Inferior Auditory Time Perception in Children With Motor Difficulties

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This is a postprint.
See the published version in Child Development, 2021

https://doi.org/10.1111/cdev.13537

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Running title: Time perception and motor difficulties

Abstract

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 non-motor 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 neural 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.

Keywords (up to 3): Developmental coordination disorder (DCD), Time perception, Event-related potential (ERP)

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). Behaviourally, 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 2 or 3 beats) (Phillips-Silver & Trainor, 2005, 2007, 2008). Auditory information also plays an important role in many essential motor behaviours. 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 behaviours, 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,

2010a; Grube, Lee, Griffiths, Barker, & Woodruff, 2010b; Ross, Iversen, & Balasubramaniam, 2018). However, most of these studies were based on healthy populations or adults with neurological disorders, and it remains unknown whether children with motor difficulties have inferior auditory time perception.

Perception for two types of temporal regularities are 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 non-isochrony 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 et al., 2017a; 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 ten 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 et al., 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 (1) motor brain regions involved in sequencing and timing are also typically recruited during time perception, and (2) 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 behavioural and neural measurements. In the Behavioural Experiment we used adaptive psychophysical 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 analyzed mismatch negativity (MMN) and P3a ERP responses to identify at which neural stage of processing 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.

Methods

Defining cases of rDCD and TD

Following the 2011 European Academy of Childhood 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 Edition (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 3 components: Manual Dexterity (e.g., posting coins, threading beads, drawing trails), Aiming & 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 percentile, assessed by the Kaufman Brief Intelligence Test 2nd Edition (KBIT-2) (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 Behavioural 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 1500 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 procedures and informed consent was obtained from parents.

In the Behavioural Experiment, we further excluded 5 TD participants and 9 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 Supplementary Materials: Details of Behavioural Experiment). Among the 47 remaining participants, 20 children met the criteria for rDCD (age: 6.88 ± 0.55 y, range 6.17-7.92 y; 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 CAD range), and 27 the criteria for TD (age: 6.68 ± 0.42 y, range 6.08-7.42 y; 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 CAD range). Furthermore, 5 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 (Centre for Disease Control and Prevention, 2015) (see Supplementary Materials 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 TD group (6.64 ± 0.42 y, range 6.00-7.42 y; 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 CAD), and 27 into the rDCD group (6.82 ± 0.50 y, range 6.25-7.92 y; 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 CAD). 4 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 Edition, 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 percentile 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 behavioural thresholds or ERP effects, suggesting that IQ is unlikely to be a confounding factor for our conclusions (see *Comparing age, working memory and IQ between groups* in *Supplementary Materials*).

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, Behavioural 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 Supplementary Materials). 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 complex 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.

Behavioural Experiment: measuring perceptual thresholds

Three behavioural 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 4 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 5 training trials, followed by 43 experimental trials intermixed with 5 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 4 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 Behavioural Experiment* in *Supplementary Materials*).

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 Supplementary Materials for more details.

In the duration discrimination test, each trial consisted of two tone-pairs (standard and target stimuli). The pairs were separated by 1120 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 ms and 500 ms in 15 ms step sizes. It began at 260 ms and changed in accordance with the UDTR algorithm. The target IOI was set at 250 ms for training and probe trials. We used an empty duration (onset-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 non-isochrony (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 1120 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 target sequence ranged between 335 and 500 ms, with a step size of 15 ms. It began at 335 ms and changed in accordance to 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.

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 1120 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 et al., 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 2 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 random IOIs ranging from 400 to 600 ms. The F0 was 500 Hz on standard trials, and 515 Hz on deviant trials. We did not make the tone interval of the pitch oddball session longer than the tones used in the other sessions, as we did for the Behavioural Experiment, because our pilot tests on TD children showed that the short 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 kΩ during recording.

Preprocessing

The EEG data was 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 was 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 averaged 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 μV were excluded. Across participants, 82.0 ± 10.0% of the total number of trials were included for ERP analyses. See Supplementary Materials 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 conducted 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, Leppänen, & 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, Lenroot, & Laurens, 2013; Cheour et al., 2000; Gumenyuk et al., 2005; Huttunen, Halonen, Kaartinen, & Lyytinen, 2007; Wetzel & Schröger, 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 & Schröger, 2007). For pitch ERPs, which appear to have later latencies than duration and rhythm ERPs, the window used for MMN was 150 to 300 ms and the window for P3a was 300 to 400 ms, consistent with previous studies of ERPs in children (Barry et al., 2014; Bruggemann, Stockill, Lenroot, & Laurens, 2013; Cheour et al., 2000; Gumenyuk et al., 2005; Huttunen et al., 2007; Wetzel & Schröger, 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 (2015b). 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

0.05. 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: $p < 0.002$; two-sample F-test for homogeneity of variance: $p < 0.022$). 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 Behavioural 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 (working memory index) (Table S1).

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Figure 1

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Mann-Whitney U-tests (number of comparisons: m = 3), the non-parametric alternative to two-sample t-tests, showed that the duration discrimination thresholds of the rDCD group were larger than those of the TD group ($z = 2.60$, $p_{corr} = 0.028$, $r = 0.45$). Rhythm discrimination thresholds were also larger in the rDCD than TD group ($z = 2.51$, $p_{corr} = 0.037$, $r = 0.43$). 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 et al., 2017). Pitch discrimination thresholds were not significantly different between the two groups ($z = 1.73$, $p_{corr} = 0.250$, $r = 0.30$), and this did not change after excluding an outlier (3.11 standard deviation above the mean) from the TD group ($z = 2.01$, $p_{corr} = 0.135$, $r = 0.35$). 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. (1) 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 Supplementary Materials). (2) 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). (3) 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 waveforms, 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 & Schröger, 2007), suggesting the design of the current study was valid.

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Figure 2

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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 ($t(52) = 3.48$, $p_{corr} = 0.004$, 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 ($t(52) = 0.41$, $p_{corr} > 0.999$, Cohen's $d = 0.11$). On the other hand, neither the amplitudes of MMN ($t(52) = 0.34$, $p_{corr} > 0.999$, Cohen's $d = 0.09$) nor P3a ($t(52) = 0.15$, $p_{corr} > 0.999$, 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 the TD group ($t(52) = 2.60$, $p_{corr} = 0.048$, Cohen's $d = 0.71$), but the MMN latency was not significantly different ($t(52) = 1.09$, $p_{corr} > 0.999$, Cohen's $d = 0.30$). On other hand, neither the amplitudes of MMN ($t(52) = -1.00$, $p_{corr} > 0.999$, Cohen's $d = 0.27$) nor P3a ($t(52) = 0.91$, $p_{corr} > 0.999$, 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 Supplementary 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 ($t(52) = -1.12$, $p_{corr} > 0.999$, Cohen's $d = 0.30$), latency of P3a ($t(52) = 0.64$, $p_{corr} > 0.999$, Cohen's $d = 0.17$), amplitude of MMN ($t(52) = -0.94$, $p_{corr} > 0.999$, Cohen's $d = 0.26$), or amplitude of P3a ($t(52) = 0.68$, $p_{corr} > 0.999$, 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 Supplementary Materials). These neural findings, and the delayed ERP latencies in particular, are consistent with the impaired processing of auditory timing deviations observed in the Behavioural Experiment.

Discussion

The present study demonstrates the novel findings that children with rDCD have deficits in auditory time perception. The behavioural 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 to 11 years (Roche et al., 2016). However, this null result should be treated with caution because the perceptual threshold estimation method used did not follow a typical adaptive psychophysical procedure (Treutwein, 1995). Finally, a third study found that children aged 6 to 12 years with both ADHD and DCD

performed worse than TD children at discriminating auditory durations and perceiving the beat of music (Puyjarinet, Bégel, Lopez, Dellacherie, & Dalla Bella, 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 (Näätänen 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 of processing (Näätänen 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., Chládková, Escudero & Lipski, 2013; Chobert, François, 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 et al., 2012b), 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 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 neural networks. Regardless, our additional analyses confirmed that latency differences between our groups were not due to scalp distribution differences between the rDCD and TD populations (See Supplementary Materials and Figure S1).

DCD has high comorbidity with other developmental 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, Snowling, & Hulme, 2011; Goswami, 2011; Ladányi, 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, Weber, & Friederici, 2004). Together, these suggest that a common timing deficit might underlie all of these developmental disorders and relate to their high co-morbidity (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 et al., 2017b; Lense, Ladányi, Rabinowitz, Trainor, & Gordon, 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 developmental 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 feedback (see Wolpert & Flanagan, 2016 for a review).

The current findings also provide novel developmental 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 behavioural studies have shown that motor manipulation can have a short-term effect on auditory time perception, including improving perceptual sensitivity or changing a bi-stable 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 et al., 2010a, 2010b). 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 to 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, Háden, Ladinig, Sziller, & Honing, 2009). Although the current behavioural 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 cuing 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 et al., 2017a; 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, Adèr, & 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). Further, 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 worthwhile 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 networks (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 behavioural and neural data were not concurrently measured, because (1) the motor system is engaged when children make responses, making it difficult to separate motor and auditory activities in EEG, and (2) many more trials are needed in EEG than in behavioural tasks in order to obtain the needed signal-to-noise ratio for EEG. It would be challenging for children of this age to attend and make behavioural decisions on sufficient numbers of trials. However, future studies simultaneously measuring behavioural and neural activities would be beneficial for further revealing auditory-motor interactions for time. Fourth, it is possible that latent factors, 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 disorders. 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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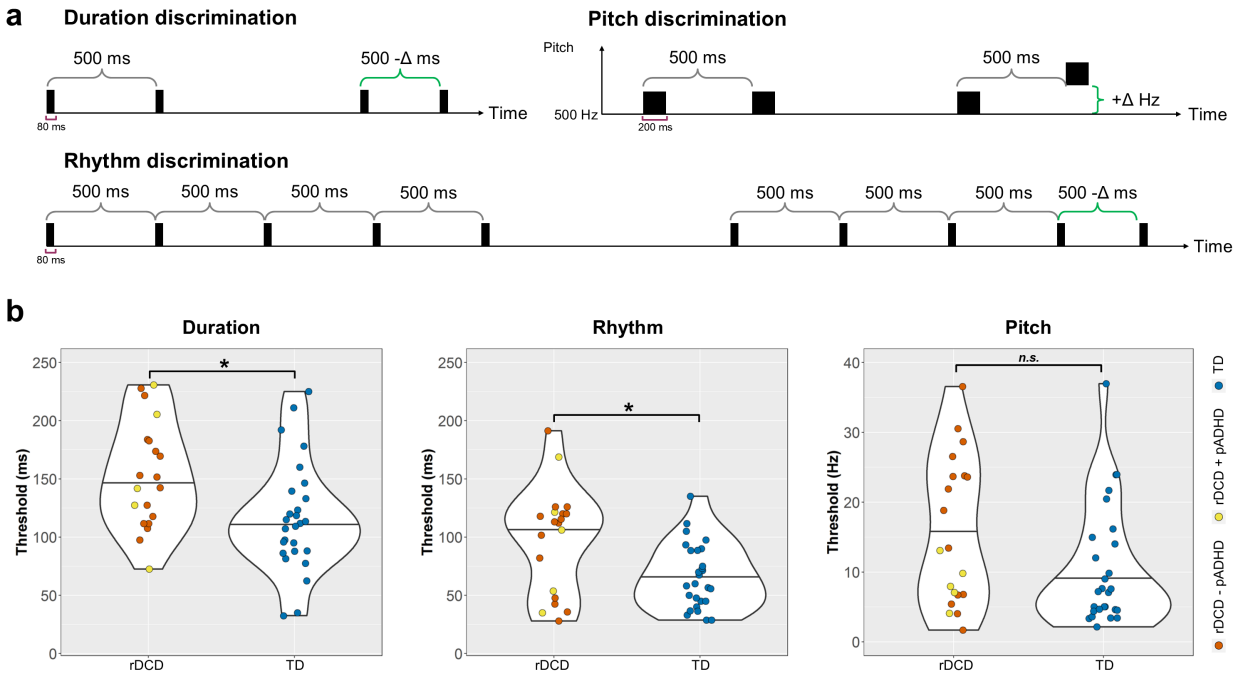

Figure 1. Perceptual discrimination thresholds in the Behavioural Experiment. (a) In the 2AFC experimental procedure, participants were requested to judge which of two stimuli was shorter (Duration), had an offbeat tone (Rhythm), or had two different tones (Pitch). The difference (Δ) represents the temporal or pitch difference between the standard and target stimuli. Δ varied from trial to trial according to the 2-up-1-down adaptive psychophysical procedure. This procedure converged at the Δ 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 rDCD group are further categorized into rDCD with pADHD (rDCD + pADHD) and rDCD without pADHD (rDCD - pADHD). *: $p_{corr} < 0.05$; n.s.: non-significant

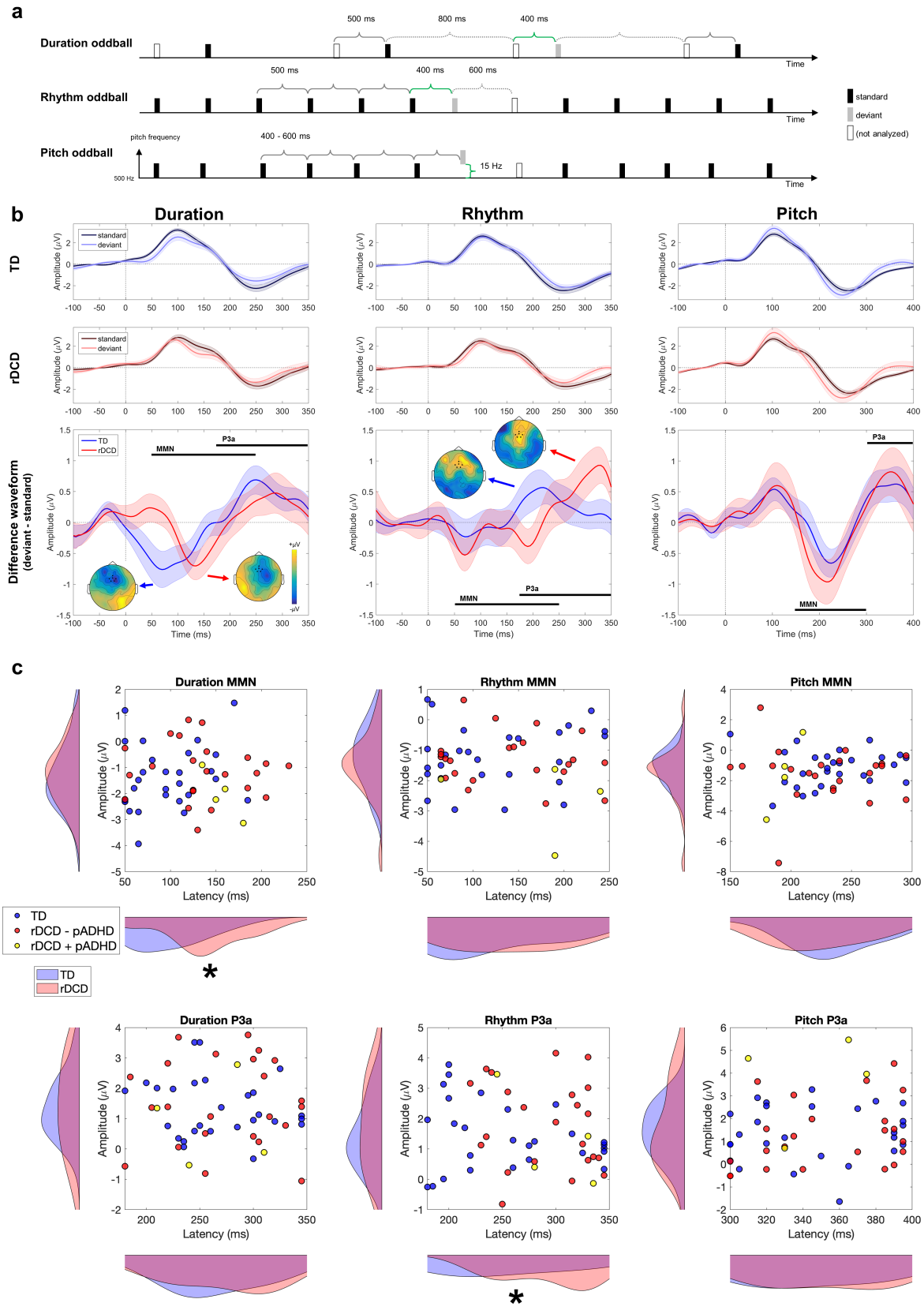
a
Duration oddball
500 ms
800 ms
400 ms
Time
Rhythm oddball
500 ms
400 ms
600 ms
Time
standard
deviant
(not analyzed)
Pitch oddball
pitch frequency
400 - 600 ms
500 Hz
15 Hz
Time
b
Duration
Rhythm
Pitch
TD
rDCD
Difference waveform (deviant - standard)
standard
deviant
TD
rDCD
MMN
P3a
Amplitude (μV)
Time (ms)
c
Duration MMN
Rhythm MMN
Pitch MMN
Duration P3a
Rhythm P3a
Pitch P3a
Latency (ms)
TD
rDCD - pADHD
rDCD + pADHD
TD
rDCD
*

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 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 TD or rDCD group was plotted on the margins of the scatter plot, and * represents $p_{corr} < 0.05$ on the indicated dimension. The subpopulation within the rDCD group (with pADHD or not) is further color-labeled on the scatter plots but not on the distribution plots.

DOI: 10.1111/cdev.13537 *Child Development*

Supplementary Information

Inferior auditory time perception in children with motor difficulties

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Motor coordination measurement

The Movement Assessment Battery for Children - 2nd Edition (MABC-2) (Henderson et al., 2007) was used as the standardized measure of motor coordination. The MABC-2 is an individually administered standardized test. Raw scores were converted into standard scores based on the child's age, and then converted into an overall percentile. Test-retest reliability and standard error of measurement for the total test scores are reported to be 0.80 and 1.34, respectively (Henderson et al., 2007). Thus, the MABC-2 is a reliable and valid tool for the assessment of movement difficulties, even in very young children (4 to 6 years of age) (Henderson et al., 2007). The MABC-2 data was collected as part of the CATCH study (Cairney et al., 2015, 2019), on average 4.02 ± 9.00 months prior to participating in the Behavioral Experiment, and 3.52 ± 8.61 months prior to participating in the Electrophysiology Experiment.

Intellectual ability measurement

The Kaufman Brief Intelligence Test - 2nd Edition (KBIT-2) was used to assess IQ (Kaufman & Kaufman, 2004). It is a standardized measure of intelligence that has been used in large studies to estimate children's cognitive ability. The KBIT-2 measures function in verbal and non-verbal domains and is a reliable measure that requires no reading or writing and is suitable for children 4 years of age and older. The KBIT-2 was conducted as part of the CATCH study, on average 18.55 ± 8.31 months prior to participating the Behavioral Experiment, and 18.15 ± 8.45 months prior to participating the Electrophysiology Experiment. Although the IQ measures were taken about 1.5 years prior to the auditory experiments, longitudinal studies suggest high stability of IQ from age 2.5-3.5 to age 6-8 (e.g., Yu et al., 2018).

Attention deficit hyperactivity disorder (ADHD) symptom checklist

An ADHD questionnaire, acquired from the Centers for Disease Control and Prevention (2015), was used to screen children for probable ADHD (pADHD) symptoms. This questionnaire follows the criteria of the American Psychiatric Association's Diagnostic and Statistical Manual, fifth edition (DSM-5), with modifications to increase accessibility to the general public. The questionnaire was completed by the parent and consists of two categories: Inattention and Hyperactivity/Impulsivity, with each category assessing 9 symptoms. When 6 or more symptoms were present, the child was identified as having pADHD. TD children who were identified as having pADHD were excluded, because poor time perception has been associated with ADHD (e.g., Noreika, Falter, & Rubia, 2013). However, the children with rDCD who were identified as having pADHD were included and categorized as the rDCD+pADHD subgroup, considering the high comorbidity between rDCD and ADHD (e.g., Gomez & Sirigu, 2015).

Digit span working memory index (WMI)

Working memory was assessed with the digit span subset of WMI from the Wechsler Intelligence Scale for Children 4th Edition (Wechsler, 2003). The WMI was used to ensure that any potential differences in perceptual performance between rDCD and TD children were not due to auditory working memory differences. Children were tested on forward and backward verbal recall of digit sequences. In the digits forward section, children repeated the digit sequence in the same order spoken by the experimenter. In the digits backward section, children repeated the digit sequence in the reverse order spoken by the experimenter. Digit sequences began with two digits, increasing by one digit every second trial. Testing ended when incorrect recall occurred for both digit sequences within a given span length. Children were given 1 point for every correctly recalled

digit sequence, and 0 points for incorrect recalls. The sum of points represented an individual child's WMI score.

Comparing age, working memory and IQ between groups

Group differences on behavioral performance and ERP responses might be confounded by other factors, such as age, WMI, and IQ. To examine this concern, we performed two-sample t-tests between TD children and children with rDCD, including analyses with and without children with pADHD. The results did not show any significant differences between groups (Table S1).

Although it was not statistically significant, there was a marginal difference in IQ between groups in the current study. Studies with large sample sizes (around 300 per group) reported that children with rDCD have significantly lower mean IQ than TD children (e.g., IQ 106.1 vs. 100.9, or percentile 65.6 vs. 52.4; Cairney et al., 2019). Nevertheless, whether IQ differs between groups was not the main interest of the current study, as long as IQ did not confound with the behavioral thresholds and ERP latency effects of the current study.

To post-hoc examine whether IQ was associated with behavioral thresholds and ERP latency effects, we used nonlinear Spearman correlations. The correlations within the TD group with IQ were: duration threshold ($r_s(25) = -0.28$, $p = 0.157$), rhythm threshold ($r_s(25) = -0.21$, $p = 0.302$), pitch threshold ($r_s(25) = -0.19$, $p = 0.352$), duration MMN latency ($r_s(25) = -0.07$, $p = 0.734$), and P3a latency ($r_s(25) = -0.40$, $p = 0.036$), uncorrected p-values. The correlations within the DCD group with IQ were: duration threshold ($r_s(18) = -0.13$, $p = 0.571$), rhythm threshold ($r_s(18) = -0.42$, $p = 0.065$), pitch threshold ($r_s(18) = 0.12$, $p = 0.606$), duration MMN latency ($r_s(25) = 0.08$, $p = 0.701$), and P3a latency ($r_s(25) = -0.17$, $p = 0.406$), uncorrected p-values. The correlations of the pooled groups with IQ were: duration threshold ($r_s(45) = -0.28$, $p = 0.058$),

rhythm threshold ($r_s(45) = -0.36$, $p = 0.014$), pitch threshold ($r_s(45) = -0.16$, $p = 0.275$), duration MMN latency ($r_s(52) = -0.08$, $p = 0.565$), and P3a latency ($r_s(52) = -0.31$, $p = 0.021$), uncorrected p-values. However, we argue that correlation is not the most appropriate approach here because (1) the correlations within each group are likely under-powered, due to small sample sizes. Also, (2) the correlational findings on pooled groups could be spurious, because the correlation can be the results of categorical differences between groups on both variables, instead of a genuine association across individuals ("Simpson's paradox", e.g., Blyth, 1972; Kievit et al., 2013). This is indeed a concern here, as the DCD and TD groups are significantly different in their timing-related measures (thresholds and ERP latencies) and there is a trend for a difference between their IQ scores. Also, the significant ($p < 0.05$, uncorrected) findings were not entirely consistent between correlations on pooled and separate groups. Therefore, we are not confident to interpret these correlational findings.

The linear mixed-effect model (LMEM) is a better approach here because it examines the association between variables (fixed effect) while taking the grouping factor (random effect) into account. Both random intercepts and random slopes were included in our LMEMs. Model fitting was implemented using the "lme4" package in R. The p-values were obtained by type-II Wald tests using the "Anova" function in the "car" package in R. The result did not show any significant associations between IQ and behavioral duration ($\beta = -0.49$, $\chi^2(1) = 2.26$, $p = 0.133$), rhythm ($\beta = -0.51$, $\chi^2(1) = 2.42$, $p = 0.119$) or pitch ($\beta = -0.02$, $\chi^2(1) = 0.04$, $p = 0.833$) thresholds. IQ also did not associate with duration MMN latency ($\beta = 0.01$, $\chi^2(1) = 0.00$, $p = 0.981$) or rhythm P3a latency ($\beta = -0.62$, $\chi^2(1) = 1.73$, $p = 0.189$), uncorrected p-values.

Together, these analyses suggest that the group differences on behavioral and ERP measures observed in the current study were unlikely to be confounded by age, working memory

or IQ. However, null results should be taken with caution as it is always possible that a study with a larger sample size might reveal small but significant effects. Future studies with higher statistical power and proper statistical approaches are needed to carefully readdress the contribution of these factors.

Table S1. Age, working memory, and IQ

Behavioral Experiment					
(mean ± SE)	TD (n = 27)	rDCD (n = 20)	rDCD-pADHD (n = 15)	TD vs. rDCD: t-value, p-value (df = 45)	TD vs. rDCD-pADHD: t-value, p-value (df = 40)
Age (year)	6.68 ± 0.08	6.88 ± 0.12	6.83 ± 0.15	-1.36, 0.180	-0.98, 0.334
WMI (digit span)	13.56 ± 0.39	13.35 ± 0.51	13.27 ± 0.43	0.32, 0.747	0.47, 0.643
IQ (percentile)	71.07 ± 4.07	58.75 ± 5.10	62.80 ± 5.75	1.91, 0.062	1.19, 0.240
Electrophysiology Experiment					
	TD (n = 27)	rDCD (n = 27)	rDCD-pADHD (n = 23)	TD vs. rDCD: t-value, p-value (df = 52)	TD vs. rDCD-pADHD: t-value, p-value (df = 48)
Age (year)	6.66 ± 0.08	6.82 ± 0.10	6.76 ± 0.11	-1.29, 0.201	-0.73, 0.471
WMI (digit span)	13.22 ± 0.44	12.26 ± 0.51	12.17 ± 0.52	1.43, 0.158	1.55, 0.127
IQ (percentile)	66.04 ± 4.22	56.63 ± 4.50	59.30 ± 4.82	1.52, 0.133	1.06, 0.296

Details of Behavioral Experiment

For each behavioral test, a two-alternative forced choice (2AFC) method was used as the task (Kingdom & Prins, 2010). The tests were presented as child-friendly games, where two clipart-style animals were presented on the screen, and each was paired to either the standard or target stimulus, counterbalanced across trials. Participants were requested to discriminate the target from the standard stimulus by responding on a touch screen as to which animal's paired sound had a certain test-specific property (e.g., shorter interval for the duration test). Response time was not recorded as it is difficult to instruct children to respond as fast as possible. Visual feedback was provided as either a green V-mark or a red X-mark after each correct or incorrect response, to motivate participants.

Across trials, we used an adaptive 2-up-1-down transformed-response (UDTR; Levitt, 1971) psychophysical procedure to estimate the perceptual threshold for each test. In this procedure, two successive correct responses increase task difficulty on the next trial (decreasing the difference between standard and target stimuli), and one incorrect response decreases task difficulty on the next trial. This procedure converges on the 70.7% discrimination threshold. The test ended once all 43 trials were completed and we estimated the threshold by averaging all reversal points.

Exclusion criteria based on participants' performances were: (1) Across the 3 tests, each participant must correctly answer at least 4 of the 5 probe trials of at least 2 tests. This criterion would exclude approximately 91% of the participants who were merely guessing. (2) Each participant must have more than 5 reversal points for each test. A small number of reversal points might result from non-convergence in the UDTR method, making the threshold estimation unreliable. Although our tasks did not have a stopping procedure after reaching a certain number

of reversal points (e.g., 5), which is typical in adaptive tasks, the exclusion criterion ensured that the robustness of threshold estimation was not compromised.

Details of ERP signal processing

Artifact Blocking (AB)

AB is an algorithm that corrects the artifacts (e.g., muscle movement) in EEG recordings, which is especially useful for EEG recordings in infants and children (Fujioka et al., 2011; Mourad et al., 2007). In the first step of AB, a reference matrix is constructed from the EEG data matrix by setting all the samples with absolute amplitude exceeding 100 μV to zero, which blocks all high-amplitude artifacts. In the second step of AB, a smoothing matrix is estimated from the EEG data and reference matrices. In the final step of AB, the cleaned EEG data matrix is obtained by multiplying the original EEG data and smoothing matrices. In short, the AB algorithm projects the reference matrix onto the range of the original EEG data matrix, and thus the cleaned EEG data matrix does not contain any high-amplitude artifacts. It is particularly useful for pediatric data as it enables a maximum number of trials to remain in the analysis.

Epoching

Epoching was done on the AB-cleaned EEG data. In the duration oddball session, the epoch -100 to 350 ms was extracted, time-locked to the onset of the second tone of each standard or deviant tone pair, which defined the duration of the interval. In the rhythm oddball session, the epoch -100 to 350 ms was extracted, time-locked to each standard or deviant tone. In the pitch oddball session, the epoch -100 to 400 ms was extracted (due to late P3a latency), time-locked to

the onset of each standard or deviant tone. The first standard trial following each deviant trial was not included in the analyses.

Because the IOIs between the tones in the duration and rhythm oddball sessions were relatively short and the time between the preceding tone and the tone of interest varied depending on whether it was a standard or deviant, it was necessary to remove the ERP waveform from the preceding tone that overlapped with the tones of interest. Thus, we estimated the waveform of the preceding tone for each participant, and then subtracted it from the trials of interest to remove the overlapping preceding ERP waveforms (e.g., Luck, 1998; Talsma & Woldorff, 2005). To estimate the waveform of the preceding tone it was necessary to measure the response to the tone when there was no closely following tone in order to get an accurate measure of the brain response to the tone alone. Specifically, for each participant, we took a time-window starting at the onset of the second tone of standard duration tone pairs that were followed by 900 ms of silence as the estimate of the waveform in response to the preceding tone. We then subtracted this estimate of the response to the preceding tone from the ERP waveforms on trials of interest, matching the preceding IOI. This approach was not used on the pitch ERP waveforms, as the IOIs varied randomly in the pitch oddball session, and thus the ERP waveforms from the preceding trials would tend to cancel out through the averaging process. Importantly, the resulting ERP waveforms in all conditions were similar to those reported in previous ERP studies with children (Barry et al., 2014; Bruggemann, Stockill, Lenroot, & Laurens, 2013; Cheour et al., 2000; Gumenyuk et al., 2005; Huttunen, Halonen, Kaartinen, & Lyytinen, 2007; Wetzel & Schröger, 2007), suggesting this procedure successfully reduced the influence of overlapping preceding ERP waveforms.

Perceptual thresholds after excluding pADHD

In order to understand whether the inferior perceptual duration and rhythm thresholds of the rDCD compared to TD group are due to comorbidity with ADHD (Gomez & Sirigu, 2015), which is associated with inferior time perception (Noreika et al., 2013), we performed the same statistical analyses of perceptual thresholds while excluding the data of children with pADHD (number of comparisons: m = 3). The rDCD group had larger duration discrimination (z = 2.45, p_{corr} = 0.042, r = 0.46) and larger rhythm discrimination (z = 2.44, p_{corr} = 0.044, r = 0.46) thresholds than the TD group, but the pitch discrimination threshold difference between two groups was not significant (z = 2.07, p_{corr} = 0.114, r = 0.39). Therefore, confirming our original findings, children with rDCD have inferior auditory time perception, including both duration timing and rhythm timing, compared to TD children, even after excluding the participants with pADHD.

ERP latencies after excluding pADHD

For the same reason as above, we excluded the data of children with pADHD and repeated the statistical analyses of MMN latency for duration oddball and P3a latency for rhythm (m = 2). In particular, for the duration oddball, the t-tests showed that the MMN latency was later in the rDCD group than the TD group (t(48) = 3.01, p_{corr} = 0.008, Cohen's d = 0.84). For the rhythm oddball, the t-tests showed that the P3a latency was later in the rDCD group than the TD group (t(48) = 2.38, p_{corr} = 0.043, Cohen's d = 0.68). Therefore, confirming our original findings, children with rDCD have delayed auditory ERP latencies, including for both duration timing and rhythm timing, compared to the TD children, even after excluding the participants with pADHD.

Duration MMN at central-right location

It can be observed from the topography that the negative voltage for duration MMN of the rDCD group was maximal at central-right locations, rather than at the typical frontal-midline locations (Figure 2b). It is possible that the latency difference we found on frontal-midline electrodes resulted from using a suboptimal location to measure MMN in the rDCD group. Therefore, additional analyses for duration MMN at central-right electrodes were performed to examine this possibility (m = 4).

The mean ERP waveform on the nine central-right electrodes is presented in Figure S1b and S1d (see Figure S3 for the complete EEG layout). The t-tests did not show any significant differences between TD and rDCD groups on the MMN amplitude ($t(52) = -2.20$, $p_{corr} = 0.128$, Cohen's $d = 0.60$) or latency ($t(52) = 1.54$, $p_{corr} = 0.516$, Cohen's $d = 0.42$). These non-significant results might be due to central-right channels being suboptimal electrodes for measuring MMN in TD children. We thus further tested whether the duration MMN measured from the electrodes with the largest MMN amplitude for each group was different between groups (Figure S1c and S1e). The results were the same as in the original analysis at frontal-midline electrodes: latency was larger for the rDCD group (measured from central-right electrodes) than the TD group (measured from the frontal-midline electrodes) ($t(52) = 3.77$, $p_{corr} = 0.002$, Cohen's $d = 1.03$), but the MMN amplitude was not different ($t(52) = -0.91$, $p_{corr} > 0.999$, Cohen's $d = 0.25$).

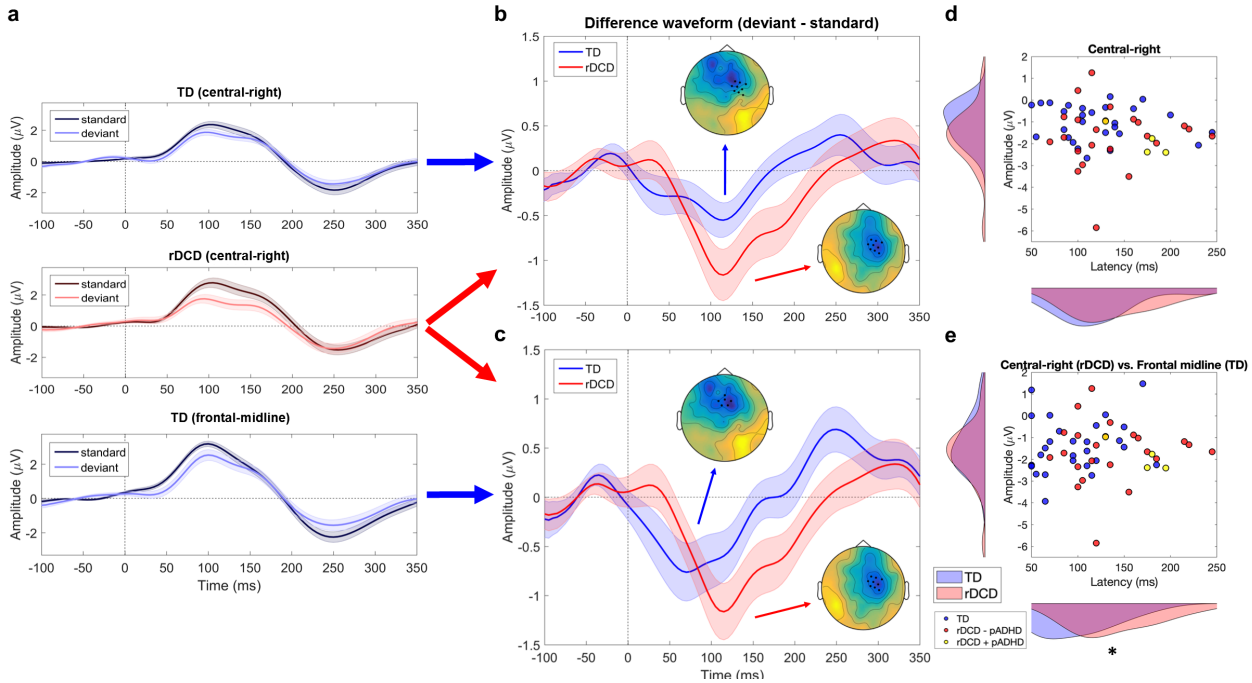

Figure S1. Mismatch negativity (MMN) of the duration oddball at central-right and frontal-midline electrodes. (a) The ERP waveforms at central-right and frontal-midline electrodes of TD and rDCD groups. The format is the same as Figure 2b. (b) The difference (deviant minus standard) ERP waveforms. Each inserted topography represents the group-averaged scalp distribution for each ERP component, and the dots on the inserted topographies mark the central-right electrodes used for extracting ERP waveforms. (c) Same format as (b), but the difference ERP waveform of TD group was extracted from frontal-midline electrodes. (d) The amplitude and latency distributions of MMN. The format is the same as Figure 2c. Each dot represents the ERP mean amplitude and peak latency of one participant. The distribution of amplitude or latency of each TD or rDCD (including both with and without pADHD) group was plotted on the margins of the scatter plot. No significant differences between TD and rDCD groups were found on either MMN amplitude or latency at central-right electrodes. (e) Same format as (d) but comparing the MMN amplitude and latency at frontal-midline electrodes for the TD group with central-right electrodes for the rDCD group. The MMN latency was later in the rDCD group (*: $p_{corr} < 0.05$), but the amplitude was not different between groups.

Bimodal peak latency distribution of rhythm MMN of the rDCD group

The group-averaged ERP plot of the rhythm MMN in the rDCD group appears to have two negative peaks, one around 75 ms and another one around 200 ms (Figure 2B). It was unclear whether many participants in the rDCD group had two negative ERP peaks, or whether the peak latency was early for some participants and late for the others. To examine this, we split the participants in the rDCD group into early and late subgroups according to a 120 ms cutoff applied

to their MMN peak latencies. Plotting the averaged ERP difference waveform for each subgroup (Figure S2) reveals that each subgroup only had one dominant negative peak, either before or after 120 ms. Therefore, it suggests that the peak latency was early for some participants and late for the others.

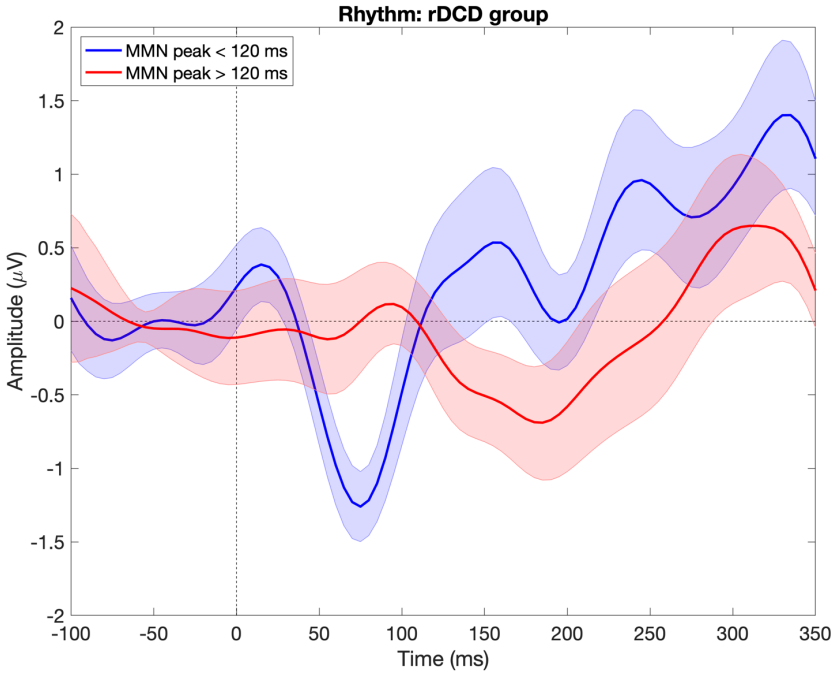

Figure S2. The averaged ERP difference waveforms (deviant minus standard) in the Rhythm condition for the rDCD group separated based on whether their MMN peak latencies were earlier (blue waveform) or later (red waveform) than 120 ms.

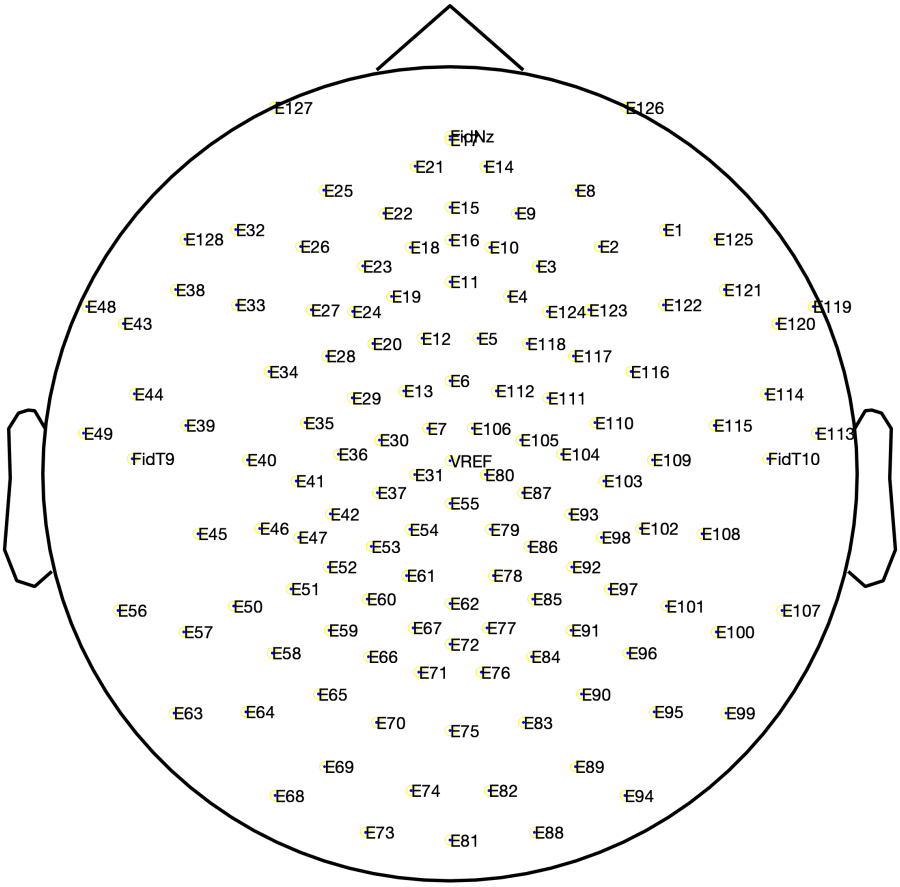

Figure S3. The layout of EEG channels. Electrodes 4, 5, 11, 12, 16, and 19 were selected as the frontal-midline channels, and electrodes 103, 104, 105, 110, 111, 112, 116, 117, and 118 were selected as the central-right channels.

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