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Inferior Auditory Time Perception in Children With Motor Difficulties

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Accurate time perception is crucial for hearing (speech, music) and action (walking, catching). Motor brain regions are recruited during auditory time perception. Therefore, the hypothesis was tested that children (age 6–7) at risk for developmental coordination disorder (rDCD), a neurodevelopmental disorder involving motor difficulties, would show nonmotor auditory time perception deficits. Psychophysical tasks confirmed that children with rDCD have poorer duration and rhythm perception than typically developing children ($N = 47$, $d = 0.95$–1.01). Electroencephalography showed delayed mismatch negativity or P3a event-related potential latency in response to duration or rhythm deviants, reflecting inefficient brain processing ($N = 54$, $d = 0.71$–0.95). These findings are among the first to characterize perceptual timing deficits in DCD, suggesting important theoretical and clinical implications.

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Perceiving the auditory world, and speech and music in particular, requires fine time perception, as does the auditory-motor coordination needed to produce speech and music. Mounting evidence suggests that the motor system is involved in auditory time perception (Merchant, Harrington, & Meck, 2013). Behaviorally, motor activation, such as finger tapping, can improve the precision of auditory time perception and temporal prediction (Butler & Trainor, 2015; Manning & Schutz, 2013; Monier, Droit-Volet, & Coull, 2019; Morillon & Baillet, 2017). Also, body movements can affect perceived temporal grouping in tone sequences, such as whether the sequence is organized as a march or a waltz (groups of two or three beats; Phillips-Silver & Trainor, 2005, 2007, 2008). Auditory information also plays an important role in many essential motor behaviors. For example, if people are given altered feedback of how their footsteps sound, it changes their walking patterns (e.g., Young, Rodger, & Craig, 2013). Furthermore, studies on mammals showed that auditory input from sounds resulting from self-produced actions such as footsteps is attenuated in real time to help distinguish the actions of others from self-generated actions (e.g., Schneider, Sundararajan, & Mooney, 2018). Thus, auditory information can be used to monitor self- and other-produced action and guide subsequent motor behaviors, such as whether to run away from a predator.

Neuroimaging evidence further shows that, during auditory time perception, motor brain regions, including the supplementary motor area (SMA), pre-SMA, premotor cortex, thalamus, cerebellum, basal ganglia, and striatum, are also activated along with auditory regions even when a task has no motor component (e.g., Fujioka, Trainor, Large, & Ross, 2012; Grahn, 2012; Teki, Grube, & Griffiths, 2012). Moreover, dysfunctions in these motor regions, either caused by neurological disorders or transient brain stimulation, are associated with worse time perception (e.g., Cope, Grube, Singh, Burn, & Griffiths, 2014; Grube, Cooper, Chinnery, & Griffiths, 2010; Grube, Lee, Griffiths, Barker, & Woodruff, 2010; Ross, Iversen, & Balasubramaniam, 2018). However, most of these studies were based on healthy populations or adults with neurological disorders, and it remains unknown whether chil- dren with motor difficulties have inferior auditory time perception.

Perception for two types of temporal regularities is particularly relevant in this context. Interval- or duration-based timing concerns the length of an individual interval, and can be measured with a duration discrimination task, while rhythm-based (or beat-based) timing concerns the temporal regularity in a continuous stream of events, and can be assessed with a test of nonisochrony or temporal perturbation detection. These two types of timing have distinct perceptual mechanisms (e.g., McAuley & Jones, 2003), and they are associated with partially overlapping but diverging cerebellum and basal ganglia motor networks in the brain (e.g., Grahn, 2012; Teki, Grube, Kumar, & Griffiths, 2011; Teki et al., 2012).

In addition to furthering fundamental understanding of auditory-motor coordination, the current study is also of potential clinical import because understanding auditory-motor associations in children with motor difficulties could be applied to interventions. Motor rehabilitations incorporating auditory-temporal cueing, such as metronomes or musical beats, have beneficial effects for adult patients with motor deficits caused by Parkinson's disease or stroke (Dalla Bella, Benoit, et al., 2017; Dotov et al., 2017; Fujioka et al., 2018; Whitall, Waller, Silver, & Macko, 2000). This approach might also be applicable to children with motor difficulties.

Developmental coordination disorder (DCD) is a neurodevelopmental disorder with onset in early childhood. It involves deficits in motor skills in the absence of intellectual disability or any other physical disorders, with an approximate 5%–15% prevalence rate in school-aged children (American Psychiatric Association, 2013). These so-called clumsy children have difficulties in fine and/or gross motor skills, including motor learning, motor planning, sequencing of movements, and motor timing, affecting tasks such as writing, tying shoes, running, and catching a ball (Debrabant, Gheysen, Caeyenberghs, Van Waelvelde, & Vingerhoets, 2013; Wilson et al., 2017). These difficulties interfere with their daily activities, including learning, academic performance, and social interaction with other children; the difficulties are also associated with social anxiety and obesity and thus have a negative impact on physical and mental health (Cairney et al., 2010; Rivilis et al., 2011; Zwicker, Harris, & Klassen, 2013). DCD is often diagnosed at a preschool age, and its symptoms often persist for more than 10 years and into adulthood (Zwicker, Missiuna, Harris, & Boyd, 2012).

One of the main features of DCD is the deficit in motor and sensorimotor timing

(Wilson et al., 2017). Although the motor difficulties are heterogeneous and the neurological etiology remains unclear (Brown-Lum & Zwicker, 2015; Zwicker et al., 2012), children with DCD commonly have less accurate, slower, and more variable motor performance than typically developing (TD) children. It appears that deficits in motor timing can explain these motor difficulties (Debrabant et al., 2013). For example, children with DCD, compared to TD children, are inferior at visually tracking moving objects (Adams, Lust, Wilson, & Steenbergen, 2014) and worse at synchronizing their tapping with visual or auditory targets presented in temporally regular sequences (de Castelnau, Albaret, Chaix, & Zanone, 2007; Roche, Viswanathan, Clark, & Whitall, 2016; Roche, Wilms-Floet, Clark, & Whitall, 2011; Whitall et al., 2006, 2008). However, an important but unexplored question is whether children with DCD have deficits in time perception, as precise time perception is often closely tied to precise motor control, such as catching a ball or tapping to musical beats (Trainor, Chang, Cairney, & Li, 2018). Also, it has been suggested that DCD includes cerebellar and/or basal ganglia dysfunctions (Bo, Bastian, Kagerer, Contreras-Vidal, & Clark, 2008; Lundy-Ekman, Ivry, Keele, & Woollacott, 1991; Vaivre-Douret et al., 2011), brain regions that are involved in perceptual timing, as reviewed earlier.

The current exploratory study aimed to investigate the auditory timing deficits in DCD because (a) motor brain regions involved in sequencing and timing are also typically recruited during time perception, and (b) children with DCD show motor timing deficits. Therefore, we investigated whether children with DCD would show auditory perceptual timing deficits in the absence of any motor task. We used both behavioral and neural measurements. In the Behavioral Experiment we used adaptive psyhophysical procedures to measure perceptual sensitivity in terms of discrimination thresholds for changes in duration (relating to interval-based timing), rhythm (or temporal perturbation, related to beat-based timing), and pitch (as a control task). We hypothesized that children at risk for DCD (rDCD) would have poorer duration and rhythm sensitivities (i.e., higher thresholds) than TD children.

In the Electrophysiology Experiment, we used electroencephalography (EEG) and extracted event- related potentials (ERPs) to measure brain responses while participants listened to auditory oddball sequences with infrequent subtle deviations in duration, rhythm, or pitch. Specifically, we ana- lyzed mismatch negativity (MMN) and P3a ERP responses to identify at which neural stage of pro- cessing potential perceptual deficits might arise, as these two ERP components reflect preattentive and attentive stages of processing infrequent perceptual deviations, respectively (Näätänen, Paavilainen, Rinne, & Alho, 2007; Polich, 2007). Beyond time perception, ERP approaches have also been shown to reflect processes related to sensory, attention, and executive function in children with DCD (e.g., Mon-Williams, Mackie, McCulloch, & Pascal, 1996; Tsai, Chang, Hung, Tseng, & Chen, 2012; Tsai, Pan, Cherng, Hsu, & Chiu, 2009; Tsai, Wang, & Tseng, 2012). We hypothesized that children with rDCD would have reduced ERP amplitudes and/or delayed ERP latencies, reflecting inefficient perceptual processing, although we did not have a priori expectations for whether the ERP effects would manifest in MMN or P3a.

Method

Defining Cases of rDCD and TD

Following the 2011 European Academy of Child- hood Disability Guidelines for identification of children with DCD (Blank, Smits-Engelsman, Polatajko, & Wilson, 2011), we defined rDCD based on the following criteria. (a) A score at or below the 16th percentile on a standardized measure of motor impairment. We used the Movement Assessment Battery for Children, 2nd ed. (MABC–2; Henderson, Sugden, & Barnett, 2007) as the standardized measure of motor coordination as it is the most widely used assessment for the identification of DCD (Ellinoudi et al., 2011; Parmar, Kwan, Rodriguez, Missiuna, & Cairney, 2014). It includes three components: Manual Dexterity (e.g., posting coins, threading beads, drawing trails), Aiming and Catching (e.g., catching a bean bag, throwing a bean bag onto a mat), and Balance (e.g., one-leg balance, walking with heels raised, jumping on mats). (b) Evidence of impact on daily function (parental interview). (c) IQ score above the 5th per- centile, assessed by the Kaufman Brief Intelligence Test, 2nd ed. (Kaufman & Kaufman, 2004) to exclude the possibility that poor motor skills were due to an intellectual disability (Cairney et al., 2019). (d) Absence of any medical condition affecting motor functioning (parent-reported). TD children were defined as failing the rDCD criterion (a) and satisfying the general development criteria (c and d). Note that criterion (b) was not directly applied in the current study because we were concerned that the difficulties in activities of daily living may not be very apparent during the early years (Cairney et al., 2019), and questionnaires to assess the impact of DCD on everyday activities have not yet been validated for this age (Cairney et al., 2015). These assessments were done in an additional session as part of the CATCH study (Cairney et al., 2015, 2019). It should be noted that participants did not receive a formal medical diagnosis of DCD from a pediatrician or physician.

Participants

Sixty-one children between 6 and 7 year of age were recruited for the Behavioral Experiment, and 54 for the Electrophysiology Experiment, and testing took place between July 2016 and July 2017. Forty participants completed both experiments. Children with any physical disabilities, diagnosed medical condition that affects motor coordination (e.g., cerebral palsy, hypotonia), or with a birth weight lower than 1,500 g were not eligible to participate. These criteria are necessary to rule out medical conditions other than DCD that may be responsible for poor motor coordination. Children who had pressure-equalizing tubes, frequent ear infections, diagnosed autism spectrum disorder, or a cold at the time of the study were also not eligible. An additional criterion for participating in the Electrophysiology Experiment was to be right-handed (by parent report). The McMaster Research Ethics Board and the Hamilton Integrated Research Ethics Board approved all the procedures and informed consent was obtained from parents.

In the Behavioral Experiment, we further excluded five TD participants and nine participants with rDCD as they met our exclusion criteria for not engaging in the task (poor performance on easy probe trials) and/or failing to converge in our adaptive procedure (see Supporting Information: Details of Behavioral Experiment). Among the 47 remaining participants, 20 children met the criteria for rDCD (age: 6.88 ± 0.55 year, range 6.17– 7.92 year; ethnicity: 1 Asian, 1 Latino, 14 White, 1 White/Asian, 1 White/Black, 2 unknown; first language: 18 English, 1 Spanish, 1 unknown; median annual household income for the 16 of 20 who reported this: 90,000–120,000 Canadian dollars range), and 27 the criteria for TD (age: 6.68 ± 0.42 year, range 6.08–7.42 year; ethnicity: 5 Asian, 1 Black, 17 White, 3 White/Asian, 1 unknown; first language: 25 English, 1 Russian, 1 unknown; median annual household income for the 26 of 27 who reported this: 90,000–150,000 Canadian dollars range). Furthermore, five participants in the rDCD group were also identified with probable attention deficit hyperactivity disorder (pADHD) by the questionnaire of the Centers for Disease Control and Prevention (2015; see Supporting Information for the details), and thus we further categorized rDCD into the rDCD - pADHD (rDCD without pADHD) and rDCD + pADHD (rDCD with pADHD) subgroups. We did not test for dyslexia because its symptoms are less obvious at age 6 and 7 when children are just starting to learn to read (cf. Handler & Fierson, 2011). No TD children met the criterion of pADHD.

In the Electrophysiology Experiment, 27 of the 54 participants fell into the D group (6.64 ± 0.42 year, range 6.00–7.42 year; ethnicity: 5 Asian, 18 White, 3 White/Asian, 1 unknown; first language: 27 English; median annual household income for the 27 of 27 participants who reported this: 120,000–150,000 Canadian dollars), and 27 into the rDCD group (6.82 ± 0.50 year, range 6.25– 7.92 year; ethnicity: 1 Latino, 21 White, 2 White/Asian, 1 White/Black, 2 unknown; first language: 24 English, 1 Spanish, 1 French, 1 unknown; median annual household income for the 23 of 27 who reported this: 120,000–150,000 Canadian dollars). Four participants in the rDCD group were categorized into the rDCD + pADHD subgroup. No TD children met the criterion of pADHD.

The two groups of participants in each experiment were not statistically different in age, IQ, or digit span working memory index (WMI; Wechsler Intelligence Scale for Children, 4th ed., Wechsler, 2003; see Table S1). Note that we do not argue that rDCD and TD children have equivalent IQ; indeed studies with larger sample sizes have shown significant differences (e.g., IQ 106.1 vs. 100.9, or per- centile 65.6 vs. 52.4; Cairney et al., 2019). Nevertheless, whether IQ differs between groups was not the main interest of the current study and, importantly, our statistical models showed that IQ did not associate with behavioral thresholds or ERP effects, suggesting that IQ is unlikely to be a con- founding factor for our conclusions (see *Comparing age, working* *memory and IQ between groups* in Sup- porting Information).

All participants were invited from the CATCH study (Cairney et al., 2015) that recruited children from various community organizations and sites within the city of Hamilton, Ontario, Canada and surrounding areas. Each participant was given a monetary reward, a toy, and the reimbursement of transportation costs.

General Procedure

Participants performed the tasks in the order of WMI test, Behavioral Experiment (~30 min), and then Electrophysiology Experiment (~30 min), all in the same visit. The MABC–2 and IQ were assessed prior to the date of auditory experiments (see Supporting Information). The study was double blind. Experimenters did not know whether a participant was categorized into the rDCD or TD group until after the experiment. Participants and their parents did not know the hypotheses of the study.

Auditory Stimuli

Auditory stimuli were computer-generated com- plex tones. Each tone was composed by summing random phase sinusoidal waves at a fundamental frequency (F0) and two overtones (F1 and F2) with slope -6 dB/oct, 10 ms cosine function rise and fall times, and 60 ms steady state in the middle (except for the Pitch test of the Behavioral Experiment, which is clarified in "Behavioral Experiment: Measuring Perceptual Thresholds" section). The stimuli were presented with a Tucker-Davis Technologies RP2 Real Time Processor and AudioVideo Methods speakers (P73), located approximately 1 m in front of the participant. Stimulus presentation occurred in a sound-attenuating room. The average sound intensity was 75.5 dB(C) sound pressure level over a noise floor of approximate 28 dB(A) at the location of the participant’s head.

Behavioral Experiment: Measuring Perceptual Thresholds

Three behavioral tests (Figure 1a), presented as child-friendly games, were used to measure the children’s auditory perceptual thresholds (sensitivity) for duration discrimination, rhythm discrimination, and pitch discrimination. Specifically, we used a two-alternative forced choice (2AFC) method (Kingdom & Prins, 2010). On each trial, a standard and a target stimulus were presented sequentially in a randomized order, with the constraint that the stimulus order was not the same for more than four consecutive trials. Across trials, an adaptive 2-up-1-down transformed-response (UDTR; Levitt, 1971) psychophysical procedure was used to measure the 70.7% discrimination threshold for each task. Each task started with at least five training trials, followed by 43 experimental trials intermixed with five probe trials. The training trials were set to a very easy discrimination level and the experimenter could help participants understand the task during the training phase but not in the testing phase. Participants moved on to the testing phase after correctly completing four consecutive training trials without experimenter assistance. The probe trials were set to the same difficulty level as training trials, and performance on probe trials was used to check whether participants were following the task instructions and concentrating on the task (see *Details of Behavioral Experiment* in Supporting Information). Only the experimental trials were used to move through the adaptive procedure and to estimate thresholds. The order of the three conditions was counterbalanced across participants to eliminate any potential sequential effects. See Supporting Information for more details.

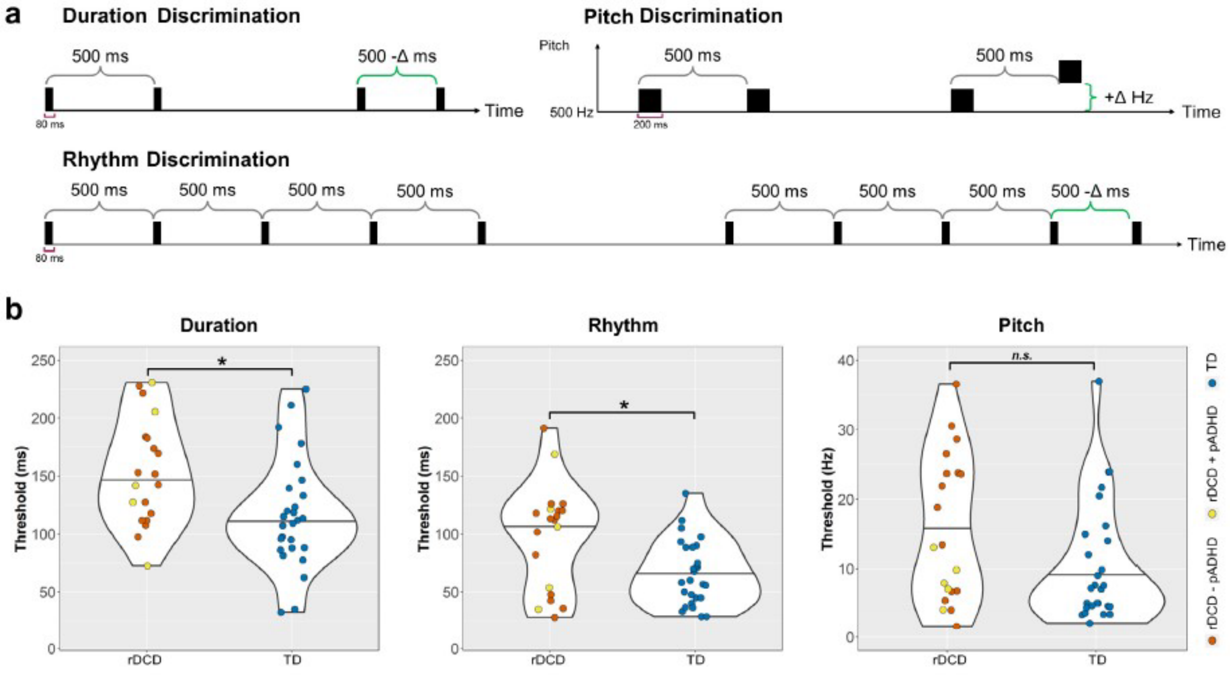

Figure 1. Perceptual discrimination thresholds in the Behavioral Experiment. (a) In the two-alternative forced choice experimental procedure, participants were requested to judge which of two stimuli was shorter (duration discrimination test), had an offbeat tone (rhythm discrimination test), or had two different

tones (pitch discrimination test). The difference (D) represents the temporal or pitch difference between the standard and target stimuli. D varied from trial to trial according to the 2-up-1-down adaptive psychophysical procedure. This procedure converged at the D level at which a participant has 70.7% discrimination accuracy (threshold). (b) Distributions of thresholds for each discrimination. Each dot represents one participant. The width of the white area represents distribution density, and the horizontal line represents the median. Participants in the risk for developmental coordination disorder (rDCD) group are further categorized into rDCD with probable attention deficit hyperactivity disorder (pADHD; rDCD + pADHD) and rDCD without pADHD (rDCD - pADHD). $*p_{\text{corr}} < .05$; *ns*, nonsignificant.

In the duration discrimination test, each trial consisted of two tone-pairs (standard and target stimuli). The pairs were separated by 1,120 ms. One tone-pair was the standard stimulus, in which the inter-onset interval (IOI) between tones was fixed at 500 ms. In the target tone-pair, the IOI was always shorter than in the standard, ranging between 260 and 500 ms in 15 ms step sizes. It began at 260 ms and changed in accordance with the UDTR algo- rithm. The target IOI was set at 250 ms for training and probe trials. We used an empty duration (on- set-to-onset duration between 2 tones) rather than a filled duration (onset-to-offset duration of a tone) to make the test as similar as possible to the rhythm discrimination test. Participants were instructed to select the tone-pair that was “faster” (i.e., shorter).

The rhythm discrimination test involved detecting a nonisochrony (i.e., a temporal perturbation) in an otherwise isochronous sequence. Each trial consisted of two 5-tone sequences (standard and target stimuli). Sequences were separated by 1,120 ms. The standard sequence was isochronous, with IOIs fixed at 500 ms. The target sequences also had IOIs fixed at 500 ms, except for the last IOI, which was always shorter than 500 ms. The last IOI of the tar- get sequence ranged between 335 and 500 ms, with a step size of 15 ms. It began at 335 ms and changed in accordance with the UDTR algorithm. The last IOI of the target sequence was fixed at 250 ms for training and probe trials. Participants were instructed to select the tone sequence that had an offbeat tone (“the funky note”). Note that there are many rhythm discrimination tests in the literature, some of which use more complex sequences that contain two or more IOIs, from which a perceptual beat can be mentally constructed (e.g., Grahn & Brett, 2009). However, the rhythm stimulus design used here has been shown to be able to pinpoint the mechanisms for perceiving rhythm or beat, which are dissociable from the mechanisms for duration (e.g., Teki et al., 2011) and is simple for children to understand.

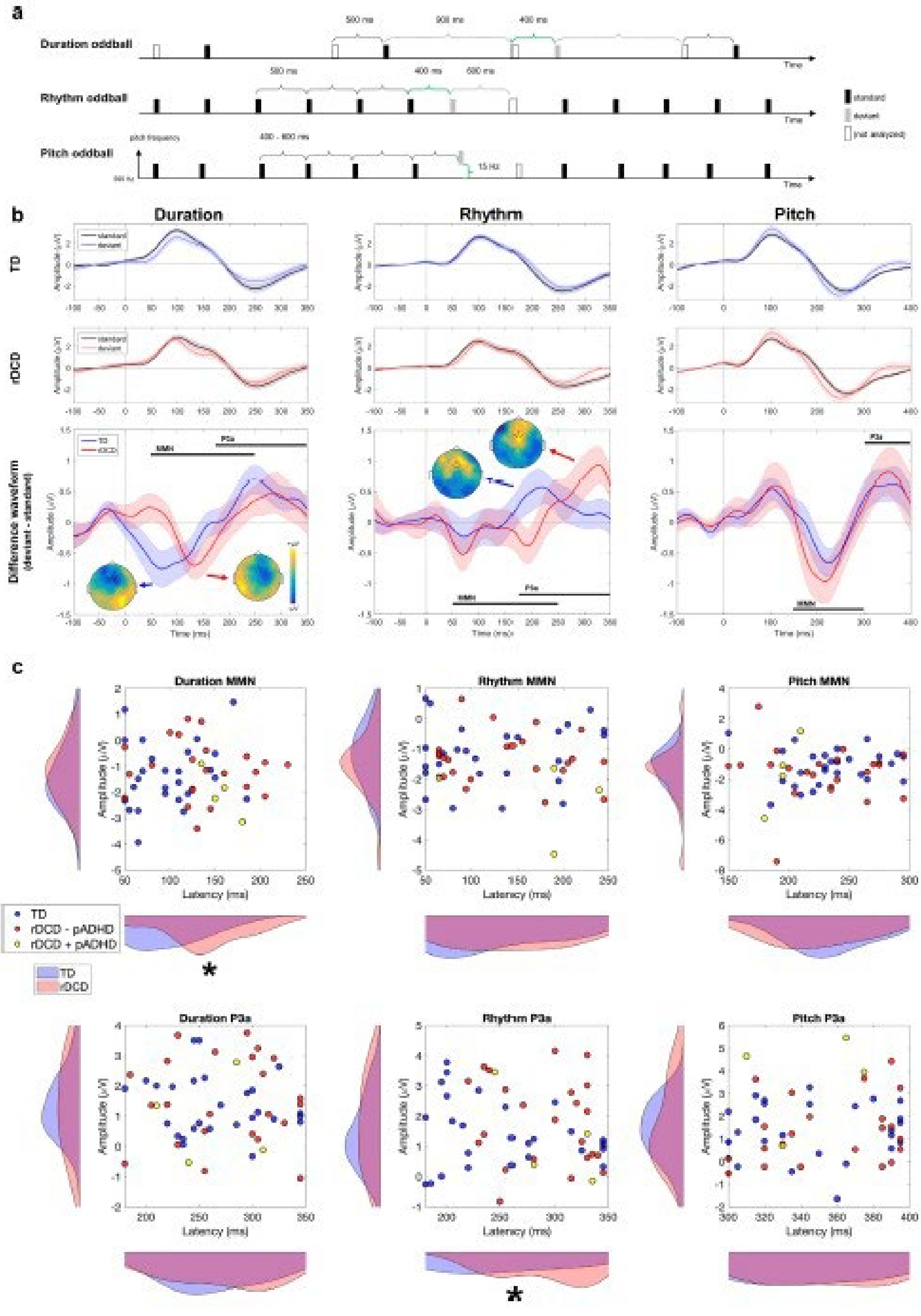

Figure 2. Event-related potentials (ERPs). (a) The oddball experimental designs for duration, rhythm, and pitch. Infrequent (13%) deviant stimuli were pseudorandomly intermixed with frequent standard stimuli. (b)

The ERP waveforms at frontal-midline channels. Each waveform represents the neural activities time-locked to the onset of standard stimuli, deviant stimuli, or their neural activity differences (deviant minus standard), averaged within each group and condition. The colored areas represent mean ± standard error of waveform. Each horizontal black line marks the time window used for searching for the mismatch negativity (MMN) or P3a peak in each individual in each session. Each inserted topography represents the group-averaged scalp distribution for each ERP component under each condition, and the dots on the topographies mark the frontal-midline channels used for extracting ERP waveforms. (c) The mean amplitude and peak latency distributions of MMN or P3a. Each dot represents the ERP amplitude and latency of one participant. The distribution of amplitude or latency of each typically developing (TD) or risk for developmental coordination disorder (rDCD) group was plotted on the margins of the scatter plot, and * represents $p_{\text{corr}} < .05$ on the indicated dimension. The subpopulation within the rDCD group (with probable attention deficit hyperactivity disorder [pADHD] or not) is further color-labeled on the scatter plots but not on the distribution plots. [Corrections added on March 02, 2021, after first online publication: In Figure 2a, the value “800” has been corrected to “900”.]

The pitch discrimination test was used as a control task to ensure that any potential differences found between the TD and rDCD groups in the other two tests were not due to any potential issues with hearing, testing procedure, engagement, or the ability to perform a 2AFC task. Each trial consisted of two tone-pairs (standard and target stimuli). The two pairs were separated by 1,120 ms. The IOI within each pair was fixed at 500 ms. Both tones of the standard tone-pair had an F0 of 500 Hz. In the target tone-pair, the first tone had an F0 of 500 Hz, but the F0 of the second tone was higher than 500 Hz. The second tone began at 530.9 Hz with exponential step size $e^{0.005}$ Hz (approximate linear step size 2.5 Hz), changing in accordance with the UDTR algorithm. The target tone was set to 550 Hz for training and probe trials. Specific for this test, each tone was 200 ms long (including 10 ms cosine function rise and fall times). The tone length was longer than in the timing tasks because it is difficult for children of this age to perceive pitch in tones of 80 ms or less (Thompson, Cranford, & Hoyer, 1999). Participants were instructed to select the tone-pair that had different tones (different pitch frequencies).

Electrophysiology Experiment: Auditory Oddball Paradigms

Three auditory oddball sessions (Figure 2a) were used to investigate the ERP neural signatures of potential differences in processing auditory time perception between the rDCD and TD groups.

The Electrophysiology Experiment consisted of two runs, each containing duration, rhythm, and pitch oddball sessions. The order of session types was the same for both runs for each participant but was counterbalanced across participants. There was a silent gap of at least 10 s between sessions. For each session, the deviant rate was fixed at 13% of 800 trials (104 deviant and 696 standard trials). Trials were presented in a pseudorandom order with the constraint that no two deviants were presented consecutively. In the duration oddball session, the standard trial was a pair of tones with 500 ms IOI, the deviant trial was a pair of tones with 400 ms IOI, and the IOI between trials was 900 ms. In the rhythm oddball session, tones were presented in a continuous sequence, with an IOI of 500 ms (standard trials). On deviant trials the IOI was changed to 400 ms for one interval. The IOI following a deviant was fixed at 600 ms to avoid overall phase shifts across the entire rhythmic sequence, caused by a deviant trial (see Figure 2a). In the pitch oddball session, the tones were presented with uniformly random IOIs ranging from tone interval was sufficient to elicit MMN and P3a responses.

EEG Data Acquisition and Preprocessing Acquisition

Children were instructed to sit still during stimulus presentation and watch a silent movie shown on a screen placed below the speaker. EEG was recorded continuously at a sampling rate of 1000 Hz from 128-channel HydroCel GSN nets (Figure S3) referenced to CZ with an Electrical Geodesic NetAmps 410 amplifier. The electrode impedances were maintained < 50 kO during recording.

Preprocessing

The EEG data were processed in MATLAB using the FieldTrip toolbox (Oostenveld, Fries, Maris, & Schoffelen, 2011, RRID: SCR_004849). Bad channels were removed based on visual inspection. The continuous EEG data were high-pass filtered at 1 Hz and then low-pass filtered at 16 Hz with zero-phase Butterworth filters. We then used the Artifact Blocking (AB) algorithm to attenuate artifacts (e.g., caused by eye blinks, eye movements, body movements) in the EEG recordings (Fujioka, Mourad, He, & Trainor, 2011; Mourad, Reilly, de Bruin, Hasey, & MacCrimmon, 2007). Based on the AB- cleaned EEG data matrix, the bad channels were reconstructed by averaging the neighboring channels. The data were then re-referenced to an aver- aged reference and downsampled to 200 Hz. After epoching, each trial was baseline-corrected to the mean amplitude of the 100 ms prestimulus period. Epochs with amplitude exceeding ± 100 IV were excluded. Across participants, 82.0 ± 10.0% of the total number of trials were included for ERP analyses. See Supporting Information for further details on the ERP signal processing.

Quantifying ERP Components

We were interested in the amplitude and latency of the MMN and P3a, which are known to be elicited in response to deviant stimuli in an auditory oddball paradigm. To extract the MMN and P3a components, for each participant and each session, we took the mean difference ERP waveforms (mean deviant-mean standard ERP waveform). We con- ducted statistical tests on the mean (unweighted average) waveform of six frontal-midline channels (Figure 2b, see Figure S3 for the electrodes selected in the context of the complete EEG layout), which usually have the strongest MMN and P3a activity in children (Barry, De Blasio, & Borchard, 2014; Cheour, Leppanen, & Kraus, 2000; Choudhury, Parascando, & Benasich, 2015; Gumenyuk et al., 2005). For the duration and rhythm ERPs of each participant, we first identified the largest negative peak in the window from 50 to 250 ms as the MMN peak (negative peak) and the largest positive peak in the window from 180 to 350 ms as the P3a peak (positive peak). We used wide time windows to capture the individual differences in ERP latencies, consistent with previous studies of children (e.g., Barry et al., 2014; Bruggemann, Stockill, Len- root, & Laurens, 2013; Cheour et al., 2000; Gumenyuk et al., 2005; Huttunen, Halonen, Kaartinen, & Lyytinen, 2007; Wetzel & Schroger, 2007). Although the time windows were wide in accordance with the literature on the passive auditory oddball paradigm, the difference ERP waveform (deviant minus standard) will typically only result in one negative component (MMN) and one positive component (P3a) in these time windows (e.g., Choudhury et al., 2015; Wetzel & Schroger, 2007). For pitch ERPs, which appear to have later latencies than duration and rhythm ERPs, the window used for MMN was 150–300 ms and the window for P3a was 300–400 ms, consistent with previous studies of ERPs in children (Barry et al., 2014; Bruggemann et al., 2013; Cheour et al., 2000; Gumenyuk et al., 2005; Huttunen et al., 2007; Wetzel &

Schroger, 2007). Then, for each participant and each component, we calculated the mean ERP amplitude in the -15 to 15 ms time window around the peak latency. The mean amplitude and peak latency were used for subsequent ERP analyses.

Statistics

The statistical tests were performed in MATLAB R2015b. Multiple comparisons of the statistical tests were controlled by family-wise Bonferroni correction, and each corrected *p*-value was reported as p_{corr}. All statistical decisions were based on two-tailed tests with alpha level at .05. Nonparametric tests were used for comparing thresholds between groups, as the data deviated greatly from a normal distribution for some cases (Lilliefors test for normality: $p < .002$; two-sample *F*-test for homogeneity of variance: $p < .022$). We report Cohen's *d* as effect size for the significant *t*-tests, and rank biserial correlation coefficient (*r*) for the nonparametric Mann– Whitney *U* tests (Kerby, 2014). The rank biserial correlation coefficient ranges from 0 (no effect) to 1 (strongest possible effect).

Results

Perceptual Thresholds

In the Behavioral Experiment, we combined 2AFC and adaptive psychophysical methods to measure auditory perceptual discrimination thresholds, separately for duration, rhythm, and pitch (Figure 1). The two groups (rDCD and TD) of children aged 6–7 years did not differ significantly in age, IQ (intelligence quotient), or WMI (Table S1).

Mann–Whitney *U* tests (number of comparisons: $m = 3$), the nonparametric alternative to two-sample *t*-tests, showed that the duration discrimination thresholds of the rDCD group were larger than those of the TD group ($z = 2.60$, $p_{\mathrm{corr}} = .028$, $r = .45$). Rhythm discrimination thresholds were also larger in the rDCD than TD group ($z = 2.51$, $p_{\mathrm{corr}} = .037$, $r = .43$). These effect sizes (converted Cohen's *d*: 1.01 and 0.95) were within the range of previous similar studies on children with ADHD (converted Cohen's *d*: 0.31 to 1.31; e.g., Gooch, Snowling, & Hulme, 2011; Puyjarinet, Begel, Lopez, Dellacherie, & Dalla Bella, 2017). Pitch discrimination thresholds were not significantly different between the two groups (z = 1.73, p_{corr} = .250, r = .30), and this did not change after excluding an outlier (3.11 *SD* above the mean) from the TD group (z = 2.01, p_{corr} = .135, r = .35). These findings suggest that children with rDCD have inferior auditory time perception for both duration and rhythm timing, compared to TD children.

Beyond these analyses, we would like to make a few notes. (a) Although ADHD has high comorbidity with DCD (Gomez & Sirigu, 2015) and also features time perception deficits (Noreika, Falter, & Rubia, 2013), we found that the pattern of results is preserved even if children with pADHD were excluded from the rDCD group (see Sup- porting Information). (b) Despite the significant group difference, six children with rDCD had rhythm discrimination thresholds below 60 ms, as low as those of TD children (indeed the distribution of rhythm discrimination thresholds in rDCD appears bimodal). (c) Although in the rDCD group there was a trend for larger pitch discrimination thresholds than in the TD group, it did not reach statistical significance, at least with the present sample size. Future studies with larger sample sizes are needed to investigate this question.

Event-Related Potentials (ERPs)

In the Electrophysiology Experiment (Figure 2a), three auditory oddball sessions (with deviants on duration, rhythm, or pitch, each with a 13% deviation rate) were presented to the participants with no response requirement. We investigated neural MMN and P3a ERP components in response to the deviants, recorded at frontal-midline channels, in the rDCD and TD groups. Again, the two groups did not differ significantly in age, IQ, or their performance on the WMI (Table S1). The ERP wave- forms, shown in Figure 2b, are similar to those of previous studies with timing deviations (Barry et al., 2014; Bruggemann et al., 2013; Cheour et al., 2000; Gumenyuk et al., 2005; Huttunen et al., 2007; Wetzel & Schroger, 2007), suggesting the design of the current study was valid.

For the duration oddball, two-sample *t*-tests (m = 4, Figure 2c) showed that the MMN latency was later in the rDCD group than in the TD group ($t(52)$ = 3.48, p_{corr} = .004, Cohen's d = 0.95); this effect size was larger than that from a previous study on

2-month-old infants at risk for specific language impairment (converted Cohen's *d*: 0.63; Friedrich, Weber, & Friederici, 2004). However, the P3a latency was not significantly different ($t(52) = 0.41$, $p_{corr} > .999$, Cohen's $d = 0.11$). In contrast, neither the amplitudes of MMN ($t(52) = 0.34$, $p_{corr} > .999$, Cohen's $d = 0.09$) nor P3a ($t(52) = 0.15$, $p_{corr} > .999$, Cohen's $d = 0.04$) were significantly different between groups.

For the rhythm oddball ($m = 4$, Figure 2c), the P3a latency was later in the rDCD group than that in the TD group ($t(52) = 2.60$, $p_{corr} = .048$, Cohen's $d = 0.71$), but the MMN latency was not significantly different ($t(52) = 1.09$, $p_{corr} > .999$, Cohen's $d = 0.30$). In contrast, neither the amplitudes of MMN ($t(52) = -1.00$, $p_{corr} > .999$, Cohen's $d = 0.27$)nor P3a ($t(52) = 0.91$, $p_{corr} > .999$, Cohen's $d = 0.25$) were significantly different between groups. Note that the bimodally distributed rhythm MMN latencies across participants in the rDCD group are the result of some participants having an early peak and others having a late peak rather than individuals having two negative peaks (see Figure S2 and *Bimodal peak latency distribution of rhythm MMN in the rDCD group* in Supporting Information). Nevertheless, for rhythm, only the P3a effect was significantly different between the rDCD and TD groups; the lack of a significant MMN effect for rhythm makes it difficult to draw conclusions about differences between groups related to preattentive stages of rhythm perception.

For the pitch oddball ($m = 4$, Figure 2c), significant group differences were not observed in any of the four measures: latency of MMN ($t(52) = -1.12$, $p_{corr} > .999$, Cohen's $d = 0.30$), latency of P3a ($t(52) = 0.64$, $p_{corr} > .999$, Cohen's $d = 0.17$), amplitude of MMN ($t(52) = -0.94$, $p_{corr} > .999$, Cohen's $d = 0.26$), or amplitude of P3a ($t(52) = 0.68$, $p_{corr} > .999$, Cohen's $d = 0.19$).

In sum, the ERP results showed that in rDCD both the latencies of duration MMN and rhythm P3a occurred later than in TD, indicative of inefficient neural perceptual processing. This pattern of ERP results did not change by excluding children with pADHD from the rDCD group (see Supporting Information). These neural findings, and the delayed ERP latencies in particular, are consistent with the impaired processing of auditory timing deviations observed in the Behavioral Experiment.

Discussion

The present study demonstrates the novel findings that children with rDCD have deficits in auditory time perception. The behavioral evidence showed that children with rDCD have significantly worse discrimination sensitivities for auditory duration and rhythm than TD children. The neural evidence showed that children with rDCD have delayed ERP latencies for timing deviations. Specifically, duration deviations elicited delayed MMN latencies, and rhythm deviations elicited delayed P3a latencies in children with rDCD. It should be noted that these time perception difficulties in children with rDCD were present regardless of whether the children had concurrent pADHD. Together, the current findings extend our basic understanding of DCD by suggesting that, in addition to motor deficits, auditory perceptual timing deficits appear to be core to the disorder as well.

The time perception abilities of children with DCD have rarely been investigated, despite extensive reporting on their motor and sensorimotor deficits. Studies on auditory-motor or visual-motor temporal synchronization, such as tapping with an auditory or visual metronome, have shown that children with DCD have lower temporal accuracy and greater temporal variance than TD children (de Castelnau et al., 2007; Roche et al., 2011, 2016; Whitall et al., 2006, 2008). However, it would be challenging for these studies to distinguish whether this inferior sensorimotor performance is due to poor time perception, motor skills, and/or sensorimotor synchronization, as successful sensorimotor performance requires efficient processing across all these stages. To the best of our knowledge, only three previous studies have investigated time perception in children with DCD or associated populations, but their findings with respect to perceptual deficits in DCD are inconclusive. One psychophysical study found that children aged 7 and 8 years who were labeled as clumsy were worse at discriminating tone duration than TD children (Lundy- Ekman et al., 1991), but, while suggestive, it is not known whether these children met the criteria for DCD as the grouping criteria they used were quite different from those used to identify DCD (Blank et al., 2011). Another study reported insignificant differences in sensitivity to rhythm timing between DCD and TD children aged 6–11 years (Roche et al., 2016). However, this null result should be treated with caution because the perceptual thresh- old estimation method used did not follow a typical adaptive psychophysical procedure (Treutwein, 1995). Finally, a third study found that children aged 6–12 years with both ADHD and DCD per- formed worse than TD children at discriminating auditory durations and perceiving the beat of music (Puyjarinet et al., 2017), but it is unclear whether DCD alone without ADHD was associated with these deficits. Therefore, the present study is novel in showing that children with DCD have auditory timing deficits.

The delayed MMN and P3a latencies following duration and rhythm deviations, respectively, suggest that the duration-based perceptual deficit is evident at a preattentive stage, whereas the rhythm-based perceptual deficit may manifest primarily at an attentive stage among children with DCD. MMN and P3a are both elicited by infrequent auditory deviants embedded in a sequence of identical stimuli. However, MMN reflects the early preattentive detection of rare deviant stimuli and is generated primarily in auditory cortex (Naananen et al., 2007), whereas P3a reflects later attention-capturing processes related to expectation violation of stimulus regularities and is mainly generated in the anterior cingulate cortex and frontal lobe (Polich, 2007). Increased latencies in both components are associated with inferior perceptual processing at each corresponding stage (Naananen et al., 2007; Polich, 2007). These findings are consistent with multiple previous studies showing that duration perception is associated with preattentive processing, including in children with dyslexia (e.g., Chladkova, Escudero, & Lipski, 2013; Chobert, Fran_cois, Habib, & Besson, 2012; Tse & Penney, 2006; but cf. Matthews & Meck, 2016). Regarding rhythm perception, it has been shown to have a strong association with attention (Large & Jones, 1999). Considerable evidence indicates that the temporal regularity of rhythmic input entrains and proactively deploys attention, which results in better perception and motor coordination (e.g., Chang, Bosnyak, & Trainor, 2018, 2019; Haegens & Zion Golumbic, 2018; Thaut, McIntosh, & Hoemberg, 2015). While most of the previous ERP studies on children with DCD focused on different domains of cognitive functions and examined different ERP components, similar delayed responses have been reported. For example, children with DCD have delayed P3 latencies in visuospatial attention tasks (Tsai, Wang, et al., 2012), again suggesting that attentional processing might be abnormal in DCD.

Interestingly, the scalp distribution of duration MMN appears to peak at frontal-midline for TD children but at central-right for children with rDCD. In addition to the auditory cortex as the primary generator of MMN, there are also contributions from frontal brain areas, including inferior frontal gyrus (Garrido, Kilner, Stephan, & Friston, 2009). It is possible that somewhat different brain networks are involved for processing duration deviation in children with rDCD and TD children. However, we were unable to reliably localize the sources of MMN as we did not have individual structural brain scans or precisely digitized coordinates of channel locations, requiring future studies to investigate differences in underlying brain net- works. Regardless, our additional analyses con- firmed that latency differences between our groups were not due to scalp distribution differences between the rDCD and TD populations (see Sup- porting Information and Figure S1).

DCD has high comorbidity with other develop- mental disorders that also feature deficits in time perception, including ADHD, dyslexia, and specific language impairment. ADHD and DCD are known to have comorbidity rates as high as 35%–50% in children at 10 years of age or older (Gomez & Sirigu, 2015). Converging evidence shows that children with ADHD have sensory and sensorimotor timing deficits involving auditory, visual, and other modalities (e.g., Noreika et al., 2013; Puyjarinet et al., 2017). Specific language impairment and reading disorders (e.g., dyslexia) have up to a 30% comorbidity with DCD (Gomez & Sirigu, 2015; King-Dowling, Missiuna, Rodriguez, Greenway, & Cairney, 2015). Children with dyslexia also have auditory timing deficits (Gooch et al., 2011; Goswami, 2011; Ladanyi, Persici, Fiveash, Tillmann, & Gordon, 2020), and MMN latency is delayed in response to duration deviations in children with dyslexia as well as in 2-month-old infants who are at risk for specific language impairment relative to healthy controls (Corbera, Escera, & Artigas, 2006; Friedrich et al., 2004). Together, these suggest that a common timing deficit might underlie all of these developmental disorders and relate to their high comorbidity (Falter & Noreika, 2014; Trainor et al., 2018), but further study with a systematic approach is needed to fully understand the role of time processing deficits in explaining comorbidity across developmental disorders (Dalla Bella, Farrugia, et al., 2017; Lense et al., under review).

Investigating perceptual timing deficits in DCD could potentially help understand the basis of the motor difficulties in this disorder. A popular hypothesis is that children with DCD have an internal modeling deficit, resulting in a reduced ability to utilize predictive motor control, so they cannot precisely anticipate the outcome of movements for rapid online correction (e.g., Adams et al., 2014). The deficits in auditory time perception might closely relate to this. The development of internal models is often dependent, at least initially, on sensory error feedback and parameters such as rate of learning depend on the precision of sensory feed- back (see Wolpert & Flanagan, 2016 for a review).

The current findings also provide novel develop- mental evidence on associations between motor function and auditory time perception. It is widely assumed that motor brain regions are involved, or even required, for processing auditory time (Morillon & Baillet, 2017; Patel & Iversen, 2014). Previous behavioral studies have shown that motor manipulation can have a short-term effect on auditory time perception, including improving perceptual sensitivity or changing a bistable percept (e.g., Butler & Trainor, 2015; Manning & Schutz, 2013; Monier et al., 2019; Phillips-Silver & Trainor, 2005, 2008). Neuroimaging studies have shown that motor brain regions such as SMA, cerebellum, and basal ganglia are involved when participants perform time perception tasks even without physically moving (Grahn, 2012; Merchant et al., 2013; Teki et al., 2011). Studies of patients with focal lesions or degenerative diseases, and studies using brain stimulation, have shown stronger or even causal evidence that these motor brain regions are necessary for time perception (e.g., Cope et al., 2014; Grube, Cooper, et al., 2010; Grube, Lee, et al., 2010). Our finding is consistent with the idea that motor functions are associated with auditory time perception, although no causality can be inferred. Nevertheless, the current cross-sectional findings suggest that longitudinal studies should be conducted in which causality could be investigated.

The connection between auditory and motor systems in the context of processing time in DCD has important clinical implications for both early identification and intervention. DCD is not typically diagnosed until the age of 3–5 years, due to the limitations of existing tools for assessing motor skills and the large variations in motor development in early childhood. This is not ideal as early identification enables early intervention. Our EEG measurements of time perception provide a potential early screening tool for identifying children with rDCD. EEG is a relatively easily accessible and child-friendly neuroimaging technique, capable of assessing neural processing of time perception in infancy (Brannon, Libertus, Meck, & Woldorff, 2008; Friedrich et al., 2004), even in the newborn period (Winkler, Haden, Ladinig, Sziller, & Honing, 2009). Although the current behavioral and neural measurements were not sensitive enough to fully separate the TD and rDCD groups, we believe it is worth investigating and optimizing auditory time perception measurements as potential early signs for DCD risk. Regarding interventions, the present results suggest that a program combining auditory and motor training may be more effective than motor interventions alone, considering that auditory signals could provide additional input via the auditory-motor brain network for coordinating motor functions. Indeed, auditory-rhythmic cueing has been observed to support motor rehabilitation in other conditions involving movement disorders (Fujioka et al., 2018; Whitall et al., 2000), including Parkinson's disease (Dalla Bella, Benoit, et al., 2017; Dotov et al., 2017), which also features deficits in auditory time perception (Grahn & Brett, 2009). One study reporting six cases showed that intervention using auditory rhythm can improve motor performance in children with DCD (Leemrijse, Meijer, Vermeer, Ader, & Diemel, 2000). Also, training on auditory time perception, without motor training, can improve the accuracy of, and reduce variability in, motor control (Meegan, Aslin, & Jacobs, 2000). Furthermore, knowing the particular auditory deficits of an individual child could enable individualized training (cf. Dalla Bella, Dotov, Bardy, & de Cock, 2018), an important feature given the heterogeneity of the DCD population. It would be worth- while to investigate whether motor skills in children with DCD might benefit from auditory timing cues.

Although the current study only investigated time perception in audition, we hypothesize that time perception deficits in children with DCD likely involve other sensory modalities (e.g., vision), given that studies in healthy adults show that engaging in visual time perception tasks activates motor net- works (e.g., Grahn, 2012), and children with ADHD also have deficits in visual time perception (Noreika et al., 2013).

The current study has some limitations. First, the sample size was relatively small as it is difficult to obtain large samples of children with rDCD, and thus the statistical power was limited. Nevertheless, the findings of this first study suggest promising directions for future studies. Second, this was a cross-sectional study, and thus the longitudinal developmental trajectory of auditory time perception and its interactions with motor development in children with DCD also remains for future work. Third, the behavioral and neural data were not con- currently measured, because (a) the motor system is engaged when children make responses, making it difficult to separate motor and auditory activities in EEG, and (b) many more trials are needed in EEG than in behavioral tasks in order to obtain the adequate signal-to-noise ratio for analysis. It would be challenging for children of this age to attend and make behavioral decisions on sufficient numbers of trials. However, future studies simultaneously measuring behavioral and neural activities would be beneficial to further revealing auditory-motor inter- actions for time. Fourth, it is possible that latent fac- tors, such as attention or multimodal processing, contributed to the observed group differences in auditory time processing. While the pitch control condition suggests that this is unlikely, further investigations are needed to address this question directly.

In conclusion, the current study shows that children as young as 6 years with motor difficulties (rDCD) have deficits in auditory time perception, including duration and rhythm-based timing, as reflected by both worse discrimination sensitivities and delayed neural activities (ERP latencies). These findings have significant implications for multiple disciplines, including extending basic neuroscientific understanding of auditory-motor interaction, characterizing DCD, and understanding the comorbidity between DCD and other developmental dis- orders. Clinically, the connection between auditory and motor systems suggested by the present study indicates that it is worth investigating whether auditory time perception could be used as an early sign for DCD, and that auditory-rhythmic cueing might be a useful addition to motor interventions for DCD.

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Appendix S1. Supporting Information.