# Learning a novel rhythmic stepping task in children with probable developmental coordination disorder

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## ARTICLE INFO

## ABSTRACT

*Background:* Developmental coordination disorder affects approximately 6% of children, interfering with participation in physical activity and can persist through adulthood. However, no studies have investigated the neuromotor mechanisms of learning of a novel task with rhythmic cueing.

*Methods:* Movement Assessment Battery for Children-2nd edition was used to identify 48 children with probable developmental coordination disorder ($13.9 \pm 0.05$ yrs., 27% male) and 37 typically developed ($13.9 \pm 0.10$ yrs., 54% male). While instrumented with an inertial measurement unit, both groups performed a novel rhythmic stepping task and with a concurrent auditory stroop test (dual-task), underwent seven weeks of intervention with step training with rhythmic cuing and were tested for retention five weeks post-intervention.

*Findings:* Initially, the group with probable developmental coordination disorder had a higher variability of step timing (coefficient of variation: $0.08 \pm 0.003$-typically developed – $0.09 \pm 0.004$-probable developmental coordination disorder, $p < 0.05$) and a frequency of peak power spectral density further from the target 0.5 Hz ($0.50 \pm 0.002$ Hz-typically developed – $0.51 \pm 0.003$ Hz-probable developmental coordination disorder, $p < 0.05$), and were more affected by the dual-task: power spectral density at 0.5 Hz ($-7.2 \pm 3.3$%-typically developed – $-13.4 \pm 4.6$%- prob_DCD, $p < 0.05$) and stroop test errors ($6.4 \pm 1.1$%-typically developed – $-11.1 \pm 2.4$%- probable developmental coordination disorder, $p < 0.05$). The intervention led to similar improvements in both groups in coefficient of variation of step timing ($0.12 \pm 0.01$-Pre – $0.07 \pm 0.002$-Post, $p < 0.05$), frequency of the peak power spectral density ($0.51 \pm 0.005$ Hz-Pre – $0.50 \pm 0.001$ Hz-Post, $p < 0.05$) and relative power spectral density bandpower ($3.2 \pm 0.2$%-Pre – $5.9 \pm 0.3$%-Post, $p < 0.05$). All improvements were retained after five weeks post-training.

*Interpretation:* Rhythmic cueing shows strong promise for enhancing motor learning in children with probable developmental coordination disorder.

*Trial registration:* Retrospectively registered on ClinicalTrials.gov with reference: NCT03150784

# 1. Introduction

Developmental coordination disorder (DCD) is a neuro-developmental condition that affects approximately 6% of children (Blank et al., 2012). Despite having normal cognitive capabilities and opportunities to learn new motor skills, children with DCD show limited motor skill acquisition and execution in a multitude of tasks, from sporting activities to activities of daily living (Battle, 2013; Gueze et al., 2001; Schoemaker and Smits-Engelsman, 2015; Smits-Engelsman et al., 2001). Consequently, these children tend to avoid engaging in physical activities (Batey et al., 2014; Bo and Lee, 2013; Rivilis et al., 2011). This withdrawal from a more active lifestyle can have a deeper impact throughout the individual's life. These motor deficits persist through adulthood, potentially affecting mental health and emotional regulation (p.e. anxiety, problems with personal adjustment, inattention and hyperactivity), the ability to perform daily tasks, such as driving and overall health (Cousins and Smyth, 2003; Kirby et al., 2013; Lee et al., 2016; Lee et al., 2020).

Although the mechanisms that underpin this neurological condition are still largely unknown, a few typical characteristics can be often identified among these children. For example, children with DCD often show deficits in the neuromuscular control and limited visual tracking that may interfere with motor planning (Johnston et al., 2002; Licari et al., 2018; Wann et al., 1998). This may corroborate the observations of impaired feedforward control and increased variability in motor commands in this population (Cignetti et al., 2018; Golenia et al., 2018; Wilson et al., 2013).

These motor control deficits not only affect motor performance, but can also interfere with motor learning. For example, while learning a new motor skill, typically developed (TD) children require an initial higher cognitive load that shifts towards increased automaticity and reduced cognitive demand with learning (Clark, 2015; Krajenbrink et al., 2018). In contrast, children with DCD tend to express greater variability in their motor control and often require greater cortical and sub-cortical load while learning a new task (Debrabant et al., 2013; Mackenzie et al., 2008; Zwicker et al., 2010). Furthermore, this population shows limited capacity to accomplish this shift (Debrabant et al., 2013; Mackenzie et al., 2008; Zwicker et al., 2010), relying more on alternate strategies and feedback control (Clark, 2015; Wilson, 2017).

Dual-tasks (motor task and a concurrent cognitive task) have often been used to probe for the automaticity of motor learning (Remy et al., 2010; Schott et al., 2016). Considering the aforementioned limitations, it becomes logical to expect that children with DCD have a more compromised ability to shift towards automatic control under conditions with concurrent cognitive loading (Schott et al., 2016; Tsai et al., 2009). This may also reflect a limited attention resource devoted to motor processing, translating into the observed additional deterioration in neuromuscular control and motor performance (Cherng et al., 2009; Laufer et al., 2008). In different clinical populations, rhythmic cueing has been used to improve motor processing and performance through enhancing cortical and subcortical connectivity associated with the cerebellum (Braunlich et al., 2019; Roerdink et al., 2009). Although there is some evidence suggesting that children with DCD potentially have deficits in cerebellar function (Schott et al., 2016; Tsai et al., 2009), training motor coordination in these children can improve psychological factors and lead to acquisition of novel motor skills, especially with task-oriented interventions (Lucas et al., 2016; Mohammadi Oranghi et al., 2018; Roche et al., 2016; Schoemaker et al., 2003; Schoemaker and Smits-Engelsman, 2015; Smits-Engelsman et al., 2013). However, to the best of our knowledge, no studies have investigated how children with probable DCD adapt their mechanisms of neuromotor control to learn a novel motor task, nor if training a novel motor task with rhythmic cueing can lead to motor learning, improvements in motor performance and enhanced automaticity.

To address these concerns this study investigated: 1) the motor performance of probable DCD (prob_DCD) and TD children on a novel rhythmic stepping task; 2) how motor learning is experienced by each group as a function of seven weeks of a multimodal step training intervention incorporating the novel rhythmic stepping task; and 3) if increased cognitive loading through a dual-task condition can affect the rhythmic stepping motor performance of prob_DCD and TD children.

We hypothesize that although children with prob_DCD will show overall lower motor performance with increased variability in the novel rhythmic stepping task than those in the TD group, they will lead to similar improvements to the TD group, and these changes will be retained after five weeks post intervention. Furthermore, we anticipate that the overall poorer motor competence of the prob_DCD group will be exacerbated by the dual-task condition.

# 2. Methods

This study used a non-randomised trial design, where participants executed a novel rhythmic stepping task in two conditions: rhythmic stepping (single-task) and dual-task (while performing an auditory stroop task). In addition, the participants performed the auditory stroop task while standing quietly. The three tasks were completed at baseline (pre), after seven weeks of intervention (post) and after five weeks post-training (follow-up).

## 2.1. Participants

A total of 1174 ninth year students from three community mainstream schools in the Oxford (UK) area were screened for coordination and fitness measures using the Movement Assessment Battery for Children-2nd edition (MABC-2) (Henderson et al., 2007) and the shuttle-run test (Leger et al., 1988).

Participants were included if they presented: 1) age between 12 and 14 years old and 2) fitness level in the lowest quartile to control for fitness level. Furthermore, if participants had 3) poor motor skill acquisition and execution (WHO, 1992), they were also included to be allocated to the children with probable DCD group. Considering the identification of children with probable DCD was only based on the outcome of the MABC-2 and no other criteria, the term 'probable DCD' was used to classify this population (Smits-Engelsman et al., 2015). The exclusion criteria for all participants consisted of: 1) teacher's reported cognitive impairment; 2) behavioural/intellectual issues that would prevent safe participation or put the participant, investigators and others at risk; 3) contraindications to perform maximal exercise or physical training; 4) muscular/neurological degenerative conditions; and 5) surgery in the previous 6 months. All participants and parents/guardians provided written consent approved by the University Research Ethics Committee of Oxford Brookes University (Registration No: 161033) in accordance with the Declaration of Helsinki.

The initial screening identified 85 children in the lowest quartile of fitness. Of these, 48 (13.9 ± 0.05 yrs., 27.1% male) also showed impaired motor skill acquisition and execution per their mABC-2 scores ≤15th percentile (WHO, 1992) and were allocated into the probable Developmental Coordination Disorder (prob_DCD) group. The remaining 37 (13.9 ± 0.10 yrs., 54.1% male) make the typically developed (TD) group (Table 1) with a mABC-2 scores >15th percentile.

Due to incomplete and/or missing data, the number of participants that were analysed at each time point differed from the total number of recruited participants in each group (pre – 33 TD, 39 prob_DCD; post – 34 TD, 43 prob_DCD; follow-up – 27 TD, 33 prob_DCD).

## 2.2. Assessments

The novel rhythmic stepping task (single-task) consisted of stepping up (approximately 20 cm) onto a step stool at a fixed alternating stepping sequence that was synchronized with a visual go cue. The visual stimulus was visible on a computer screen for 1.5 s followed by 0.5 s of a blank screen, creating a fixed stepping frequency target of 0.5 Hz. This

**Table 1**
Participant demographics for typically developed (TD) and children with probable Developmental Coordination Disorder (prob_DCD).

|  | TD | prob_DCD |
|---|---|---|
|  | (n = 37, 54.1% male) | (n = 48, 27.1% male) |
| Age (years) | 13.9 (0.1) | 13.9 (0.05) |
| Height (m) | 1.65 (0.02) | 1.60 (0.02) |
| Weight (kg) | 58.4 (2.1) | 60.6 (2.0) |
| BMI | 21.4 (0.6) | 24.1 (1.1) |
| MABC-2 scores | 33.5 (2.5) | 5.5 (0.5)* |
| Training Sessions | 16.3 (0.2) | 16.6 (0.3) |

Data shown as Mean (SEM). MABC-2 – movement assessment battery for children (2nd edition).
* Significantly different from TD group ($p < 0.05$).

sequence repeated for the total duration of 42.5 s, including an initial 2.5 s 'get ready' time interval (Fig. 1). The participants were instructed to initiate stepping synchronously with the visual 'go cue' and to alternate the stepping foot. This allowed for 10 cycles initiated with the right foot and 10 with the left foot.

The auditory stroop task was completed during quiet stance and consisted of listening to the words "high" and "low" at a high and a low pitch and quickly specify the pitch of the word as accurate as possible (Plummer-D'Amato et al., 2012).

In the dual-task condition, participants performed exactly the same protocol as in the rhythmic stepping, simultaneously with the auditory stroop task (Morgan and Brandt, 1989).

Each of the three tasks (single-task, dual-task and stroop test) were completed three times for a total of nine blocks ordered pseudo-randomly, so the first block of the testing session would be the first rhythmic stepping block.

An inertial measurement unit (IMU, LPMS-B, Life Performance Research, Japan) was used to record tri-axial accelerometry during the rhythmic stepping and dual-tasks. The IMU was fixed with adhesive tape over the participant's fourth lumbar vertebra (L4) to emulate the motion of the participant's centre of mass (CoM). The device collected data at a sampling frequency of at 100 Hz and it was positioned so the X, Y and Z axis would correspond to the antero-posterior (AP), medio-lateral (ML) and vertical directions (Esser et al., 2009).

### 2.3. Intervention

The present study was part of a larger project where the enrolled participants underwent a multimodal exercise intervention. Specifically, both groups participated in an exercise intervention twice a week for seven weeks, while wearing an accelerometer in the dominant wrist sampling at 100 Hz (AX3, Axivity, UK). Each session included an initial warm-up, 20 min moderate to vigorous aerobic physical activity (MVPA) (50–85% predicted maximum heart rate), 30 min of personalised strength training for upper and lower limbs.

In addition, a stepping training was also conducted, consisting of four blocks separated by 20s rest breaks: 'slow' (fixed alternating stepping initiation, starting at 0.4 Hz cycles and increasing to 0.49 on week seven); 'attention' (fixed-random sequence of stepping initiation, starting at 0.4 Hz cycles and increasing to 0.53 Hz at week seven); 'assessment' (fixed alternation stepping initiation, 0.5 Hz cycle throughout whole intervention); and 'medium' (starting at 0.44 Hz cycles on week two and increasing to 0.54 Hz in week seven).

During the five weeks after the intervention, up-to the 'follow-up' testing session, the participants were instructed to live their lives normally.

### 2.4. Data analyses

This study used custom LabView2015 (National Instruments, Newbury, UK) and MATLAB (Mathworks, MA, USA) programs to analyse the
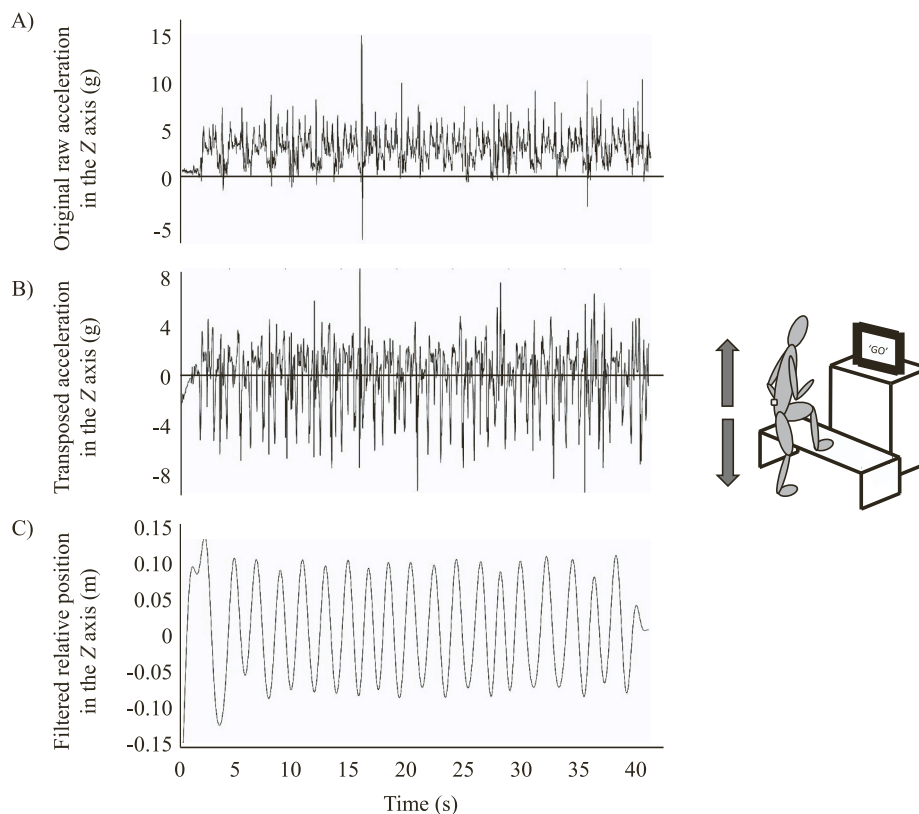


**Fig. 1.** Exemplar of original raw vertical acceleration (A), transposed vertical acceleration (B) and filtered vertical relative position (C) of a representative rhythmic stepping trial.

collected data and calculate the main outcome variables defined and detailed below.

Three-dimensional linear acceleration in the global reference frame was recorded from the IMU dataset. Similar to previous reports, the transposed linear acceleration was filtered using a 4th order Butterworth band-pass filter (0.2-15 Hz) (Chidean et al., 2018; Shahabpoor and Pavic, 2018). The filtered acceleration was used to integrate velocity and relative position using a mathematical approach previously described in detail (Fig. 1) (Esser et al., 2009).

Due to limitations inherent to the use of the accelerometer on the wrist, the intervention dataset was used to calculate the acceleration single vector magnitude (SVM) corrected for gravity by the following equation:

$$SVMg = \sqrt{\left(a_x^2 + a_y^2 + a_z^2\right)} - 1$$

The step incidence was defined as the total number of peaks in the relative vertical position data, corresponding to when the participants reached the top of the step stool. Whereas, step timing was defined as the time interval between every relative vertical position peak.

ML weight-transfer magnitude consisted of the difference between the right and left IMU maximum relative positions in each step-up.

Jerk, the third derivative of position and a measure of smoothness of motion, was calculated as the change in the filtered vertical acceleration from the instant immediately prior to step-up (IMU elevation) and the instant where the IMU reaches the vertical relative peak position. Considering that duration and length of the movement can affect the magnitude of jerk, we normalized it using the following Eq. (Aboelnasr et al., 2017; Osumi et al., 2017; van Kordelaar et al., 2014):

$$Normalized\ Jerk = \sqrt{\left(1 \Big/ 2 \bullet \int_{Tstart}^{Tend} Jerk^2\ (t)\ dt \right) \bullet duration^5 \Big/ length^2}$$

Spectral analysis was performed by applying a 256 point Fast Fourier Transform (FFT) to the filtered acceleration in the time domain and Power spectral density (PSD) was calculated using Welch's method and periodic Hanning windows with a 50% overlap (Ly et al., 2016).

Considering that during the assessment sessions the stepping task had a target frequency of 0.5 Hz, the frequency of the peak PSD was defined as the frequency where the peak PSD occurs between 0.2 and 0.8 Hz.

Relative PSD bandpower was calculated as the proportion of PSD within the band closely surrounding the target frequency 0.5 Hz (0.48 Hz–0.52 Hz), and expressed as a percentage of the total PSD of the full spectrum.

For each outcome variable, the results from the dual-task were calculated as the difference between dual and single-task (rhythmic stepping) and expressed as a percentage.

Stroop test error was calculated as the percent difference in auditory stroop task errors between performing it during dual-task and quiet standing conditions.

### 2.5. Statistical analyses

Group and time main effects, and group*time interactions were determined with a repeated-measures linear mixed-effects model, where Groups (TD and prob_DCD) and Time (pre, post and follow-up) were set as fixed factors and gender as a covariate (SPSS v22, IBM, Armonk, NY). An identical secondary analysis was also performed for the training data, where Time was composed of the different training sessions. Post-hoc calculations in all models used Sidak correction for multiple comparisons. Significance was set at $p < 0.05$.

## 3. Results

### 3.1. Rhythmic stepping

Main effects and interactions for the main outcome variables during the single-task condition are shown in detail in Table 2.

Specifically, a significant main effect for Group was observed for the CV of step timing, where the prob_DCD group had an overall greater CV than TD children ($p < 0.05$).

Group x Time interactions showed that the frequency of peak PSD was greater in the prob_DCD group at pre compared to post and follow-up ($p < 0.05$, Fig. 2A). Additionally, prob_DCD group's frequency of peak PSD was significantly larger than in the TD group at pre ($p < 0.05$, Fig. 2A). The step-up peak vertical acceleration was marginally larger in TD children compared to the prob_DCD group at pre ($p = 0.051$, Fig. 2B).

Main effects for Time (pre, post, follow-up) were found for the majority of the outcomes. Namely, step incidence was significantly greater at pre, compared to follow-up ($p < 0.05$) and marginally achieved significance compared to post ($p = 0.057$). In addition, the coefficient of variation (CV) of step timing, the CV of medio-lateral (ML) weight-transfer magnitude, the step-up peak vertical acceleration, the step-up peak vertical deceleration were smaller at post and follow-up than at pre ($p < 0.05$). The frequency of peak power spectral density (PSD) became close to the target frequency of 0.5 Hz after training and maintained at follow-up ($p < 0.05$). Lastly, the PSD at 0.5 Hz and the relative PSD bandpower increased significantly at post and follow-up compared to pre ($p < 0.05$).

No main effects or interactions were found for duration of step-up, ML weight-transfer magnitude, or normalized Jerk ($p > 0.05$).

### 3.2. Dual-task

The addition of the auditory stroop test to the rhythmic stepping task, expressed as the percent change from the motor performance observed during the rhythmic stepping condition, led to several significant main effects and interactions that are detailed below (Table 3).

A main effect for Group showed that TD children had a significantly larger increase in CV of step timing compared to the prob_DCD group ($p < 0.05$). The step-up mean vertical velocity also showed a significant main effect for Group, with greater decreases observed in the prob_DCD group ($p < 0.05$).

Group x Time interactions revealed that in the pre testing session, the dual-task resulted in decreases in step incidence in the prob_DCD group and increases in TD children ($p < 0.05$, Fig. 3A). In the same session, the prob_DCD group observed larger decreases in PSD at 0.5 Hz ($p < 0.05$, Fig. 3B) and marginally greater increases in stroop test error ($p = 0.060$, Fig. 3C) compared to TD individuals. CV of ML weight-transfer magnitude at follow-up significantly increased for prob_DCD and decreased in TD ($p < 0.05$, Fig. 3D). This decrease observed in the TD group resulted in a significant difference from pre ($p < 0.05$, Fig. 3D). At follow-up, step incidence was significantly decreased in the TD group ($p < 0.05$, Fig. 3A), and in PSD at 0.5 Hz was increased for prob_DCD ($p < 0.05$, Fig. 3B), compared to pre.

Several main effects for Time were also observed ($p < 0.05$). The effects of dual-task observed during post and follow-up compared to pre were significantly smaller for CV of step timing ($p < 0.05$) and stroop test error ($p < 0.05$), and greater for normalized jerk ($p < 0.05$) and relative PSD bandpower ($p < 0.05$). Step-up peak vertical acceleration and deceleration were only greater than pre at post ($p < 0.05$). The dual-task effects for vertical acceleration prior to step-up and PSD at 0.5 Hz were only larger than pre at follow-up ($p < 0.05$).

### 3.3. Intervention

Data collected during the training sessions showed main effects for Time in CV of step timing, relative PSD bandpower and frequency of

**Table 2**

Summary of descriptive statistics for typically developed (TD) and children with probable Developmental Coordination Disorder (prob_DCD) groups at Pre, Post and Follow-up, and statistical analyses of Group and Time main effects and Group x Time interactions.

| | Groups | Pre (TD, $n = 33$; prob_DCD, $n = 39$) | Post (TD, $n = 34$; prob_DCD, $n = 43$) | Follow-up (TD, $n = 27$; prob_DCD, $n = 33$) | Group | | Time | | Group x Time | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | F | p | F | p | F | p |
| Step incidence | TD | 20.97 (0.14) | 20.58 (0.09) | 20.63 (0.09) | 0.58 | 0.45 | 3.90 | <0.05 * | 0.16 | 0.85 |
| | prob_DCD | 20.87 (0.14) | 20.63 (0.11) | 20.62 (0.09) | | | | | | |
| Duration of step up (s) | TD | 0.988 (0.005) | 0.990 (0.007) | 0.997 (0.003) | 0.12 | 0.73 | 2.70 | 0.08 | 0.18 | 0.84 |
| | prob_DCD | 0.989 (0.006) | 0.996 (0.005) | 0.998 (0.003) | | | | | | |
| CV of step timing | TD | 0.106 (0.009) | 0.068 (0.001) | 0.065 (0.002) | 5.95 | <0.05 * | 60.63 | <0.01 * | 2.23 | 0.12 |
| | prob_DCD | 0.131 (0.009) | 0.072 (0.003) | 0.069 (0.002) | | | | | | |
| ML weight-transfer magnitude (m) | TD | 0.079 (0.009) | 0.076 (0.007) | 0.079 (0.009) | 1.40 | 0.24 | 0.42 | 0.66 | 0.30 | 0.74 |
| | prob_DCD | 0.082 (0.008) | 0.079 (0.007) | 0.092 (0.009) | | | | | | |
| CV of ML weight-transfer magnitude | TD | 0.31 (0.02) | 0.26 (0.01) | 0.26 (0.02) | 0.38 | 0.54 | 7.27 | <0.01 * | 0.38 | 0.68 |
| | prob_DCD | 0.30 (0.01) | 0.26 (0.02) | 0.24 (0.01) | | | | | | |
| Step up peak vertical acceleration (m.s$^{-2}$) | TD | 5.4 (0.3) | 3.9 (0.1) | 3.9 (0.2) | 0.06 | 0.80 | 28.50 | <0.01 * | 3.07 | 0.05 ** |
| | prob_DCD | 4.5 (0.2) | 3.8 (0.2) | 4.0 (0.2) | | | | | | |
| Step up peak vertical deceleration (m.s$^{-2}$) | TD | −5.01 (0.04) | −3.77 (0.16) | −3.82 (0.17) | 0.44 | 0.51 | 28.32 | <0.01 * | 2.38 | 0.10 |
| | prob_DCD | −4.51 (0.24) | −3.80 (0.21) | −4.04 (0.22) | | | | | | |
| Normalized Jerk | TD | 54.4 (8.9) | 46.3 (6.5) | 44.4 (7.9) | 0.53 | 0.47 | 0.47 | 0.63 | 0.70 | 0.50 |
| | prob_DCD | 48.0 (6.9) | 47.2 (6.2) | 53.1 (6.7) | | | | | | |
| Frequency of peak PSD (Hz) | TD | 0.500 (0.004) | 0.500 (0.001) | 0.498 (0.001) | 2.96 | 0.09 | 4.43 | <0.05 * | 3.16 | <0.05 * |
| | prob_DCD | 0.518 (0.008) | 0.499 (0.002) | 0.498 (0.001) | | | | | | |
| PSD at 0.5 Hz (dB/Hz) | TD | 1.17 (1.43) | 4.21 (1.16) | 5.56 (0.95) | 0.30 | 0.59 | 7.67 | <0.01 * | 0.34 | 0.72 |
| | prob_DCD | −0.51 (1.52) | 4.21 (1.28) | 4.62 (1.47) | | | | | | |
| Relative PSD bandpower (%) | TD | 3.0 (0.4) | 5.8 (0.4) | 6.3 (0.4) | 0.52 | 0.47 | 67.90 | <0.01 * | 0.50 | 0.61 |
| | prob_DCD | 3.3 (0.3) | 5.9 (0.4) | 6.0 (0.4) | | | | | | |

Group data expressed as Mean (SEM). CV – coefficient of variation; ML – medio-lateral; PSD – power spectral density. * represents statistical significance ($p < 0.05$). ** represents $p = 0.051$.

peak PSD ($p < 0.05$, Table 4). However, due to the large number of pairwise comparisons, the Sidak correction for multiple comparisons revealed no significant pairwise differences for frequency of peak PSD ($p > 0.05$).

A progressive reduction in CV of step timing was observed throughout the training sessions, where sessions 8, 9, 15 and 16 being significantly reduced compared to session one and session 15 also showing a smaller CV of step timing than sessions 2 and 3 ($p < 0.05$, Fig. 4A).

In contrast, there was a progressive increase in relative PSD bandpower, with a significant increase from session one being observed in sessions 9 and 15 and session 9 also having a greater PSD bandpower than session 3 ($p < 0.05$, Fig. 4B).

## 4. Discussion

The present study generally supported the proposed hypotheses that children with impaired motor skill acquisition and execution affecting daily function (probable DCD) identified by the Movement Assessment Battery for Children (MABC-2) criteria would have impaired motor performance in a novel rhythmic stepping task, that these deficits would be exacerbated by increasing the cognitive load during a dual-task condition and that these children could learn the task and improve motor performance with a training intervention.

### 4.1. Rhythmic stepping

Before the training intervention, children with probable DCD showed an overall limitation in the ability to keep up with the specified stepping frequency, as evidenced by greater step timing variability and having the peak spectral energy at a frequency that was further from the targeted 0.5 Hz. In contrast, at pre the TD group was already able to maintain a stepping frequency very close to the imposed target, even with a larger step-up peak acceleration. It is conceivable that deficits in feedforward and feedback control mechanisms, the reported limitations in motor competence and motor processing may have led to the observed poorer stepping performance of the prob_DCD group (Cherng et al., 2009; Cignetti et al., 2018; Golenia et al., 2018; Wilson et al.,

2013).

Nonetheless, when exposed to seven weeks of a multimodal exercise intervention that incorporated training of the novel rhythmic stepping task, the prob_DCD group demonstrated a motor learning capacity at least similar to TD children. Potentially driven by the training-induced improvements in variability in the step timing and medio-lateral control of the centre of mass, both groups demonstrated a reduced error in the number of steps. The spectral analysis indicated similar findings as a function of the intervention, showing a shift in the overall spectral power towards the target stepping frequency.

Furthermore, previous reports show significant motor training dose-response to be achieved with approximately 900 min of intervention (Yu et al., 2018). The analysis of the data collected during the training sessions revealed that both groups experienced a progressive improvement in motor performance that was significant, as early as session eight/nine (approx. Total 1156 steps) of the training program. This may be earlier than the reported 900 min threshold. It is conceivable that the rhythmic characteristics of the intervention used in this study elicited a stronger dose-response in this population.

The training-induced motor learning was robust enough that was retained after five weeks post-training, with no observable trends towards pre values. These results suggest that training a novel motor task with rhythmic cueing can similarly improve motor performance in TD and children with probable DCD. Interestingly, other modalities of rhythmic cueing (p.e. auditory) can develop the activation of the cerebellum, supplementary motor area (SMA), pre-motor cortex (PMC) and basal ganglia (Bengtsson et al., 2009; Grahn and Brett, 2007). Considering that children with probable DCD potentially have deficits in central nervous system (CNS) connectivity and function, particularly in the cerebellum (Schott et al., 2016; Tsai et al., 2009), it is plausible that besides the observed neuromotor adaptations, training with visual rhythmic cueing elicited improvements in cerebellar function involved in the development of internal models and feedforward control, similar to what has been observed with other rhythmic cueing modalities (Lonini et al., 2009).
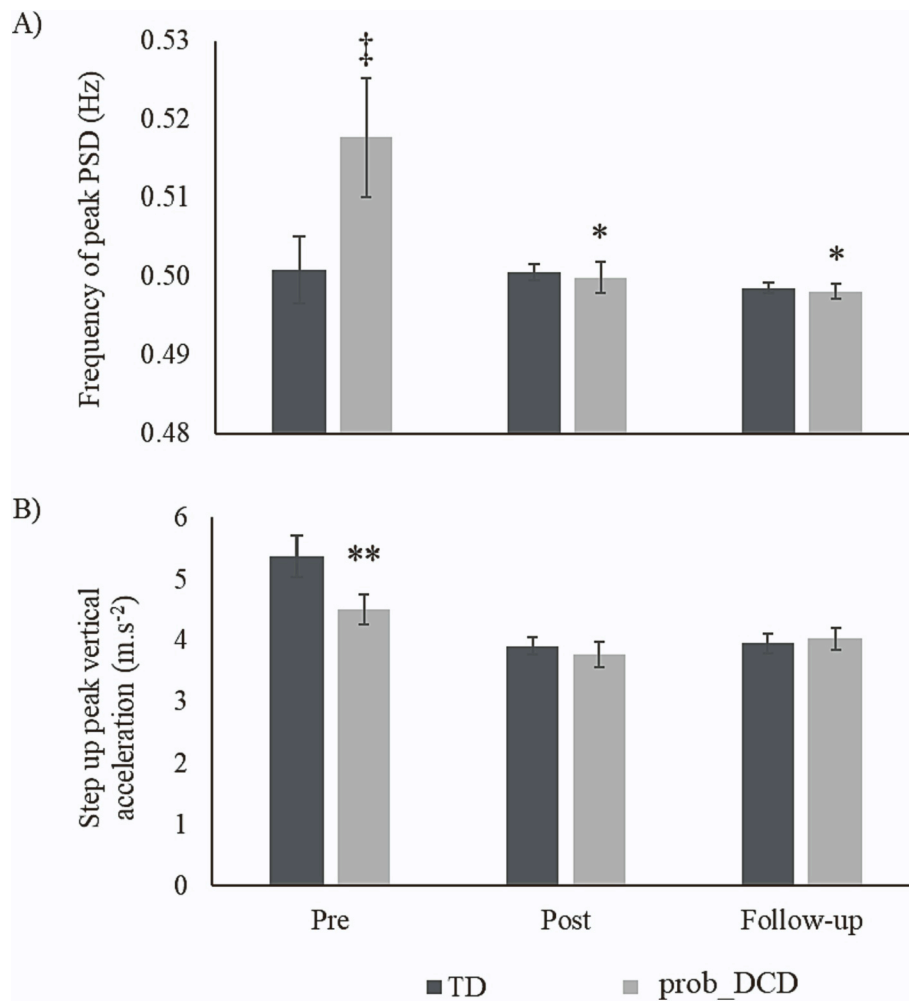
**Fig. 2.** Group x Time interaction for the frequency of peak power spectral density (PSD) (A) and step up peak vertical acceleration (B). * represents a within-group significant difference from Pre. ‡ represents a within-session significant difference from the TD group. ** represents $p = 0.051$ between TD and prob_DCD groups in Pre.

### 4.2. Dual-task

When cognitive load was increased at pre during the rhythmic stepping, through the addition of the auditory stroop test, the TD group experienced a greater increase in step timing variability, a smaller decrease in overall step-up velocity and increased the stepping error (step incidence). Conversely, prob_DCD group observed a greater reduction in the PSD at 0.5 Hz and increased errors in the stroop task. Possibly, these results are a reflection of the biomechanical strategy used by each group and a trade-off between the performances of both tasks. While, TD children may have used a less biomechanically optimized strategy to complete the task, leading to greater variability and errors in stepping, but reduced amount of errors in the stroop, the opposite was observed for children with probable DCD. Nonetheless, even with the biomechanical deficits imposed by the dual-task on the TD group, their potentially greater motor competence allowed them to better adhere to the targeted frequency and have less stroop task errors than prob_DCD participants. These results may indicative of slightly better motor automaticity in the TD children when performing this novel stepping task at pre (Schott et al., 2016; Tsai et al., 2009).

Similar to the observations during the single-task (rhythmic stepping) condition, the training intervention generally allowed both groups to reduce motor performance deficits induced by the dual-task. Considering these results and that the intervention led to an overall improvement and optimization of the rhythmic stepping task in both

groups, one could speculate that when exposed to the dual-task after training, both groups behaved more similarly to TD group's performance at pre. Hence, these results reiterate that the proposed intervention with rhythmic cueing allowed for successful motor learning and potentially increased motor automaticity, that was similarly experienced in children with probable DCD and TD children.

Some of the limitations of this study can include the relatively small sample size. Although, main effects for Time were found for the majority of the outcome measures, some of the observed trends for the main effect of Group and the Group x Time interaction could become significant with an increased number of participants in each group. While the narrow age-range found in the ninth year of the community schools used in this study could limit the potential interpretation for DCD, this study still found several meaningful significant differences between typically developed children and children with probable DCD.

In addition, gender had different proportions in each group. Although there is evidence that females and males do not share similar levels of motor performance in a variety of tasks (Moreno-Briseno et al., 2010; Toole and Kretzschmar, 1993), it is unlikely that gender had a significant impact in the overall results, as the majority of the analysed outcomes was not affected by gender. The covariate analyses only showed significant gender effects ($p < 0.05$) in the rhythmic stepping condition for step-up peak vertical acceleration and deceleration, normalized Jerk and the relative PSD bandpower. For the dual-task, significant effects ($p < 0.05$) were only found for the step-up mean

**Table 3**

Summary of descriptive statistics of the effects of the dual-task on the stepping motor performance, for typically developed (TD) and children with probable Developmental Coordination Disorder (prob_DCD) groups at Pre, Post and Follow-up, and statistical analyses for Group and Time main effects and Group x Time interactions.

| | Groups | Pre (TD, n = 33; prob_DCD, n = 39) | Post (TD, n = 34; prob_DCD, n = 43) | Follow-up (TD, n = 27; prob_DCD, n = 33) | Group | | Time | | Group x Time | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | F | p | F | p | F | p |
| Step incidence (%) | TD | 1.53 (0.85) | −0.71 (0.75) | −1.27 (0.57) | 0.30 | 0.58 | 1.08 | 0.34 | 3.59 | <0.05 * |
| | prob_DCD | −1.04 (0.66) | −0.07 (0.57) | −0.47 (0.09) | | | | | | |
| CV of step timing (%) | TD | 28.8 (8.5) | 3.7 (4.5) | −1.8 (3.7) | 4.12 | <0.05 * | 7.44 | <0.01 * | 1.18 | 0.31 |
| | prob_DCD | 10.1 (6.3) | −4.5 (4.2) | −1.1 (4.7) | | | | | | |
| CV of ML weight-transfer magnitude (%) | TD | 18.5 (9.5) | 11.7 (7.9) | −12.1 (6.8) | 0.09 | 0.77 | 1.97 | 0.15 | 3.27 | <0.05 * |
| | prob_DCD | 14.5 (8.6) | 0.2 (5.8) | 11.1 (6.7) | | | | | | |
| Normalized Jerk (%) | TD | −5.44 (2.32) | 2.78 (2.18) | 6.46 (1.86) | 0.04 | 0.84 | 6.95 | <0.01 * | 2.98 | 0.06 |
| | prob_DCD | −1.57 (2.11) | 5.16 (1.67) | 1.66 (1.74) | | | | | | |
| Vertical acceleration prior to step up (%) | TD | −45.3 (18.7) | −15.6 (10.5) | 13.8 (12.5) | 1.38 | 0.24 | 4.94 | <0.01 * | 1.94 | 0.15 |
| | prob_DCD | −19.6 (12.9) | 9.4 (14.6) | 1.9 (8.4) | | | | | | |
| Step up peak vertical acceleration (%) | TD | −9.97 (3.03) | −0.15 (4.00) | 0.53 (2.77) | 2.02 | 0.16 | 3.66 | <0.05 * | 1.98 | 0.14 |
| | prob_DCD | −1.98 (4.19) | 6.19 (2.57) | −4.49 (2.00) | | | | | | |
| Step up peak vertical deceleration (%) | TD | −5.44 (3.68) | 4.05 (3.62) | 2.57 (2.86) | 0.14 | 0.71 | 4.04 | <0.05 * | 0.81 | 0.45 |
| | prob_DCD | −2.44 (4.32) | 8.50 (6.71) | −1.95 (2.51) | | | | | | |
| Step up mean vertical velocity (%) | TD | −69.9 (35.1) | −49.5 (23.5) | −65.8 (49.4) | 5.82 | <0.05 * | 1.60 | 0.20 | 0.57 | 0.57 |
| | prob_DCD | −151.1 (26.5) | −68.1 (32.7) | −120.3 (33.3) | | | | | | |
| PSD at 0.5 Hz (%) | TD | −7.10 (7.90) | −8.25 (3.01) | −5.87 (4.14) | 0.93 | 0.34 | 3.99 | <0.05 * | 2.78 | 0.07 ‡ |
| | prob_DCD | −31.28 (12.03) | −7.66 (3.01) | 0.57 (4.75) | | | | | | |
| Relative PSD bandpower (%) | TD | −18.66 (4.61) | −7.04 (3.25) | −1.06 (3.73) | 0.01 | 0.92 | 5.65 | <0.01 * | 0.48 | 0.62 |
| | prob_DCD | −15.55 (5.41) | −5.64 (3.10) | −6.10 (3.10) | | | | | | |
| Stroop test error (%) | TD | 6.56 (1.18) | −0.30 (0.56) | 2.78 (2.81) | 0.03 | 0.86 | 17.67 | <0.01 * | 2.96 | 0.06 ** |
| | prob_DCD | 10.96 (2.62) | −1.10 (1.20) | −1.56 (0.74) | | | | | | |

Group data expressed as Mean (SEM). CV – coefficient of variation; ML – medio-lateral; PSD – power spectral density. * represents statistical significance ($p < 0.05$). ** represents $p = 0.057$. ‡ represents $p = 0.067$.
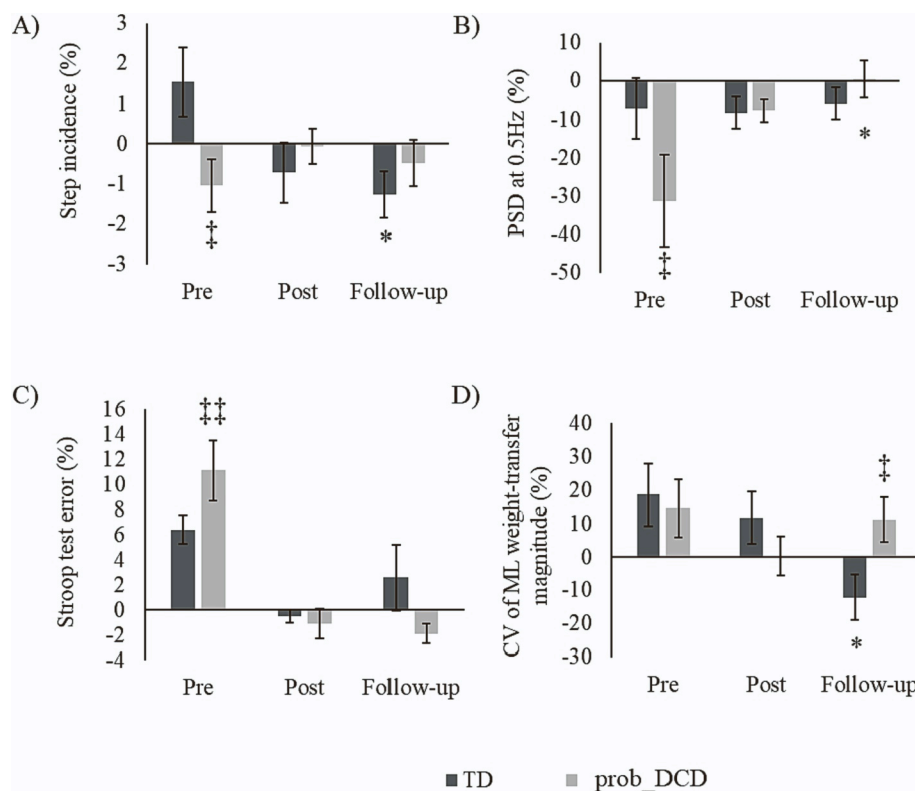


**Fig. 3.** Group x Time interaction for the effects of the Dual task on: step incidence (A), PSD at 0.5 Hz (B), stroop test error (C) and coefficient of variation of medio-lateral (ML) weight-transfer magnitude (D). * represents a within-group significant difference from Pre. ‡ represents a within-session significant difference from the TD group. ‡‡ represents $p = 0.060$ between TD and prob_DCD groups in Pre.

vertical velocity. Lastly, besides the step training with rhythmic cueing, the proposed training intervention also consisted of 20 min of moderate to vigorous aerobic physical activity and 30 min of personalised strength training for upper and lower limbs. Although possible, it is unlikely that

these other components of the training intervention could have affected the results observed during the stepping tasks. The performance of the stepping task was strictly related to the target stepping frequency of 0.5 Hz and the participants did not train a similar movement frequency nor

**Table 4**
Statistical analyses for Group and Time main effects and Group x Time interactions for the stepping motor performance during 16 sessions of the training intervention, for typically developed (TD) and children with probable Developmental Coordination Disorder (prob_DCD) groups.

| | Group | | Time | | Group x Time | |
|---|---|---|---|---|---|---|
| | F | p | F | p | F | p |
| CV of step timing (%) | 0.16 | 0.69 | 3.27 | <0.01* | 1.11 | 0.36 |
| Relative PSD bandpower (%) | 0.003 | 0.958 | 3.12 | <0.01* | 0.87 | 0.60 |
| Frequency of Peak PSD (Hz) | 0.04 | 0.84 | 1.90 | <0.05* | 0.71 | 0.77 |

CV – coefficient of variation; ML – medio-lateral; PSD – power spectral density. * represents statistical significance ($p < 0.05$).

stepping in any of the other intervention components.

Overall, this study may have substantial implications for clinical practice, as it has shown that rhythmic visual cueing can be helpful for children with probable DCD to learn novel motor tasks. This cueing paradigm can be incorporated in interventions to enhance motor learning in this population.

## 5. Conclusions

In conclusion, this study demonstrated that children with probable DCD identified by the Movement Assessment Battery for Children (MABC-2) criteria showed a diminished motor performance when exposed to the novel stepping task. Nonetheless, these children demonstrated, at least, a similar ability to learn a novel motor task, achieve and retain comparable motor performance as TD individuals, with seven weeks of a combined exercise and stepping training with rhythmic cueing. Furthermore, when a cognitive task was added to the rhythmic stepping, children with probable DCD showed greater impairments than the TD group, even while employing a potentially more beneficial biomechanical strategy. Similar to the training effects observed in the motor performance of the rhythmic task, the dual-task induced smaller deficits after training that were also retained. These results may help the development of interventions that target children with probable DCD to elicit motor learning and improve motor performance to levels similar to TD children.

## Author contributions

This statement is based on CRediT taxonomy. Authors MI, PE and HD contributed to conceptualisation, data analysis, writing and editing of this manuscript. HD is senior author and contributed to conceptualisation, resources, writing review and editing, supervision and funding acquisition. PE, AD, DS, SK, TW, HI, HJ and HD contributed to conceptualisation and funding acquisition. PE, BW, SJ and AM contributed to the investigation, project administration, data curation and writing review.
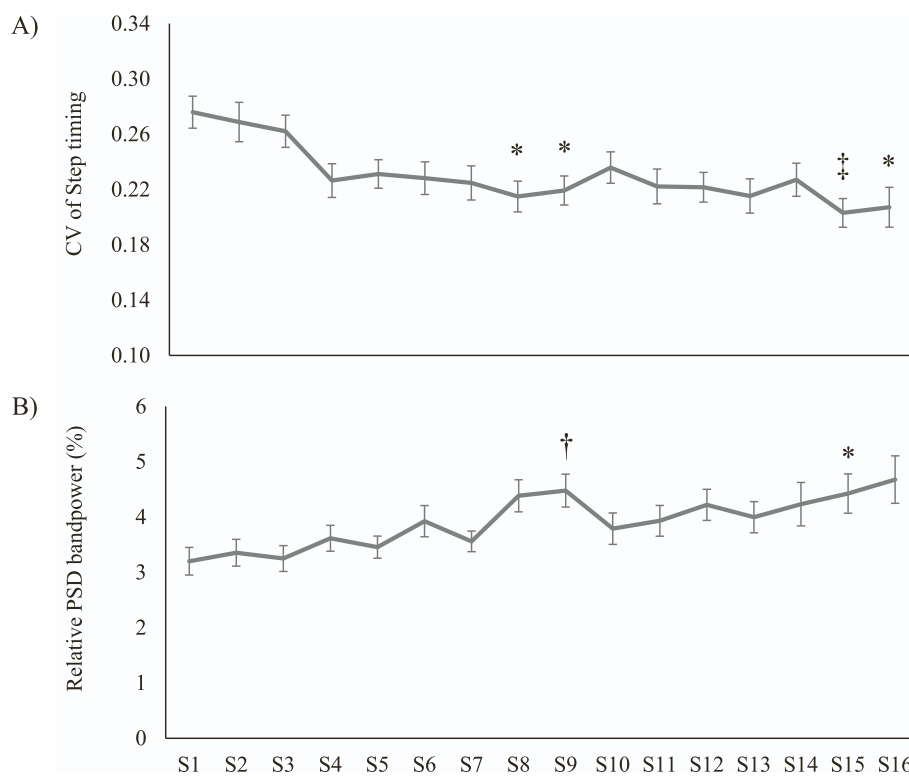


**Fig. 4.** Main effect of Time during the training intervention (sessions one (S1) through session 16 (S16)) for the coefficient of variation of step timing (A) and the relative PSD bandpower (B). * represents a significant difference from S1. ‡ represents a significant difference from S1, S2 and S3. † represents a significant difference from S1 and S3.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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