed faster task completion times,

360 significantly smoother movement kinematics, and more effective eye-hand coordination. The

361 improvements in performance and gaze behaviour were interpreted as improved internal modelling as

362 a result of AOMI.

363   Although there are currently no studies investigating the neurophysiological effects of AOMI

364 in DCD, if AO and MI alone can target suppressed motor regions in those with DCD then AOMI may

365 do this to a greater extent. Furthermore, this would align with the recent call by Brown-Lum &

366 Zwicker (2017) for mental training interventions to target supressed brain regions in children with

367 DCD. Two AON regions reported to be impaired in this population are the precentral gyrus and pars

368 opercularis of the IFG (Kilroy et al., 2020; Reynolds et al., 2015b). While the evidence for the

369 suppression of these motor regions has only been obtained through AO and imitation in DCD

370 (Reynolds et al., 2015b; 2015a), these regions also play a role in MI and action execution in adults

371 (Hardwick et al., 2018) and children (Reynolds et al., 2015b). Greater activation of the precentral

372 gyrus has been reported during AOMI compared to AO and MI separately in adults (Taube et al.,

373 2015). As the precentral gyrus has been found to be impaired in children with DCD (Mcleod et al.,

374 2014; Reynolds et al., 2015a), using AOMI may have the potential to increase activity within this area

375 to that of a TD individual (Taube et al., 2015).

376   Reduced BOLD activity has also been reported in both the left (Licari et al., 2015; Zwicker et

377 al. 2010) and right IFG (Debrabant et al., 2013; Kilroy et al., 2020; Reynolds et al., 2015b) in children

378 with DCD. Bilaterally, the IFG is involved during MI, AO and action execution (Hardwick et al.,

379 2018). Within the IFG is the pars opercularis, a structure associated with imitation (Kilner et al., 2009;

380 Molnar-Szakacs et al., 2005), MI generation and maintenance (Hétu et al., 2013), and AO (Molnar-

381 Szakacs et al., 2005; Vogt et al., 2007). Region of interest analyses by Kilroy et al. (2020) and

382 Reynolds et al. (2015b) revealed the pars opercularis of the right IFG to be activated less during

383 imitation in this population. Studies by Nedelko et al. (2012) and Taube et al. (2015) found greater

384 activations in the left and right IFG, respectively. If AO and MI can co-exist and coalesce during

385 AOMI (Bruton et al., 2020; Eaves et al., 2016a; Vogt et al., 2013), activity in the bilateral IFG could

386 be enhanced (Nedelko et al., 2012; Taube et al., 2015). This process could explain the enhanced

387 imitation for DCD children reported by Scott et al. (2019; 2020) following AOMI.

388   Additional regions reported to be impaired in children with DCD are the precuneus (Reynolds

389 et al., 2015b; Reynolds et al., 2019; Zwicker et al., 2011) and the cerebellum (Debrabant et al., 2013;

390 Zwicker at al., 2011). Greater activity in both of these regions has been reported during AOMI than

391 either or both AO and MI (Nedelko et al., 2012; Taube et al., 2015). Independent MI can facilitate

392 activity to regions of the cerebellum (Hardwick et al., 2018). Although cerebellar activity has been

393 associated with the suppression of physical movement (Decety, 1996), the enhancement of activity in

394 this region could also explain the improvements for motor skills via MI interventions in DCD (Adams

395 et al., 2017; Bhoyroo et al., 2019; Wilson et al., 2016). The cerebellum has been proposed to generate

396 forward models to predict the sensory consequences of movement (de Xivry & Ethier, 2008), which

397 are thought to be impaired in DCD (Adams et al., 2014). Accordingly, and in alignment with the IMD

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398   hypothesis, it is conceivable that AOMI could facilitate the generation of more accurate forward

399   models in children with DCD, to a greater extent than AO and MI alone. By this process, AOMI could

400   further enhance predictive motor control for children with DCD, as found by Marshall et al. (2020).

401   The synthesis of evidence above suggests that AOMI may be a superior motor simulation

402   technique for increasing the activation of motor regions and producing better behavioural outcomes

403   for children with DCD (Marshall et al., 2020b; Scott et al., 2019; 2020), compared to either AO or MI

404   alone. So why does AOMI provide such benefits? While MI interventions require an individual to use

405   both visual and kinaesthetic imagery, there is an inherent assumption that they have the abilities to

406   support both modalities of motor simulation. A principal characteristic of AOMI is the presence of a

407   visual guide *during* MI. The visual guide provided during AOMI may allow greater cognitive

408   resources to focus on the kinaesthetic aspect of the imagery rather than the generation of a visual

409   component. Earlier it was highlighted that there is a temporal incongruence for the MI processes of

410   children with DCD, which could potentially distort the content of prior AO. Indeed, this incongruence

411   would still exist during AOMI, at least during early training; however, this incongruence may be

412   offset with continual training and the additional structure provided for the MI by the AO content. This

413   should provide the user with opportunities to refine their MI through simultaneous and consistent

414   feedback from a congruent observed action. This could be particularly beneficial for those of a sub 5th

415   percentile MABC-2 score who have been reported to have difficulty utilising explicit MI instructions

416   (Williams et al., 2008). In addition, providing a proficient model to observe *during* MI provides

417   appropriate action content with which the user can synchronise their MI, potentially improving

418   sequencing and timing of action execution (Wright et al., 2018). This could be advantageous for

419   children with DCD in particular, as the MI for these individuals is temporally incongruent with their

420   physical actions when the visual component of the MI has to be generated alongside the kinaesthetic

421   (Ferguson et al., 2015; Wilson et al., 2002; Williams et al., 2013).

422   **4. Future directions**

423   There are currently no neurological studies on AOMI in children with or without DCD. The above

424   section, however, has evidenced the relationship between the potential neurophysiological deficits in

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425 DCD and the neural correlates of AOMI. Preliminary investigations of AOMI in children with DCD

426 suggest behavioural benefits when using AOMI compared to independent AO and MI (Scott et al.,

427 2019; 2020); research should now investigate the neurological activations in children with and

428 without DCD during AOMI. In accordance with adult AOMI literature (Eaves et al., 2016; Taube et

429 al., 2015; Wright et al., 2014), it could be hypothesised that the activations of AOMI would be greater

430 than AO and MI separately. The overlap between motor simulations, however, might not occur to the

431 same degree in children (Morales et al., 2019) and the increased activity associated with AOMI might

432 be reduced in children compared to adults.

433 While AOMI interventions benefit adult populations with and without motor impairments

434 (Bek et al., 2020; Scott et al., 2017; Sun et al., 2016; Taube et al., 2014), future research should

435 investigate the efficacy of longitudinal AOMI training in children with DCD. To date, only acute

436 AOMI training benefits have been shown for children with DCD (Marshall et al., 2020b; Scott et al.,

437 2019; 2020). Furthermore, research by Marshall et al. (2020b) and Scott et al. (2019; 2020)

438 demonstrated the benefits of AOMI on abstract tasks (a visuomotor rotation task and rhythmical

439 actions, respectively). As AO followed by MI has been shown to be beneficial for this population over

440 interventions of five (Wilson et al., 2016) and nine (Adams et al., 2017) week durations, a comparison

441 of AOMI with the aforementioned AO and MI protocols could allow the progression and optimisation

442 of motor simulation treatments in DCD. The addition of meaningful tasks such as ADLs, which are

443 problematic within the DCD population (Summers et al., 2007), would also improve the ecological

444 validity of this research. Such work would offer the opportunity for the development of more cost-

445 effective, home-based AOMI interventions delivered using mobile devices (e.g., Bek et al., 2020).

446 An assumption in AOMI research focusing on adults is that greater motor activity facilitates

447 skilled movement. Indeed, greater activity during AO and MI separately is indicative of expert level

448 capability in performing a simulated movement; however, neural activity during actual physical

449 performance in experts is reduced – a neural efficiency effect (Mizuguchi & Kanosue, 2017).

450 Although the benefits of the increased neurophysiological activity induced by AOMI across motor

451 learning stages is yet to be established in adults, promoting activity across deficient motor areas in

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452 DCD may accelerate learning to that of a TD individual. To examine such effects in children with

453 DCD, utilising neuroimaging techniques (e.g., fMRI and EEG) across AOMI interventions would

454 provide a welcome insight to changes in neurological markers. AON related regions (i.e., the PMC,

455 IPL, superior parietal lobule) may show decreased (early training) or increased activity (later training)

456 during AO and MI separately (Mizuguchi & Kanosue, 2017), this however is dictated by the level of

457 learning achieved which will likely be slower in DCD children. Similar trends may be observed for

458 AOMI across these motor related regions after training phases and could act as an indicator of motor

459 learning through fMRI. Alternatively, greater event-related desynchronization of alpha and lower beta

460 frequency bands during EEG can be an indicator of mastery of an observed movement (Orgs et al.,

461 2008). While it remains to be determined whether children with DCD can achieve the level of

462 expertise assessed within these neuroimaging studies, these trends in activities may provide indicators

463 of motor learning throughout AOMI interventions. Once the long term behavioural and

464 neurophysiological effects of AOMI are better understood, there may be greater confidence in the

465 delivery and optimisation of this instruction.

466 To date beneficial behavioural effects have been reported following AOMI interventions in

467 children with DCD when the action observation content has been recorded from both first- (Marshall

468 et al., 2020b) and third-person (Scott et al., 2019; 2020) visual perspectives. Research should now

469 determine the best perspective for training movement skills in DCD, and how this may vary across

470 different tasks. A first-person perspective is associated with greater corticomotor excitability (Maeda

471 et al., 2002) and greater activity in the sensorimotor cortex (Jackson et al., 2006). In line with MI

472 literature, however, it could be hypothesised that third-person perspective would be advantageous for

473 training gross motor skills where movement form is important (Hardy & Callow, 1999), and

474 accordingly, first-person perspective would be preferable for fine motor tasks where movement form

475 is less important. A comparison of these individual perspectives and their combination would allow

476 the further development of AOMI interventions for children with DCD. Furthermore, the studies of

477 Marshall et al. (2020) and Scott et al. (2019; 2020) used observations of others. Recent research has

478 investigated the benefits of self-modelled AOMI in adults (McNeill et al., 2021), showing benefits for

479   refining well-learned motor skills. Research should now investigate the benefits of self vs. other

480   modelling in AOMI contexts for children with DCD. Although the observation of a skilled other has

481   provided benefits for children with DCD (Marshall et al., 2020b), self-observation may allow a

482   greater experience of agency for this population (Holmes & Calmels, 2008), and improvements in

483   self-efficacy (Ste-Marie et al., 2020). Showing a skilled other performing a task could be

484   counterproductive for a child with DCD, as the gap in motor ability, may reduce self-efficacy and

485   engagement in the task. Therefore, comparisons of self vs. other models could provide a welcome

486   insight to the physical and psychological benefits of AOMI in individuals with movement

487   impairments. An alternative use of self-modelling that has received attention in sport populations is

488   feed-forward self-modelling. This involves compiling and splicing recorded videos of the individual

489   performing movements to create a complete movement sequence beyond the individual's current

490   ability (Vertes & Ste-Marie, 2013). Should self-observations be helpful for children with DCD, feed-

491   forward self-modelling could provide a fruitful avenue for future research.

492   In the case of co-occurring DCD and ADHD, using AOMI could prove to be difficult. Using

493   AOMI requires attentional focus principally on the internal MI content while observing external AO

494   content. This may prove to be troublesome for individuals with attentional difficulties. Alternatively,

495   Adams et al. (2017) outlined a participant inclusion criterion in their feasibility study where they

496   included those with co-occurring ADHD if the occupational therapists confirmed they had the

497   attentional capacity to maintain MI. The use of a video display showing the same action they are

498   required to imagine (AOMI) may provide cues to help them maintain their MI and may allow the

499   inclusion of these children. Further research should, therefore, seek to identify the capacity of

500   individuals with ADHD or other attentional deficits to engage with AOMI in order to verify the

501   efficacy of this technique in these populations. The use of eye tracking techniques may provide an

502   effective modality to assess the benefits of the accompanying visual display during MI in populations

503   with attentional difficulties. Children with ADHD typically make more saccades and have poor

504   fixation capabilities (Levantini et al., 2020). Meanwhile, gaze strategies of TD individuals during MI

505   share similar patterns to actual movement execution (Heremans et al., 2008). Children with ADHD

506   would presumably exhibit more frequent saccades during MI; however, the presence of a video

507   showing actions in meaningful environments, combined with kinaesthetic imagery (AOMI), may help

508   improve the attention of gaze to the relevant stimuli during AOMI and actual performance.

509   Determining these effects may help to broaden the inclusion criteria for future DCD interventions

510   instructing MI.

511   ## 5.   Conclusion

512   There is growing evidence for the efficacy of MI training and some promising evidence for AO

513   training in children with DCD. Based on the recent findings of Marshall et al. (2020b) and Scott et al.

514   (2019; 2020), further exploration of the combined use of these motor simulations (i.e., AOMI) in

515   children with DCD is warranted. Future investigations should focus on identifying the neural

516   correlates of AOMI in children with DCD and the benefits of manipulating perspective and agency

517   during its use. Research should also focus on the development of more complex interventions

518   assessing the efficacy and effectiveness of the AOMI approach, in a similar manner to previous MI

519   research with DCD (Wilson et al., 2016; Adams et al., 2017). Despite further research required to

520   fully understand the underlying mechanisms of DCD, AOMI may provide a promising training tool to

521   alleviate neuromotor deficits reported for children with DCD.

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526

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