ANNALS OF THE NEW YORK ACADEMY OF SCIENCES

Is auditory perceptual timing a core deficit of developmental coordination disorder?

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Time is an essential dimension for perceiving and processing auditory events, and for planning and producing motor behaviors. Developmental coordination disorder (DCD) is a neurodevelopmental disorder affecting 5–6% of children that is characterized by deficits in motor skills. Studies show that children with DCD have motor timing and sensorimotor timing deficits. We suggest that auditory perceptual timing deficits may also be core characteristics of DCD. This idea is consistent with evidence from several domains, (1) motor-related brain regions are often involved in auditory timing process; (2) DCD has high comorbidity with dyslexia and attention deficit hyperactivity, which are known to be associated with auditory timing deficits; (3) a few studies report deficits in auditory–motor timing among children with DCD; and (4) our preliminary behavioral and neuroimaging results show that children with DCD at age 6 and 7 have deficits in auditory time discrimination compared to typically developing children. We propose directions for investigating auditory perceptual timing processing in DCD that use various behavioral and neuroimaging approaches. From a clinical perspective, research findings can potentially benefit our understanding of the etiology of DCD, identify early biomarkers of DCD, and can be used to develop evidence-based interventions for DCD involving auditory–motor training.

Keywords: developmental coordination disorder (DCD); motor deficit; auditory–motor interaction; time perception; child development

Introduction to developmental coordination disorder

Developmental coordination disorder (DCD) is a chronic neurodevelopmental disorder that affects 5–6% of school-aged children. It is defined as significant fine and/or gross motor, dynamic, and static balance; postural control; and motor learning deficits that interfere with activities of daily living and self-care in the absence of intellectual impairment or otherwise identifiable physical disorder.[1] These so-called "clumsy" children have trouble with tasks from tying shoes to running and jumping to throwing and catching a ball. Coordination between limbs is also impaired, making bimanual tasks such as using pencils and scissors difficult.[2–4] Because their motor impairments affect their ability to interact socially with other children, and can have a direct negative impact on participation in active free play, sports, and everyday activities of life, DCD often leads to anxiety, depression, childhood obesity, decreased fitness levels, decreased self-esteem, poor academic performance, increased behavioral problems, and increased risk of further physical and mental health problems.[5–10] Furthermore, without intervention, the deficits continue into adulthood.[11–13] Of children diagnosed with DCD before starting school, the problems persist in 40% 10 years later.[14]

Compared to other developmental disorders such as autism, dyslexia, and attention deficit hyperactivity (ADHD), little basic or applied research has been done on DCD. Most current researchers in the field use the 2011 European Academy of Childhood Disability Guidelines,[15] which specify: (1) a score at or below the 16th percentile on a standardized measure of motor impairment (e.g., the Movement Assessment Battery for Children—Second Edition (MABC-2)[16]), (2) evidence of impact on daily function, (3) IQ score above 70, and (4) absence of any medical condition affecting motor functioning. Despite being recognized as a motor disorder in the category of neurodevelopmental disorders in the Diagnostic and Statistical Manual of Mental Disorders—Fifth Edition (DSM-V),[1] DCD is often undiagnosed. Given the prevalence of DCD and the associated psychiatric and cognitive outcomes if not treated, it is probable that the lack of diagnosis, lack of basic understanding of the condition, and lack of treatment availability result in a considerable cost to healthcare systems as well as affect the productive contribution of these individuals to society.

The motor difficulties are heterogeneous among individuals with DCD[17] and the etiology and neural basis of DCD remains unclear.[18,19] Recent functional magnetic resonance imaging (fMRI) studies suggest that children with DCD show different brain activation patterns compared to typically developing (TD) children, particularly in motor and attentional networks, although not all studies show consistent findings.[17,20,21] Deficits in motor timing and sensorimotor timing among individuals with DCD are consistent findings in the literature.[21] This suggests that deficits in perceptual timing are also likely a core characteristic of DCD, given that precise perceptual timing ability is prerequisite for controlling precise motor coordination.[22] In this regard, it is interesting that DCD also has high comorbidity with ADHD and dyslexia (e.g., see Refs. 20 and 23) because both have also been associated with auditory perceptual and sensorimotor timing deficits.[24–26] It is possible that these developmental disorders have high comorbidity because of a common or overlapping deficit in timing, whether it manifests primarily in motor control, attentional control, or perception/production of speech.[18]

The current paper evaluates the proposal that auditory perceptual timing is a core deficit of DCD. Rather than presenting an exhaustive review of timing in DCD, we focus on studies related to three modalities of timing (auditory perceptual timing, motor timing, and auditory–motor timing) across two timing types (duration timing, beat-based timing). Auditory perceptual timing is defined as the temporal dimension of auditory perception. Auditory perceptual timing tasks typically require participants to make a perceptual judgment without measuring the speed and/or the precision of participant's motor movements. Motor timing is defined as the ability to accurately coordinate and perform self-paced intra- or interlimb actions (e.g., finger tapping).[27,28] In the present paper, motor timing specifically refers to motor timing without external sensory temporal cues. Auditory–motor timing is defined as the precision of synchronizing motor movements to temporal cues in an auditory stimulus. Timing in other perceptual modalities (such as visual and tactile) or other sensorimotor domains (such as visual–motor) is considered only when relevant to timing issues covered in this paper. In an orthogonal dimension, timing can also be categorized into duration and beat-based (rhythmic) timing. Duration timing concerns the length of an interval that is isolated, discrete, and discontinuous. Beat-based timing concerns the temporal regularity of an event sequence that is repetitive and continuous. Table 1 gives examples of each type of timing for each modality.

Evidence for motor timing and sensorimotor synchronization deficits in DCD

Among the main characteristics of DCD are difficulties in motor learning, motor planning, adapting to change, automatization, sequencing of movements, use of feedback, timing, and anticipation.[18,22] These characteristics rely on timing, temporal prediction (anticipation), and being able to learn from timing errors. In sensory and perceptual processes, predictive timing (*when* an event will happen) and predictive coding (*what* the event will be) are critical for efficient sensory processing and sensorimotor responses, as processing load is greatly reduced if *what* will happen in the immediate future and *when* it will happen can be predicted and planned for.[29,30] Sensory predictions are formulated via extracting regularities from the preceding context (e.g., predicting the next beat from the preceding tempo of a music excerpt) or

Table 1. Examples of duration and beat-based timing for each modality: auditory perceptual, motor, and auditory–motor

	Timing type	
Timing modality	Duration	Beat-based (rhythm)
Auditory perceptual	The accuracy of judging whether one tone is longer than another tone	The accuracy of perceiving whether the tempo of an auditory sequence, such as a metronome, matches the beat of a simultaneous musical piece
Motor	The precision of timing needed to coordinate two or more actions to complete a discrete task, such as two hands simultaneously reaching and grasping a stationary object (note that there is no visual timing cue)	The precision of maintaining a consistent tempo of continuous movements, such as walking
Auditory–motor	The precision of pressing a button at a specific time interval after an auditory cue	The precision of moving along with the tempo of an external auditory sound sequence, such as tapping to a metronome

from memory. Additionally, neural feedback is generated when sensory predictions are incorrect and thus promotes learning and efficient online prediction updating. In the motor domain, prediction is also part of the internal modeling system for action that appears to be defective in DCD.[21,23,31–33] The internal modeling system includes inverse models that transform desired motor outcomes into motor commands to be executed and forward models that use efference copies of motor commands to predict future motor outcomes. Error correction arises from a comparison of the predicted outcome and the actual outcome once it occurs. The inverse and forward models act in concert to enable rapid online motor control. Predictions in sensory and motor domains work hand-in-hand for sensorimotor synchronization. Sensory prediction anticipatorily guides the inverse model for preparing a motor command (e.g., preparing to tap on the next beat of a music excerpt), and errors in both the forward motor models (e.g., tapping earlier than a beat) and sensory prediction (e.g., the predicted beat being later than the actual beat) are used to update both sensory and motor predictions online.

Evidence shows that internal models are not operating efficiently in DCD. For example, children with DCD were poorer than TD children at visually predicting the trajectory of and intercepting moving objects,[34–36] and less accurate in temporally synchronizing their eye tracking to moving objects,[37] suggesting difficulties in sensory predictive timing and online motor error correction. Furthermore,

they were poorer at making use of sensory priming cues when required to reach to grasp, whether the cues were static[38] or dynamic.[39]

There is considerable evidence for a visual–motor synchronization deficit in DCD. Studies show that children with DCD are impaired at finger tapping to a repeating (rhythmic) visual target, and that they show less stable bimanual coordination.[40,41] Following Kelso's dynamic pattern theory of coordination,[42] coordination between two effectors or between an effector and sensory stimulus show two stable states, namely in-phase (0°; e.g., two fingers tapping synchronously) and anti-phase (180° or syncopation; e.g., two fingers tapping on alternate beats).[43] Compared to TD children, those with DCD show more variability in general in their tap times both when tapping in-phase and anti-phase with a visual stimulus, but their deficit is particularly marked for anti-phase tapping and when required to tap to a rapid sequence of visual stimuli,[44] likely because anti-phase tapping has no event to synchronize with and thus requires extra mental effort to subdivide the time interval between events.[45] Further evidence for deficits in predictive timing comes from an fMRI study in which children pressed a button to synchronize with visual stimuli that occurred at regular (predictable) durations or irregular (unpredictable) durations.[22] TD children performed much better with predictable than nonpredictable durations, whereas children with DCD showed no difference. Furthermore, children with DCD reacted slower in general.

fMRI results indicated that TD children recruited right dorsolateral prefrontal cortex and right inferior frontal gyrus during unpredictable trials, but children with DCD did not,[22] suggesting difficulty changing strategy with task demands.

Are there auditory perceptual timing deficits in DCD?

Whether perceiving speech or music, events unfold over time. The auditory system is highly sensitive to time at both small (e.g., millisecond differences distinguish some speech sounds) and large (e.g., hierarchical beat patterns in speech and music) temporal intervals, and both the duration of individual sounds and the rhythm (beat) patterns of groups of sounds carry important information. Research suggests that auditory perceptual timing arises through interactions between neural circuits involving auditory and motor systems,[46–55] and simply listening to auditory rhythms activates the motor system even when there is no instruction to move.[48,51,56,57] Further evidence indicates that when adults hear an ambiguous rhythm (e.g., one that could be interpreted as a march if every second beat was accented, but as a waltz if every third beat was accented), movement on every second versus third beat will bias perceptual interpretation as a march or waltz, respectively,[58,59] even in infants.[60]

Given that DCD involves a motor timing deficit,[21] and given that time perception and prediction for auditory signals appears to involve auditory–motor synchronizations, we hypothesize that individuals with DCD will show auditory perceptual timing impairments. Only a few studies have investigated this topic in the auditory–motor domain: one reports that children with DCD are more variable than TD children in a continuation tapping task in which they tapped initially with an auditory beat and continued to tap once the beat was removed.[61] Another reports deficits in DCD in moving various effectors to an auditory metronome.[62] A few other studies report higher variance in bimanual tapping performance among children with DCD than TD children.[63–66] Although one study reported that auditory perceptual sensitivity for beat-based timing was not significantly different between TD and DCD groups,[64] their adaptive psychophysical measurement of perceptual sensitivity was prob-

lematic,[a] so this null finding should be treated with caution. Finally, one study reported that children with ADHD and DCD have deficits in tapping along to the beat of music, and in extracting the beat from complex temporal structures (i.e., music).[67]

However, the deficits in auditory–motor synchrony performance could result from an auditory perceptual timing deficit, a motor timing deficit, and/or an auditory–motor synchronization timing deficit. It is thus unclear whether auditory perceptual timing deficits are part of the DCD syndrome. To the best of our knowledge, there is only one perceptual auditory timing study, which found that "clumsy" children are inferior to TD children in discriminating auditory tone duration.[68] Although these "clumsy" children do not necessarily meet the criteria for DCD, this study supports the possibility that children with DCD have auditory perceptual timing deficits.

Many developmental disorders involve auditory perceptual, motor, and/or auditory–motor timing deficits, including dyslexia, autism, ADHD, and stuttering,[22,24–26,62,67] and DCD has high comorbidity with them.[20,23] Most research studies attempt to isolate pure cases of each disorder, but the comorbidity likely speaks to critical shared aspects of brain dysfunction that lead to the multiple observable behavioral deficits.[20,23] If DCD is indeed associated with a deficit in auditory perceptual timing, auditory timing training might be a useful strategy that could contribute to improve the motor performances of children with DCD.

Directions for investigating auditory timing processing in DCD

To understand potential auditory timing deficits in DCD, it is important to consider both duration timing and rhythm or beat-based timing. Duration

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[a]The study of Roche *et al.*[64] used an adaptive procedure to track participants' auditory beat-based perceptual timing sensitivity: the trial difficulty increased after a participant made one correct same/different judgment, and the difficulty decreased after one error. The sensitivity threshold was estimated at the point at which participants make three errors. However, the threshold should be estimated by averaging the peaks and troughs of the development of difficulty levels across trials.[97] Therefore, it is not clear how to interpret the nonsignificant perceptual difference reported by Roche *et al.*[64]

timing perception is one of the most commonly investigated aspects of time perception and is usually measured in terms of discrimination of filled intervals (onset to offset of a sound) or unfilled intervals (silent time between two short marker sounds). Research suggests that subsecond intervals are primarily processed by subcortical networks including basal ganglia and cerebellum, while intervals longer than a second are primarily processed by cortical areas, such as supplementary motor area and prefrontal cortex.[55] Functionally, compared to processing subsecond intervals, processing suprasecond intervals relies on other cognitive functions, such as working memory, attention, and cognitive control.[26] A full understanding of timing in DCD therefore needs to consider cognitive factors in addition to perceptual factors, and how they interact, especially because there are reports of deficits in DCD for some of these functions.[21]

Rhythm refers to a pattern of time intervals (onset-to-onset times of sounds) in a stimulus sequence. From a rhythm pattern with some regularity, people are able to extract a beat, which is the underlying regular pulse (what you would clap your hands to) on which sound event onsets in the rhythm are placed.[69] A beat can be heard for tempos from about 200 to 2000 ms onset-to-onset,[70] with the optimal range being around 300–800 milliseconds.[71] Furthermore, different beat tempos can often be perceived for a given rhythm pattern, forming an interrelated hierarchy of beat levels.

Many movements (e.g., walking, talking) and auditory communication signals (e.g., speech, music) are also rhythmically organized, with beats occurring at regular or quasi-regular time intervals. In speech, for example, this roughly corresponds to the alternate opening and closing of the jaw for production of vowels and consonants. Important events most often occur at beat onsets, so temporal regularity enables prediction of when important events are likely to happen in speech and music and action sequences.[72] This is highly useful for planning motor movements or focusing attention to important points in an auditory stream of speech or musical sounds (e.g., see Refs. 46, 50, and 73).

Various tasks have been employed to investigate auditory perceptual beat-based timing.[74] In anisochrony detection tasks, the participant detects if the timing in a sequence of tones deviates from isochrony.[49] In beat alignment tasks (e.g., BAT[75,76] and complex BAT[77]) the participant is asked whether the tones in a click track superimposed on a musical piece are on the beats of the music, whether the tempo of the click track is too fast or too slow, and/or whether the click track is phase aligned with the beats of the music. To distinguish duration and beat-based timing, one approach is to have participants compare the duration of two successive unfilled intervals as a function of the preceding context which is either anisochronous (where the task relies on encoding the absolute duration of intervals) or isochronous (where the regular beat provides an extra cue).[54] While duration timing tasks are typically perceptual, beat-based tasks can be perceptual (as just described) or involve sensorimotor synchronization, where the participant needs to produce a motor act, such as tapping or clapping, in time to a stimulus such as a metronome sequence or a piece of music.[74]

Evidence suggests that auditory perceptual timing and motor timing share a common brain network within each of duration and beat-based timing types. Duration and beat-based timing serve somewhat different functions. In auditory perceptual timing, different motor-related brain networks appear to be activated during auditory beat compared to duration perception. Specifically, there is evidence that the olivocerebellar network is activated during duration perception, whereas the striato–thalamo–cortical network is activated during rhythm perception[49,54] (although a couple recent studies suggest the anatomical division into duration and beat-based timing is not so clearcut[78,79]). For example, patients with cerebellar lesions or degeneration have deficits in performing discontinuous but not continuous movement,[80] and they also have deficits in perceiving auditory duration timing but not beat-based timing,[49] supporting the idea that the timing system in the brain is separated according to the type of timing across perceptual or motor modalities. These different types of timing are also reflected in individual differences across children with DCD. One study reported that, compared to TD children, some children with DCD were worse in continuous drawing while others were worse in discontinuous drawing, suggesting that DCD is heterogeneous.[81] A complete characterization of DCD requires investigation of perceptual, motor, and sensorimotor

modalities in both duration and beat-based timing. It is possible that DCD subgroups might exist that show different patterns of impairments across these different aspects of timing.

Beyond behavioral measurements, neuroimaging techniques can contribute to our understanding of the brain mechanisms underlying perceptual and motor timing. To date, only a few studies have applied neuroimaging techniques to children with DCD, and most of them have focused on the neural substrates of motor difficulties.[17,20] However, fMRI studies (e.g., see Refs. 56 and 57) and magnetoencephalography (MEG) studies (e.g., see Refs. 47 and 48) of typical adults suggest that motor-related brain regions are involved in auditory time perception. Therefore, it would be informative to examine in children with DCD how auditory time processing activates motor brain regions that may be compromised in DCD, and how such brain activation patterns relate to the behavioral performance of these children. While fMRI can contribute to understanding the particular brain regions compromised in DCD, EEG (electroencephalography) and MEG can reveal brain activity associated with time perception with high temporal resolution. The event-related potential (ERP) derived from EEG/MEG responses to sound events is a useful dependent measurement. In a typical oddball paradigm, if the presentation of a sequence of repetitive stimuli is infrequently altered by the presentation of a deviant stimulus (such as a change in tone duration or an early/delayed tone in an isochronous sequence), the mismatch negativity (MMN) and the P3-family ERP components will reflect whether the deviant stimulus is encoded in preattentive and attentive stages, respectively (e.g., see Refs. 82–84). Neural oscillatory entrainment activities can also be extracted from EEG/MEG recordings. Neural entrainment has been proposed as the neural instantiation of rhythm perception and time tracking (e.g., see Refs. 46–48, 73, and 85). In particular, EEG is an appropriate neuroimaging technique for infant and children participants because it has higher tolerance for movement artifacts than fMRI and MEG.[86] EEG has been widely applied to investigate time perception in TD children and children with developmental disorders (e.g., see Refs. 87–90).

We have begun to examine auditory timing in a population of children with DCD, who perform lower than the 16th percentile on the MABC-

2.[16] This preliminary study from our laboratory showed that children with DCD at age 6 and 7 perform considerably worse in auditory duration and rhythm discrimination than TD children. Furthermore, using an oddball ERP paradigm, we found that the peak of the MMN component was later in children with DCD than in TD children, indicating inferior perceptual discrimination abilities.[82] Interestingly, we found that the performance of children on the rhythm discrimination task formed two subgroups: about 75% of the children showed a substantial deficit while the rest were indistinguishable from the TD children. Pitch perception (a control task) was not different between children with DCD and TD children. These preliminary results support the idea that there are auditory perceptual timing deficits in DCD.

Clinical implications

Uncovering the nature of the timing deficits in DCD can contribute to both understanding the etiology of DCD and earlier diagnosis. DCD has high comorbidity with ADHD and dyslexia, which are known to involve deficits in auditory perceptual timing. Therefore, understanding the potential auditory perceptual timing deficit in DCD will help understanding of the shared etiology and neural basis of these developmental disorders. As for diagnosis, the commonly used MABC-2 cannot be used prior to age 3 years, and DCD is usually not identified until children go to kindergarten around age 5 years,[15] where their motor difficulties become obvious in comparison to their TD peers. This is not ideal because early identification of a developmental disorder allows early intervention, which likely has more benefit than starting intervention later in life. In particular, EEG measures of time processing could be developed as a screening tool for identifying children at risk for DCD in infancy. EEG is inexpensive, easily accessible, does not require intentional movement control, and timing deviations in rhythmic tone sequences are evident in EEG recordings as early as the newborn period.[90]

Once we understand perceptual and motor timing deficits in DCD, and how they vary across different subtypes, the knowledge can be applied to developing therapeutic interventions. Parkinson's patients can show marked improvements in walking in the presence of an auditory metronome,[91] and speech processing can improve in dyslexic

children following an auditory rhythmic priming stimulus,[92,93] presumably because auditory signals activate motor areas. Audition is a favored perceptual modality for rhythmic-cueing of motor control because rhythm perception is more common in the auditory than visual domain,[94] and people are much more likely to synchronize movements to auditory than to visual rhythms.[45] We hypothesize that motor control in children with DCD would benefit from the addition of rhythmic auditory cues. Indeed one study reports six single case studies that suggest rhythmic training might be a useful intervention.[95]

More broadly, the early diagnosis and interventions approaches proposed here might be applied to other developmental disorders (e.g., ADHD, dyslexia, and autism) associated with timing deficits, and the interventions could be individually designed to accommodate the specific timing deficits of each child. A similar approach has been successfully applied on Parkinson's patients.[96]

Conclusions

We propose that auditory perceptual timing deficits might be a core symptom of DCD. Previous research has shown evidence for motor timing deficits and sensorimotor timing deficits in DCD. We speculate that auditory perceptual timing deficits are also central to DCD. This idea is consistent with the high comorbidity between DCD and dyslexia and ADHD, which are known to have auditory perceptual timing deficits. Indeed, our preliminary behavioral and neuroimaging results support the idea that children with DCD at ages 6 and 7 have deficits in auditory perceptual timing discrimination compared to TD children. Uncovering the nature of the timing deficits in DCD will extend our understanding of its etiology and neural basis. From a practical perspective, auditory perceptual timing deficits may be an early marker of DCD, and evidence-based interventions involving auditory perceptual and auditory–motor training may improve current interventions.

Acknowledgments

Competing interests

The authors declare no competing interests.

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