Motor imagery during action observation enhances automatic imitation in children with and without developmental coordination disorder

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Key: developmental coordination disorder (DCD); typically developing (TD); action observation (AO); motor imagery (MI); combined action observation and motor imagery (AO+MI); action observation network (AON)

Abstract

Developmental coordination disorder (DCD) is a neurodevelopmental disorder characterised by uncoordinated movement relative to age. While action observation (AO) and motor imagery (MI) can both independently enhance movement skills in children, we report the first study to assess the effects of combined action observation and motor imagery (AO+MI) on automatic imitation in children aged 7-12 years, both with (n = 12) and without DCD (n = 12). On each trial participants planned to execute an instructed rhythmical action (face washing or paint brushing). Before responding, participants observed a rhythmical distractor showing the same or different action, with a subtle speed manipulation across trials (fast vs slow). Automatic imitation was quantified as an imitation bias in subsequent response cycle times. Across blocks of trials participants engaged in AO, MI, or combined AO+MI during the distractor phase, or intentionally imitated the distractor speeds. While there were no between-group differences, combined AO+MI instructions produced a significantly greater imitation bias (115%) than both AO (109%) and MI (109%), with intentional imitation yielding the strongest effects overall (128%). Within-subjects analyses revealed a significant bias for AO and MI in both groups. Combined AO+MI effects were significantly greater than AO in typically developing children, and greater than both AO and MI in DCD children. These results demonstrate a clear capacity for different forms of motor simulation in children both with and without DCD. Moreover, combined AO+MI instructions represent an advantageous method for training movements in children with different motor abilities, compared to separate AO and MI.

Key words: developmental coordination disorder; action imitation; demonstration; mental practice; combined action observation and motor imagery; neurodevelopmental disorder.

Introduction

Developmental coordination disorder (DCD) is a neurodevelopmental disorder characterised by uncoordinated movement relative to age. Around 5-6% of school children are clinically diagnosed and typically experience poor social and academic progress as a secondary impact (Zwicker et al., 2012). While the aetiology of DCD is still unclear, research often focuses on reducing symptoms through different forms of practice. Motor imagery (MI) is one tool recommended as an effective adjunct to physical practice for improving movement skills (Adams et al., 2017; Wilson et al., 2002; 2016; Blank et al., 2019). MI is defined as the internal generation and mental rehearsal of an action without physical execution (Eaves et al., 2016a; Jeannerod, 2006). Another common method for teaching movement skills in children involves action observation (AO; see Hodges et al., 2007). Traditionally, AO and MI have been viewed as two useful but separate techniques. An emerging body of neurophysiological and behavioural research now suggests, however, that the combined and simultaneous use of action observation and motor imagery (i.e., AO+MI) can more directly impact movement outcomes compared to either AO or MI alone (Eaves et al., 2016a). While previous AO+MI experiments have studied only adult participants, here we report the first behavioural experiment to investigate the effects of combined AO+MI instructions in children both with and without DCD, compared to the two separate conditions of either imagining or observing the same movement.

The use of both AO and MI as separate training tools is predicated on neuroimaging research showing the brain areas involved in AO at least partially overlap with those involved during MI, and that these regions overlap extensively with those involved in motor execution (Hardwick et al., 2018). On these grounds, Jeannerod's (2006) influential hypothesis was that AO and MI represent two forms of motor simulation that are functionally equivalent. Despite this early integrative account, however, research involving adults and children has largely studied AO and MI in isolation from each other (Vogt et al., 2013).

With regards to MI ability, children with DCD often exhibit reduced performance in imagery tasks compared to TD children (Adams et al., 2014; Fuchs & Caçola, 2018; Reynolds et al., 2015a). In TD children and healthy adults, MI typically abides by the biomechanical constraints associated with physical execution (for e.g., Fitts' Law; Fitts, 1954). While this is not the case for DCD children in some tasks (e.g., visual guided pointing tasks; Wilson et al., 2001), hand rotation tasks show a trend whereby their MI does abide by biomechanical constraints but is slower and/or less accurate than TD children (Deconinck et al., 2009; Williams et al., 2011; Barhoun et al., 2019). Despite these potential deficits, MI training can still improve motor skills in DCD (Adams et al., 2017; Wilson et al., 2002; 2016; for reviews see Blank et al., 2019; Smits-Engelsman et al., 2018).

With respect to action observation and imitation, neurophysiological research has also identified that the associated brain regions (i.e., the action observation network; AON), may be impaired in DCD. For example, functional magnetic resonance imaging (fMRI) experiments have shown decreased activation in AON regions (Licari et al., 2015; Zwicker et al., 2010; 2011); although this finding is not unequivocal (Reynolds et al., 2017a). Reynolds et al. (2015b) initially reported whole brain analyses showing reduced activation in the pre-central gyrus and inferior frontal gyrus during observation, while region of interest analyses showed reduced activation in the inferior frontal gyrus during imitation in DCD compared to healthy children. One possibility is that these findings offer a potential explanation for the related impairments found in imitative behaviour in DCD children.

Imitation accuracy is often reduced in DCD compared to TD children (see Reynolds et al. 2015a); although one study has reported no group differences (Dewey et al., 2007). Notably, however, Dewey et al.'s (2007) findings are likely due to both the limited number of gestures used and the simplicity of these actions, which necessitates an interpretation of imitative ability in DCD with respect to task difficulty. To assess *intentional* imitation, most experiments have instructed children to observe and then copy the experimenter's gestures (e.g., Dewey et al., 2007; Sinani et al., 2011). This approach is limited, however, in two ways. First, the observation-based rating scales used to assess imitation are purely subjective. Second, intentional imitation studies are inherently confounded by inevitable fluctuations in the participants' motivation for the task, and their cognitive strategy across trials. In the present study, we addressed these issues by quantifying automatic imitation effects, which characterise an unintentional form of imitation known to reflect activation of the AON (Heyes, 2011). Automatic imitation is a type of stimulus-response compatibility effect, whereby observing a task-irrelevant action can facilitate execution of similar, or impede execution of different actions (Heyes, 2011). Next, we briefly review both the neurophysiological and behavioural evidence for combined AO+MI effects in adults, before describing the automatic imitation paradigm used in the present study.

Both AO and MI alone are recommended as separate intervention tools for improving motor outcomes in children. While earlier DCD studies have used action videos to prime subsequent MI (Adams et al., 2017; Wilson et al., 2002; 2016), no previous DCD study has instructed participants to undertake motor imagery *while* they simultaneously observe the same action (i.e., AO+MI). For AO+MI, participants imagine the kinaesthetic experience of action, and synchronise this simulation with a concurrent visual display of the same action (Eaves et al., 2016a). Multimodal neuroimaging research shows this combined AO+MI instruction significantly increases the cortical activity across motor and motor-related brain areas, compared to either AO or MI; using fMRI (e.g., Taube et al., 2015), electroencephalography (EEG; e.g., Eaves et al., 2016b) and transcranial magnetic stimulation (TMS; e.g., Wright et al., 2014; 2018; see Eaves et al., 2016a; Vogt et al., 2013). This cogent body of neurophysiological research now warrants a more comprehensive examination of AO+MI effects on behavioural outcomes, but the available evidence to date is relatively sparse, and confined to adults.

The existing behavioural studies consistently show significant benefits for combined AO+MI instructions compared to either AO or MI alone. Improvements have been shown in balance training (Taube et al., 2014), instantaneous imitation (Bek et al., 2016), peak force development (Scott et al., 2017), target aiming (Romano-Smith et al., 2018), grip strength in stroke patients (Sun et al., 2016) and rehabilitation post hip arthroplasty (Marusic et al., 2018).

While the above research focused on intentional imitation, combined AO+MI instructions can also modulate unintentional (i.e., automatic) imitation effects in adults (Eaves et al., 2014; 2016b). Automatic imitation studies allow a more direct investigation of the neurocognitive mechanisms underlying imitation (i.e., the AON), negating the aforementioned confounds regarding motivation and cognitive strategy. While automatic imitation has been studied extensively in adults (see Cracco et al., 2018), to the best of our knowledge O'Sullivan et al. (2018) were recently the first to study automatic imitation effects in children (aged 3-7 years), who were presumably free of neurodevelopmental disorders. Those authors found a significant automatic imitation effect in the movement initiation times for children within this age range, and also that these initiation times reduced with increased age. In the present study, we extend this research to examine automatic imitation in children aged 7-12 years using movement kinematic measures.

Although automatic imitation has primarily been assessed using movement initiation times, it can also be quantified using kinematic measures, as an imitation bias in rhythmical execution. This method of studying automatic imitation is advantageous since the topographical match between the observed and executed actions can be quantified. Eaves et al. (2012) initially showed that, during a brief motor planning phase, observing a task-irrelevant rhythmical action in either a fast or slow pace (distractor action) across trials significantly biased subsequent rhythmical execution speeds (i.e., an imitation bias). The magnitude of this bias was then modulated by the compatibility between the instructed and distractor actions. The imitation bias was significantly pronounced for fully-compatible trials, in which the instructed and distractor actions matched both in action type and plane of motion (e.g., prepare to execute a vertical face washing action while observing a distractor showing vertical face washing). Relative to the fully-compatible trials, the imitation bias was reduced but still present when the two actions differed in either action type (e.g., face washing vs paint brushing) or plane of motion (e.g., horizontal vs vertical). Relative to these two incompatible conditions, the imitation bias was again present but not reduced further in trials where both the action type and plane were simultaneously incompatible. While participants could have used the 'task-irrelevant' distractor as a guide for their own actions in the compatible trials, the fully-incompatible trials provide evidence for a genuine automatic imitation effect, whereby the distractor's impact on motor processing was generally reduced whenever this was not functionally relevant to the observer's own motor planning.

In two subsequent studies, a robust imitation bias was found for both AO and MI of actions at different speeds, but this bias significantly increased for combined AO+MI of the distractor action (Eaves et al., 2014; 2016b). Using EEG recordings in the same paradigm, Eaves et al. (2016b) confirmed AO+MI significantly increased event-related desynchronization of the MU rhythm over the primary motor cortex, indicating greater involvement of the action observation network, in comparison to both AO and MI alone.

Given that both imagery and imitation ability is reduced in DCD compared to TD children (Reynolds et al., 2015a); and given the evidence indicating reduced AON activity in

DCD (Reynolds et al., 2015b), it is encouraging that MI training can still enhance motor skills in DCD (Wilson et al., 2002; 2016). A pertinent question that follows is whether combined AO+MI instructions can more directly influence motor preparation in this population, compared to either AO or MI alone? In the present study, we employed the same automatic imitation paradigm as in Eaves et al.'s (2012; 2014; 2016b) work to investigate this issue. We quantified automatic imitation following AO+MI compared to both AO and MI in children, both with and without DCD, as an imitation bias in rhythmical execution.

Combined AO+MI methods incorporate a visual guide that may help structure and refine the imagined action. We predicted this would lead to stronger behavioural effects for the AO+MI compared to the separate AO and MI conditions overall, but that the magnitude of this effect would be reduced in DCD compared to TD children. The neurophysiological evidence in adults showing that combined AO+MI instructions can increase both the AON involvement and the related behavioural effects within this paradigm is tentative support in favour of this outcome. Alternatively, it is not yet clear whether children (either with or without DCD) are developmentally capable of following AO+MI instructions, given the initial evidence for the cognitive involvement required (Eaves et al., 2016b). We compared the effects for these three unintentional imitation conditions (AO, MI and AO+MI), against an intentional imitation control condition. To summarise, the main research questions in the present study were:

1. *Between-groups*

Is the imitation bias:

1.1. Significantly weaker for DCD compared to TD children, in each of the three unintentional imitation conditions (AO, MI and AO+MI), and also in the intentional imitation condition?

1.2. Modulated by the compatibility between the instructed and distractor action in DCD and TD children?

2. Within-subjects

Is the imitation bias:

2.1. Present following rhythmical action observation (AO)?
2.2. Present following motor imagery of a rhythmical action at different speeds (MI)?
2.3. Significantly stronger following combined action observation and motor imagery (AO+MI) compared to both AO and MI?
2.4. Significantly greater for intentional imitation overall?

Material and methods

Participants

Twenty-four children volunteered for the study aged 7 - 12 years. Twelve met the inclusion criteria for TD (4 male, mean age = 10 years; *SD* = 1 years) and twelve met the DSM-V diagnostic criteria (American Psychiatric Association, 2013) for DCD (11 male, mean age = 9.6 years; *SD* = 0.9 years). All had normal or corrected-to-normal vision. Participants were naïve to the study's purpose, right-hand dominant (Edinburgh Handedness Inventory; Oldfield, 1971), and without physical injuries. Written informed consent was obtained prior to participation from a parent or legal guardian, and ethical approval had been granted by Teesside University.

Motor ability was assessed relative to chronological age via the Movement Assessment Battery for Children-2 (Movement ABC-2; Henderson et al., 2007). Children with a $\geq 20^{th}$

percentile score were allocated to the TD group, while those with a ≤ 16th percentile score were assigned to the DCD group (see Table 1). Disruption of daily activities and routine was confirmed via the Developmental Coordination Disorder Questionnaire '07 (Wilson et al., 2007). An IQ > 70 was assumed, since all participants attended mainstream education with no diagnosis of additional learning disorders (confirmed via a health questionnaire). Finally, the health questionnaire and Vanderbilt ADHD Diagnostic Parent Rating Scale (Bard et al., 2013) confirmed the children were free of neurological and visual impairments that could explain movement difficulties.

Table 1. Movement ABC-2 scores (mean ± SD) and comparisons between children with developmental coordination disorder and typically developing children.

Group	Movement ABC-2 subcategory			Mean standardised score	Mean percentile score
	Manual dexterity	Aiming and catching	Balance		
Developmental coordination disorder	13.3 ± 4.8	12.9 ± 2.9	23.1 ± 7.9	49.3 ± 13.2	5.2 ± 5.7
Typically developing	24.4 ± 5.2	18.9 ± 3.9	32.2 ± 3.2	75.5 ± 6	40.1 ± 15.3
Comparison (*p*)	< .001	< .001	= .001	< .001	< .001

Task and Design

In each experimental trial, participants saw a picture of a to-be-pantomimed everyday rhythmical action (instructed action), followed by a short, task-irrelevant movie (distractor action) of either the same or a different action (see Figures 1 and 2). They then executed the instructed pantomime action. Across trials slow and fast versions of each distractor action were used.

The experiment consisted of four blocks of sixteen trials. A four-factorial mixed design was used, involving a between-groups factor (DCD vs TD). For the within-subjects factors, instruction condition was manipulated across blocks of trials (AO vs MI vs AO+MI vs intentional imitation) while the remaining factors of distractor speed (slow vs fast) and distractor compatibility (same vs different action) were manipulated within blocks.

Stimuli and apparatus

A digital video camera (Panasonic NV-MX500B) was used to create the instructed picture and distractor movie stimuli. The two instructed stimuli were face washing and paint brushing, performed in the vertical and horizontal plane (see Figure 1). Given the relatively complex design, and given that we were only interested in the compatibility between instructed and distractor actions, rather than in the separate effects for each individual action, we pooled the data across instructed actions. The model performed all actions with the left hand to provide mirror images of the participants' subsequent actions, who always used their right hand. This arrangement provided spatial compatibility between the displayed and performed actions, which can facilitate imitation relative to an anatomically matched but spatially incompatible arrangement (e.g., Buccino et al., 2004).

Eight distractor movies were used in the main experiment, one slow and one fast version of each of the two instructed actions, performed in the horizontal and vertical plane. During filming, the model's performance was paced by a metronome to speeds of 60 and 90 BPM, but presented without sound in the main experiment. Each instructed picture action was displayed with the relevant object (sponge or paintbrush), which enabled quick discrimination between the actions, whereas participants performed pantomimed actions without objects. The latter meant participants did not need to select the relevant object in the beginning of each trial. The distractor movies showed pantomimed actions to allow participants to better distinguish between instructed and distractor stimuli, and to potentially strengthen the impact of the distractor stimuli on the subsequently pantomimed action.

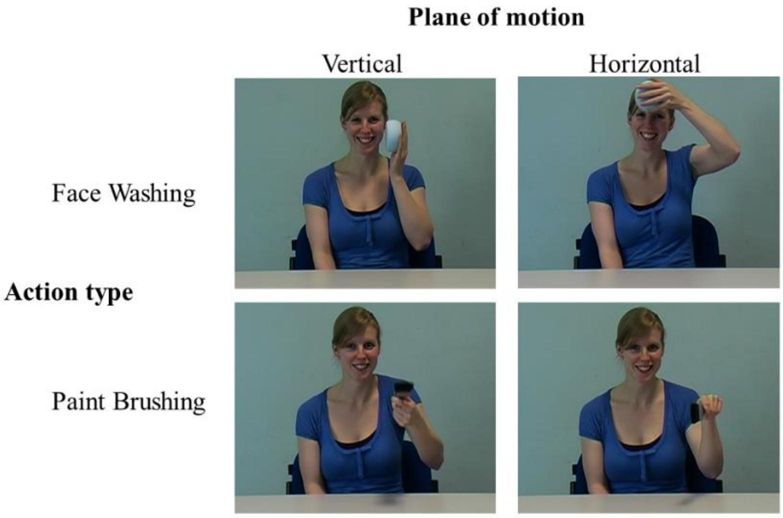

Figure 1. Instructed action stimuli with the factors of action type and plane of motion.

Participants sat at a wooden desk in a dimly-lit room facing a 17-in LCD computer monitor (Hewlett Packard) positioned approximately 80 cm away from their head. All stimuli were displayed against a black background via SuperLab 4.5 software (Cedrus Corp.). The start location for the participants' hand was on a black cross located 20 cm ahead of them on the desk. A magnetic motion sensor was fitted to the distal end of the second metacarpal bone of the right hand. Participants' kinematic data were sampled at 103 Hz in 3-D space for 4 second periods using a Minibird Magnetic Tracking System (Ascension Technology Corp.), and were stored on a separate PC. At the end of each trial, kinematic data plots were displayed on a second monitor, unseen by participants.

Procedure

Familiarisation. *Phase 1*. Participants learned to pantomime each action from a set of four familiarisation movies (two actions in each plane, one attempt each). These matched the movies for the main experiment, except the cycle times were 75 BPM, that is, mid-way between the two experimental distractor speeds. Participants received verbal feedback about their movement based on the kinematic plots visible to the experimenter. This ensured their movement amplitude and cycle time aligned closely with the medium-paced stimuli. *Phase 2.* Participants saw a picture of each action while simultaneously pantomiming the same action for 4 seconds (8 trials). This confirmed that participants could discriminate between the different instructed actions and planes. *Phase 3*. Next they experienced the structure of trials in the main experiment (see Figure 2), including the compatibility manipulation, but using the medium-paced distractors (8 trials). Phases 4 and 5 were then administered after the first block of AO trials had been completed.

The action observation block was presented first because it was important to try to reduce the chance of participants engaging in spontaneous or deliberate motor imagery during this condition. Providing imagery training prior to this block could encourage this possibility, by virtue of the imagery instructions themselves. Withholding this training prior to the block should instead promote a more naturalistic and perhaps passive form of action observation (c.f., Eaves et al., 2012). The presentation order for the subsequent MI and AO+MI blocks was fully counterbalanced across the participants within each group. The first three blocks assessed unintentional imitation, for which the subtle distractor speed manipulation was not disclosed to participants. It was therefore important to run the intentional imitation block last, as this would encourage attention toward the distractor action kinematics.

Phase 4. Participants completed the Movement Imagery Questionnaire-3 (Williams et al., 2012) prior to participating in the three subsequent blocks of trials. They executed overt followed by imagined actions and then self-reported the vividness of their experiences on three subscales: visual internal, visual external and kinaesthetic imagery (see Table 2). An imagery script based on the Physical, Environment, Task, Timing, Learning, Emotion, and Perspective (PETTLEP; Holmes & Collins, 2001) principles was then read out, instructing participants to engage in internal, 1st person kinaesthetic MI for each of the instructed actions (see Supplementary Material 1).

Table 2. Mean scores for the Motor Imagery Questionnaire-3 with standard deviations in three imagery subcategories for children with developmental coordination disorder and typically developing children.

Group	Movement imagery questionnaire-3 subcategory		
	Internal visual imagery	External visual imagery	Kinaesthetic imagery
Developmental coordination disorder	6.1 ± 0.8	5.7 ± 0.7	5.1 ± 1.1
Typically developing	5.9 ± 0.9	5.9 ± 1	5.4 ± 1.2

Phase 5. Participants were then trained to either perform MI *during* AO or MI in the absence of AO, depending on the counterbalanced presentation order for these two blocks. For the AO+MI familiarisation, participants imagined from a 1st person perspective the physical sensation and effort involved in performing a dynamic version of the instructed action. This motor simulation was instructed to be time-synchronised with the observed rhythmical distractor. For the MI familiarisation, participants were shown a 2 second rhythmical distractor action that primed their subsequent MI, as discussed below. These two instructions were always administered after AO and were counterbalanced across participants to avoid order effects.

Main experiment. The core manipulation was that of distractor speed, with a slow:fast ratio of 150% across trials. Participants were not informed of the distractor speed changes. We ensured participants attended to the distractor movie content by asking them to verbally report both the match between the instructed and distractor actions (same or different), and the distractor properties (action type and plane of motion) four times per block in a pseudo-random order. A single warm-up trial preceded each block and a 5 min rest was provided between blocks.

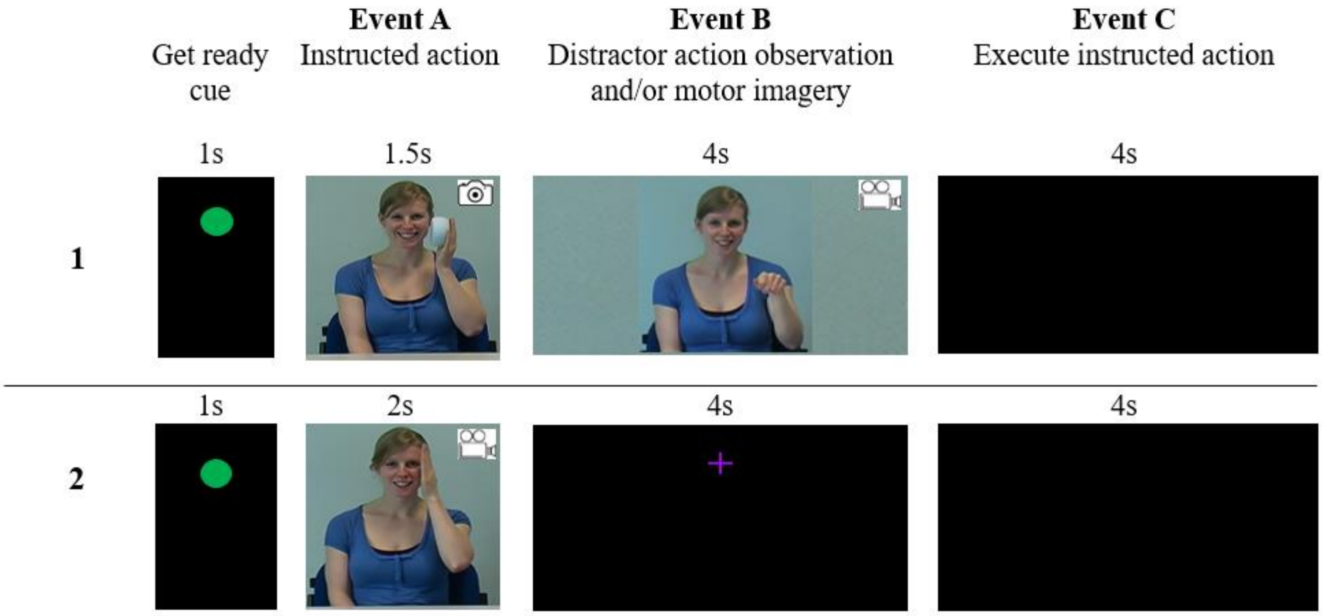

Figure 2. Participants began each trial by pressing the keyboard space bar. Next they observed a green 'get ready' cue for 1 second, followed by a picture of the instructed action (either face washing or paint brushing in either the vertical or horizontal plane, see Figure 1). This was followed by observation and/or imagery for 4 seconds (Event B), before participants executed the instructed action for 4 seconds (Event C) at either their own preferred speed, or as close as possible to the distractor speed (intentional imitation condition only). Movement kinematics were recorded throughout Event C. The same trial structure (row 1) was used for the following three instruction conditions: action observation (AO), combined action observation and motor imagery (AO+MI), and intentional imitation. A modified trial structure was used for the MI condition (row 2). For AO, participants were simply instructed to: 'watch the girl's face' during Event B. For combined AO+MI, participants were told to 'imagine performing the instructed action in time with the observed distractor action'. For intentional imitation, participants were asked to 'copy the distractor speeds as closely as possible' during Event C. In these three conditions participants verbally reported the match between the instructed and distractor action on 25% of the trials. The trial structure in panel B was used for the block of MI trials. Participants observed a 2 second movie of the instructed action (Event A), after which they were to 'imagine performing the instructed action while fixating on the purple cross' (Event B). They then executed the instructed action at their own preferred speed during Event C.

Action observation (AO). When participants pressed the space bar, a green circle was displayed for 1 second ('get ready' cue; see Figure 2). Then a picture of the to-be-pantomimed 'instructed' action was shown for 1.5 seconds (Event A), followed by a distractor movie of the same actor pantomiming either the same or a different rhythmical action for 4 seconds (Event B). During the movie, participants fixated on the model's face to minimise any visual coupling to the model's rhythmical arm movements (Schmidt et al., 2007). In this condition, participants were told the distractor action was irrelevant to their task. Instead, they were told this was a memory game: prepare to execute the instructed action regardless of the action shown in the movie. Upon distractor movie offset, participants executed the instructed action at their own preferred speed while movement kinematics were tracked in 3-D (Event C). The end of the 4 second recording interval was indicated by a computer-generated auditory signal, after which participants could verbally report distractor characteristics (four times per block) before moving their hand back to the start location.

Combined action observation and motor imagery (AO+MI). In Event A, participants observed a picture of the to-be-pantomimed instructed action for 1.5 seconds, followed by a distractor movie showing either the same or a different action for 4 seconds (Event B). As in the study by Eaves et al. (2014; 2016b), participants imagined from a 1st person perspective the physical sensations and effort involved in performing a dynamic version of the instructed action with their right hand, in synchrony with the displayed rhythmical distractor action. At the end of each trial participants executed the instructed action at their own preferred pace for 4 seconds (Event C), before occasionally reporting the distractor characteristics (four times per block) and then starting the next trial.

Motor imagery (MI). Participants observed a movie of the to-be-pantomimed instructed action for 2 seconds (Event A), followed by a purple fixation cross for 4 seconds (Event B). With their eyes open throughout this event, they imagined from a 1st person internal perspective the physical sensation and effort involved in performing the instructed action with their right hand at the pace shown in the preceding movie. The appearance of a black screen (Event C) cued motor execution of the instructed action at their own preferred cycle time for 4 seconds, during which kinematic data were recorded. As in the AO and AO+MI conditions, a computer-generated auditory tone signalled the end of this period, whereupon participants returned to the start position to begin the next trial. Note, unlike in the other three conditions it was not possible to manipulate the compatibility between the instructed and distractor action in the MI condition. The picture duration (1.5s) in the other conditions served to increase the difficulty in the verbal task of identifying differences between the instructed and distractor actions. For MI, the video lasted 2s to ensure complete cycles were always displayed, regardless of distractor speed.

Intentional imitation. The trial structure for this condition was identical to the AO and AO+MI conditions. For action execution (Event C), however, participants were instructed to imitate the cycle times of the ‘distractor’ movies as closely as possible. This condition was administered last to ensure participants were naïve to the distractor speed manipulations in the three preceding unintentional imitation conditions.

Data analysis

Mean cycle times (ms) were calculated between peak maximum kinematic positions using a customised signal processing tool within Matlab (Mathworks, Inc., Natick, MA). For both horizontal and vertical actions, the first data point taken was the peak maximum of the second movement cycle. The first cycle was not used as this additionally reflected the spatial positioning of the hand before a stable workspace could be reached. Mean cycle time was calculated across all peak positions available within a 2 second time window across all speed conditions. This typically involved between 2 - 4 complete cycles. All trials with erroneous responses (incorrect or no action) were discarded (n = 40).

The two main dependent measures were the mean response cycle time (ms) and the ratio (%) between slow and fast distractor trials. For economy of exposition, we restricted the analysis of the mean cycle time data to a within-subjects analysis using one factor of interest, namely the distractor speed, which was only available for this measure. All other factors were assessed in the cycle time ratio data.

Between-groups analysis. Since compatibility was not manipulated in the MI condition, we collapsed across this factor in the other three instruction conditions to run a two-factorial mixed-measures ANOVA in the cycle time ratio data (%). This assessed the factors of group (DCD vs TD) and instruction (AO vs MI vs AO+MI vs intentional imitation), which addressed research question 1.1. Two-factorial ANOVAs were used as simple main effect analyses to assess the factors of group and compatibility in the AO, AO+MI and intentional imitation conditions (to address research question 1.2). Note, compatibility was not manipulated in the MI condition.

Within-subjects analysis. The overall mean response cycle times (ms) for each group were subjected to a paired samples t-test comparing distractor speeds (fast vs slow). Paired samples t-tests were then used to examine distractor speed effects within the AO and MI conditions specifically (research questions 2.1 and 2.2), and for completeness, in the AO+MI and intentional imitation conditions.

As in the between-groups analysis, we collapsed across the compatibility factor in the ratio data (%) to run a one-way ANOVA assessing the factor of instruction (AO vs MI vs AO+MI vs intentional imitation) within each group data set (research questions 2.3 and 2.4). To address research question 2.3 further, paired samples t-tests were then used to compare the imitation bias for the AO+MI compatible condition compared to AO compatible, AO incompatible, and the single MI condition.

Two *a priori* power analyses were conducted using G*Power (Faul et al., 2007), to identify adequate power needed to detect both between and within-group effects. The between-group power analysis indicated that the total number of participants needed to observe an effect size of $f = 0.78$ in the between-group comparison was $n = 12$ per group. The effect size used in this calculation was based on a comparable analysis reported in Eaves et al.'s (2014) experiment, which used the exact same paradigm as in the present study, including the same stimuli and task, but used healthy adult subjects instead of children. Their specific between-group analysis compared an AO condition (group 1) with an AO+MI condition (group 2). In the present power analysis, a mixed measures ANOVA was the statistical test used as a basis for the assumptions, along with an alpha level of .05 and power of $(1-\beta) = 0.80$. The sample used in the present study ($n = 24$) was therefore considered sufficient to observe such an effect.

The effect size used in the within-group power analysis was based on Eaves et al.'s (2014) study reporting a strong effect for the instruction condition. A repeated measures ANOVA was the statistical test used as a basis for the assumptions with an alpha level of .05 and power of $(1-\beta) = 0.80$. For the within-subjects analysis the total number of participants needed to observe an effect size of $f = 1.2$ was $n = 4$.

The main analyses were conducted using SPSS Statistics 24 (IBM). Where appropriate, these were adjusted for any violation of the homogeneity of variance assumption using the Greenhouse–Geisser correction. Alpha levels were set to 0.05, and effect sizes were calculated as partial eta squared values (η_p^2), or Cohen's d (*d*), using Cohen's scale of effect (Cohen, 1992): small (0.20), medium (0.50) and large (0.80). All significant main effects were investigated further using pairwise comparisons with Bonferonni correction applied for multiple comparisons and confidence intervals reported (CI, %).

Results

Between-groups analysis: DCD vs TD children

Ratio data (%). The two-factorial ANOVA on the mean cycle time ratios (%) revealed no significant main effect of group, $F(1,22) = 0.75$, $p = .396$, $\eta_p^2 = .03$. There was, however, a significant main effect of instruction, $F(1,66) = 34.26$, $p < .001$, $\eta_p^2 = .61$. The mean cycle time ratios for intentional imitation (*M* = 128%, *SE* = 2.17) were significantly more pronounced compared to all three unintentional instruction conditions (all *p*s < .001). The imitation bias for AO+MI (*M* = 115%, *SE* = 1.70) was also significantly stronger than both the AO (*M* = 109%, *SE* = 1.45, *p* = .003, CI = 2.25 – 9.85%) and MI conditions (*M* = 109%, *SE* = 1.30, *p* = .002, CI = 2.47 – 9.81%). No differences were found between AO and MI (*p* = .960). The two-way interaction between group and instruction condition was not significant, $F(3,66) = 1.06$, $p = .370$, $\eta_p^2 = .04$. Running more focused simple main effect analyses (in accordance with research question 1.2) confirmed there were no significant main effects of group or compatibility, nor significant interactions between group and compatibility within the AO, AO+MI, and intentional imitation conditions (*p*s > .05).

We examined if the non-significant main effect of group was weaker than a small effect size (*d* = 0.2) using the TOSTER library and the Two One-Sided Test (TOST) procedure in R (Lakens, 2017). This equivalence test compared the mean cycle time ratios of DCD and TD children. With equivalence bounds based on Cohen's *d* (-0.2 to 0.2), the equivalence test was not significant, $t(21.23) = 0.338$, p = 0.369.

Within-groups analysis

Response cycle times (ms). Analysis of the mean response cycle times (ms) revealed a significant main effect of distractor speed within the DCD, $t(83) = 10.7$, $p < .001$, $d = 1.16$, and TD children, $t(83) = 11.52$, $p < .001$, $d = 1.25$. Viewing slow distractor actions resulted in longer cycle times in comparison to viewing fast distractor actions for DCD (M = 800ms, SE = 14.41 vs M = 698ms, SE = 12.03, respectively) and for TD (M = 889ms, SE = 14.51 vs M = 763ms, SE = 10.72, respectively). See Figure 3. Paired samples t-tests revealed significantly longer mean response cycle times following slow distractor actions compared to fast distractor actions within each compatibility level for AO, AO+MI and intentional imitation and for the single MI instruction condition for both DCD and TD (ps < .050).

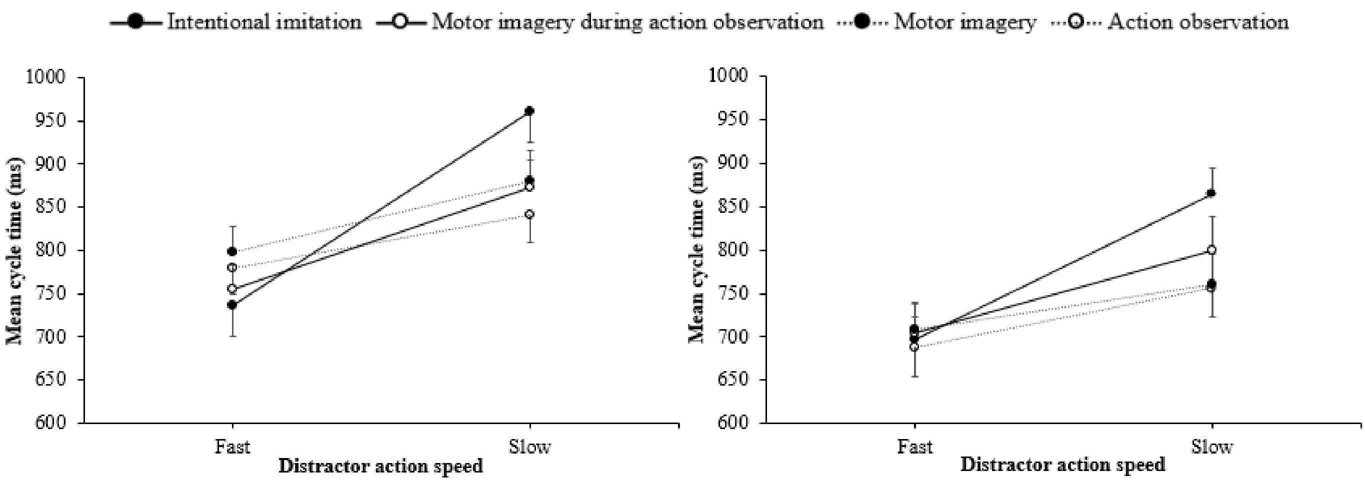

Figure 3. Mean response cycle times (ms) for children with developmental coordination disorder (left) and for typically developing children (right) for the factors of distractor speed and instruction condition, with error bars showing standard error of the mean.

Ratio data (%). The one-way ANOVAs yielded a significant main effect of instruction for both DCD, $F(3,33) = 15.78$, $p < .001$, $\eta_p^2 = 0.59$, and for TD children, $F(3,33) = 19.00$, $p < .001$, $\eta_p^2 = .63$. See Figure 4. As to be expected, the mean cycle time ratios for the intentional imitation in DCD and TD (*M* = 125%, *SE* = 2.57, and *M* = 131%, *SE* = 3.50, respectively) were significantly more pronounced than all other instruction conditions (*p*s < .050). For DCD, the imitation bias for AO+MI (*M* = 114%, *SE* = 2.42) was significantly greater than for MI (*M* = 107%, *SE* = 1.73, *p* = .017, CI = 1.49 – 12.29%), but not AO (*M* = 110%, *SE* = 2.13, *p* = .085, CI = -.69 – 9.31%). In contrast, for the TD group AO+MI (*M* = 116%, *SE* = 2.38) was significantly greater than AO (*M* = 108%, *SE* = 1.98, *p* = .020, CI = 1.48 – 14.11%) but not MI (*M* = 110%, *SE* = 1.94, *p* = .058, CI = -.22 – 11.01%). There were no further significant differences among these four instruction conditions for each within-group comparison (*p*s > .050).

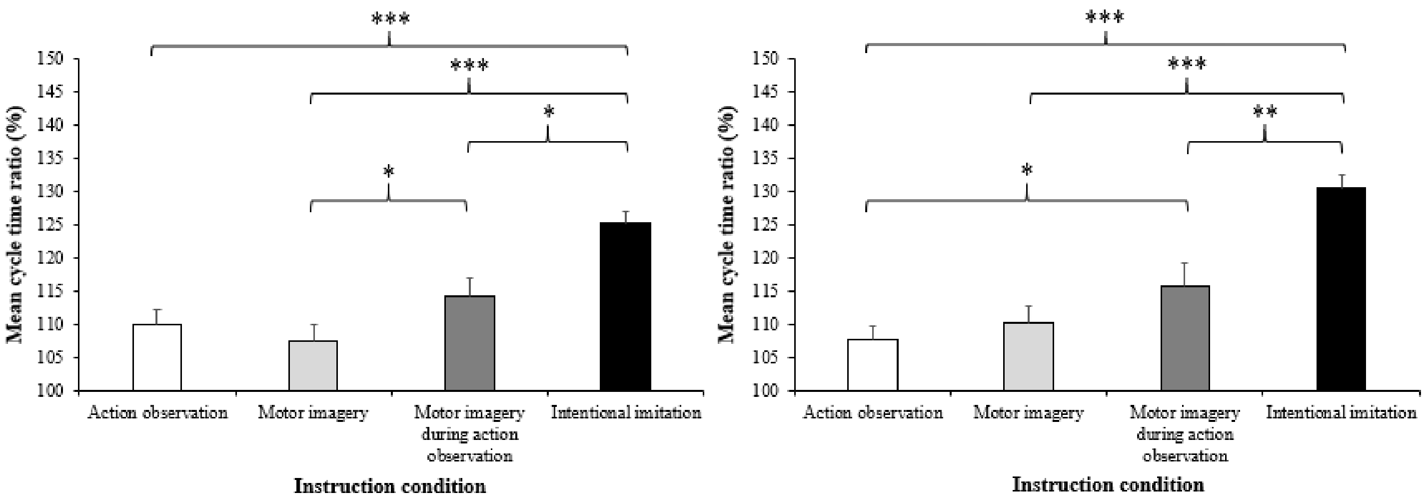

Figure 4. Mean cycle times ratios (%) for children with developmental coordination disorder (left) and for typically developing children (right) for the factor of instruction condition, with error bars showing standard error of the mean.

In line with research question 2.3, the main effect of instruction condition was examined further using paired samples t-tests. This was to assess the imitation bias for the AO+MI compatible condition, compared to both the AO compatible and AO incompatible conditions, and the single MI condition. See Table 3. In the DCD group, the imitation bias was significantly stronger for AO+MI compatible compared to both AO incompatible and MI, but not compared to AO compatible. For the TD group, the imitation bias was only significantly stronger for AO+MI compatible when compared to AO incompatible.

--- insert Table 3 about here; see end of manuscript ---

Discussion

This was the first study to investigate automatic imitation effects for combined AO+MI instructions using rhythmical execution in both DCD and TD children. Since the between-group analysis showed no significant group differences, this experiment builds on DCD studies with similar outcomes for intentional imitation (Dewey et al., 2007), and motor imagery instructions (Lust et al., 2006).

Collapsing the data across groups yielded a significant main effect of instruction condition. While intentional imitation produced significantly greater modulations in the participants' response cycle times overall (128%), in the unintentional imitation conditions the imitation bias for combined AO+MI (115%) was significantly greater than for the two separate AO (109%) and MI instructions (109%). The within-subjects analyses identified an asymmetry for these AO+MI effects across the two groups. Namely, the bias for compatible AO+MI was significantly greater than incompatible AO in TD children, and significantly greater than both MI and incompatible AO in DCD children. Since a significant bias was obtained across fast and slow distractor trials in both the AO and MI conditions, our results confirm that children both with and without DCD are capable of different forms of motor simulation. Moreover, this study is the first of its kind to show combined AO+MI instructions can significantly enhance automatic imitation effects in children with significantly different motor abilities.

Between-group findings: DCD vs TD children

A key finding in the present study was that collapsing the data across groups yielded a main effect of instruction condition. For the first time, this demonstrates children aged between 7-12 years are developmentally capable of following combined AO+MI instructions, and that this instruction can significantly modulate their subsequent behaviour, even when they are not consciously aware of it. This occurred despite the substantial differences between the two groups, in terms of their physical motor abilities (as assessed via the Movement ABC-2). Since previous research using adult participants shows significant increases in motor performance for combined AO+MI instructions are accompanied by significant increases in the activity in motor regions in the brain (Eaves et al., 2016a; 2016b), we would submit this as the primary explanation for the behavioural findings in the present study. While further neuroimaging research must now investigate this proposal in DCD children, an intriguing question is whether combined AO+MI instructions mitigate the potential reductions in AON function in DCD.

The automatic imitation effect was present equally in the kinematics for both groups within each instruction condition (research question 1.1). Automatic imitation effects directly reflect the neurocognitive mechanisms underlying action simulation (Heyes, 2011). Our findings therefore indicate that the action observation network (AON) was at least partially intact for the sample of DCD children obtained in this study. This may initially appear to contradict the majority of behavioural and neurophysiological findings, which show reduced imitation in DCD children (Reynolds et al., 2015a). Those studies, however, primarily assessed performance in either novel or complex actions, whereas the current study used simple actions already in the participants' motor repertoire.

Dewey et al. (2007) also studied familiar gestures and showed no impairments in intentional imitation for DCD children both with and without attention deficit hyperactivity disorder, compared to TD children. In Reynolds et al.'s (2017a) fMRI study, intentional gesture imitation and MI ability were both reduced in DCD compared to TD children, but no differences were reported in the corresponding neurophysiological activity in the AON. Those authors suggested the simplicity of their scanner-compatible task, along with impairments in other neural networks supporting action planning would likely explain their results. Similarly, the familiarity and simplicity of the everyday actions used in the present study (face washing and paint brushing), would potentially explain our null result for the between-groups comparisons.

Relative to the three unintentional conditions, the intentional imitation condition presumably involved more complex attention and action planning components, which could have been more challenging for DCD children. Seemingly, however, the simplicity of these actions reduced the task difficulty for the DCD children sufficiently, which potentially explains the null result for the between-group comparison in this condition. Despite previous research reporting deficits in the timing of rhythmical actions in both dual and single limb movements (Wilson et al., 2013), we found no between-group differences in the ability to execute simplistic everyday rhythmical actions. Perhaps more complex and novel gestures should therefore be used to investigate imitative impairments in DCD children in the future (Reynolds et al., 2017b).

In the present study, we explored rhythmical alignment in a single limb action. Rather than focusing on intentional imitation, the task was primarily designed to explore automatic imitation effects in familiar actions, as indicative of AON function (Heyes 2011). This paradigm was used to quantify the impact of three different motor simulation states (AO vs MI vs AO+MI) during a 4 second period of action planning, prior to motor execution. In this context, the intentional imitation task mainly represents a type of experimental control condition; whereby the significantly stronger cycle time modulations help substantiate the automaticity of the effects obtained in the other three unintentional conditions (research question 2.4). It is noteworthy, however, that since the remaining factors were manipulated within-subjects, the design of the present experiment ensured the participants acted effectively as their own control.

Within-subjects findings

Within both the DCD and TD groups there was a significant distractor speed effect in the cycle time data (ms) for both the compatible and incompatible AO conditions (research question 2.1). It is important to note, however, that a potential confound applies to the compatible AO condition, as discussed previously by Eaves et al. (2012). When the instructed and distractor actions match, participants may intentionally use the 'task-irrelevant' distractor action as a valid guide for their motor planning. Accordingly, we submit that only the present incompatible AO condition can be taken as evidence for a genuine automatic imitation effect. The significant though numerically reduced distractor effect within the incompatible AO condition is therefore particularly important. For this condition there was no logical reason why participants would intentionally imitate the observed distractor speed when this action differed from the intended action both in type and plane of motion.

In the present study the significant distractor speed effects obtained for the incompatible AO condition provide the first concrete evidence of automatic imitative alignment using movement kinematics in children aged 7–12 years, both with and without DCD. This extends the available literature in this area. To our knowledge, O'Sullivan et al. (2018) is the only other study reporting automatic imitation effects in children, and they employed reaction time measures in a healthy population aged 3-7 years.

In line with previous research using the same paradigm in adults (Eaves et al., 2016b), imagining rhythmical actions at fast and slow speeds across trials resulted in a significant modulation of response cycle times in children both with and without DCD (research question 2.2). A reduced MI ability is widely reported across a range of tasks in DCD children (Ferguson et al., 2015; Fuchs & Caçola, 2018; Williams et al., 2008; Wilson et al., 2001). The task used in the present study, however, was unlike those typically used in DCD studies. As such, the combination of familiarity and action simplicity may together have contributed to the null result with regards to the between-groups analysis for the MI condition.

Cumming and Eaves (2018) recently proposed MI ability is more multifaceted than has previously been acknowledged. MI ability can thus be assessed across three different components: biological (e.g., neurophysiology), cognitive (e.g. image generation, transformation and inspection), and behavioural (e.g., performance outcomes). The current findings suggest that imagining a familiar rhythmical action at different speeds is entirely possible in DCD children, quantified as a bias in subsequent execution speeds across trials. Notably, this imagery task and measure was not designed to investigate if DCD children experienced cognitive difficulties relating to image transformation and inspection. The current findings do however support the proposal that DCD children are capable of MI at least for simple everyday actions, and therefore that imagery training can be used for improving their motor skills in simple tasks (Adams et al., 2017; Wilson et al., 2002; 2016).

Overall there were no significant group differences, nor was there an interaction involving the factors of group and instruction condition. The exploratory nature of this study, however, was in the context that no previous work has investigated automatic imitation effects following AO, MI, and AO+MI using movement kinematic measures in children, within a single experiment. It was therefore important to investigate the instruction effects separately within each sub-population. This approach was defined *a priori* in research question 2.3, which represented a core objective of the study. Given the lack of significant group effects, however, the outcome of the within-subjects analysis should be approached with some caution. In the following section we discuss a subtle asymmetry obtained for the combined AO+MI effects across the two groups.

For the TD children, combined AO+MI instructions significantly increased the imitation bias compared to the incompatible AO condition. For the DCD group, AO+MI produced a significantly greater imitation bias compared to the incompatible AO condition, and also compared to the MI condition. Indirectly, this indicates a marginally reduced capacity for MI in the DCD compared to TD children. This pattern likely explains the non-significant difference between the MI and combined AO+MI conditions in the TD group. More importantly, this result shows combined AO+MI instructions could offer a more direct means for impacting motor behaviour in DCD children, compared to *both* AO and MI. Note we assessed this effect relative to the compatible AO+MI condition only, as this condition represents the most practical choice in a motor learning context. The effects of incompatible AO+MI on physical practice are yet to be investigated, whereas compatible AO+MI instructions have already shown training benefits (Marusic et al., 2018; Romano-Smith et al., 2018; Scott et al., 2017).

Overall, these findings have direct importance for practitioners who wish to improve motor skills in children both with and without DCD. MI training has previously been promoted as an adjunct to physical practice in DCD children, based on sound evidence showing it positively impacts motor learning (Adams et al., 2017; Wilson et al., 2002: 2016). Alternatively, the present study provides the first behavioural evidence showing combined AO+MI instructions can be more beneficial than MI alone for impacting movement skills in DCD children. This supports recommendations from recent neurophysiological studies (e.g., Eaves et al., 2016b; Taube et al., 2015), calling for new approaches to training and rehabilitation to involve combined AO+MI instructions (see Eaves et al., 2016a; Emerson et al., 2018; Vogt et al., 2013).

Using the same paradigm as in the current study, Eaves et al. (2016b) reported EEG recordings in adults showing combined AO+MI instructions significantly increased the electrophysiological activity in regions of the AON compared to both AO and MI. It is therefore plausible that the combined AO+MI instruction in the current study similarly modified the AON involvement in both the DCD and TD children. This is despite both the mixed evidence for an impaired AON in DCD children, and recent work in healthy adults showing AO+MI requires additional cognitive mechanisms involving pre-frontal regions of the brain (Eaves et al., 2016b). Substantial maturational and developmental change will occur in the pre-frontal regions from young childhood, across adolescence, and into early adulthood. It will thus be important for future research to investigate potential differences in the neurophysiological correlates of AO+MI across age groups.

Imagining an action that is congruent and synchronised with an observed action offers a potentially rich opportunity for 'layering' or combining the contents of two concurrent action representations. The contents of the imagined action can be refined and updated online using the observed action as a visual guide. While Jeannerod's (2006) popular hypothesis was that AO and MI processes generate two functionally equivalent action representations, a related and more recent proposal is the *dual-action simulation* account of AO+MI effects (Eaves et al., 2016a; Vogt et al., 2013). This view submits that both an observed and an imagined action can be represented simultaneously, in the sense of two concurrent sensorimotor streams. These two streams could either merge or compete with one another, depending on their contents and usefulness for on-going action plans (Eaves et al., 2012; 2014; 2016). While the present findings are in line with this account, this hypothesis now requires further empirical validation in children.

As in previous studies that used the same paradigm, the main effect of compatibility (research question 1.2) was not significant in both the AO+MI condition (Eaves et al., 2014;

2016b), and the intentional imitation condition (Eaves et al., 2012). Unexpectedly, the compatibility effect was also not significant in the AO condition, despite a numerical trend in the anticipated direction (see Table 3). This was likely due to the increased variability in the data, which was associated with the reduced age and motor ability of the participants in the current sample, compared to the adult population studied by Eaves et al. (2012). More importantly, however, the distractor effects were highly significant in the cycle time data (ms) for both AO conditions in both groups, reflecting a robust automatic imitation effect overall.

Future research opportunities

As this is the first AO+MI study in children, future research should now focus on the neurocognitive mechanisms underlying the effects reported here. Activation of the AON can now be studied in children using neurophysiological techniques (e.g., fMRI, EEG) within the present paradigm, to assess the cortical involvement during AO+MI. Despite the behavioural effects obtained in the present study, the brain is still developing throughout childhood and adolescence, and so it should not be assumed that AON involvement will be comparable to that in adults.

Neurophysiological research using transcranial magnetic stimulation (TMS) in young adults with DCD has recently shown reduced activation of the primary motor cortex during mental rotation tasks (Hyde et al., 2018). There is now a robust body of TMS literature showing greater cortical spinal activation during AO+MI than either AO or MI alone in TD adults (e.g., Wright et al., 2014; 2018; see Eaves et al., 2016a). While only a small sample of individuals meeting the criteria for DCD were included in Hyde et al.'s (2018) research, similar findings have been found in fMRI (Kashuk et al., 2017). Research should now investigate the possible neurophysiological effects of AO+MI in DCD as an alternative method for both enhancing motor activation and as a potential tool for motor training.

In the current study the DCD population met the criteria of ≤ 16th percentile on the Movement ABC-2. While this meets diagnostic criteria, research could now focus on the lower boundary (≤ 5th percentile) of this population. This lower percentile typically exhibits movement difficulties across all categories (i.e. catching and throwing, balance and fine motor). A stricter inclusion criterion may thus result in more contrasting findings between DCD and TD children.

This study was not without some potential limitations. DCD is reportedly more prevalent in males than females (American Psychiatric Association, 2013), and so it was difficult to balance for gender within each group. Although the model presented in the videos was female, we have no clear evidence to suspect a possible gender bias in our results, but at this stage we are also not able to rule this out completely. Future research should therefore aim to match groups by both age and gender to allow stronger comparisons between DCD and TD populations.

Longitudinal research could now compare the effects of a combined AO+MI training programme. Wilson et al. (2002; 2016) and Adams et al. (2017) showed improvements in Movement ABC-2 scores following the use of separate video and MI training techniques. While this method is close to the current AO+MI protocol, it would most likely not provide the enhanced cortical and behavioural effects widely reported for combined AO+MI instructions. Future research could also incorporate more extensive MI training prior to the study, rather than the single training session that was employed in the present study.

Conclusion

Overall, the current findings show combined action observation and motor imagery significantly enhanced automatic imitation effects. This was relative to AO (in children both with and without DCD), and relative to MI (only in children with DCD). Combined AO+MI instructions therefore represent a more effective tool for impacting motor skills in children with varying motor abilities compared to the two independent techniques of AO and MI. Our research now paves the way for future studies to investigate the efficacy of specific AO+MI training methods for developing functional movement skills children both with and without DCD.

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Table 3. Mean cycle time ratios (%), standard error (*SE*) and t-test results with Cohen's *d* (*d*) reported for specific comparisons. This involved the compatible combined action observation and motor imagery (AO+MI) condition compared to both the compatible and incompatible action observation (AO) conditions, and the single motor imagery (MI) condition, both for children with developmental coordination disorder and typically developing children. Significant results highlighted in bold font.

			Developmental coordination disorder		Typically developing	
Comparisons			Mean cycle time ratio, % (*SE*)	t-test result	Mean cycle time ratio, % (*SE*)	t-test result
AO+MI compatible	vs	AO compatible	113 (3.26) vs 113 (2.23)	$t(11) = 4.00$, $p = .861$, $d = 0.05$	117 (3.83) vs 109 (2.45)	$t(11) = 1.71$, $p = .116$, $d = 0.49$
		AO incompatible	113 (3.26) vs 107 (2.95)	$t(11) = 0.17$, $p =$ **.002**, $d = 1.15$	117 (3.83) vs 106 (2.02)	$t(11) = 3.66$, $p =$ **.004**, $d = 1.05$
		MI	113 (3.26) vs 107 (1.73)	$t(11) = 2.51$, $p =$ **.029**, $d = 0.72$	117 (3.83) vs 110 (1.94)	$t(11) = 1.66$, $p = .126$, $d = 0.47$

Supplementary Material 1

Imagery scripts for MI conditions

*To be provided before undertaking the first block of MI trials

Face washing: Please close your eyes. Now imagine that you are holding a flannel in your right hand. Please imagine what the material feels like, along with dampness and weight of the flannel. Now please imagine that you are raising your right-hand to the side of your head, to begin washing your face. From your own point of view, please imagine how your hand and arm now feel as you begin to rhythmically wash the side of your face up and down. Please focus on what that rhythm feels like to you. Keep imagining that your right hand is moving rhythmically up and down. Imagine what the flannel actually feels like as you are rubbing it across your cheek. Now imagine stopping the washing action and imagine placing the flannel on the table in front of you.

Paint brushing: With your eyes still closed please imagine that you are now holding a paint brush in your right hand. Please imagine what the grip and weight of the brush feels like. Now imagine that you are raising your right arm and moving your hand into position, to the side of your upper body. Imagine that you are now moving your arm to paint on a wall in front of you. You are spreading the paint up and down the wall in front of you. From your own point of view, please imagine how your hand and arm now feel as you begin to rhythmically move the brush up and down. Please focus on what that rhythm feels like to you. Keep imagining that your right hand is moving rhythmically up and down. Now imagine stopping the brushing and imagine placing the paint brush on the table in front of you.