SYNCHRONIZING MOVEMENT IN DANCE

SYNCHRONIZING MOVEMENT: FROM DISORDERS TO EXPERTISE

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Lay Abstract

Moving in time with others is a skill we use every day, whether clapping along at a concert or walking in step with a friend. This ability, called movement synchrony, is important for social bonding, development, and performance. My thesis explores movement synchrony across two very different groups: children with motor coordination difficulties and expert dancers. In children at risk for developmental coordination disorder, I show that difficulties in synchronizing movements with music are linked to broader motor challenges, but that rhythmic cues can improve their performance, highlighting the potential for dance-based interventions. In professional dancers, I show that precise synchrony with others strongly impacts how performances are judged, and that individual timing skills predict success in group coordination. By studying synchrony from disorders to expertise, this research reveals the importance of moving in time with music and with others.

Abstract

Auditory-motor and interpersonal synchrony are core human abilities that support both everyday activities and artistic performance. This dissertation investigated synchrony across two ends of a spectrum: children at risk for developmental coordination disorder (DCD), where auditory-motor synchrony is challenged, and expert dancers, where interpersonal synchrony is refined through extensive training. In Chapters 2 and 3, I examined children with and without risk for DCD. Using both a simple tapping task and a full-body step-clap task, I showed that children at risk for DCD exhibited impairments in auditory timing perception and in synchronizing movements to auditory stimuli. Importantly, their performance improved when provided with rhythmic cues, suggesting that auditory rhythms may provide a valuable framework for motor interventions. Chapters 4 and 5 turned to expert hip hop dancers. Motion capture analysis of live competition performances demonstrated that interpersonal synchrony was a significant predictor of judges' and audiences' evaluations, highlighting its role in dance expertise. Individual differences in auditory-motor synchronization and timing perception were then found to predict dancers' ability to synchronize movements with others in performance. Together, these studies provide new insights into the important role movement synchrony plays across contexts of developmental impairment and expert performance. The findings demonstrate that synchrony difficulties in DCD extend beyond motor deficits to include auditory timing and auditory-motor synchronization deficits, and highlight the potential of intervention with rhythmic auditory cueing. Conversely, in expert dancers, interpersonal synchrony is both a determinant of performance quality and associated with basic auditory-motor skills. By bridging experimental tasks with ecologically valid settings, this dissertation advances understanding of how the ability to move in synchrony shapes development, motor skills, and artistic expression.

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List of All Abbreviations and Symbols

2AFC: Two-Alternative Forced Choice

ADHD: Attention-Deficit/Hyperactivity Disorder

ANOVA: Analysis of Variance

ASD: Autism Spectrum Disorder

CI: Confidence Interval

CP: Cerebral Palsy

CPRS-R: Conners' Parent Rating Scale Revised - Short Version

CR(t): Compression Ratio as a function of time

CV: Coefficient of Variation

d: Cohen's d

DCD: Developmental Coordination Disorder

DCDQ: Developmental Coordination Disorder Questionnaire

DSM-V: Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition

EEG: Electroencephalography

F: F-Statistic

fMRI: Functional Magnetic Resonance Imaging

GLMM: Generalized Linear Mixed Model

HH: Hip Hop Dancers (audience subgroup)

Hz: Hertz

ICC: Intraclass Correlation Coefficient

IOI: Inter-Onset Interval

KBIT-2: Kaufman Brief Intelligence Test – 2nd Edition

M: Mean

MABC-2: Movement Assessment Battery for Children – 2nd Edition

Min: Minutes

MREB: McMaster Research Ethics Board

ms: Milliseconds

n: Sample Size

ND: Non-Dancers (audience subgroup)

NH: Non-Hip Hop dancers (audience subgroup)

p_{bonf}: Bonferroni-corrected p-value

p_{corr}: p-value corrected for multiple comparisons

R: Mean vector length in circular statistics (represents consistency)

RAS: Rhythmic Auditory Stimulation

rDCD: At Risk for Developmental Coordination Disorder

RMS: Root Mean Square

s: Seconds

SD: Standard Deviation

SE: Standard Error

SES: Socioeconomic Status

SPL: Sound Pressure Level

t: t-statistic

TD: Typically Developing

W: Mann-Whitney U statistic

X^2: Chi-square statistic

β: Regression Coefficient (Beta)

η^2: Eta-squared

π: Pi

χ^2: Chi-squared

Declaration of Academic Achievement

I, Chantal Carrillo, declare that this thesis titled "Synchronizing Movement: From Disorders to Expertise" and the work presented in it are my own. The following thesis contains six chapters in the format of a sandwich thesis. The first chapter is a general introduction, followed by four data chapters. Two of the data chapters are published articles, one data chapter is under review for publication, and one data chapter will be submitted later this year. The sixth and final chapter is a general discussion of the main findings of the thesis. I am the primary author of all four data chapters. In each data chapter, I conceptualized the research with supervision from Dr. Laurel Trainor, led the study designs and data collection with help from Elaine Whiskin, Susan Marsh-Rollo, and many undergraduate students, completed all the data preparation and analyses, and wrote the manuscripts. Dr. Laurel Trainor is the last author on all the published and submitted manuscripts, as she supervised and provided funding for the research, and contributed to the preparation of the manuscripts. Dave Thompson provided technical support for Chapter 2. In Chapter 2, Dr. Andrew Chang, Hannah Armstrong, and Dr. Devin McAuley are all coauthors as they worked on the conceptualization of the research, the data collection, and the methodology. Dr. John Cairney is also a coauthor for Chapter 2 for his collaboration in collecting our participants. Dr. Dobromir Dotov is coauthor on the manuscript for Chapter 3, as he contributed to our motion tracking analysis. Susan Marsh-Rollo is a coauthor on the manuscript for Chapter 4 for her work on designing the study and collecting the data.

Chapter 2 is a published article in *Scientific Reports*.

Carrillo, C., Chang, A., Armstrong, H., Cairney, J., McAuley, J. D., & Trainor, L. J. (2024). Auditory rhythm facilitates perception and action in children at risk for developmental coordination disorder. *Scientific Reports*, *14*(1), 12203. https://doi.org/10.1038/s41598-024-62322-6

Chapter 3 is a published article in *Human Movement Science*.

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Chapter 4 is an article under review in *Scientific Reports*. A preprint is available on *Research Square*.

Carrillo, C., Marsh-Rollo, S., & Trainor, L. J. (2025). The role of synchrony in expert hip hop dance competitions. *Research Square*. Manuscript Under Review. https://doi.org/10.21203/rs.3.rs-7521603/v1

Chapter 1: General Introduction

Introduction

Moving in synchrony is a crucial aspect of everyday life, whether it be coordinating movements with others or coordinating movements to music through dance. The ability to synchronize movements, defined as the temporal alignment of movements with an external stimulus, is a complex process involving both spatial and temporal dimensions (Cross et al., 2024). From walking in step with a friend to clapping along with a crowd, moving together helps facilitate social connection, cooperation, and a sense of belonging (Anshel & Kipper, 1988; Hove & Risen, 2009; Reddish et al., 2013; Stupacher et al., 2022; Wiltermuth & Heath, 2009). This thesis aims to understand movement synchrony in a range of different contexts, from supporting children with motor difficulties to optimizing performance in the skilled domain of dance.

To better understand how synchrony shapes human interaction, it is useful to distinguish between two forms: auditory-motor synchrony, in which movements are aligned with an auditory stimulus, and interpersonal synchrony, in which movements are coordinated with those of other people. Both emerge early in life and remain crucial throughout adulthood, as seen in their relevance for skills such as social connection (e.g. Tarr et al., 2018), motor development (Monier & Droit-Volet, 2019), and language (Tierney & Kraus, 2014). Yet, the ability to synchronize movements varies widely both across and within populations. Neurodevelopmental disorders such as developmental coordination disorder (DCD), dyslexia, and developmental language disorder are all associated with impairments in auditory timing and movement synchrony, which can cascade into challenges in language, motor skills, and social interaction (e.g. Lense et al., 2021). At the other extreme, expert performers such as professional dancers refine synchrony to high levels, where precise alignment of movements with music and with one another becomes central to aesthetic impact and performance evaluation.

While movement synchrony occurs in many daily contexts, music and dance can provide especially rich and structured environments in which to study these processes. Dance activities naturally require coordinated movement, in both individual and group settings, and are at the same time intrinsically motivating for children and adults (Kragness et al., 2022; Salimpoor et al., 2011, 2011). The inclusion of music provides a clear rhythmic structure and engages movement from an early age (Cameron et al., 2023; Kirschner & Tomasello, 2009; Kragness et al., 2022; Mcauley et al., 2006). Dance, in turn, integrates auditory-motor and interpersonal synchrony, requiring performers to coordinate with both external rhythms and fellow dancers. This dual demand makes dance uniquely well suited for investigating movement synchrony in both children with neurodevelopmental disorders as well as expert dancers. This thesis therefore takes a broad approach to understanding the role movement synchrony plays in daily life, examining synchrony where it is most challenged and where it is most refined.

I begin this research by investigating movement synchrony in a population of children at risk for DCD in Chapters 2 and 3 with a focus on three main questions. First, do children with DCD show impairments in auditory-motor synchronization as measured by tapping to an auditory beat? Second, does their tapping performance improve with the presence of an auditory beat? Third, do these auditory-motor synchronization impairments in DCD extend to complex gross-motor movements? I then focus my research on an investigation of movement synchrony in a population of expert dancers in Chapters 4 and 5, with two main additional research questions. First, how important is interpersonal synchrony in the evaluation of expert hip hop dancers' performance in a competition setting? Second, how does the ability to synchronize movements with others relate to the basic auditory-motor timing skills that are impaired in children with DCD? My results provide evidence that synchrony is critically important for both motor skill development in children with DCD and in the expertise of experienced dancers.

Distinguishing Types of Movement Synchrony

Movement synchronization can be broadly divided into two related but distinct forms: auditory-motor synchronization and interpersonal synchronization. Both forms of synchrony involved the temporal coordination of movement, but they differ in whether movements are aligned with an external auditory stimulus or with the actions of another person.

Auditory-motor synchronization refers to the ability to align movements with an auditory rhythm, such as clapping or dancing in time with music. This is of particular interest, as growing evidence shows that auditory and motor brain areas are intricately connected, and that these connections are especially important for rhythm and timing (Cannon & Patel, 2021; Patel & Iversen, 2014). Motor synchronization has also been shown to be more precise with auditory stimuli than with visual stimuli (Comstock et al., 2018). Both the perception and production of speech and music involve coordination between auditory and motor systems. A large body of evidence shows that the perceptual processing of rhythmic regularity in speech (e.g., Fiveash et al., 2021; Grisoni & Pulvermüller, 2022; Poeppel & Assaneo, 2020; Schomers & Pulvermüller, 2016; Wu et al., 2014) and music (e.g., Cannon & Patel, 2021; Fujioka et al., 2012; Grahn & Brett, 2007; Lima et al., 2016; Morillon & Baillet, 2017; Nozaradan et al., 2015; Patel & Iversen, 2014) involves neural networks spanning auditory and motor cortical regions, even in the absence of overt motor movement. Auditory-motor synchronization requires successfully predicting the timing of upcoming events in an auditory stimulus in order to plan motor movements (Mills et al., 2015; Pecenka & Keller, 2011; Repp, 2005). It therefore also requires the formation of expectations for the target movement to be executed (Adams et al., 2014), and correction in response to errors or changes in the auditory stimulus (Repp, 2011). The importance of auditory-motor synchronization is further emphasized by how early the skill develops. Infants begin to spontaneously coordinate movements to music as early as five months, such as adjusting the speed of their movements to the tempo of music (Zentner & Eerola, 2010). By 2.5 years, children can begin to synchronize their movements (e.g. hand tapping) with other people (Kirschner & Tomasello, 2009), and this ability strengthens throughout childhood, with improvements continuing to occur after age 11 (Phillips-Silver et al., 2024).

The consequences of impaired auditory-motor synchronization extend beyond the ability to keep a beat. Because auditory-motor synchrony relies on accurate timing and integration across perceptual and motor systems, impairments may manifest in a range of interrelated domains, including speech, reading, and both fine and gross motor skills (Tierney & Kraus, 2014; Trainor et al., 2018). Indeed, many neurodevelopmental disorders are associated with difficulties in auditory-motor synchronization, including DCD, autism spectrum disorder, developmental language disorder, and dyslexia (Lense et al., 2021). For example, auditory-motor synchrony skills have been linked to language skills in children with developmental language disorder (Corriveau & Goswami, 2009) and to social skills in children with autism spectrum disorder (Kaur et al., 2018). These findings highlight that difficulties in auditory-motor synchronization are not isolated to rhythmic movement, but may cascade into broader developmental domains.

Interpersonal synchronization, by contrast, involves the coordination of movements between two or more individuals without necessarily requiring an external auditory stimulus. This can include walking in synchrony with others, mimicking gestures, or dancing in a group. Moving in sync with others promotes interpersonal relationships, as seen by an increase in trust and cooperation within groups who coordinate their movements (Behrends et al., 2012; Good et al., 2017; Jackson et al., 2018; Tomashin et al., 2022; Wiltermuth & Heath, 2009). As young as 14 months, bouncing a baby in synchrony with an adult has been shown to increase the infant's prosocial behaviours towards that person (Cirelli et al., 2014, 2016). At age 4, children are more likely to help and cooperate with one another after a joint dancing and music-making task compared to playing together in a non-musical setting (Kirschner & Tomasello, 2010). Physiologically, moving in synchrony with others has shown to increase pain thresholds (Tarr et al., 2015). There is also an aesthetic benefit when observing people moving in synchrony. For example, people watching pairs or groups of dancers provide higher ratings of movement quality when the dancers are moving with higher interpersonal synchrony (Cross et al., 2024; Tang Poy & Woolhouse, 2020; Vicary et al., 2017). This preference for observing movement with high interpersonal synchrony is likely related to the social benefits, such that synchronized movements communicate strong group cohesion (Hagen & Bryant, 2003; Marques-Quinteiro et al., 2019).

An impairment in the ability to synchronize with others may therefore have consequences in both social functioning and performance contexts. On the social side, reduced interpersonal synchronization could limit opportunities for forming trust and social bonds. For example, adolescents with autism spectrum disorder - a neurodevelopmental disorder characterized by difficulties in social interaction - show reduced interpersonal synchronization compared to typically developing (TD) peers (Fitzpatrick et al., 2016). Such findings raise the possibility that challenges in interpersonal synchrony may contribute to broader social difficulties. However, it remains unknown how these difficulties relate to other forms of synchrony such as auditory-motor synchronization, and whether impairments in one domain might exacerbate or predict challenges in the other. From a performance perspective, impairments in interpersonal synchronization could also alter how skilled movement is perceived. In dance, where observers prefer highly synchronized group performances (Cross et al., 2024; Tang Poy & Woolhouse, 2020; Vicary et al., 2017), difficulties in coordinating with others may diminish the aesthetic impact of even technically proficient dancers. Thus, interpersonal synchronization serves as a bridge between the social and aesthetic domains: when successful, it enhances social connection and elevates artistic expression, but when impaired, it may contribute to both social challenges and reduced performance evaluations.

These two forms of movement synchrony are not mutually exclusive. In the context of dance, both auditory-motor and interpersonal synchronization are frequently performed simultaneously. This dual demand highlights why dance is uniquely positioned as a context in which to investigate how different forms of synchrony intersect, and how their consequences unfold across motor, cognitive, and social domains.

Investigating Differences in the Ability to Synchronize Movements

Whether considering group-level differences in neurodevelopmental disorders or individual-level differences in experts, it is important to understand what contributes to the ability to synchronize movements. In this dissertation, I begin by studying children at risk for DCD compared to TD peers, focusing on group-level differences in auditory-motor synchronization. Using both a simple hand-tapping task in the lab and a full-body step-clap task at home, I examine how a population of children with coordination difficulties differ from TD children across multiple contexts. I then turn to expert dancers, where the emphasis shifts from group comparisons to individual variation within a highly skilled population. By analyzing interpersonal synchrony during a high-level dance competition, I explore how even high-level dancers differ from one another in their ability to synchronize movements in an ecologically valid performance setting. Finally, I connect these two strands of work by examining how individual differences in interpersonal synchrony among dancers relate to their auditory-motor synchronization skills. Together, these studies provide complementary perspectives: group-level comparisons highlight the impact of a coordination disorder on synchrony, while individual-level analyses reveal the mechanisms that distinguish expertise within an already skilled population.

Studying both disorders and expertise provides insight into the systems and consequences of movement synchrony. Group-level investigations of children with coordination disorders reveal the developmental foundations of synchrony by showing what happens when these processes are disrupted, highlighting the perceptual systems that are most critical for motor development. In contrast, individual-level investigations of expert dancers illustrate what is possible when movement synchrony is highly trained, revealing the strategies that enable precise temporal alignment and the aesthetic value of highly synchronized performance. Together, these two perspectives capture both the vulnerabilities and the potential of synchrony. By examining populations at opposite ends of the spectrum, from developmental risk to expert skill, this dissertation provides a more complete understanding of how synchrony shapes human movement and expression.

Auditory-Motor Synchrony in Movement Coordination Disorders

In Chapters 2 and 3, I investigate auditory-motor synchronization skills in children with DCD. While most research on DCD focuses on motor skills, recent research has found that children with DCD also have impairments in their auditory timing perception (Chang et al., 2021). My research expands on this finding by investigating auditory-motor synchronization in both simple repetitive motor skills (i.e., hand tapping) and full-body movement coordination (i.e., a step-clap dance step). This work aims to fill gaps in our knowledge by characterizing the deficits associated with DCD, as well as contributes to research on potential intervention strategies for motor skills in children with DCD.

DCD is a neurodevelopmental disorder defined by the DSM-V as a marked impairment in the acquisition and performance of coordinated motor skills (American Psychiatric Association, 2013). DCD affects 5-6% of children and has a significantly negative impact on the execution of simple daily tasks across a wide range of fine and gross motor abilities. Children with DCD are often described as "clumsy", as they struggle with tasks such as handwriting, playing sports, using scissors, and even walking. These deficits often lead to decreased academic achievement, lower self-esteem, anxiety, depression, and childhood obesity (Lingam et al., 2012; Rivilis et al., 2011; Yasunaga et al., 2024). DCD is viewed as chronic, and an estimated 75% of cases will continue into adulthood if there is no intervention (Blank et al., 2019; Kim et al., 2023; Kirby et al., 2014). Children with DCD often do not receive the support they require, particularly in schools, highlighting the need for more understanding of the disorder and more accessible options for support (Reynolds et al., 2024).

DCD is typically diagnosed using a standardized motor assessment (Henderson et al., 2007), and is highly comorbid with other neurodevelopmental disorders such as attention-deficit hyperactivity disorder (ADHD), dyslexia, and developmental language disorder (American Psychiatric Association, 2013; Lachambre et al., 2021; Lino & Chieffo, 2022; Nemmi et al., 2023). The main deficits in DCD can be clustered broadly into poor motor performance, poor motor learning, deficits in motor imagery, reduced automatization of movement, poor anticipatory control, and decreased manual control compared to TD children (Adams et al., 2014; Al-Yahya et al., 2023; Biotteau et al., 2015; Debrabant et al., 2013; Jover et al., 2010; Kane & Barden, 2012; Schott et al., 2016; Wilson et al., 2013). These reductions in prediction and automatization of movement can lead to a larger reliance on slower feedback-based control, external feedback, and compensatory strategies during motor tasks (Wilson et al., 2017). Despite the heterogeneous nature of DCD, studies of motor performance have found overall less accurate, less precise, less consistent, and slower motor performance compared to TD children (Ferguson et al., 2014; Knaier et al., 2023). In bimanual tapping coordination tasks, children with DCD are also more variable and less accurate than TD children (Volman et al., 2006; Whitall et al., 2008), suggesting impairments in rhythmic movement.

Auditory Timing Impairments in Children with DCD. Recently, research on motor impairments in DCD have shifted to include auditory timing perception and auditory-motor synchronization skills in children with DCD. Given that the perception of auditory rhythms involves interactions between auditory and motor brain regions, it was predicted that children with DCD would have impairments in auditory time perception in addition to their motor impairments (Trainor et al., 2018). Converging evidence has also emerged for auditory timing perception and auditory-motor synchronization impairments in many of the neurodevelopmental disorders comorbid with DCD, such as ADHD, autism spectrum disorder, dyslexia, and developmental language disorder (Lense et al., 2021), which is consistent with the idea that auditory-motor coordination might be prevalent in in DCD as well. Research from my lab has shown that children with DCD have higher thresholds for auditory duration and auditory rhythm discrimination tasks that do not involve overt motor responses (Chang et al., 2021). In this dissertation I continue to investigate auditory timing perception deficits in children with DCD and extend this research to examine auditory-motor synchronization in both simple and complex motor tasks. As parents of children with DCD report a need for more accessible and effective options for intervention (Maciver et al., 2011), I aim to further our understanding of the impairments associated with DCD in order to contribute to future research on appropriate interventions for the disorder.

In Chapter 2, I investigated whether children at risk for DCD (rDCD) showed impairments in auditory timing perception and auditory-motor synchronization skills compared to TD children. Chapter 2 also investigated whether both groups could benefit their motor performance with the presence of an auditory cue. The results of Chapter 2 showed that children with rDCD did have impairments both in their auditory timing perception as well as their auditory-motor synchrony compared to TD children. However, both groups showed significant improvements in both their perception and motor production with the presence of a rhythmic auditory cue. This suggests that children with rDCD can use auditory rhythms to their benefit. These findings provide evidence that interventions for DCD could include the use of auditory cues to provide a temporal framework for their motor skill practice.

Chapter 3 further investigated auditory-motor synchronization in children with rDCD compared to TD children by examining full-body, gross motor coordination through a step clap dance step. This study was conducted entirely online, providing evidence that research on complex motor synchrony can be studied even from participants' homes. As predicted, the results showed that children with rDCD have impairments in coordinating their movements to an auditory cue. However, this study also revealed significant effects of tempo, such that performance between groups was similar at slower tempi, whereas children in the rDCD group performed worse than TD children at faster tempi. Children with rDCD also were found to perform the dance step overall slower compared to TD children regardless of the musical tempo. This study provides evidence that children with rDCD are capable of performing gross motor dance steps and coordinating them with music if the tempo is slow enough. The results also highlight that it is important to consider the tempo of the music or auditory cue when designing interventions.

Interpersonal Synchrony in Expert Dancers

While studies of children with DCD reveal the consequences of impaired auditory-motor synchrony, expert dancers illustrate how movement synchrony can be refined through extensive practice and training. In Chapters 4 and 5 of this dissertation, I examine interpersonal synchrony in expert hip hop dancers, both in a real-world hip hop competition and in more controlled laboratory-based experiments.

Interpersonal synchrony is central to the aesthetics and evaluation of dance: observers judge highly synchronized groups as more cohesive, enjoyable, and skilled than less synchronized groups (Cross et al., 2024; Tang Poy & Woolhouse, 2020; Vicary et al., 2017). Thus, dance expertise depends not only on individual technical ability but also on the capacity to align movements with others. However, in competitive settings, particularly in hip hop dance, it is less clear whether synchrony is consistently prioritized in evaluations. The role of interpersonal synchrony in fostering social connection has been well studied in laboratory experiments (e.g., Wiltermuth & Heath, 2009), but has been less studied in culturally significant and ecologically valid group settings such as dance competitions. From a social and cultural perspective, hip hop competitions are not only artistic performances but also meaningful community events, where judgments of movement synchrony directly influence reputation, group identity, and success (Sato, 2022). Investigating synchrony in these settings therefore allows us to understand its role in both the technical evaluation of expertise and the broader social impact of coordinated movement. However, understanding how movement synchrony operates in group performances also requires examining the individual-level skills and capacities that enable or constrain the ability to move in time with others.

Even within expert populations, there are meaningful individual differences in the ability to achieve interpersonal synchrony. Dance training encompasses the important skill of precisely aligning one's movements with other dancers, so the fact that expert dancers exhibit a large range of abilities in interpersonal synchrony makes them an interesting cohort to study, as it highlights the presence of other underlying factors impacting this skill. While there are many possible factors associated with interpersonal synchrony, skills such as beat perception, auditory-motor synchronization, and auditory timing perception have been found to be improved in dancers compared to novice control groups, making them good candidates for underlying skills that may impact interpersonal synchrony (Nam et al., 2024; Nguyen et al., 2022; Skoe et al., 2021). Linking these laboratory-based measures with interpersonal synchrony in ecologically valid performance contexts provides a powerful test of how sensorimotor skills relate to high-level artistic performance.

In Chapter 4, I investigated the role of dancers' interpersonal synchrony in judges' and audiences' evaluation of a hip hop dance competition. I found that movement synchrony, measured through exacting motion capture technology, was a significant predictor of observer scores, both for expert judges as well as novice audience members, emphasizing how important a role movement synchrony can play in ecologically valid environments such as dance competitions. This study was the first hip hop dance competition to collect live, in-person movement data.

In Chapter 5, I examined the connection between the results of Chapter 4 with those of Chapters 2 and 3. The hip hop dancers who participated in the dance competition of Chapter 4 revisited the lab to complete a battery of tasks, including those from Chapter 2, on which children with rDCD were shown to have impairments. This included measures of auditory timing perception (duration and rhythm discrimination) and auditory-motor synchronization (tapping production). I found that both rhythm discrimination thresholds and tapping consistency were related to the ability of dancers to synchronize their movements with other members of their performing group. I also found that individual tapping consistency was a significant predictor of movement synchrony during the hip hop dance competition. This was the first study to investigate the relation between complex motor synchrony during dance with auditory timing perception and production.

Summary: Thesis Outline and Contributions

Chapters 2, 3, 4, and 5 examine the performance of motor synchrony ranging from children at risk for DCD to expert dancers in a dance competition setting. Previous research suggests that children with DCD have auditory timing perception impairments in addition to their motor timing impairments, but their ability to synchronize their movements with an auditory stimulus, and whether the presence of an auditory stimulus can improve their performance, was not previously studied. Additionally, how important movement synchrony is in the observation of hip hop dance, addressed in Chapters 4, had not been studied previously in a highly ecologically valid context. In Chapter 5, I connected this performance-level synchrony to laboratory-based measures of auditory timing perception and auditory-motor synchronization, asking whether individual differences in basic auditory-motor skills predict dancers' ability to coordinate movements with one another.

This dissertation contributes to our understanding of movement synchrony across the spectrum from developmental impairments to expert skill. By examining both children at risk for DCD and expert dancers, the findings illuminate how underlying sensorimotor and auditory timing abilities shape the capacity to synchronize movements, whether with external auditory cues or with other individuals. The work demonstrates that impairments in DCD are not simply isolated motor deficits, but extend to impairments in auditory timing perception and auditory-motor synchrony. Conversely, in expert dancers, fine-grained differences in auditory-motor synchrony predict interpersonal synchrony, highlighting the specific mechanisms that allow highly trained individuals to achieve precise coordination in ecologically valid performance contexts. By linking basic laboratory measures of timing and motor coordination to complex, real-world performance, this research bridges a critical gap between experimental and applied settings, offering a framework for understanding how core sensorimotor abilities scale to social and artistic contexts.

In sum, the present research underscores that synchrony is a fundamental aspect of human movement with wide-ranging consequences: from supporting motor development and social interaction in children with DCD to shaping aesthetic evaluation and technical success in expert dancers. By integrating findings across diverse populations and methodologies, this dissertation provides a comprehensive perspective on the mechanisms and outcomes related to movement synchrony. Future research can build on these insights to explore how synchrony training might enhance motor and social development, improve therapeutic approaches for developmental disorders, and optimize group coordination in artistic and professional domains.

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Chapter 2: Auditory rhythm facilitates perception and action in children at risk for developmental coordination disorder

Carrillo, C., Chang, A., Armstrong, H., Cairney, J., McAuley, J. D., & Trainor, L. J. (2024). Auditory rhythm facilitates perception and action in children at risk for developmental coordination disorder. *Scientific Reports*, *14*(1), 12203. https://doi.org/10.1038/s41598-024-62322-6

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Preface

In Chapter 2, I present the first investigation of whether children at risk for developmental coordination disorder (rDCD) show impairments in auditory-motor synchronization. While motor difficulties in DCD are well documented, less is known about how auditory timing perception and auditory-motor synchrony may be affected. Using both a speech identification task and a simple tapping paradigm, this chapter investigates whether children with rDCD differ from typically developing peers in their ability to perceive and produce rhythmic timing, and whether rhythmic auditory cues can enhance performance. I found that children with rDCD are more negatively impacted by distorted rhythms in the speech identification task, and that their tapping was less consistent compared to typically developing children. I also found that both groups tapped significantly better when an auditory cue was present. This suggests that children with rDCD can use auditory rhythms to their benefit during speech identification and tapping production, and that removing or modulating these cues impacts their performance.

Abstract

Developmental Coordination Disorder (DCD) is a common neurodevelopmental disorder featuring deficits in motor coordination and motor timing among children. Deficits in rhythmic tracking, including perceptually tracking and synchronizing action with auditory rhythms, have been studied in a wide range of motor disorders, providing a foundation for developing rehabilitation programs incorporating auditory rhythms. We tested whether DCD also features these auditory-motor deficits among 7- to 10-year-old children. In a speech recognition task with no overt motor component, modulating the speech rhythm interfered more with the performance of children at risk for DCD than typically developing (TD) children. A set of auditory-motor tapping tasks further showed that, although children at risk for DCD performed worse than TD children in general, the presence of an auditory rhythmic cue (isochronous metronome or music) facilitated the temporal consistency of tapping. Finally, accuracy in the recognition of rhythmically modulated speech and tapping consistency correlated with performance on the standardized motor assessment. Together, the results show auditory rhythmic regularity benefits auditory perception and auditory-motor coordination in children at risk for DCD. This provides a foundation for future clinical studies to develop evidence-based interventions involving auditory-motor rhythmic coordination for children with DCD.

Introduction

Developmental Coordination Disorder (DCD) is a neurodevelopmental disorder defined as a marked impairment in the acquisition and performance of coordinated motor skills. DCD affects 5-6% of children across a wide range of fine and gross motor abilities and has a significantly negative impact on the execution of simple daily tasks [1]. The main deficits in

DCD include poor motor performance, poor motor learning, reduced automatization of movement, poor anticipatory control, and decreased manual control compared to typically developing (TD) children [2]. Children with DCD are often described as "clumsy", as they struggle with tasks such as handwriting, tying their shoes, using scissors, and riding a bike. These deficits are later associated with decreased academic achievement, lower self-esteem, anxiety, depression, childhood obesity, and a higher reluctance to partake in leisure activities [3-7]. DCD is viewed as chronic, and an estimated 75% of cases will continue into adulthood if there is no intervention [8]. Despite the high prevalence and negative outcomes, very little is known about DCD and how to effectively treat it.

A crucial component of motor performance is temporal coordination, and poor motor timing is one of the core deficits of DCD [9-11]. As children navigate the world and interact with their environment, they often need to temporally coordinate their movements with external stimuli, whether it be catching a ball, walking in synchrony with a friend, or moving along to music. Research on sensorimotor timing skills in children with DCD has increased in recent years [12,13]. In the visual-motor timing domain, children with DCD show deficits in intercepting moving objects [14], perceiving visual temporal gaps [15], bimanual tapping to a visual stimulus [16], and synchronization of verbal responses to isochronous visual and auditory cues [17].

Sensorimotor coordination is particularly intriguing and important in the auditory domain, as both the perception and production of speech and music involves auditory and motor systems. Specifically, a large body of evidence suggests that the perceptual processing of rhythmic regularity in speech and music involves neural networks spanning auditory and motor cortical regions, even in the absence of overt motor movement [18-24]. In a study using nonmotor perceptual tasks, children at risk for DCD have been shown to have worse thresholds for detecting auditory duration and rhythm deviations, but not pitch deviations, compared to typically developing children [25]. This auditory-motor connection is also closely tied to social interaction – for example, moving in synchrony with others along with musical rhythms increases cooperation, helping behaviours, and feelings of affiliation [26-28]. Thus, a deficit in auditory-motor skills could have consequences for perceptual, cognitive, and social development. However, whether the motor deficits among individuals with DCD are associated with poorer auditory-motor timing abilities remains a largely unexplored hypothesis [29].

To the best of our knowledge, auditory-motor skills in DCD have only been sporadically reported in a few studies. Children with DCD are less accurate at tapping to an auditory metronome [30], and "clumsy" children (who are likely to have DCD) have higher variability in sustaining their tapping tempo after removing auditory cues [31]. In a bimanual tapping coordination task, children with DCD are more variable and less accurate than typically developing (TD) children at coordinating with an auditory cue [32]. Children with both attention-deficit hyperactivity disorder (ADHD) and DCD showed deficits in paced and unpaced tapping tasks compared to typically developing children and children with ADHD alone [33]. It is unclear, however, how well children with DCD can synchronize with a variety of more complex auditory stimuli, and how auditory rhythm perception and auditory-motor synchronization skills relate to the general motor skills that define DCD, such as those measured by the Movement Assessment Battery for Children (MABC-2).

Rhythmic tracking behaviour (or entrainment), a key component of auditory-motor synchronization, may be a domain-general deficit in DCD. Rhythmic tracking requires prediction of the timing of upcoming auditory events. To accurately synchronize movements to an auditory stimulus, an individual must successfully predict upcoming events in the auditory stimulus, form expectations for the target movement [34], and correct for errors or changes in the stimulus [35]. Rhythmic regularity in auditory stimuli can facilitate perception by proactively guiding attention to rhythmic events [36-38], or be used to precisely coordinate movements [39,40]. Thus, if DCD features a deficit in rhythmic tracking, it should be observed on both perceptual tasks that require temporal tracking without an overt motor component as well as on auditory-motor synchronization tasks.

The present study is centered around the question of whether children at risk for DCD (rDCD) flexibly use rhythmic tracking of auditory temporal cues to improve (1) auditory perception of speech and (2) auditory-motor performance in comparison to TD children. The auditory perception of speech task employed distorted timing to compare speech recognition in rhythmically intact and rhythmically modulated sentences. This task, which did not involve any overt motor component, aimed to understand whether children with DCD use rhythm as a cue in the highly overlearned skill of speech recognition, and whether they could flexibly adjust when the rhythm of the speech was modulated. Specifically, we used a task in which children identified key words in target sentences (among distractor sentences) when the sentences were normally timed and when their timing was modulated. Adults perform worse on this task when the speech rhythms are modulated [41,42], as rhythm provides a temporal cue for where to focus attention when identifying target words. However, the degree to which their performance suffers can be a measure of how flexible they are in adjusting to modulated rhythmic cues. Although previous research found that children with rDCD show poorer rhythm discrimination than TD children [25], they did not investigate whether children with rDCD can utilize rhythmic temporal regularity to proactively improve their perception of an upcoming auditory signal. We expected children with rDCD to be less able to use the rhythmic cues in speech to their benefit, and thus perform overall worse at the task compared to TD children. We also expected children with rDCD to be less adaptable to rhythmic modulation, and for modulated speech rhythms to have a stronger negative impact on performance compared to in TD children, consistent with previous findings showing less flexibility in DCD on visual-motor timing [43].

The auditory-motor synchronization tasks investigated whether the presence of auditory rhythmic cues would improve rhythmic motor tapping performance in children with rDCD in comparison to TD children. We examined performance on (1) tapping in synchrony with a simple auditory metronome, (2) continuation tapping (maintaining tapping behavior after the auditory rhythm stops), and (3) tapping to the beat of musical excerpts where the beat needs to be extracted from the complex rhythmic structure. We expected that children with DCD would be more variable or imprecise in their tapping compared to TD children, but that both TD and DCD groups would tap more accurately and with less variability when an auditory cue was present compared to when there was no auditory cue.

Methods

Participants

46 children aged 7 to 10 were recruited through collaboration with the Infant and Child Health (INCH) lab [44]. All participants were part of a longitudinal coordination and activity tracking in children (CATCH) study, and written consent was received from parents/guardians to share their MABC-2 scores. The CATCH study recruited a large number of children (n = 588) from communities in southern Ontario, and measured them every year for six years on a variety of motor tasks, including the MABC-2, which is the most widely used assessment for DCD

based on an established threshold [45,46]. We identified the participants at risk for DCD following the diagnostic and statistical manual of mental disorders (DSM-5) criteria and the 2011 European Academy of Childhood Disability Guidelines for identification of children with DCD [45]. These included significant motor deficits, as assessed by the MABC-2 (participants with scores in the lower 16th percentile were considered at risk for DCD) and that these motor deficits were not due to existing intellectual disability (all participants had IQ scores above 70) or neurological conditions affecting movement [1,44,45]. The study was double blind: experimenters did not know whether a participant was categorized into the rDCD or TD group at the time of testing, and participants and their parents did not know the hypotheses of the study. Participants of the CATCH study who were interested in participating in this study were identified as being in "group A" or "group B" by the CATCH research team. This allowed participants to be recruited in even numbers across the two groups, while our experimenters remained blind to group allocation during data collection. Three children were excluded from the analysis due to an additional diagnosis of autism spectrum disorder. Thus 43 participants were included in the analyses (n = 21 in rDCD). This research was reviewed and approved by the McMaster Research Ethics Board (MREB) #0411, and informed consent was obtained from both the parents/guardians and the participants. As of October 2020, parents/guardians signed an additional informed consent form outlining the lab's procedure for testing with additional precautions due to COVID-19. All experiments and protocols were carried out in accordance with MREB ethical guidelines. The participants received a small toy, a certificate of participation, and a $40 gift certificate.

General Procedure

Participants performed the tasks in the following order: digit span test (~5 minutes), speech recognition with distorted timing task (~20 minutes), and tapping production tasks (~25-35 minutes), all in the same visit. The tapping tasks were always in the order of spontaneous motor tapping, metronome tapping, continuation tapping, and music tapping. Both groups (rDCD and TD) performed the experiment in the same order. Spontaneous motor tapping was performed first so that the tempi of the subsequent tasks would not influence the results. The MABC–2 and IQ were administered by the CATCH study prior to the date of the experiment (see “previously collected measures”).

Speech Recognition with Distorted Timing Task

Stimuli. Participants were presented with speech stimuli through a pair of binaural Sennheiser headphones. Stimuli were sentences from the Coordinate Response Measure (CRM) corpus [47]. All sentences followed the same format: “Ready [call sign], go to [colour] [number] now.” Participants were asked to report the colour and the number they heard from a target sentence, which could always be identified with the call sign “Baron”. The target sentence was presented in a masking background of two sentences that were similar to the target sentence but used a different call sign. There were seven possible distractor call signs in the background sentences (“Eagle”, “Charlie”, “Tiger”, “Ringo”, “Hopper”, “Arrow”, and “Laker”). The target words were simple and highly familiar colours and numbers. Across the sentences, there were seven different possible target numbers (1-8, excluding seven as it has two syllables) and four possible target colours (“red”, “white”, “blue”, “green”). All conditions had two background talkers, with call signs, colours, and numbers that differed from the target sentence. Each trial consisted of one target sentence overlapped with two distractor background sentences. The target sentence with call sign "Baron" always used the same male voice, and the background sentences on each trial consisted of one female voice and one male voice. Background voices were randomly selected from six possible unique voices, which differed from the target voice. The two background sentences had onset asynchronies of -50 and 50 ms, respectively, with respect to the onset of the target sentence. The three sentences together were presented at 55-60 SPL(A), and the signal-to-noise ratio between the target sentence and background sentences was always 2 dB.

In one condition block (intact speech rhythm), the rhythm of the target sentence was left intact. In the second condition block (modulated speech rhythm), the rhythm of the target sentence was modulated. The effect of this rhythm modulation was the key factor being investigated in this task, and the background sentences served as distraction in order to make the task optimally difficult for revealing potential differences. Modulation was applied by adjusting the rhythmic information of the target sentence in a sinusoidal pattern, causing the tempo to increase and decrease periodically within the same sentence. Rhythmic changes were applied using the Pitch Synchronous Overlap and Add (PSOLA) algorithm in Praat, which compressed and expanded the timing of the sentence using a compression ratio: $CR(t) = 1 + m*\sin(2\pi f_m t + \Theta)$, where m equals the depth of modulation and $f_m = 1$ Hz[43]. In this experiment, $m = 0.5$ for the modulated speech condition. There were four possible phase shifts of the target modulation ($\pi/4$, $3\pi/4$, $5\pi/4$, and $7\pi/4$), making the rhythm of the adjusted sentences unpredictable to the participants. Background sentences were always left intact.

Procedure. To begin, participants completed one block of 20 trials where the target sentence rhythm was modulated, but there were no background talkers. This was used to ensure participants were familiar with the modulated speech rhythms and were able to identify the target words in modulated speech when there were no distractor sentences. Participants then completed the two conditions (intact speech rhythm and modulated speech rhythm, both in the presence of distractor sentences), with two 20-trial blocks of each condition. The four condition blocks alternated between modulated and intact speech rhythm conditions, with initial block type counterbalanced across participants, for a total of 80 trials. Responses were considered correct when the participant reported both the colour and the number of the target sentence accurately. The only visual stimuli present during the task were buttons with all the possible colour and number choices. The participants provided their responses verbally, and the experimenter clicked the response button on the screen. The task was explained to participants in the context of a game: experimenters described a super spy mission to the children and said that they would be decoding secret messages.

Tapping Tasks

Stimuli. In all tapping task conditions, the stimuli were presented to the participants through a speaker in a sound attenuated room on average at 75.5 dB SPL(A) over a noise floor of approximately 28 dB SPL(A). A drum was placed on a table at a comfortable distance in front of the participant, and audio recordings of tapping data were collected through Audacity (version 2.1.0) at a sample rate of 8000 Hz. All auditory stimuli were 20 s in length. For the metronome and metronome-continuation tasks, sequences of percussive woodblock sounds (each 120 ms in duration) were presented at 400, 550, and 700 ms inter-onset intervals (IOIs). For the music excerpts, IOIs ranged from 500 to 700 ms, and the amplitude was ramped up and down over 500 ms at the beginning and end of each excerpt. The "true" beat onsets for each musical excerpt were determined by averaging the tapping data of two adult semi-professional drummers (for each excerpt, taps from nine trials were averaged, six trials from one drummer and three trials from the other), and the tempo of each excerpt was determined by the mean interval of beat onsets.

Procedure. Four different tapping tasks were adapted as a variation of the beat alignment test [48]. Participants were required to tap on a drum with their dominant hand while following prompts from the experimenter and visual signs on a screen indicating when to start and stop tapping. The visual signs included a green circle representing when the trial was in progress, and a red circle representing the end of a trial. Participants were allowed to talk to the experimenter between trials, and were motivated between trials by images of "Ziggy the Zebra" who gained stripes as the experiment progressed.

i. *Spontaneous Motor Tapping*. Participants tapped three trials of 20 seconds each at their preferred tempo. The experimenter instructed the participants to tap at a speed that was most comfortable to them, and to try to tap "steady like a clock". Participants were allowed to practice a couple of times to find their preferred tempo before the trials began.

ii. *Metronome Tapping*. A metronome consisting of isochronous woodblock sounds was presented for participants to tap along to. Three different tempi (400, 550, and 700 ms IOIs) were presented for two 20-s trials each. The order of trials was randomized within the 6-trial block.

iii. *Metronome-Continuation Tapping*. On each 20-s trial, a metronome consisting of isochronous woodblock sounds was presented for 10 beats, at one of three different tempi (400, 550, and 700 ms IOIs). Participants synchronized their taps to the metronome, and after the 10 beats, participants were required to continue tapping at the same tempo for the remainder of the 20 seconds, without any external auditory cue. Two trials were completed at each tempo. The order of trials was randomized within the 6-trial block.

iv. *Music Excerpts*. Participants tapped along to the perceived beat of six different 20-s musical excerpts, chosen from pop and hip-hop genres (Table 1). Each excerpt was presented twice, and trials were randomized within the 12-excerpt block. To ensure participants understood the task was to tap to the beat and not the rhythm of the songs, before testing began, the experimenter sang "Happy Birthday" and had the participant tap along the beat. Before continuing with the testing, the experimenter ensured the participant understood how to tap the isochronous beat underlying the rhythm of the song and not the actual rhythm (which contained different event durations).

Table 1

Song Title	Artist	Tempo (IOI)
Sing	Ed Sheeran	500 ms
Can't Stop the Feeling	Justin Timberlake	530 ms
Yeah	Usher ft. Lil Jon	570 ms
Superstition	Stevie Wonder	600 ms
Love On Top	Beyoncé	638 ms
Umbrella	Rihanna ft. Jay-Z	690 ms

Semi-Professional Musician Ratings

For the music tapping conditions, a semi-professional percussionist (20 years of percussion experience, and 10 years of teaching experience) rated all trials on the following questions: (1) How synchronized was the tapping to the music, regardless of whether they tapped the beat or the rhythm?, (2) Is the participant always tapping the beat, or do they sometimes tap the rhythm?, (3) What percentage of the trial were they tapping the beat?, (4) When tapping the beat, how synchronized was the tapping to the music?, (5) When tapping the rhythm, how synchronized was the tapping to the music?, and (6) Was the tapping too quiet to hear? All questions were answered on a scale of 0-100. The percussionist was blind to the participants' group allocations.

Working Memory Task: Digit Span

The sum of the forward and reverse conditions of the digit span test from the Wechsler Intelligence Scale for Children, 4th Edition [49,50] was used to measure participants' working memory capacity.

Questionnaires

Parents/guardians filled out two questionnaires: one regarding background in music, dance, and art; and the second the Conners' Parent Rating Scale Revised, 27-item Short Version (CPRS-R:S) to assess for behaviours of ADHD. Children with T-scores 60 or above on the CPRS-R:S are considered to show atypical behaviour [51].

Previously Collected Measures

The MABC-2 was conducted by the INCH lab for all participants within one to two years prior to the collection of the data reported here. We used the sum of the aiming and catching, manual dexterity, and balance subtests. IQ scores were collected at the beginning of the INCH lab's CATCH study using the Kaufman Brief Intelligence Test 2nd Edition (KBIT-2), when participants were five years old (two to four years prior to when the presented data were collected) [44].

Collection and Analysis of Tapping Data

Tapping data were collected through Audacity in a WAV file format, time-locked with the auditory stimulus. We identified taps using an amplitude threshold identified individually for each participant, based on the intensity of their tapping. Each tap was then paired with the closest stimulus beat in time, and the distances from each tap to its associated beat were used to calculate circular statistics. Circular (or directional) statistics were used to calculate phase and consistency of tapping across metronome, continuation, and music trials. As shown in Figure 2A, taps can be represented on a 360^{o} polar scale, plotted by their relative angles from the metronome onset. The metronome/beat onsets are represented at angle 0, and the differences from 0 in tap times are measured in radians. A mean vector *R* was calculated by circularly averaging all taps from a single trial. The angle of vector *R* represents the mean phase, or the accuracy with which the participant tapped relative to the metronome/beat. Positive angles represent tapping after the onset of the metronome/beat, and negative angles tapping before. The length of *R* represents consistency, which can be thought of as the reciprocal of variability. Values range between 0 and 1, where 1 represents perfect consistency (i.e., the asynchrony between every tap and metronome/beat onset is identical across every tap in the trial), and 0 represents a circular-uniform random distribution of tap times relative to the beat. Consistency data was submitted to a logit transformation before further analysis to reduce data skewness, as is common in tapping synchronization research [52,53].

Data Availability

The data that support the findings of this study are available on request from the corresponding author.

Results

Demographics

43 children between the ages of 7 and 10 years were tested (Table 2). The rDCD group (n=21) averaged in the 10th percentile on the MABC-2 (SD=4.9), ranging from the 0.5th-16th percentile, while the TD group (n=22) averaged in the 53rd percentile (SD=24.2), ranging from the 25th-95th percentile (see Figure S1 for a histogram of MABC-2 percentiles). Performance on the digit span task did not differ significantly between groups ($t(40.1) = 1.11$, $p = .273$). There was no significant difference between groups on the CPRS-R:S ($t(35.2) = 1.86$, $p = .072$). Six participants had T-scores >60, which fall in the range of atypical behaviour; however, they were spread across the rDCD (four) and TD (two) groups and none of these participants reported a diagnosis of ADHD. This questionnaire is intended to be interpreted by a trained medical doctor in combination with teacher reported questionnaires and further interviews and assessments. Further, four of the six children were female and the CPRS-R:S requires higher raw scores for female participants to be assigned a T-score over 60 [51]. Given these factors, we did not exclude participants with T-scores >60, but we have identified them in all figures.

The two groups did not differ in their years of music training, $t(39.4) = -0.05$, $p = .957$. The ratio of female to male participants in the rDCD group was large (only 4 of the 21 participants were female) compared to the TD group (13 female out of 22 participants). This is not unusual for studies involving children with DCD, as reports of the ratio of males to females who are diagnosed with DCD range from 2:1 to 7:1 [54]. No significant differences between male and female participants were found for any main outcome variables in the TD group (see supplementary data for details). Age was used as a covariate for analyses in both the speech recognition with distorted timing task and the tapping tasks, as tapping synchronization and beat perception change significantly across the 7-10 year age groups [55], and age has been found to be a significant factor in previous studies using the same age range [56].

Table 2

Variable	rDCD (±SD)	TD (±SD)	T-Test P-Value
Sample Size	21	22	N/A
Females:Males	4:17	13:9	N/A
Age	8.9±0.7	8.8±0.8	.861
MABC-2 Percentile	10±4.9	53±24.8	<.001
Digit Span †	16.3±3.3	15.2±3.0	.273
Years of Music Training	1.38±1.8	1.41±1.6	.957
CPRS-R:S ‡	54.1±8.3	50.1±5.7	.072
SES §	4.2±1.4	5.0±2.0	.131

†Maximum digit span score = 32.
‡Conner's Parent Rating Scale Revised (Short): T-scores > 60 represent atypical behaviour.
§SES (socioeconomic status) was estimated by average household income per year, scored on a scale of 1–7, where 1 = < $30,000, 2 = $30,000–60,000, 3 = $60,000–90,000, 4 = $90,000–120,000, 5 = $120,000–150,000, and 6 = > $150,000.

Speech Recognition with Distorted Timing Task

Proportion of Correct Responses

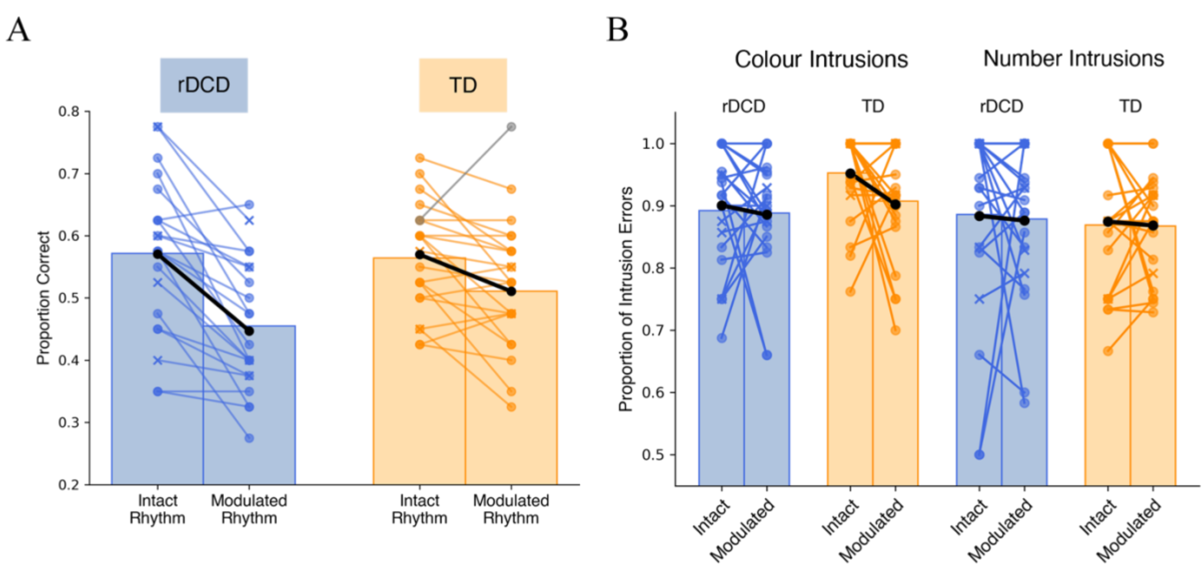
Proportion of correct color and number word recognition was calculated for the speech recognition with distorted timing task by dividing the number of trials where both the colour and the number were correctly identified by the total number of trials per condition. In the first block with modulated rhythms and no background talkers, both groups had near perfect scores (rDCD:

M = 0.99, SD = 0.01; TD: M = 0.99, SD = 0.02). For the intact and modulated speech conditions, mean proportion of correct scores across groups are summarized in Figure 1A. One outlier in the TD group was removed, as it exceeded the upper inner fence of the 1.5 interquartile range (a common threshold for identifying outliers [57]) of responses in the modulation condition. A 2x2 mixed-design analysis of variance (ANOVA) was conducted to compare the within-subject variable of rhythm condition (intact vs. modulated speech rhythm) and the between-subject variable of participant group (rDCD vs. TD) with age as a covariate. Data was found to be normally distributed, assessed by the Shapiro-Wilk test, and sphericity assumptions were met. Results revealed a significant interaction between group and condition, $F(1,39) = 6.20$, $p = .017$, $\eta^2 = .023$. The group effect was non-significant, $F(1,39) = 0.69$, $p = .410$, $\eta^2 = .014$, as was the effect of condition, $F(1,39) = 0.002$, $p = .963$, $\eta^2 < .001$. To investigate this interaction, a post-hoc paired t-test showed a significant difference between proportion of correct responses in the intact compared to modulation conditions for the rDCD group alone, $t(20) = 5.86$, $p = .005$, $d = 1.28$ (Bonferroni corrected). To further investigate, a difference score was calculated for each participant by their average performance on the modulated rhythm condition subtracted from their average performance on the intact rhythm condition. A t-test (Bonferroni corrected) showed a significant difference between groups for difference scores ($t(37.5) = 2.51$, $p = .033$, $d = 0.78$), with the rDCD group (M = 0.12, SD = 0.09) showing a larger difference between conditions than the TD group (M = 0.05, SD = 0.07).

Intrusion Errors as a Proportion of Incorrect Responses

Intrusion errors were defined as trials where the participants' responses were words from one of the two background sentences instead of the target sentence. These trials reflect poor attention at the critical locations in time [42]. A 2x2 mixed-design ANOVA on proportion of colour intrusions revealed a significant effect of group, $F(1,40) = 4.52$, $p = .040$, $\eta^2 = .05$; although the TD group had fewer colour response errors, a higher proportion of these errors were intrusions compared to the rDCD group (Figure 1B). There was no effect of condition, $F(1,40) = 1.22$, $p = .276$, $\eta^2 = .014$, or interaction. For number intrusions, there were no effects of group, $F(1,40) = 0.20$, $p = .653$, $\eta^2 = .003$, condition, $F(1,40) = 0.26$, $p = .611$, $\eta^2 = .003$, or interaction (Figure 1B).

Figure 1



Mean proportion of correct responses and intrusion errors on the speech recognition with distorted timing task. rDCD (blue) and TD (orange) with group means represented in black. Participants with CPRS-R:S T-scores > 60 are represented by Xs. (A) Mean performance and individual data across conditions for intact rhythm and modulated rhythm conditions (each dot represents one participant, with lines connecting data from the same participant, and an outlier in grey) showing a significant interaction of group and condition ($p = 0.017$). (B) Intrusion errors (trials where the incorrect responses were words from one of the two background sentences) as mean proportions of incorrect responses, showing a significant group effect for colour intrusions ($p = 0.040$), but not number intrusions ($p = 0.653$).

Tapping Production Tasks

Spontaneous Motor Tapping

Spontaneous motor tapping tempos were defined as the median IOI averaged across the three spontaneous tapping trials. Within each trial, tap intervals were removed if they were identified as outliers by the interquartile range method. Although the rDCD group (M = 806 ms IOI, SD = 297) tended to tap faster than the TD group (M = 860 ms IOI, SD = 296), an independent samples t-test revealed no significant difference between the two groups, $t(41) = -0.60$, $p = .553$, $d = -0.18$ (Figure S2A). Tapping variability was defined by the coefficient of variation of the IOI (SD of IOIs / mean IOI). The rDCD group (M = 0.06, SD = 0.007) had a similar variability to the TD group (M = 0.06, SD = 0.05), and the difference was non-significant, $t(38.1) = 0.12$, $p = .905$, $d = 0.04$ (Figure S2B).

Analyses of Metronome, Music and Continuation Tapping

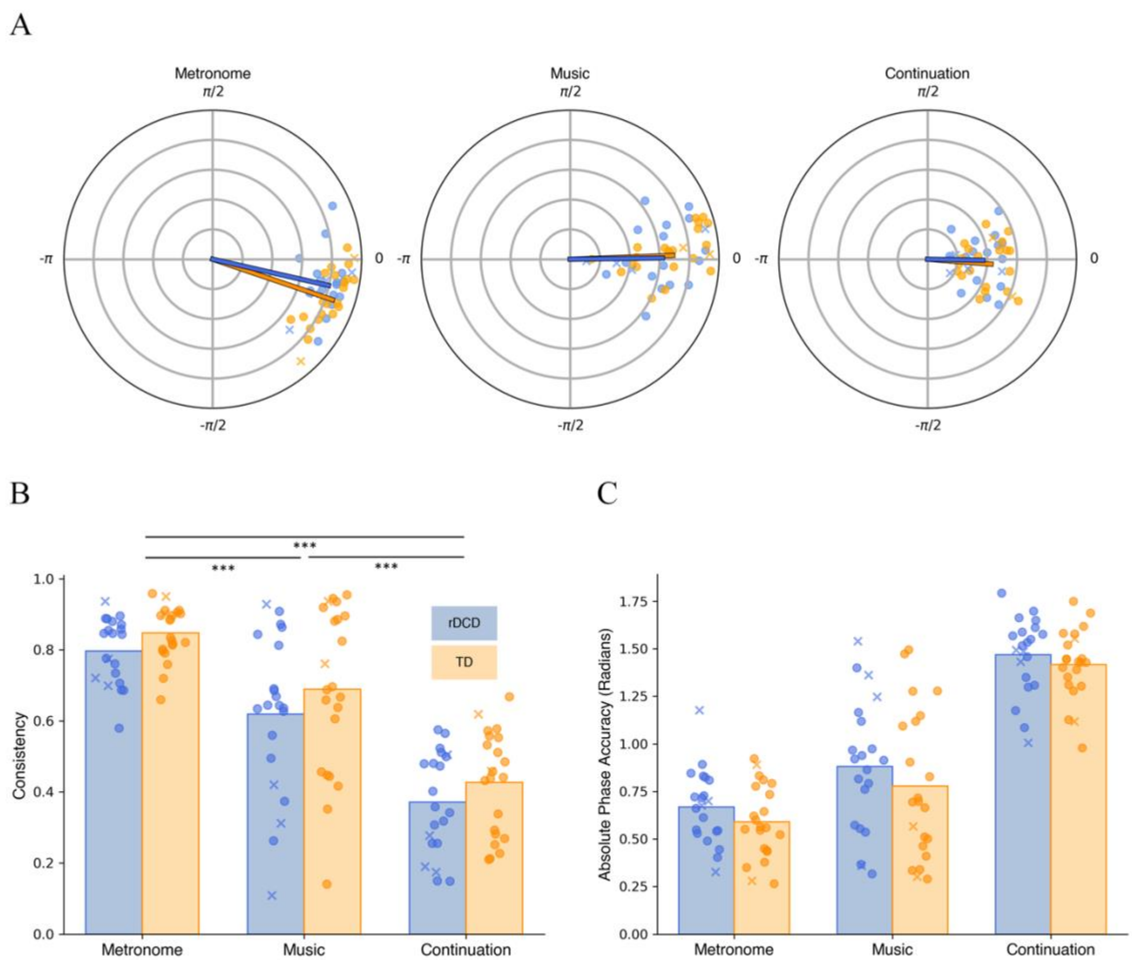
Trials were excluded from analysis that were identified by the semi-professional musician rater as “rhythm tapping”, in which the participant tapped the rhythm of the musical excerpt rather than the beat. In the rDCD group, 35 out of 252 trials were identified as the participant tapping a rhythm as opposed to the beat and 13 of the 21 participants had at least one trial of rhythm tapping. In the TD group, only 15 out of 264 trials were identified as rhythm tapping, and only 5 of the 22 participants had at least one trial of rhythm tapping. These proportions were significantly different between groups, $X^2(1) = 14.97$, $p < .001$. The pattern of results remained the same if these ‘rhythm tapping’ trials remained in the analysis (see supplementary data).

In the metronome condition, all taps were analyzed. In the metronome-continuation condition, only taps during the continuation phase were analyzed (i.e., taps during the initial 10 metronome beats were excluded), and taps were analyzed relative to where the metronome would have been if the auditory cue had continued. To ensure results weren't skewed by one group speeding up or slowing down more than the other group, linear regression lines for each continuation trial were calculated using the tapping intervals (Figure S3). A repeated measures ANOVA showed no difference in regression slopes between groups ($F(1,41) = 0.01$, $p = .907$, $\eta^2 < .001$), but there was a significant effect of tempo ($F(1.4, 57.5) = 6.49$, $p = .007$, $\eta^2 = .086$). Slopes during the 700 ms IOI tempo differed significantly from both the 550 ms tempo, $t(42) = 2.92$, $p_{corr} = .017$, $d = 0.60$, and the 400 ms tempo, $t(42) = 4.11$, $p_{corr} < .001$, $d = 0.84$ (Bonferroni corrected), indicating that participants sped up more during the slowest tempo. There was no significant interaction between group and tempo ($F(1.4, 57.5) = 1.61$, $p = .213$, $\eta^2 = .02$). In metronome and continuation conditions, trials were averaged across the three tempi (400, 550, and 700 ms IOI), as no effect of tempo was found in either consistency or phase accuracy. For detailed analyses of consistency and phase scores with tempo as a factor, see supplementary data (Figure S4). For the tapping data, the assumption of sphericity was violated, such that the variances of the differences between conditions were not homogeneous ($X^2 = 10.23$, $p = .006$ for consistency, $X^2 = 7.55$, $p = .023$ for phase). Degrees of freedom for effects of condition and its interactions were corrected using Greenhouse-Geisser estimates ($\varepsilon = .813$ for consistency, $\varepsilon = .850$ for phase). Data was found to be normally distributed, as assessed by the Shapiro-Wilk test.

Tapping consistency for the musical excerpts was calculated similarly as for the metronome and continuation data, but with the stimulus beat locations defined by the tapping of the semi-professional musicians (see Methods). Music tapping trials were averaged across all six songs (for data separated by song, see Figure S5). An ANOVA with factors condition (metronome, music, and continuation) and group (rDCD, TD) and age as a covariate showed a significant effect of group, $F(1,40) = 4.46$, $p = .041$, $\eta^2 = .045$, and a significant effect of condition, $F(1.63, 65) = 6.05$, $p = .007$, $\eta^2 = .053$ (Figure 2B), but no interaction of group and condition, $F(1.63, 65) = 0.29$, $p = .702$ $\eta^2 = .003$. To further explore whether both metronome and music tapping (conditions with an auditory cue) had higher consistency than continuation tapping (condition without an auditory cue) in the rDCD alone, t-tests (Bonferroni corrected) were used to compare each pairwise combination of conditions in the rDCD group. Metronome tapping was significantly more consistent than both music tapping ($t(20) = 4.20$, $p = .001$, $d = 0.92$) and continuation tapping ($t(20) = 12.0$, $p < .001$, $d = 2.62$), and music tapping was more consistent than continuation tapping ($t(20) = 5.89$, $p < .001$, $d = 1.28$). Similar to the speech recognition task, a t-test examined difference scores between consistency when the beat was present (metronome) and when it was it was removed (continuation), and showed no difference between groups, $t(40.8) = 0.46$, $p = .645$, $d = 0.14$.

Phase accuracy (vector angle), analyzed using a 2x3 mixed design ANOVA with age as a covariate, revealed no significant effects of condition ($F(1.7,68) = 0.19$, $p = .796$, $\eta^2 = .003$), group ($F(1,40) = 0.57$, $p = .457$, $\eta^2 = .006$), or interaction of group and condition ($F(1.7,68) = 0.55$, $p = .552$. $\eta^2 = .008$) (Figure 2A). To investigate the absolute angular offset regardless of direction (tapping before vs. after the beat), we calculated the absolute value of the distance of taps from the beat in radians. A 2x3 mixed design ANOVA with age as a covariate found a significant effect of condition ($F(1.8,72.6) = 3.60$, $p = .037$, $\eta^2 = .040$), but no significant effect of group ($F(1,40) = 2.19$, $p = .146$, $\eta^2 = .023$) or interaction of group and condition ($F(1.8,72.6) = 0.17$, $p = .823$, $\eta^2 = .002$) (Figure 2C).

Figure 2

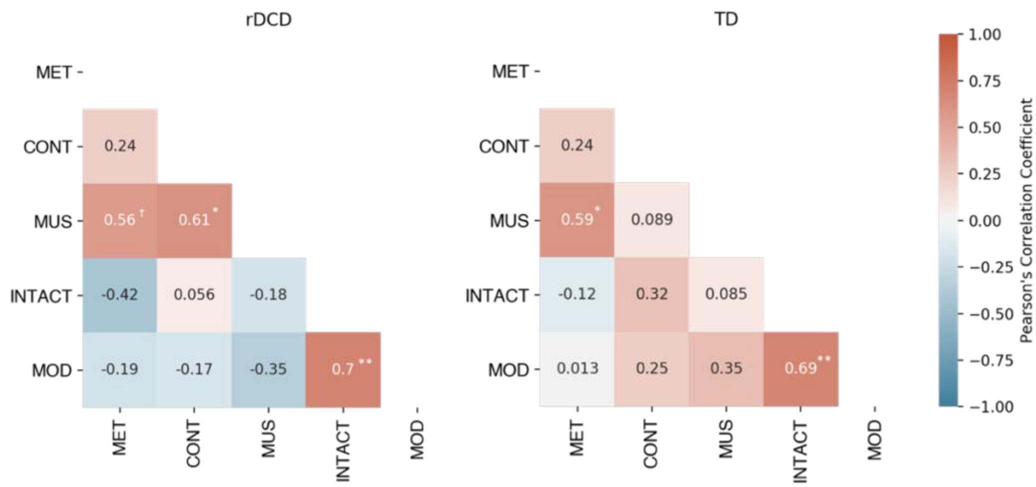


Consistency and phase accuracy scores for rDCD and TD groups in each tapping condition, averaged across tempi. Dots show individual data for rDCD (blue) and TD (orange) groups. Participants with CPRS-R:S T-scores > 60 are represented by Xs. (**A**) Polar plots in which tapping consistency is represented by the length of the mean vector R and accuracy is reflected by the angle (phase) of the mean vector R, measured in radians. The time of the stimulus beats is at 0. (**B)** Consistency scores in tapping production tasks showing significant effects of group ($p = 0.041$) and condition ($p = 0.007$). (**C**) Absolute value of tapping accuracy scores (radians) in tapping production tasks show a significant effect of condition ($p = 0.032$). * $p_{corr} < 0.05$; ** $p_{corr} < 0.01$; *** $p_{corr} < 0.001$ (Bonferroni corrected).

Relations among Motor Skills, Speech Recognition with Distorted Timing Conditions and Tapping Consistency

To investigate relations among the five tasks in the present study, Pearson's correlation coefficients were calculated for each pair of conditions (accuracy scores for the two speech recognition conditions [with and without modulated timing] and consistency scores for the three tapping conditions). Correlations for tapping conditions were conducted on logit-transformed consistency scores. For speech recognition with distorted timing conditions, correlations were conducted on proportion of correct responses. In the rDCD group, the three tapping conditions had correlation coefficients in the positive direction (metronome to continuation: $r(19) = .24$, $p_{corr} > .999$; metronome to music: $r(19) = .56$, $p_{corr} = .071$; continuation to music: $r(19) = .61$, $p_{corr} = .030$). The two speech recognition with distorted timing conditions were highly correlated, $r(19) = .70$, $p_{corr} = .004$, and both speech recognition conditions had negative or close to zero correlation coefficients with the tapping tasks, with none reaching significance. The TD group showed similar results, with correlation coefficients in the positive direction for metronome tapping with continuation and music tapping (metronome to continuation: $r(20) = .27$, $p_{corr} > .999$; metronome to music: $r(20) = .64$, $p_{corr} = .015$), although continuation and music tapping showed no relation ($r(20) = .04$, $p_{corr} > .999$). Again, the two speech recognition with (and without) distorted timing conditions were highly correlated ($r(20) = .69$, $p_{corr} = .005$), and showed a mix of positive and negative correlations to the three tapping conditions, but none reached significance. All p-values were corrected for multiple comparisons by Holm's method, and all correlations are summarized in Figure 3 and plotted in Figure S6.

Figure 3



Heatmap of Pearson's correlation coefficients for both rDCD and TD groups. MET = Metronome Tapping; CONT = Continuation Tapping; MUS = Music Tapping; INTACT = Intact Speech Rhythm Recognition; MOD = Modulated Speech Rhythm Recognition. * $p_{corr} < 0.05$; ** $p_{corr} < 0.01$; *** $p_{corr} < 0.001$; † $p_{corr} < 0.08$ (Holm's corrected).

To explore the relations between motor skills and the timing tasks of the present study, Pearson's correlations were calculated between MABC-2 scores and (1) modulated speech recognition accuracy scores (of interest as rDCD and TD groups differed on this measure) and (2) general tapping performance ("tapping scores" were calculated as the average of consistency scores in metronome, continuation, and music tapping conditions). Given that the rDCD and TD children came from the same sample of children and the MABC-2 scores are a continuous measure ranging from the 1st to 95th percentile, it is justified to include both groups together in an exploratory correlational analysis (Figure S7). Performance on the modulation condition of the speech recognition with distorted timing task correlated significantly with MABC-2 scores ($r(40) = .37$, $p_{corr} = .033$). There was also a trend for tapping consistency to correlate with MABC-2 scores, $r(40) = .29$, $p_{corr} = .053$, but it did not reach significance after correcting for multiple comparisons (p-values corrected by Holm's method).

Discussion

The present study showed that children with rDCD can use rhythmic tracking to benefit their performance during speech recognition and auditory-motor synchronization. Children with rDCD showed deficits in identifying target words in the presence of distractor sentences when speech is rhythmically modulated, although their performance was indistinguishable from TD children when the sentences were normally-timed. Children with rDCD also tapped to a beat less consistently than TD children, but (like TD children) tapped with significantly higher consistency when an auditory cue (i.e., a metronome or music) was present compared to when there was no auditory cue. As the multimodal integration of auditory-motor synchronization of DCD has rarely been investigated, our findings provide a novel connection between deficits in auditory timing perception [25] and on repetitive motor tasks [12] in DCD. These findings imply that research on task-oriented interventions for children with DCD should include an auditory rhythmic cue, as the presence of an auditory cue may help to guide the timing of the motor skill during training, which in turn may provide additional benefit compared to motor-only therapeutic strategies [58].

Children with rDCD rely on rhythmic cues in speech recognition more than TD children

Both groups were able to identify target words in the presence of distractor sentences with similar accuracy when the rhythm of the sentences was left intact. However, when the rhythm of the sentences was modulated, the rDCD group's recognition of target words suffered more, suggesting that, in comparison to TD children, those with rDCD were more reliant on the familiar rhythmic cues in language and less flexible in adapting to modulated speech rhythms. The lack of a difference between rDCD and TD children for the rhythmically intact sentences appears, at first glance, at odds with the previous finding that children at risk for DCD had higher thresholds for detecting small timing deviations in isochronous metronomes [25]. However, the two tasks differ in that our speech task requires using rhythmic tracking to detect speech content whereas the previous task of detecting timing deviations in a metronome requires retrospective evaluation of the rhythm itself. Another major difference is that children must recognize speech with intact rhythms every day of their lives, whereas metronome listening is not part of normal life, and our results indicate that children with rDCD are well able to use rhythmic cues to decipher speech. However, the fact that children with rDCD exhibit greater performance decline than TD children when speech rhythm was modulated implies less flexible adaptability in their rhythm perception. This is consistent with previous visual-motor work showing children with DCD are slower to adapt to changes in visual information [43]. To our knowledge, this is the first study to show the impact of poor adaptation to modulated auditory rhythmic timing in a context that does not involve an overt motor component.

Although the rDCD group had more colour name errors overall, the TD group displayed a higher proportion of intrusion errors from the background (to be ignored) sentences, whereas children with rDCD were more likely to guess a random colour, suggesting the TD group displayed greater misdirected attention while the rDCD group displayed a more general distraction associated with the modulated speech rhythms.

Auditory-Motor Synchronization in DCD

Being able to perform movements at specific times and in rhythmic patterns are important skills in the development of motor abilities, as many everyday motor tasks involve predicting and executing specific timing. Children with rDCD showed significantly less consistent tapping across metronome, continuation, and music conditions than TD children. However, importantly, both groups had significantly greater tapping consistency (in relation to the beat or implied beat) in conditions with an auditory cue (metronome and music) than without (continuation tapping). This performance benefit of having the auditory cue present was shown similarly in both groups, as evidenced by the non-significant difference between groups in the difference scores for consistency between metronome and continuation. This shows that children with rDCD can rhythmically track auditory cues, integrate the auditory cues and motor commands, and the auditory cues help them to perform more consistent movements. More specifically, performance was more consistent for tapping to the metronome than to music for both rDCD and TD groups. This is perhaps not surprising as the beat is directly given by the metronome, but must be extracted from the complex acoustic signals of music. Still, children with rDCD benefitted and showed more consistent tapping to music than in the continuation condition where auditory cues were absent.

For phase, both groups performed very similarly to one another across conditions, suggesting both groups were able to accurately track the beat of the stimuli. This is similar to Lê et al.'s (2021) finding that children with DCD had similar accuracy to TD children when synchronizing a verbal response to an isochronous rhythm [17]. When tapping to an auditory stimulus, adults typically tap ahead of the beat [52,59]. Consistent with this, in the metronome condition, children showed a mean negative asynchrony, demonstrating the operation of predictive processes for when they expected the next beat. On the other hand, mean asynchronies for continuation and music tapping were close to zero, with some participants tapping before the beat, and some tapping after. It is likely that this reflects that the children sometimes anticipated the beat, as with metronome tapping, while sometimes reacted to the beat, and hence tapped on the late side, as the absolute values of phase differences between taps and stimuli show the metronome to have the least absolute asynchrony, followed by the music, followed by continuation trials. In any case, the trends across conditions are similar to studies in adults that have found metronome tapping to have a larger negative asynchrony than music tapping [52,60]. Most importantly, children with rDCD showed very similar mean phase alignment to the beat as TD children across all the conditions indicating that they are able to coordinate motor tapping to auditory cues.

While phase alignment was similar across the groups, it is interesting that in the music conditions, a significantly higher proportion of the rDCD group tapped the rhythm of the music as opposed to the beat, compared to the TD group. This group difference was seen not only in the total proportion of music tapping trials, which could be driven by a few participants tapping the rhythm to all of the songs, but also in the number of participants who had at least one trial of rhythm tapping. As mentioned above, unlike with metronome tapping for which every auditory sound is a beat, tapping to music requires the participant to extract the steady isochronous beat from multiple cues in the music, including different note durations (e.g., quarter notes, eighth notes, etc.), pitch and harmonic cues to beats, and multiple instruments playing simultaneously. The difference between groups in the frequency and number of children who tapped the rhythm rather than the beat in the music condition aligns with our interpretation of the speech perception results, in which the rDCD group was less adaptable to changes in what they expected the speech timing to be. This effect is unlikely to be due to a misunderstanding of the task, as the experimenter ran a practice trial with the participants to ensure they understood what the "beat" of the song was, and reminded participants between trials to tap the beat if they noticed any rhythm tapping. It is possible that the rDCD group had more difficulties with inhibition (i.e.

inhibiting their desire to tap the rhythm), increased cognitive demands (i.e. extracting the beat of the music instead of tapping the more obvious rhythmic pattern), or an increase in distraction by the rhythm.

In the spontaneous motor tempo task, both groups showed slower tapping than has been reported previously in the literature. For example, McAuley et al. (2006) reported that children of this age prefer to tap around 520 ms intervals [55], whereas we found mean tapping intervals to be 806 ms and 860 ms for the rDCD and TD groups, respectively. We believe this difference may have arisen from our instruction, in which we asked the participants to tap, "steady like a clock," in an effort to explain that the goal of the task was to tap as consistently as possible. However, this may have led the participants to attempt to match the timing of a clock, thus influencing them to tap slower than they otherwise would have.

Relations among Motor Skills, Speech Conditions and Tapping Consistency

Previous studies in TD adults show a positive correlation between perception and production skills for auditory timing and auditory-motor synchronization [48,52,61,62]. In the present study, perceptual and perceptual-motor consistency was not significantly correlated. This might be because we used a speech task for our perceptual measure, but metronome and music tasks for auditory-motor synchronization. It is also worth noting that our speech task was not a beat-based task, whereas the tapping tasks were, which may affect the relation between the two. As well, our speech task also cannot be directly compared directly to Chang et al.'s (2021) finding of auditory perceptual timing deficits in children with rDCD. Not only did they use rhythm and duration discrimination tasks rather than speech-based tasks, but the nature of the tasks was different, as our speech recognition with distorted timing task did not require the participants to make judgments about speech timing. Our speech task also contained an auditory distraction component, which Chang et al.'s (2021) task did not [25]. A possible interpretation of these null correlational findings is that music and speech tasks may be tapping into somewhat different underlying processes, future work should explore the relation between auditory-motor synchronization and perceptual beat perception using more relatable tasks.

We also did an exploratory investigation on whether an overall measure of auditory motor synchronization (tapping consistency on the metronome, continuation, and music tapping tasks) and performance on the rhythmically modulated speech perception task were correlated with the MABC-2 percentiles. Though most of the analyses in this study used group (rDCD or TD) as a factor, as group differences were the main focus of this research, using the MABC-2 percentiles as a continuous measure allowed a broader investigation into the relation of general motor skills and our tasks. Both tapping consistency and modulated speech recognition had positive correlations with the MABC-2. We did not have the sample size to examine these correlations in the groups separately, so more research is necessary to fully understand the relationship between auditory timing perception and general motor skills.

Rhythm Deficits in Neurodevelopmental Disorders

Our study excluded participants with autism spectrum disorder, but we did not assess for dyslexia or developmental language disorder. While this can be seen as a limitation, DCD is reported to be highly comorbid and overlap in symptoms with other developmental disorders [1,29,63], so attempting to identify groups of participants with "pure" DCD would not reflect the true heterogenous nature of the group. We did, however, exclude participants with autism spectrum disorder, as there is some debate as to whether children with ASD can have an additional diagnosis of DCD [64,65]. Beyond DCD, evidence is accumulating that timing and rhythm deficits are associated with many neurodevelopmental disorders, including dyslexia, attention deficits and autism spectrum disorder [29,66]. Our findings of impaired synchronized tapping production, along with Chang et al.'s (2021) findings of impaired rhythm and duration perception fit in well with these studies [25]. However, as noted by Lense et al.'s (2021) review, there is not a clear or linear relation between neurodevelopmental disorders and associated rhythm deficits [63]. More research is needed to further understand individual differences in DCD, and how they relate to rhythm and beat perception and production.

Conclusion

Compared to age-matched typically developing children, children at risk for DCD were found to be significantly less consistent during auditory-motor synchronization tapping tasks, as well as more reliant on intact rhythms during a speech recognition task involving no overt motor component. At the same time, motor tapping performance in children with rDCD showed similar benefit as for TD children with the presence of an auditory cue. These results fit in well with research showing that neurodevelopmental disorders that are highly comorbid with DCD, such as attention deficits and dyslexia, also have associated deficits in auditory timing perception and auditory-motor tapping consistency. Given that children in both the rDCD and TD groups had more consistent tapping when an auditory cue was present, it is worth investigating interventions for children with DCD that combine rhythmic auditory stimuli and repetitive movements.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

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Supplementary Material

Movement Assessment Battery For Children – 2nd Edition

The Movement Assessment Battery for Children - 2nd Edition (MABC-2) [1] was used as the standardized measure of motor coordination. Individually administered 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 [1]. All participants were in the same age band, and thus were all tested on the same installment of the MABC-2 (Age Band 2). The MABC-2 data was collected as part of the CATCH study [2,3], on average 11.15 ± 6.03 months prior to participating in the experiment. Participants' MABC-2 scores ranged from the 0.5th-95th percentile. Children scoring at or below the 16th percentile were placed in the probable developmental coordination disorder (rDCD) group, and children above the 16th percentile were in the typically developing (TD) group (Figure S1).

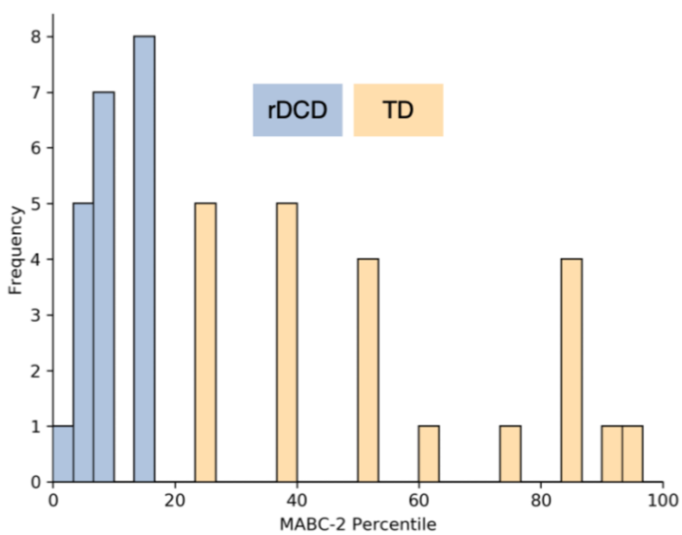


Figure S1. Histogram of MABC-2 Percentile Scores.

The Effect of Sex on Speech Recognition and Tapping Production Consistency

Sex was not included as a covariate in any of the main analyses due to the low number of female participants in the rDCD group (four out of 21 participants). To ensure sex was not a significant predictor of major outcome variables, t-tests between male and female participants were conducted for the TD group alone, as the TD group has a much more even distribution of boys and girls (13 of 22 participants were female). A Welch's t-test of overall tapping score (mean consistency for metronome, continuation, and music tapping) found no significant difference between boys and girls, $t(19.8) = 0.03$, $p = .976$, $d = 0.01$. A Welch's t-test of the difference score in the speech recognition task (difference in proportion of correct responses between intact and modulated conditions) also found no significant difference between boys and girls, $t(14.7) = 0.65$, $p = .524$, $d = 0.29$.

Investigating Differences Between Groups During Spontaneous Motor Tempo Tapping

T-tests comparing group differences during spontaneous motor tempo tapping revealed no significant differences in preferred tempo ($t(41) = -0.60$, $p = .553$, $d = -0.18$) or coefficient of variation ($t(41) = 0.12$, $p = .905$, $d = 0.04$). Coefficient of variation was defined as the standard deviation of intervals divided by the mean interval across a trial. Individual data is shown in Figure S2.

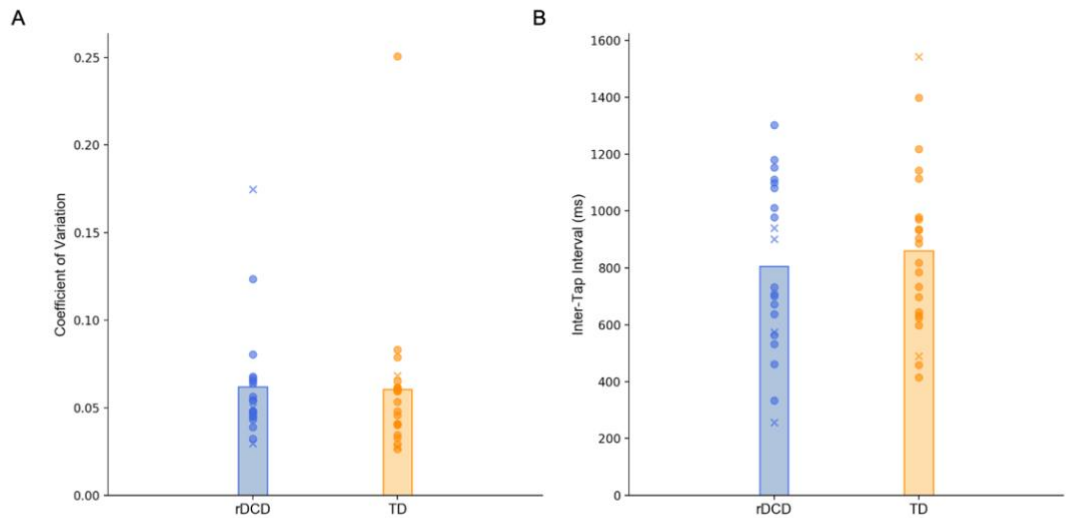


Figure S2. Spontaneous motor tempo tapping. Participants with CPRS-R:S T-scores >60 are represented by Xs. (A) Mean inter-onset intervals for both rDCD and TD. (B) Mean coefficient of variation of inter-onset intervals. Dots represent individual data.

Investigating Whether Participants Sped Up or Slowed Down During Continuation Tapping

During continuation tapping, consistency and phase scores were calculated using the difference in time between where the participants tapped and where the auditory metronome would have been, had it continued. To ensure these results weren't being skewed by one group slowing up or speeding down over the course of a trial more than another group, we ran a linear regression analysis on the inter-tap intervals of each trial for each participant. The slope of the calculated regression lines were compared between groups and tempi in a 2x2 mixed ANOVA, and no effect of group was found ($F(1,41) = 0.01$, $p = .907$, $\eta^2 < .001$). A significant effect of tempo was observed ($F(1.4, 57.5) = 6.49$, $p = .007$, $\eta^2 = .086$) in which the slowest tempo (700 ms IOI) had the greatest amount of change in speed, and the fastest tempo (400 ms IOI) had the least. Mean regression lines are shown in Figure S3.

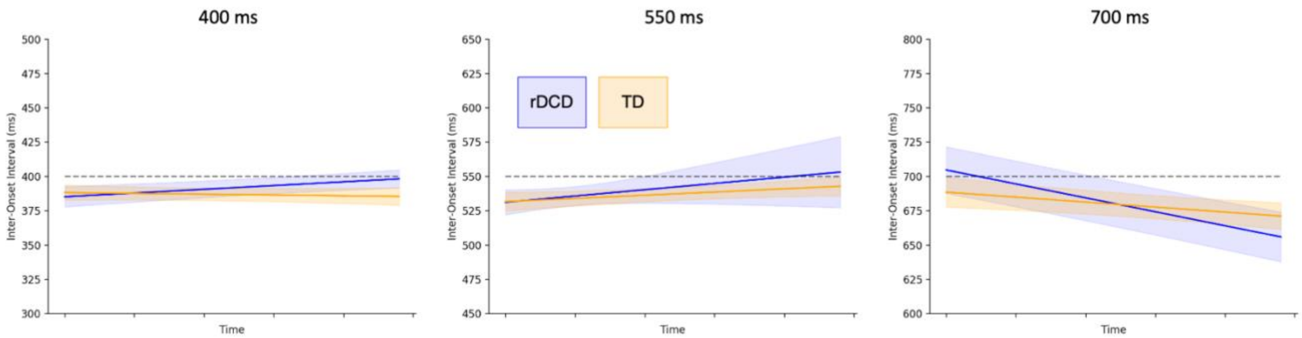


Figure S3. Mean regression lines for inter-tap intervals during continuation tapping, representing participants speeding up or slowing down their tapping speed across a trial. The grey dotted line is at the stimulus tempo, thus represents what the regression line would look like if participants tapped at the correct speed with no speeding up or slowing down (slope = 0).

The Influence of Tempo on Tapping Production Consistency

Consistency scores during tapping production tasks were calculated using circular statistics to find the length of the average vector *R* (Figure S4A). Scores range from 0-1, and were submitted to a logit transformation before further analysis. Consistency scores were first compared between the metronome and continuation conditions (excluding the music condition), as the tempi in these two conditions were matched (Figure S4B). For both conditions, there were two trials per tempo, and these were averaged prior to conducting the statistical analysis. All sphericity and normality assumptions were met. A 2x2x3 mixed-design ANOVA was performed to examine logit-transformed consistency scores with and without an auditory cue (metronome vs. continuation conditions), with tempo (400, 550, 700) and group (rDCD, TD) as factors, and age as a covariate. Results revealed a significant effect of group, $F(1,40) = 5.25$, $p = .027$, $\eta^2 = .03$, with higher consistency in the TD group (rDCD = 0.58, SD = 0.09; TD = 0.64, SD = 0.08), and a significant effect of condition, $F(1,40) = 6.80$, $p = .013$, $\eta^2 = .03$, with higher consistency in metronome tapping (metronome = 0.82, SD = 0.09; continuation = 0.40, SD = 0.14). There was no significant effect of tempo, $F(1.97, 78.81) = 1.05$, $p = .352$, $\eta^2 = .006$ or interactions (condition x group: $F(1,40) = 0.02$, $p = .89$, $\eta^2 < .001$; tempo x group: $F(2, 80) = 0.32$, $p = .73$, $\eta^2 = .002$; condition x tempo: $F(2, 80) = 2.45$, $p = .09$, $\eta^2 = .013$; tempo x group x condition: $F(2, 80) = 0.56$, $p = .57$, $\eta^2 = .003$).

The Influence of Tempo on Tapping Production Accuracy

Phase accuracy scores during tapping production tasks were calculated using circular statistics to find the angle of the average vector *R* (Figure S4A). Scores were measured in radians. Tapping production was measured during three tempi (400, 550, and 700 ms inter-onset intervals). All sphericity and normality assumptions were met. To first compare just metronome and continuation with tempo as a factor, a 2x2x3 mixed design ANOVA with factors condition (metronome and continuation), tempo (400, 550, and 700 ms IOI), and group (rDCD and TD) with age as a covariate was performed. We found no main effects of condition, $F(1,40) = 0.24$, $p = .628$, $\eta^2 = .001$, group, $F(1,40) = 1.17$, $p = .285$, $\eta^2 = .006$, tempo, $F(2, 80) = 1.10$, $p = .338$, $\eta^2 = .007$, or interactions (Figure S4C).

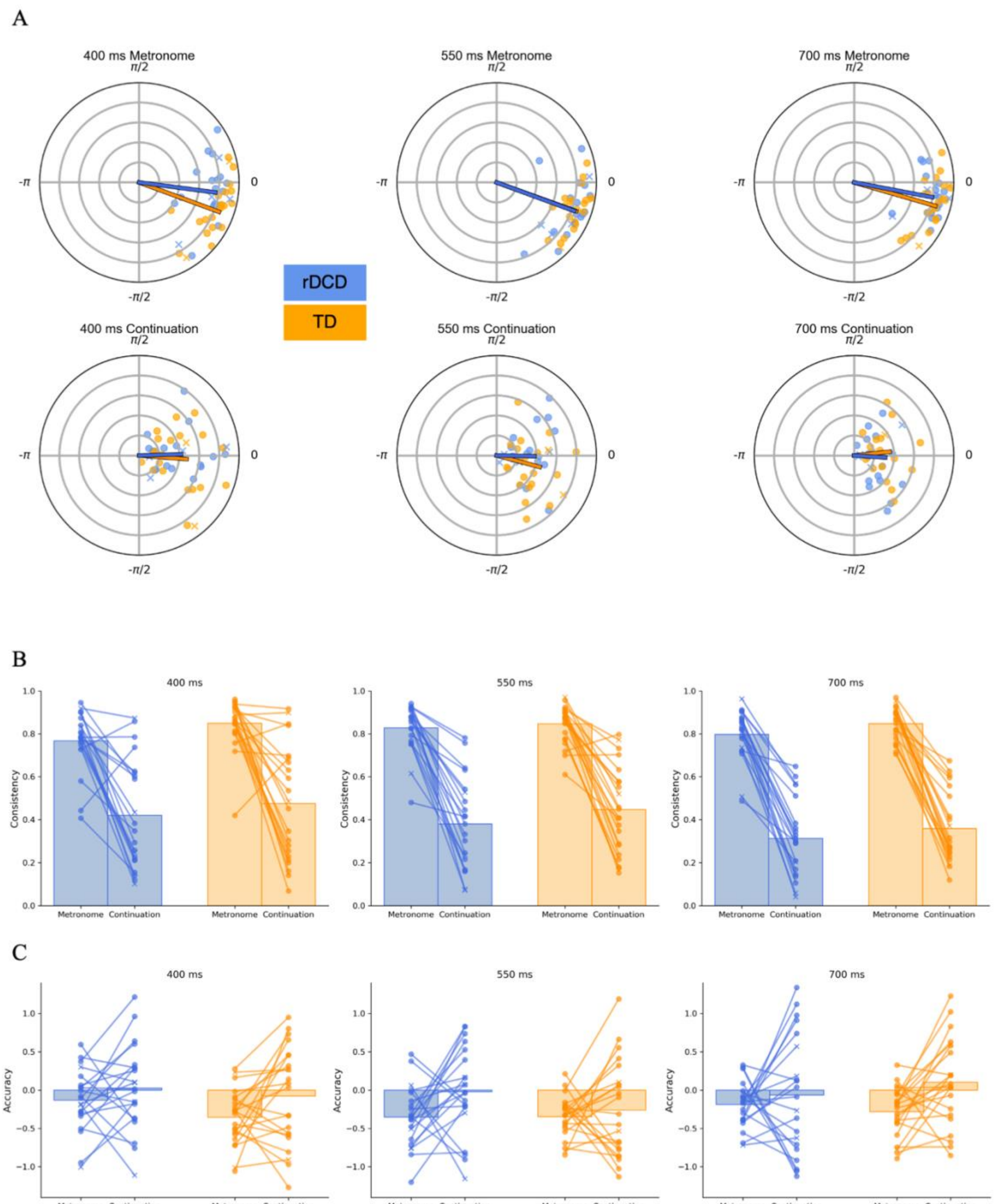


Figure S4. Consistency and phase accuracy scores for rDCD and TD groups in metronome and continuation tapping across three tempi. Participants with CPRS-R:S T-scores >60 are represented by Xs. (A) Polar plots of tapping production during metronome and continuation tapping, separated by tempo. Tapping consistency was calculated by the length of the mean vector R, and tapping accuracy was calculated by the angle of the mean vector R. (B) Tapping consistency separated by group and tempo. (C) Tapping accuracy (radians) separated by group and tempo. Negative values represent tapping before the beat.

The Influence of Song Excerpt on Consistency and Phase During Music Tapping

During music tapping production, participants tapped along to the beat of six different musical excerpts ranging in tempi from 500-700 ms IOIs. For consistency scores, a 2x6 mixed ANOVA with age as a covariate and factors group (rDCD and TD) and song (six excerpts) showed no significant effects of group ($F(1,35) = 1.08$, $p = .305$, $\eta^2 = .017$), song ($F(5, 175) = 1.05$, $p = .390$, $\eta^2 = .008$), or interactions. Consistency scores for both rDCD and TD groups, separated by song, are summarized in Figure S5A. For phase accuracy, a 2x6 mixed ANOVA with age as a covariate and factors group (rDCD and TD) and song (six excerpts) showed no effects of group ($F(1,36) = 0.008$, $p = .929$, $\eta^2 < .001$), song ($F(3.94, 141.7) = 0.34$, $p = .85$, $\eta^2 = .006$, or interaction. Greenhouse-Geisser corrections were applied to the phase data ($\varepsilon = .787$) as the assumption of sphericity was not met ($X^2 = 29.32$, $p = .010$). Accuracy scores are summarized in Figure S5B.

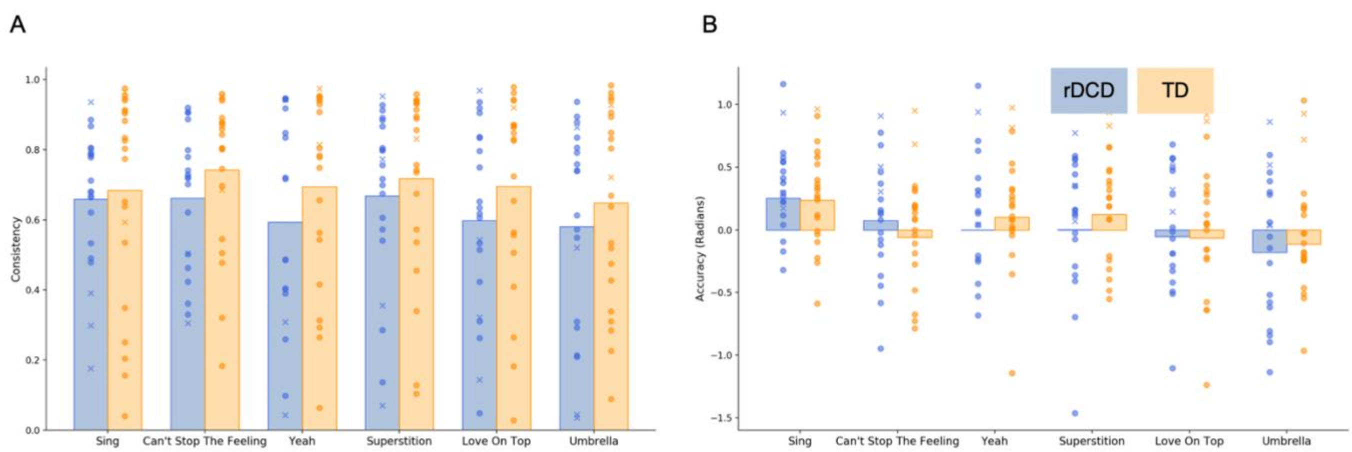


Figure S5. Consistency and Accuracy scores for rDCD and TD groups in music tapping for each of the six musical excerpts. Participants with CPRS-R:S T-scores >60 are represented by Xs. (A) Consistency scores during music tapping separated by song. (B) Phase accuracy scores (radians) during music tapping separated by song. Negative values represent tapping before the beat.

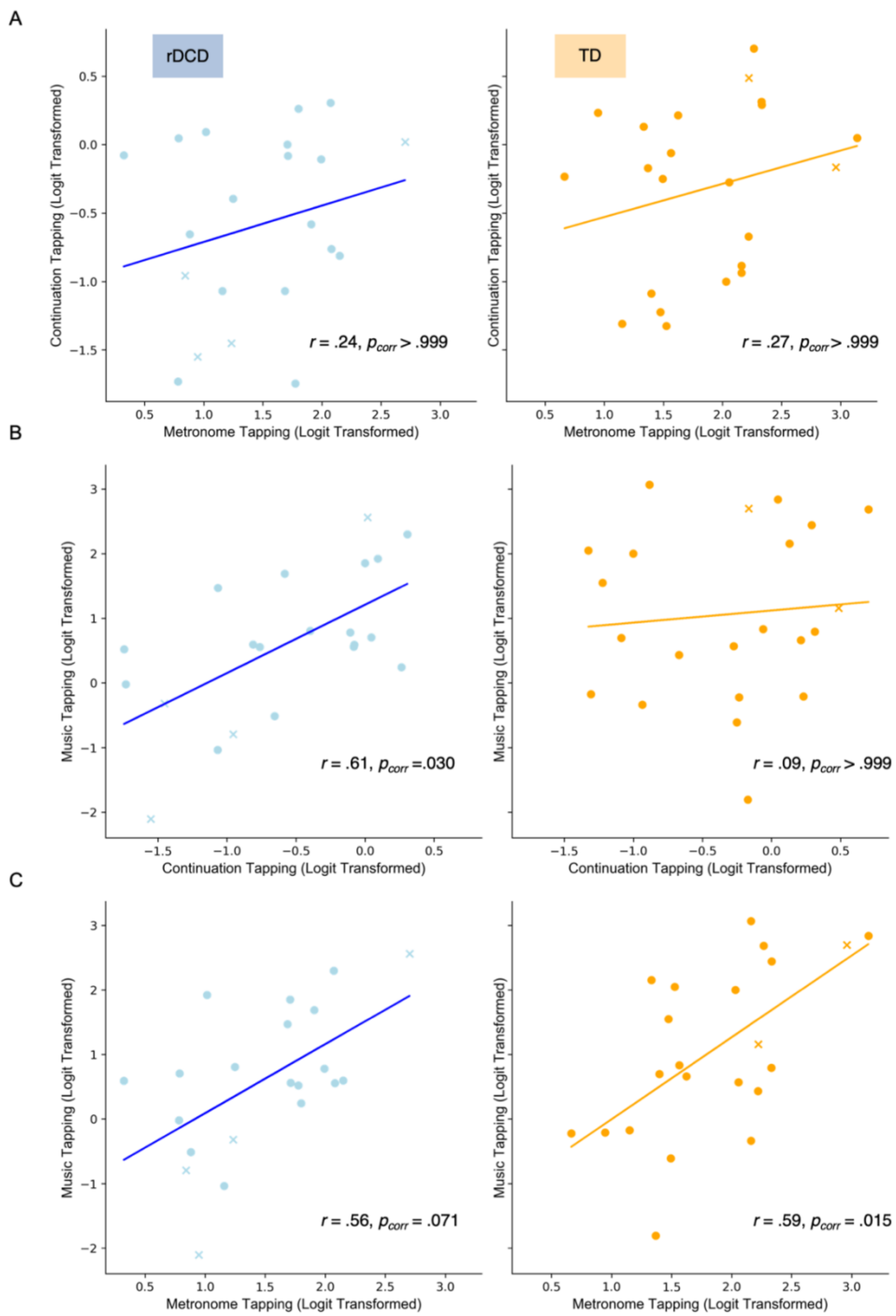
Results of Tapping Production Analyses if All Trials Kept

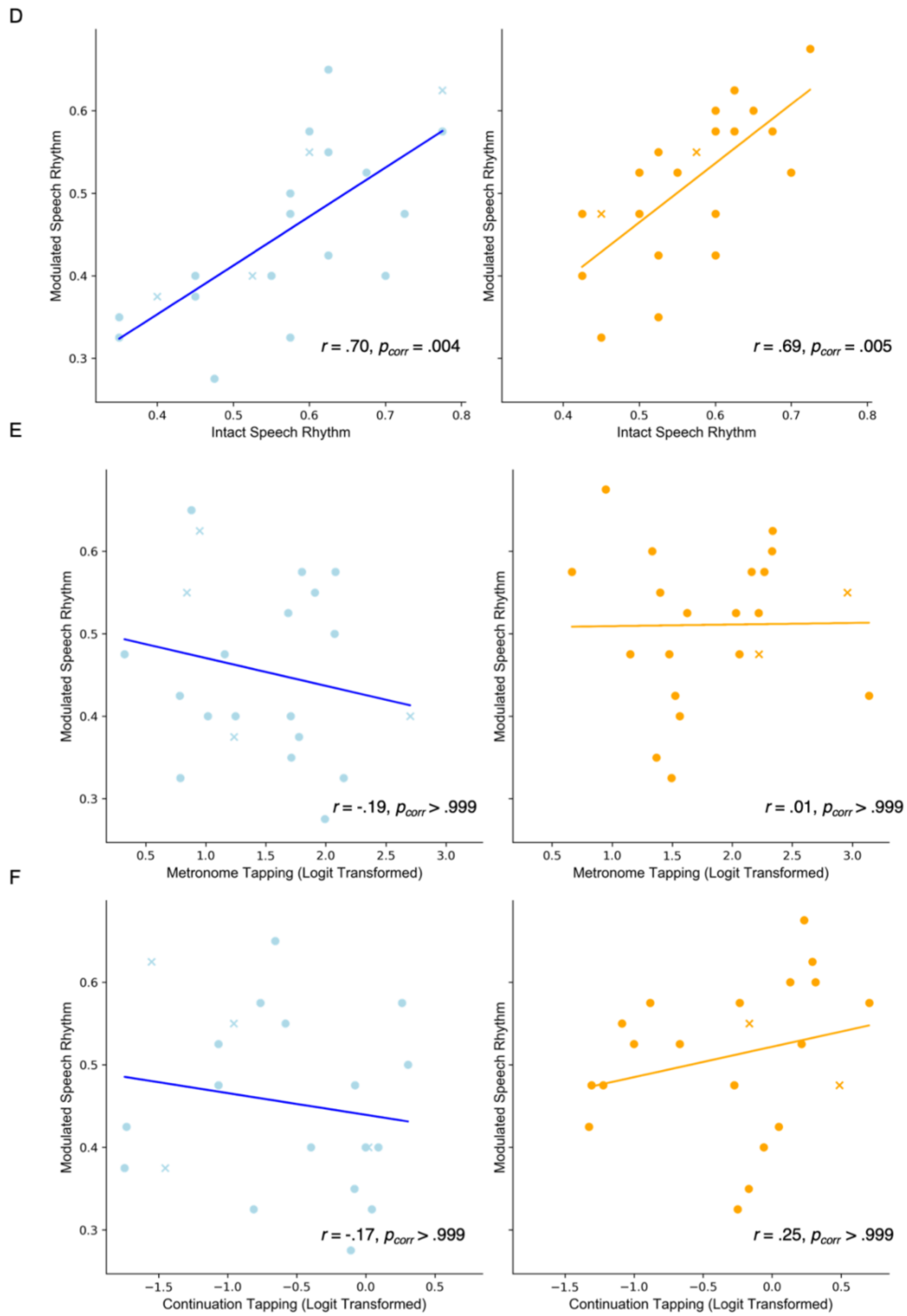
To account for trials where participants did not tap the beat of the song, but instead tapped a more complex rhythm, any trials flagged by the semi-professional musician rater as 'rhythm tapping' were removed. Given that these trials were flagged using the rater's judgement, the analysis investigating tapping consistency across conditions was run with all trials included. An ANOVA with factors condition (metronome, music, and continuation) and group (rDCD, TD) and age as a covariate showed a significant effect of group, $F(1,40) = 5.67$, $p = .033$, $\eta^2 = .051$, a significant effect of condition, $F(1.52, 60.75) = 4.31$, $p = .027$, $\eta^2 = .040$, and no interaction, $F(1.52, 60.75) = 0.61$, $p = 0.505$, $\eta^2 = .006$. Greenhouse-Geisser corrections were applied (ε =

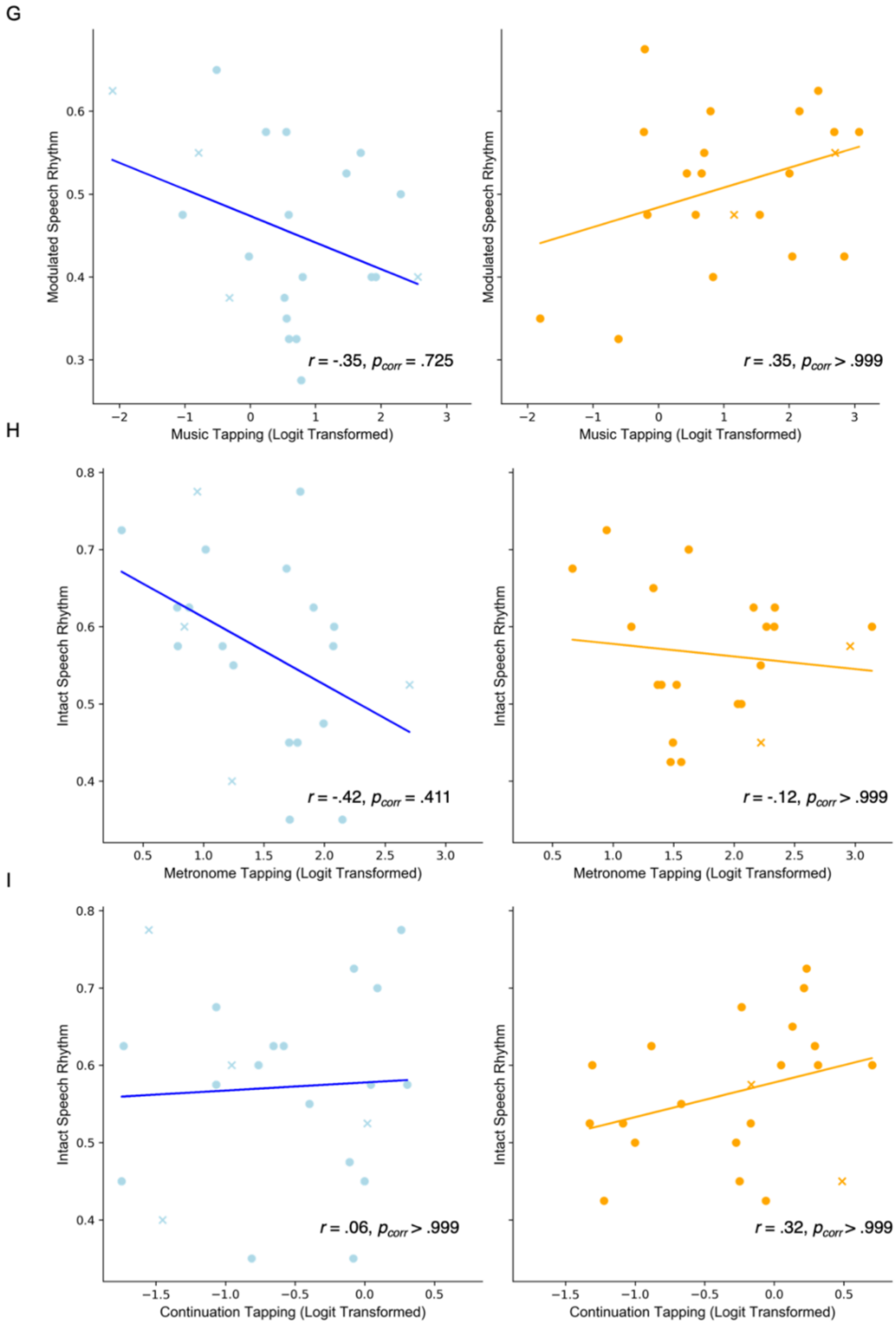
.759) as the assumption of sphericity was not met (X^2 = 14.86, p < .001). T-tests between pairs of tapping conditions were significant, such that music tapping was significantly more consistent than continuation tapping (t(42) = -4.75, p < .001) and significantly less consistent than metronome tapping (t(42) = 6.14, p < .001). The correlation between MABC-2 scores and a general tapping score (all three conditions averaged for each participant) nearly reached significance, r(40) = 0.34, p = .053, after correcting for multiple comparisons.

Relations Between Each Set of Task Conditions

Pearson's correlation coefficients were calculated for each possible pair of tasks. For tapping production tasks, consistency scores were used to calculate correlations. For speech timing distortion tasks, proportion of correct responses were used. All correlation plots are shown in Figure S6. To further investigate the relations of these tasks with general motor skills, a tapping score (mean consistency of tapping production averaged across metronome, continuation, and music conditions) and scores on the modulated speech timing task were correlated with MABC-2 percentiles (Figure S7). To understand which of the tapping tasks were most related to the MABC-2 percentiles, each of the metronome, continuation, and music tapping tasks were correlated separately to the MABC-2, corrected for multiple comparisons (Bonferroni). Metronome tapping and MABC-2 percentiles were significantly correlated before Bonferroni correction (r(41) = .34, p = .023), but did not reach significance after correction (p_{corr} = .085). Continuation tapping and MABC-2 percentiles were not significantly correlated (r(41) = .25, p_{corr} = .324), nor were music tapping and MABC-2 percentiles (r(41) = .22, p_{corr} = .810).


A
rDCD
TD
Continuation Tapping (Logit Transformed)
Metronome Tapping (Logit Transformed)
r = .24, p_corr > .999
r = .27, p_corr > .999
B
Music Tapping (Logit Transformed)
Continuation Tapping (Logit Transformed)
r = .61, p_corr =.030
r = .09, p_corr > .999
C
Music Tapping (Logit Transformed)
Metronome Tapping (Logit Transformed)
r = .56, p_corr = .071
r = .59, p_corr = .015


D
Modulated Speech Rhythm
Intact Speech Rhythm
r = .70, p_corr = .004
r = .69, p_corr = .005
E
Metronome Tapping (Logit Transformed)
r = -.19, p_corr > .999
r = .01, p_corr > .999
F
Continuation Tapping (Logit Transformed)
r = -.17, p_corr > .999
r = .25, p_corr > .999


G
Modulated Speech Rhythm
Music Tapping (Logit Transformed)
r = -.35, p_{corr} = .725
r = .35, p_{corr} > .999
H
Intact Speech Rhythm
Metronome Tapping (Logit Transformed)
r = -.42, p_{corr} = .411
r = -.12, p_{corr} > .999
I
Intact Speech Rhythm
Continuation Tapping (Logit Transformed)
r = .06, p_{corr} > .999
r = .32, p_{corr} > .999

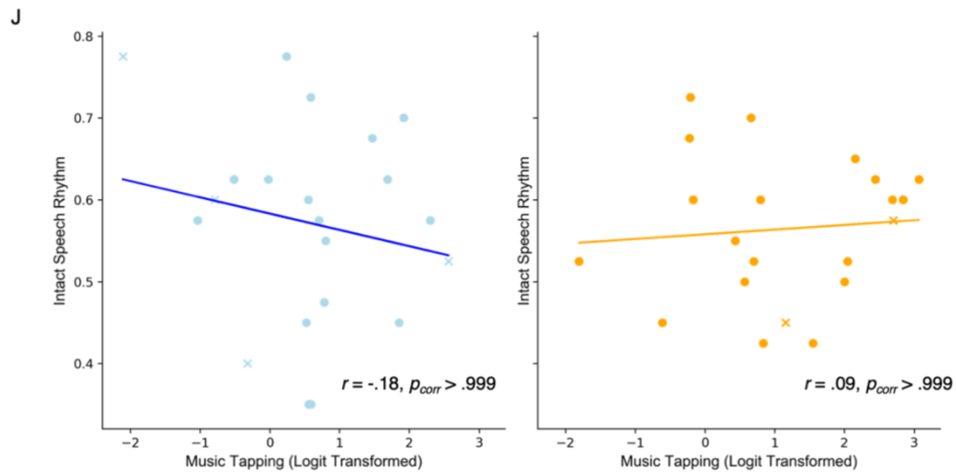


Figure S6. Correlation plots of each pair of tapping production conditions (metronome, music, and continuation) and speech recognition with distorted timing (intact rhythm, modulated rhythm). All correlations are separated by group (rDCD in blue), and the plotted line represents the line of best fit. Participants with CPRS-R:S T-scores >60 are represented by Xs. (A) Metronome and Continuation Tapping. (B) Continuation and Music Tapping. (C) Metronome and Music Tapping. (D) Intact Speech and Modulated Speech. (E) Metronome Tapping and Modulated Speech. (F) Continuation Tapping and Modulated Speech. (G) Music Tapping and Modulated Speech. (H) Metronome Tapping and Intact Speech. (I) Continuation Tapping and Intact Speech. (J) Music Tapping and Intact Speech.

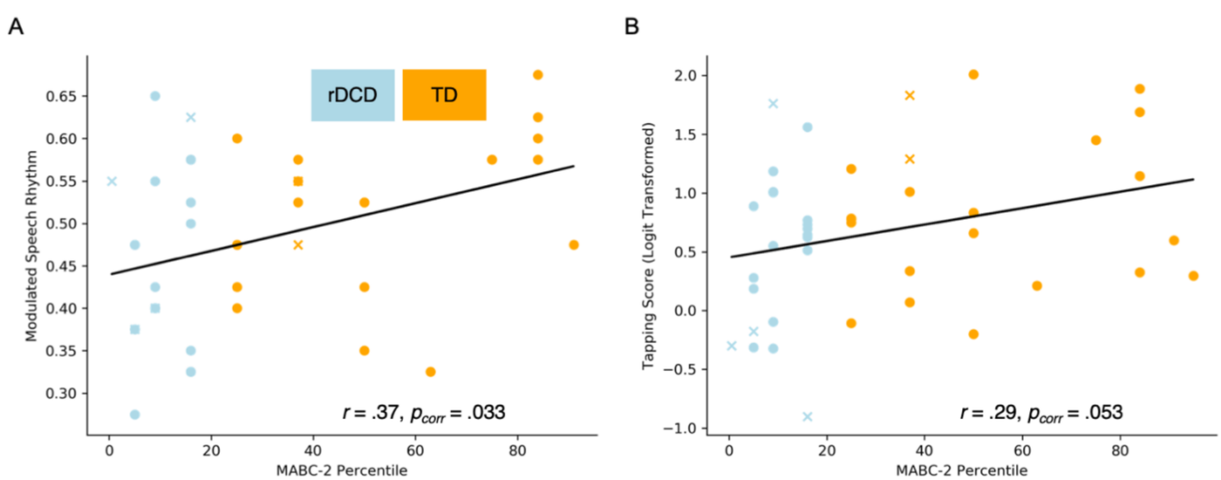


Figure S7. Correlation plots of MABC-2 scores with modulated speech rhythm scores and tapping scores. Tapping score is calculated as the average consistency in music, continuation, and metronome tapping. Groups are combined; rDCD is represented in blue, TD is represented in orange. Participants with CPRS-R:S T-scores >60 are represented by Xs. (A) MABC-2 percentile and proportion of correct responses in the modulated speech rhythm condition. (B) MABC-2 percentile and tapping score.

Relation of Semi-Professional Musician Ratings to Circular Statistics

To ensure quality of the circular statistical analyses performed on the consistency data, a semi-professional musician rated every music tapping trial on a scale of 0-100 for the question: How synchronized was the tapping to the music, regardless of whether they tapped the beat or the rhythm? Results showed a significant positive correlation between the ratings of synchronization and the calculated consistency scores, $r(512)=0.75$, $p < .001$.

Influence of Music Training on Task Performance

To ensure that the group effects present in the speech recognition with distorted timing were not affected by music training, the ANOVA was run including years of music training as a covariate. Results showed a trend towards an effect of music training ($F(1,38) = 3.89$, $p = .056$, $\eta^2 = .071$), but the interaction of group and condition remained significant ($F(1,38) = 6.12$, $p = .018$, $\eta^2 = .023$), and the main effects of group ($F(1,38) = 0.91$, $p = .346$, $\eta^2 = .017$) and condition ($F(1,38) = 0.02$, $p = .884$, $\eta^2 < .001$) remained insignificant. To ensure the group effects present in the tapping tasks were not affected by music training, the ANOVA was run including years of music training as a covariate. The effect of music training was not significant ($F(1,39) = 0.04$, $p = .840$, $\eta^2 < .001$) and the effect of group remained significant ($F(1,39) = 4.36$, $p = .043$, $\eta^2 = .046$), as did the effect of condition ($F(1.63, 63.37) = 5.10$, $p = .013$, $\eta^2 = .047$).

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Chapter 3: Can Children at Risk for Developmental Coordination Disorder Step-Clap to the Beat? Evidence From an Online Motion Tracking Study

Carrillo, C., Dotov, D., & Trainor, L. J. (2025). Can children at risk for developmental coordination disorder step-clap to the beat? Evidence from an online motion tracking study. *Human Movement Science*, *102*, 103387. https://doi.org/10.1016/j.humov.2025.103387
This is a preprint in compliance with the policies of *Human Movement Science*.

Preface

Building on the findings from the previous chapter, Chapter 3 expands the study of auditory-motor synchronization in children with rDCD to more complex, whole-body movements. Whereas tapping tasks capture fine motor coordination in a controlled setting, everyday motor activities often require integrating larger movements with rhythmic cues. Here, I used an online step-clap dance task to investigate gross-motor synchronization to different auditory stimuli. I found that children with rDCD performed the step significantly slower than typically developing children, and their performance was less coordinated to the auditory rhythms at faster tempi compared to typically developing children. These findings expand our understanding of auditory-motor synchrony deficits in rDCD, and emphasize the importance of considering tempo if auditory cues are to be used in motor interventions for DCD.

Abstract

Developmental coordination disorder (DCD) is a neurodevelopmental disorder involving deficits in motor coordination. Recent evidence has shown children at risk for DCD have associated

auditory timing perception and auditory-motor synchronization deficits, but it remains unclear how these deficits would appear in full-body coordination tasks, particularly as DCD is often associated with gross motor impairments such as balance and gait. Current interventions for DCD focus on motor training alone, although preliminary findings suggest that motor interventions with rhythmic auditory cueing may confer additional benefit. To investigate auditory-motor synchronization during full-body coordination, we tested whether children aged 9-12 at risk for DCD could synchronize a step-clap dance step to various auditory stimuli using online data collection. Frequency analysis of the tracked head, hands, and feet showed that children at risk for DCD perform the dance step overall slower compared to typically developing children. Cross-correlations of the movements to an interpolated harmonic wave representing the auditory beats showed the group at risk for DCD were less coordinated to the auditory beat compared to typically developing children at the fast tempi, but that both groups performed similarly at slower tempi. Additionally, both groups were more coordinated and less variable at slower compared to faster tempi. These results indicating better performance in children at risk for DCD at slower auditory tempi are important for informing decisions on auditory stimuli during the design of auditory-motor interventions for DCD.

1. Introduction

Motor impairments in children with neurodevelopmental disorders are common and strongly impact the quality of life of children experiencing them (Lucas et al., 2016). Developmental coordination disorder (DCD) in particular is a common neurodevelopmental disorder characterized by deficits in motor skills. DCD affects 5-6% of the population and is defined as impairments in the acquisition and execution of fine and/or gross motor skills (American Psychiatric Association, 2013). Children with DCD are often referred to as "clumsy", and struggle with simple daily tasks such as playing sports, riding a bike, walking, writing, or using utensils. These impairments negatively impact their daily lives, and can lead to increases in anxiety, depression, and social difficulties. If left untreated, 75% of cases will continue into adulthood (Kirby et al., 2014). Recent evidence has revealed that in addition to motor difficulties, children at risk for developmental coordination disorder show auditory perceptual timing deficits (e.g., difficulty telling whether two rhythms are the same), as well as auditory-motor synchronization (e.g., difficulty tapping in time with a beat) deficits (Chang et al., 2021; Carrillo et al., 2024, Pranjic et al., 2023), although interventions continue to focus on motor impairments alone. This study aims to investigate whether children at risk for DCD can coordinate a full-body simple dance step to the beat of auditory stimuli to further our understanding of auditory-motor synchronization deficits associated with disorder.

The deficits associated with DCD can be broadly clustered into impairments of motor planning, postural and manual control, anticipatory control, automatization of movement, balance, and motor performance and learning (Wilson et al., 2013). Research on DCD has typically focused on motor skills, but recent studies have found deficits also in auditory timing perception and auditory-motor synchronization. Chang et al. (2021) found children at risk for

DCD have increased thresholds for auditory rhythm and duration discrimination, but not for pitch discrimination. Further, electroencephalography results showed children at risk for DCD, compared to typically developing children, had delayed Mismatch Negativity responses (a neural event related potential response to occasional unexpected changes in a stream of sounds) during a duration oddball task and delayed P3a (an event-related potential response reflecting attention capture) latency during a rhythm oddball task, suggesting inferior auditory perceptual timing processing in DCD (Chang et al., 2021). Carrillo et al. (2024) found children at risk for DCD to rely more on familiar speech rhythms, such that modulating the rhythm of speech led to a greater decrease in performance on target word recognition compared to typically developing children. Carrillo et al. (2024) also found that children at risk for DCD synchronized their hand tapping less consistently to an auditory stimulus compared to their typically developing peers. This fits in well with previous research showing children with DCD have increased variability and less accurate bimanual tapping (Whitall et al., 2008). A recent review by Pranjic et al. (2023) revealed that children with DCD have impairments in rhythmic movement both when an auditory cue is present or absent. Similar deficits in auditory timing perception and tapping synchronization have also been found in other neurodevelopmental disorders that are highly comorbid with DCD, such as attention deficit hyperactivity disorder (ADHD), dyslexia, developmental language disorder, and autism spectrum disorder (ASD) (Lense et al., 2021).

The relationship between auditory and motor systems is complex, and recent research has highlighted the ways in which the two systems interact. A large body of evidence suggests that the perceptual processing of rhythmic regularity in speech and music involves neural networks spanning auditory and motor cortical regions, even in the absence of overt motor movement (e.g., Cannon & Patel, 2021; Zalta et al., 2024; Fujioka et al., 2012; Patel & Iversen, 2014; Grahn

& Brett, 2007; Morillon & Baillet, 2017; Nozaradan et al., 2015; Lima et al., 2016). Movement can affect the auditory perception of rhythms, such as whether an ambiguous rhythm is perceived as in groups of two or three (Phillips-Silver & Trainor, 2005; 2007). Moving along to a beat can also increase the accuracy of timing perception (Manning & Schutz, 2013; Butler & Trainor, 2015). Detailed models have been proposed on the motor system's involvement in auditory timing prediction (e.g. Large et al., 2023), including the action simulation for auditory prediction (ASAP) hypothesis, which proposes that motor planning regions of the brain are crucial for the prediction of the timing of upcoming beats in a rhythm. One of the key predictions of the ASAP hypothesis is that if the motor system is disrupted (such as in children with DCD), this should interfere with beat perception (Patel & Iverson, 2014). It is thus unsurprising that impairments in auditory timing perception are found in children with motor impairments (Trainor et al., 2018).

Many auditory-motor synchronization studies, especially in children, use a tapping task to measure synchrony (e.g., Carrillo et al., 2024; Colling et al., 2017; Puyjarinet et al., 2017). While hand tapping is a very useful measure, it is not the only way to measure synchronization, and may not be the best reflection of rhythmic motor skills in school-age children. It requires minimal coordination between body parts and can be executed by moving just a single effector. It may also be less ecologically valid (and less enjoyable) compared to a simple dance step. Studies of children with motor coordination impairments using more full body, complex movements can potentially provide additional information on the motor skill impairments associated with the disorder and how they may affect daily living, as well as what types of interventions might be most effective.

Studies of gross motor synchronization to different sensory stimuli (e.g. auditory or visual) have shown children at risk for DCD perform more variably overall. Mackenzie et al.

(2008) found that when synchronizing their marching and claps to an auditory stimulus, children with DCD have a larger coefficient of variation across their steps compared to TD children and adults, and also show decreased limb coherence. Volman et al. (2006) found children with DCD to be more variable during hand-hand and hand-foot synchronization to an auditory metronome. Similarly, children with DCD were found to have increased variability of relative phase and higher variability of cycle duration in an interlimb jumping and clapping task, compared to TD children (Ferracioli et al., 2014). One study found that children with probable DCD showed significant difficulties in keeping up with a target frequency during a rhythmic stepping task synchronized with a visual cue compared to TD children, although their performance improved after an intervention (Inacio et al., 2023). Contradicting this finding, Al-Yahya et al., (2023) did not find differences between groups in a novel visual-motor rhythmic stepping task, although they did find that performance improved with intervention in both DCD and TD groups. Children with DCD have been found to be less synchronized to auditory cues during walking and running tasks, compared to typically developing children (Goetschalckx et al., 2024).

There is a need for more diverse and accessible motor interventions for children with DCD. The recent research showing evidence for auditory timing perception deficits and auditory-motor synchronization deficits in DCD suggests interventions that include rhythmic movement and auditory cues may confer additional benefits. However, the extent to which children with DCD might benefit from interventions using gross rhythmic movement and synchronization to an auditory cue remains unclear, as minimal research exists on their baseline abilities.

The current study aimed to investigate how well children at risk for DCD can perform a step-clap motor dance step and synchronize their movements to various auditory cues. Children were recruited through the online data collection platform LookIt. DCD risk was determined by a standardized questionnaire. They watched videos from a dance instructor to practice the step-clap movement. We examined synchronization of the step-clap motor performance to: (1) a simple auditory metronome, (2) continuation of an auditory metronome (maintaining the step-clap after the auditory rhythm stops), and (3) the beat of musical excerpts where the beat needs to be extracted from the complex rhythmic structure. We predicted that children at risk for DCD would be less accurate in their tempo matching, and that their movements would be less synchronized to the auditory cue. Importantly, we also predicted both groups would be less variable when an auditory cue was present. To date, no study has examined whether children with rDCD can synchronize whole-body movements such as dance steps to music – a skill highly relevant for social and recreational activities. This study is novel in its investigation of a motor skill that uses multiple effectors, the inclusion of synchronizing to both a simple metronome and complex music, and the comparison of synchronization and continuation performance. The results of this study will further our understanding of auditory-motor coordination impairments in DCD, as well as provide evidence for whether interventions combining auditory cues with rhythmic movements should be further investigated as an option for children with DCD.

2. Methods

2.1 Participants

Participants were recruited through the online data collection platform LookIt (Scott & Schulz, 2017). Parents/guardians provided verbal consent through recorded videos at the beginning of the study, and all consent videos were reviewed by researchers before any additional data could be accessed. Parents/guardians filled out a general demographics survey and the DCD questionnaire (DCDQ) to assess for risk of DCD (Wilson et al., 2009; Park & Kim, 2024). Children aged 9 years 0 months to 9 years 11 months with DCDQ scores between 15-55 and children aged 10 years 0 months to 11 years 11 months with scores between 15-57 were classified as in the group at risk for DCD (rDCD). Participants with scores higher than 55 or 57, respectively, were classified as in the TD group. All participants were compensated with a $5.00 Amazon gift card. Data was collected entirely online through LookIt, and participants could complete the study at any time that was convenient to them (Scott & Schulz 2017). This research was reviewed and approved by the McMaster Research Ethics Board (MREB) #0411.

2.2 Stimuli

Auditory stimuli were presented via the LookIt platform through the participant's computer or laptop speakers. Parents/guardians were instructed to set the volume at a level that was comfortable to the participants and that could be heard in the recorded video. All stimuli were presented in the form of MP4 videos, which were temporarily downloaded to the participant's computer at the beginning of the experiment to prevent any lagging in stimuli presentation. Music and metronome stimuli were included to assess whether rhythmic complexity affects performance, and different tempi were used to examine the impact of the tempo of auditory pacing. All inter-onset intervals (IOIs) of auditory beats were between 375 and 640 ms, as is a common range of preferred motor tempi for children aged 9-12 (McAuley et al., 2006). Stimuli for the metronome and continuation conditions used sequences of isochronous percussive woodblock sounds (GarageBand) each 120 ms in duration (Einarson & Trainor, 2016; Carrillo et al., 2024). All trials had 50 beats each (20 and 30 seconds long for 400 and 600 ms IOIs, respectively). Music excerpts were 30 seconds long, chosen from pop and hip-hop genres

(Table 1), and the amplitude ramped up and down over 500 ms at the beginning and end of each sequence. The "true" beat onsets for each musical excerpt were determined by averaging the tapping of two adult semi-professional drummers (for each excerpt, taps from nine trials were averaged, six trials from one drummer and three trials from the other, see supplementary materials for more details).

2.3 Procedure

The study began with participants setting up their "dance space", which included setting up a webcam to ensure their entire body could be seen in the video. Parents were encouraged to find a space with good lighting and enough space for their child to dance, but no further specifications of the environment were required. A 5-foot line was taped on the floor to keep the participants moving on a consistent plane and distance from the camera. Participants were then presented with videos of a dance instructor teaching a side-to-side step-clap movement. This movement involved stepping one foot out to the side, and then clapping at the same time the second foot stepped together (Fig. 1A). This sequence was then repeated starting on the other foot, and continued in this way for the duration of each trial (Fig. 1C). This dance step involves primarily movement along the line participants set up on the floor. Participants were not specified whether to start the step with their left versus right foot, and which foot they chose to start stepping with did not affect the analyses. No auditory cue was provided during the instructions for practicing the dance step. The instructional video was 1:24 minutes in length and aimed to teach the dance step without biasing the participants towards a particular tempo of movement, as the first condition block was a measure of spontaneous motor tempo. The instructor taught the sequence at an approximate movement frequency of 0.24 Hz (calculated using the instructor's head movements). As this study was conducted asynchronously, no feedback was provided to the participants on their performance during the instructional video, and no data was collected at this time. Participants then performed the step-clap in four blocked conditions, with the blocks occurring in the same order for each participant. Before each block, they watched the instructor explain the instructions and performed a practice trial together with the instructor (except for the spontaneous motor tempo condition, which had no practice trial to prevent biases in tempo). No visual cue was provided during the test trials, apart from a green GO sign that indicated when participants should be performing the movement, and a red STOP sign to indicate the trial had ended. At the start of every trial, participants clapped once to ensure proper audio-visual synchrony in the recorded videos. The four blocked conditions were as follows:

i. *Spontaneous Motor Tempo*. Participants performed the step-clap movement for 20 seconds at a tempo that was most comfortable to them. They were instructed to move "not too slow, not too fast, at a speed just right". Two trials were performed, and there was no practice trial prior to completing this task.

ii. *Metronome*. A metronome consisting of isochronous woodblock sounds was presented to which participants were required to synchronize the step-clap movement. Two trials of two different tempi (400 and 600 ms IOI) were presented, and the order of the four trials in the block was randomized. At the beginning of the block, they performed a practice trial at 500 ms IOI with the dance instructor (25 s in length).

iii. *Synchronization-Continuation*. On each trial, a metronome consisting of isochronous woodblock sounds was presented for 10 beats only. Participants synchronized the step-clap movement to the metronome and, after the 10 beats, were required to continue the step-clap at the same tempo for the remaining 40 beats, without any external auditory cue.

Two trials were completed at each tempo (400 and 600 ms IOIs) for a total of four trials, presented in random order. At the beginning of the block, they performed a practice trial at 500 ms IOI with the dance instructor (25 s in length).

iv. *Music Excerpts*. Participants synchronized the step-clap movement to the perceived beat of each of three different songs. Each song was presented twice, and the six trials were counterbalanced within the block. At the beginning of the block, they performed a practice trial with the dance instructor to *Can't Stop the Feeling* by Justin Timberlake at a tempo of 531 ms IOI (20 s in length).

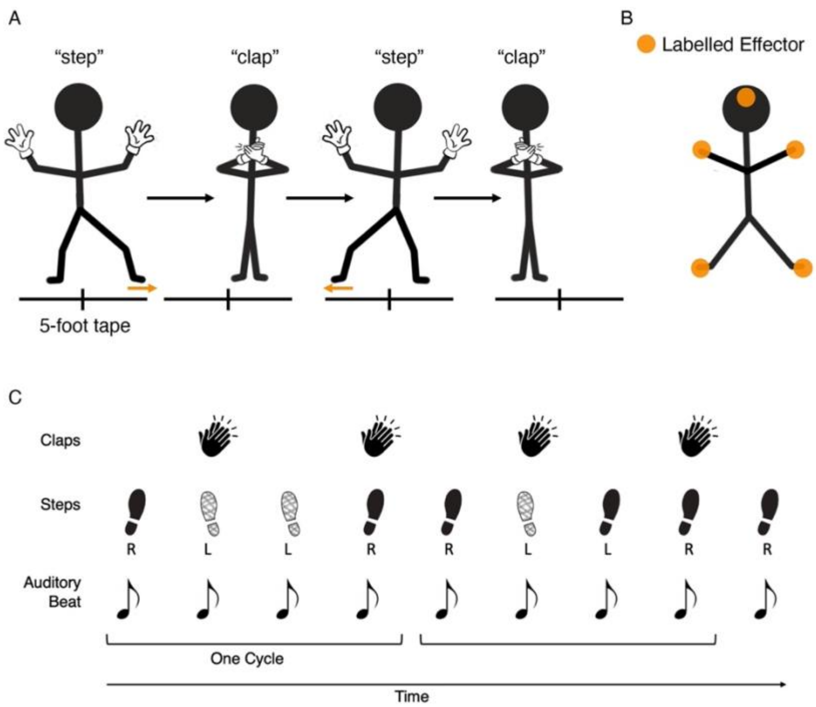
Table 1

Songs and Tempi Used in the Music Excerpt Conditions

Song Title	Artist	Tempo (IOI)	Tempo (Beats Per Minute)
Happy	Pharrell Williams	375 ms	160
Uptown Funk	Bruno Mars	522 ms	115
Love On Top	Beyonce	638 ms	94

Figure 1

Schematic of Step-Clap Task



(A) Representation of one cycle of step-clap movement. Participants were asked to place a piece of 5-foot-long tape on the floor to help stay in the camera frame. (B) Orange circles represent effectors labelled during markerless tracking of movement. (C) Timing schematic of claps, steps, and the auditory beat.

2.4 Data Preprocessing

2.4.1 Markerless Motion Capture

All of the collected videos were first analyzed using the open source Python software package DeepLabCut, a method for pose estimation (Mathis et al., 2018). The hands, feet, and head were tracked throughout each trial to obtain pixel positions of the five body parts over time in the 2D coordinate system of the camera frame of view (Fig. 1B). For every participant, the five effectors of interest were manually labelled in 55 frames across the 22 trials to train a model, and that model was then used to label the remaining frames for all trials for that participant. A new model was trained for each participant, as each participant had a different background in the collected videos. X-coordinates were outputted across time for each of the five labelled effectors, along with likelihood estimates for each data point. Data points with likelihood estimates less than 0.7 or data points more than three standard deviations from the mean were removed and interpolated using cubic interpolation. An average of 5.4% of the data points in a trial were interpolated, with interpolation percentages ranging from 0.5% to 22.3% across participants. After interpolation and smoothing using a quadratic spline smoothing function in Python, each trial was down sampled to 15 Hz to account for differences in the frame rate of collected data. Data in the metronome and continuation trials only examined movement during the latter 40 beats, excluding the first 10 beats of each trial. An experimenter verified that the participants were following instructions and executing the tasks appropriately before including these trials in the analyses.

2.4.2 Wavelet Analysis of Motor Rhythms

Each trial was submitted to a time-frequency analysis with the goal of identifying the most prominent movement frequency for each condition and tempo. We convolved the signal with a set of complex Morlet wavelets, defined as complex sine waves tapered by a Gaussian (Cohen, M., 2019). A total of 218 frequencies were examined logarithmically in the range 0.01-3.05 Hz. Resulting amplitudes were converted to power, and mean and standard deviations of the power were calculated across the time domain. Power results were averaged across the two trials with the same stimulus, with the exception of the spontaneous motor tempo trials. For the spontaneous motor tempo trials, the second trial was used, except in participants where no peak was identified for the second trial, in which case the first trial was used. Movement frequency was calculated for every participant in each condition by identifying peaks in the frequency domain (ranging from 0.20-3.05 Hz) and identifying the peak with the highest power. After finding the peak frequency, the coefficient of variation (CV) for that frequency was calculated as the standard deviation of power divided by the mean power for each trial. Frequencies and CVs were submitted to a logarithmic transformation to help normalize the data (West, 2021). The movement frequency and the CV of power for each trial were each compared between groups. Any violations of sphericity were adjusted by applying a Greenhouse-Geisser correction

2.4.3 Cross-Correlation

Interpolated harmonic waves were created using cosine waves at the beat frequency to represent the locations of the stimulus beats (example trial shown in Fig. 3A). The positive peaks of the waves corresponded to every fourth beat in the stimulus, which represents the tempo at which the participants would be stepping with each foot or clapping to the beat. Cross-correlation coefficients were calculated between the interpolated harmonic wave and the continuous movement data across each trial for each of the five effectors (head, right hand, left hand, right foot, left foot), as shown in Fig. 3A. Correlation coefficients were calculated by obtaining the maximum (absolute value) coefficient with lags between movement and interpolated harmonic waves ranging from -25 to 25 data points (corresponding to ±1.67 seconds). Allowing different participants to have different maximum lags also accounts for any audio-visual mismatch in the recorded data. Correlation coefficients were submitted to a Fisher transformation before further analysis, as is common in correlation data (Asuero et al., 2006; Winterbottom, 1979). As there was no effect of effector, the results were averaged across effectors.

2.4.4 Statistical Analyses

For all analyses of movement speed derived from the wavelet transform, repeated-measures analyses of variance (ANOVAs) were conducted. Group (rDCD, TD) was treated as a between-subjects factor in all models. Effector (head, right hand, left hand, right foot, left foot) was included as a within-subjects factor. In the metronome and continuation conditions, two within-subjects factors were included: condition (metronome, continuation) and tempo (400 ms, 600 ms IOI). In the music condition, song (fast, medium, slow) was included as a within-subjects factor. The effects of tempo and song were analyzed primarily to confirm that participants modulated their movement speed in response to auditory stimuli with different tempi. For movement variability, quantified by the CV of wavelet power, repeated-measures ANOVAs were used for the spontaneous motor tempo, metronome, and continuation conditions. Where data violated assumptions of normality (e.g., in the music condition), generalized linear mixed models (GLMMs) with Gamma distributions and inverse link functions were employed and fixed effects were estimated using likelihood-ratio tests. All GLMMs included participant ID as a random intercept to account for repeated measures. Post-hoc comparisons were Bonferroni-corrected where applicable. For coordination analyses, calculated as the maximum cross-correlation coefficient between the movement signal and an interpolated auditory rhythm, GLMMs were used due to non-normal distributions. Fixed factors included group and relevant task variables (condition, tempo, or song), and participant ID was included as a random intercept. Finally, to explore whether spontaneous motor tempo may be related to the ability to synchronize to music of varying tempi, Pearson's correlations were calculated between the spontaneous motor tempo frequency and movement coordination with the auditory rhythm for both the fast and slow songs, which represented the fastest (375 ms IOI) and slowest (638 ms IOI) stimuli presented in the experiment. All significant effects are reported, as well as all effects of group, as it was the main effect of interest. Means and standard deviations (*M*±*SD*) are reported for each level of the significant main effects. Detailed results of the ANOVAs and GLMMs can be found in the supplementary material (Table S2-4), including detailed reports of all non-significant effects.

3. Results

3.1 Demographics

87 children between the ages 9 and 12 years were tested (Table 2). 14 participants were removed from analysis due to poor video quality or occlusion of more than half of the participant's body from the camera's field of view. Eight participants were excluded due to an additional diagnosis of autism spectrum disorder, and 14 participants were removed as their parent or guardian did not fill out the DCD questionnaire. A total of 55 participants were included in the analysis. The rDCD group (n = 19) had a mean score on the DCD questionnaire of 46.63 (SD = 10.1), while the TD group (n = 36) had a mean score on the DCD questionnaire of 67.89 (SD = 5.9). In the rDCD group, 10 participants identified as White, 5 participants as Asian, one participant as mixed race, one participant as Hispanic, one participant as Black, and one participant did not report ethnicity. In the TD group, 21 participants identified as White, four participants as Hispanic, two participants as Black, four participants as Asian, one participant as Native American, one participant as Indian, two participants as Middle Eastern, and one participant did not report ethnicity. The groups did not differ in their socioeconomic status as calculated by household income ($t(21.3) = 1.63$, $p = .118$) or years of dance training ($t(19.9)$ =

0.22, $p = .830$). In the rDCD group, only 11 of 19 participants answered the question whether they had any music training, with 3/11 participants reporting training in an instrument. In the TD group, 29 of 36 participants answered the question as to whether they had any music training, with 16/29 participants reporting training in an instrument. Given the low rates of responding, this data was not analyzed. Demographic information is summarized in Table 2.

Table 2

Participant Demographics (±SD) of Study Sample

Variable	rDCD (*n* = 19)	TD (*n* = 36)	*t*-test *p*-value
Female:Male	7:12	19:17	N/A
Age	10.1±1.2	10.0±1.1	.817
DCD-Q[a]	46.63±10.1	67.89±5.9	<.001
Years of Dance Training	0.77±1.4	0.88±1.5	.830
SES[b]	5.1±1.2	4.3±1.6	.118

[a]DCD Questionnaire was used to allocate participants into the rDCD or TD group.
[b]SES (socioeconomic status) was estimated by average household income per year, scored on a scale of 1-7, where 1 = <$30,000, 2 = $30,000-60,000, 3 = $60,000-90,000, 4 = $90,000-120,000, 5 = $120,000-150,000, and 6 = >$150,000 CAD.

3.2 Frequency Domain

To examine the preferred tempo during the spontaneous motor tempo trials, movement frequencies of the wavelet transformation were compared between groups. A 2x5 mixed analysis of variance (ANOVA), with the between-subject factor of group (rDCD, TD) and the within-subject factor of effector (head, right hand, left hand, right foot, left foot) found no significant effects of group ($F(1,49) = 0.21$, $p = .651$, $\eta^2 = .004$), effector, or interaction between group and effector.

A two-way mixed ANOVA examined the movement frequency in metronome and continuation conditions, with within-subject factors of condition (metronome, continuation), tempo (400, 600 ms IOI), and effector (head, right hand, left hand, right foot, left foot) and the between subject factor of group (rDCD, TD). Results showed significant main effects of group ($F(1,44) = 4.63$, $p = .037$, $\eta^2 = .100$; $M_{rDCD} = 0.48 \pm 0.12$ Hz, $M_{TD} = 0.51 \pm 0.10$ Hz), tempo ($F(1,44) = 63.51$, $p < .001$, $\eta^2 = .540$; $M_{400ms} = 0.55 \pm 0.12$ Hz, $M_{600ms} = 0.44 \pm 0.06$ Hz), effector ($F(3, 132.1) = 2.82$, $p = .042$, $\eta^2 = .008$; $M_{head} = 0.49 \pm 0.09$ Hz, $M_{right\ hand} = 0.51 \pm 0.14$ Hz, $M_{left\ hand} = 0.50 \pm 0.09$ Hz, $M_{right\ foot} = 0.50 \pm 0.11$ Hz, $M_{left\ foot} = 0.50 \pm 0.10$ Hz), and an interaction between condition and tempo ($F(1,44) = 4.16$, $p = .048$, $\eta^2 = .090$). There was no main effect of condition, or any other interactions. Post-hoc t-tests investigating the interaction between tempo and condition found significant differences in movement frequency between the 400 and 600 ms IOIs in the metronome ($t(53) = 8.42$, $p_{corr} < .001$, $d = 0.99$) and continuation conditions ($t(53) = 7.27$, $p_{corr} < .001$, $d = 1.15$), but no significant differences between metronome and continuation (Bonferroni corrected). Despite no significant differences between conditions after Bonferroni correction, there was a trend for both groups to move slower during continuation compared to metronome in the 600 ms tempo alone. Finally, no significant correlations were found between spontaneous motor tempo and movement frequency during the continuation conditions at either 400 ms ($r(52) = 0.22$, $p = .112$) or 600 ms ($r(52) = -0.03$, $p = .812$), suggesting participants did not simply perform at their spontaneous tempo when the auditory cue was removed.

A similar ANOVA examined the movement frequency in the music condition with within-subject factors of song (fast, medium, slow) and effector (head, right hand, left hand, right foot, left foot) and the between-subject factor of group (rDCD, TD). Results showed significant main effects of song ($F(1.3, 60) = 19.46$, $p < .001$, $\eta^2 = .300$; $M_{\text{fast song}} = 0.52 \pm 0.09$ Hz, $M_{\text{medium song}} = 0.50 \pm 0.05$ Hz, $M_{\text{slow song}} = 0.45 \pm 0.06$ Hz) and effector ($F(2.4, 109.7) = 4.01$, $p = .015$, $\eta^2 = .080$; $M_{\text{head}} = 0.48 \pm 0.07$ Hz, $M_{\text{right hand}} = 0.49 \pm 0.07$ Hz, $M_{\text{left hand}} = 0.49 \pm 0.07$ Hz, $M_{\text{right foot}} = 0.49 \pm 0.07$ Hz, $M_{\text{left foot}} = 0.49 \pm 0.08$ Hz). The effect of group did not reach significance ($F(1,45) = 3.64$, $p = .063$, $\eta^2 = .070$; $M_{\text{rDCD}} = 0.47 \pm 0.06$ Hz, $M_{\text{TD}} = 0.50 \pm 0.08$ Hz). To investigate the main effect of effector, post-hoc t-tests were performed between each pair of effectors. The only significant effects were between the head and the left hand ($t = 3.75$, $p_{corr} = .002$) and the head and the left foot ($t = 2.93$, $p_{corr} = .038$), and these remained even after correcting for multiple comparisons, indicating that the head was moving slightly slower than the left effectors. No interactions were significant, including no interactions involving group. Results for all movement frequencies are summarized in Fig. 2A. Difference scores between target frequency and actual frequency are summarized for visualization in supplementary material (Fig. S1).

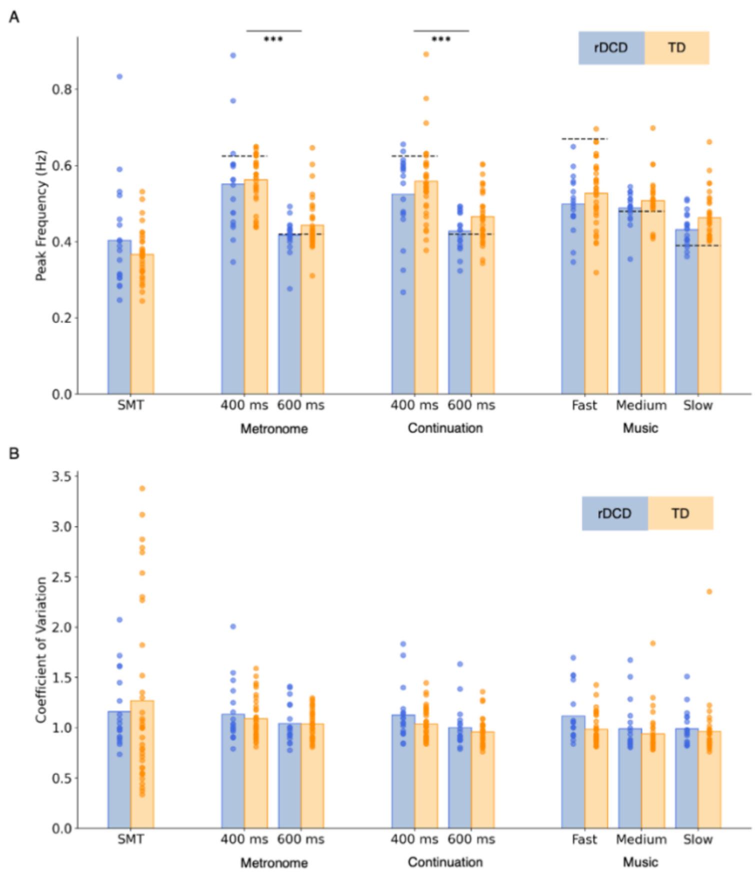
To examine variability of power over time, the coefficient of variation (CV) of the power for each trial's movement frequency was calculated (CV = standard deviation of power / mean power). CV was averaged across effectors. Results are summarized in Fig. 2B.

In the spontaneous motor tempo condition, a Welch's t-test showed no differences in CV between groups, $t(51.3) = 0.89$, $p = .377$, $d = 0.22$. An ANOVA examined CV in the metronome and continuation conditions with within-subject factors of condition (metronome, continuation) and tempo (400, 600 ms IOI) and the between subject factor of group (rDCD, TD). Results showed a significant effect of tempo ($F(1,52) = 23.98$, $p < .001$, $\eta^2 = .320$; $M_{\text{400ms}} = 1.07 \pm 0.25$, $M_{\text{600ms}} = 1.00 \pm 0.21$) and condition ($F(1,52) = 8.35$, $p = .006$, $\eta^2 = 0.140$; $M_{\text{metronome}} = 1.06 \pm 0.24$, $M_{\text{continuation}} = 1.01 \pm 0.22$). There was no significant main effect of group ($F(1,52) = 0.72$, $p = .399$,

$\eta^2 = .010$) or any interactions. In the music condition, data were not normally distributed as assessed by the Shapiro-Wilks test, therefore a GLMM was performed with the fixed factors group (TD, rDCD) and song (fast, medium, slow) on the outcome measure of CV, with participant ID as a random intercept. The model used a Gamma distribution with an inverse link function (*AIC* = -162.6 and *BIC* = -138.2), and fixed effects were estimated using likelihood-ratio tests. Results showed a significant effect of song ($\chi^2(2) = 12.62$, $p = .002$; $M_{\text{fast song}}$ = 1.02±0.25, $M_{\text{medium song}}$ = 0.93±0.19, $M_{\text{slow song}}$ = 0.95±0.20). There was no significant effect of group ($\chi^2(1) = 1.22$, $p = .269$), and the interaction between group and song did not reach significance ($\chi^2(2) = 4.67$, $p = .097$). However, as the GLMM had shown a significant interaction between group and song for the fast song only (β = -0.029, *SE* = 0.014, $p = .034$), a post-hoc Mann-Whitney U-test was conducted for the fast song, which revealed the rDCD group (*M*=1.11±0.25) had a significantly higher CV compared to the TD group (*M*=0.98±1.5), *W* = 413, $p = .022$, $d = 0.64$.

Figure 2

Movement Frequency and Coefficient of Variation of Power



(A) Movement frequencies for each trial indicating movement tempo (averaged across effectors for visualization). Dotted black lines represent the target tempo of the trial (Hz) divided by four, to represent one full step-clap cycle. For metronome and continuation conditions, main effects of Group (p = .037), Effector (p = .042), and Tempo (p < .001) were found, as well as a significant Condition X Tempo interaction (p = .048), For music conditions, main effects of Effector (p = .015) and Song (p < .001) were found. (B) Coefficients of variation of the power of the movement frequency across time, calculated over the duration of the trial (averaged across effectors). For metronome and continuation conditions, main effects of Condition (p = .006) and Tempo (p < .001) were found. For music conditions, a main effect of Song (p = .002) was found.

3.3 Coordination of Movement with Auditory Stimulus

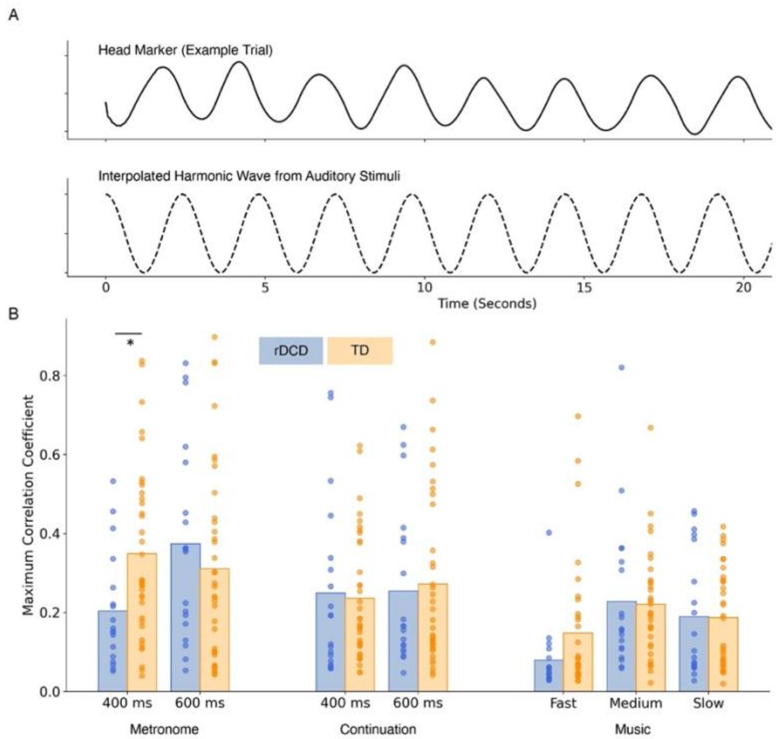
Coordination of movement was calculated as the maximum cross-correlation coefficient (lags ±25 equivalent to ±1667 ms of time shift) between the continuous movement (x-coordinates) with the interpolated harmonic wave representing the auditory beat. As the data were not normally distributed, a GLMM was conducted for the metronome and continuation conditions to examine the fixed effects of group, condition, and tempo on the mean correlation coefficient, with participant ID as a random intercept. Fixed effects were estimated using likelihood-ratio tests with a Gamma distribution and an inverse link function (*AIC* = -122.2 and *BIC* = -88.3). Results showed a significant effect of tempo ($\chi^2(1) = 4.91$, $p = .027$; $M_{400ms} = 0.30±0.25$, $M_{600ms} = 0.35±0.33$). Additionally, a significant three-way interaction was found between group, tempo, and condition ($\chi^2(1) = 6.37$, $p = .012$). No other main effects or interactions reached statistical significance ($p > 0.05$). Post-hoc Mann-Whitney U-tests were conducted to investigate the three-way interaction, comparing between groups for metronome and continuation conditions at both 400 and 600 ms IOIs. Results showed a significant difference in the 400 ms metronome condition between the rDCD (*M* = 0.21±0.16) and TD (*M* = 0.40±0.30) groups ($W = 186$, $p_{corr} = .043$, $d = 0.78$, Bonferroni corrected), but no significant difference between groups for 600 ms metronome or either continuation condition ($p > .05$). Results are summarized in Fig. 3B.

A similar GLMM was conducted for the music condition to examine the fixed effects of group and song on the mean correlation coefficient, with random intercepts for participant ID. Fixed effects were estimated using likelihood-ratio tests with a Gamma distribution and an inverse link function (*AIC* = -232.5 and *BIC* = -208.1). The main effect for group did not reach significance ($\chi^2(1) = 3.04$, $p = .081$), but the effect of song was significant ($\chi^2(2) = 24.40$, $p < .001$; $M_{fast\ song} = 0.13±0.18$, $M_{medium\ song} = 0.24±0.20$, $M_{slow\ song} = 0.20±0.15$). There was also a significant interaction between group and song ($\chi^2(2) = 9.45$, $p = .009$). Post-hoc Mann-Whitney U-tests showed the difference between groups approached significance for the fast song

($W = 208$, $p = .081$, $p_{corr} = .324$), but did not reach significance after Bonferroni correction. The medium and slow songs did not show differences between groups ($p > .05$).

Figure 3

Coordination of Movement with Auditory Stimulus

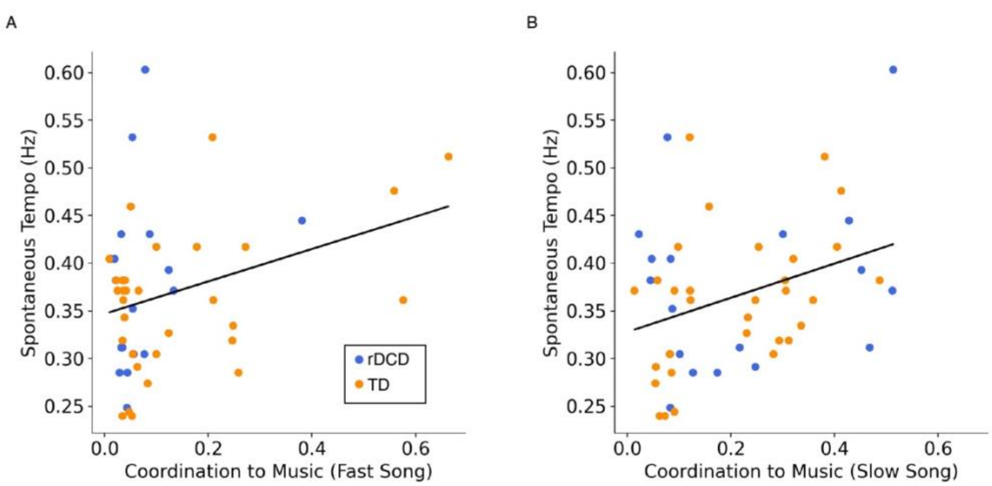


(A) Example trial of the head's horizontal movement over time compared with the harmonic wave interpolated from the auditory stimuli. (B) Maximum correlation coefficients between groups across all trials, calculated in a range of ±25 lags. Results are averaged across the five effectors. In the metronome and continuation conditions, a main effect of Tempo was found ($p = .027$). In the music conditions, a main effect of Song ($p < .001$) and an interaction between Group X Song ($p = .009$) was found.

To explore whether spontaneous motor tempo may be related to the ability to synchronize to music of varying tempi, Pearson's correlations were calculated between the spontaneous motor tempo frequency and movement coordination with the auditory rhythm (cross-correlations to harmonic wave) for both the fast and slow song, which represented the fastest (375 ms IOI) and slowest (638 ms IOI) stimuli presented in the experiment (Fig. 4). Only the head effector was used in order to compare between the two measures. Positive correlations were found between spontaneous motor tempo frequency and cross-correlation coefficients for both the fast song ($r(47) = 0.32$, $p = .025$, $p_{corr} = .049$) and the slow song ($r(48) = 0.34$, $p = .015$, $p_{corr} = .030$). P-values were corrected for multiple comparisons using Bonferroni correction.

Figure 4

Correlation between Spontaneous Motor Tempo and Movement Coordination with the Music



Correlation between spontaneous motor tempo (Hz) and coordination to music, as measured by the maximum lagged correlation coefficient during (A) the fastest song ($r = 0.32$, $p_{corr} = .049$), and (B) the slowest song ($r = 0.34$, $p_{corr} = .030$).

4. Discussion

The present study is novel in showing that children with rDCD can perform a step-clap dance step along to various auditory rhythmic stimuli, but show impairments in their performance compared to TD children when required to execute the movements at faster speeds.

This study was the first to explore coordination of a full-body dance step in children with rDCD and implored novel techniques for both online data collection and analysis using markerless motion tracking. Frequency analyses showed children with rDCD move at an overall slower tempo for paced tasks (metronome, continuation, and music), but not for unpaced tasks (spontaneous motor tempo). They also show higher variability compared to TD children at fast tempi, but similar variability to TD children at slower tempi. In addition, children with rDCD show lower correlations between their movement trajectories and the target trajectories, as defined by the auditory stimuli, at faster tempi, but similar performance to TD children at slower tempi. The results of this study inform the design of auditory-motor interventions for children with rDCD, as well as provide new techniques for data collection in special populations.

4.1 Children with rDCD perform the step-clap overall slower than TD children

Frequency domain results showed that children at risk for DCD moved significantly slower compared to their TD peers during paced tasks, regardless of the target tempo. This is similar to Volman et al., (2006), who found children at risk for DCD tapped overall slower during a bimanual synchronization task. This is an interesting finding, as the rDCD group did not show a slower movement frequency during the unpaced task (spontaneous motor tempo) compared to the TD group, which is consistent with previous research finding similar preferred tempi in children with DCD and TD children (Tallet et al., 2013). In addition, the CVs of spontaneous tempi were similar between groups. However, both groups had a relatively slow mean tempo during the spontaneous tempo task, indicating that although both groups preferred a slower tempo, the TD group was more flexible than the rDCD in adapting to faster tempi. This is consistent with a previous finding that children with DCD are less adaptive during motor tasks that require adjustment (Wilson et al., 2017).

The movement frequencies also showed a significant effect of tempo (i.e., differences across songs that were at different tempi) and effector, as expected. The main effect of tempo indicates that both groups were able to adapt the speed of their movement to the tempo of the auditory stimulus. This main effect appears to remain meaningful even with the significant interaction between tempo and condition, as the difference in movement frequency across tempi was significant for both metronome and continuation conditions. The main effect of effector is also unsurprising, as different effectors needed to synchronize to different patterns of the beat (i.e. both hands clapped every second beat, while the feet stepped at different times on every first and fourth beat).

These findings are important for designing potential interventions that include an auditory cue, as they indicate that the tempo of the auditory cue will affect the child's ability to perform the movement. The results suggest that auditory stimuli with slower tempi (e.g. 90-120 beats per minute) may provide a better timing cue for practicing movements. It is also worth noting that previous research investigating preferred tempo (e.g. McAuley et al., 2006) typically examines the amount of time between singular beats, as hand tapping is the most common action for determining preferred motor tempo. However, if the motor tasks being trained in an intervention are more complex, with multiple effectors synchronizing at different interwoven rhythmic patterns, as is the case in the current study, the tempo of the music should consider the fastest effector. Given the more complex nature of the pattern of the movement during dance, it is possible that the effects of fast tempi increase the difficulty of performing the pattern in the correct sequence and moments in time, as opposed to, or in addition to, a general difficulty in moving quickly. More research is needed in determining the most effective tempo for auditory stimuli in intervention settings.

4.2 Children with rDCD are more variable in their tempo during faster stimuli trials

At the fastest tempo (375 ms IOI), the rDCD group was significantly more variable in their movement frequency (averaged across effectors). This is unsurprising given the findings that the rDCD group moved overall slower, and that this tempo is the furthest away from the mean spontaneous motor tempo of both groups. This further emphasizes that the rDCD group has more difficulty adapting to tempi outside of their spontaneous tempo, compared to the TD group. In the metronome and continuation conditions, both groups were significantly less variable in their movement frequency at the 600 ms tempi compared to the 400 ms tempi, which additionally emphasizes a performance benefit during slower tempi across both groups. Surprisingly, there was a significant effect of condition such that the metronome condition showed slightly higher variability compared to the continuation condition. We predicted that both groups would show higher variability in the continuation condition, similar to previous findings of lower tapping consistency in continuation compared to music and metronome tapping (Carrillo et al., 2024). However, it is possible that in the metronome condition, attempting to adjust their pace to the incoming auditory information might have led to more variability in the movement frequency. In the continuation condition, no external auditory cue may have led to less error correction and thus less variability in movement frequency. It is important to note that this measure does not account for CV of the target frequency, but instead looks at the CV of the actual frequency performed.

4.3 Children with rDCD are less coordinated to the beat at faster tempi

The correlation between the side-to-side movement trajectory with an interpolated harmonic wave representing the auditory beat was used as a measure of coordination to the beat. This method allows the trajectory of the entire movement to be considered in the analysis, instead of just investigating the synchrony of end time points (i.e. the step or the clap). Importantly, this method also accounts for any asynchronies in the audio-visual information of the video, as this could be corrected for in the correlation lags.

Results showed the rDCD group was significantly less coordinated than the TD group for the 400 ms metronome, and there was a similar trend (although it did not reach significance) for the fastest song (375 ms IOI). This result is unsurprising given that the rDCD group moved slower overall, and that these fast tempi are the furthest from both group's spontaneous tempi. However, significant positive correlations between each participant's spontaneous tempo for both the fast and slow songs suggests that those with slower spontaneous tempos were overall less good at coordinating to auditory rhythms regardless of tempo. The main effects of tempi (in the metronome and continuation conditions) and song (music conditions) should be interpreted with caution, as they also interacted significantly with the group factor, highlighting that group differences seem to occur at specific tempi.

4.4 Interventions using rhythmic cueing for DCD

The converging evidence of auditory timing perception deficits and auditory-motor synchronization deficits in children with DCD suggests that interventions that train auditory-motor integration could benefit children with DCD. Carrillo et al. (2024) found that, while children at risk for DCD were less consistent overall during tapping production, they were significantly more consistent when an auditory cue was present (i.e. music or a metronome) compared to without (continuation tapping). They also found children with rDCD were more reliant on familiar rhythmic cues during a speech recognition task. Both results suggest that children with rDCD are able to use auditory rhythmic cues to benefit their perception and production.

Preliminary research on interventions including rhythmic movement and the presence of an auditory cue show promising results. A study by Diaz-Perez et al. (2020) investigated the efficacy of an intervention involving music, movement, and dance for children at risk for DCD. They found an increase in MABC-2 scores for children who participated in the intervention, and no significant change in scores in the rDCD group that did not receive any intervention. In a different population, a pilot study on ballet training for children with cerebral palsy (CP) found improvements in the pediatric balance scale for children who participated in the intervention, and no changes for children who did not (Lopez-Ortiz et al., 2016). A review on the effectiveness of dance training for children with CP found preliminary evidence for improvements in gait, balance, and cardiorespiratory fitness in children with CP (Lopez-Ortiz et al., 2019). Rhythmic auditory stimulation (RAS), a neurological technique which uses the physiological effects of auditory rhythms on the motor system in the brain to improve control of movement, has been found to improve stride length, velocity, and symmetry in gaiting training for children with CP (Kwak, 2007) and significant improvements in gross motor skills in children with ASD (El Shemy and El-Sayed, 2018). While additional research is needed, the present results suggest that dance interventions involving rhythmic auditory cuing of movement across effectors could be effective for children with DCD. Parents/guardians also provided feedback through the LookIt online platform after the completion of the study, offering positive comments describing the task as "fun" and "awesome", as well as indicating their interest in future research. This qualitative feedback suggests the participants were engaged and enjoyed the task. Children with DCD have been found to have low motivation to participate In physical activity (Purcell et al., 2023), so finding options for intervention that are fun and engaging is an important factor when considering future research into new intervention options. The positive feedback from parents on this task holds promise for the inclusion of rhythmic dance steps in longitudinal intervention strategies which aim to be both effective and captivating for children. The present study is an important step towards designing practical and affordable at-home interventions. Importantly, as the present approach is not bound by therapist availability, it allows for a much larger intervention dosage which is often a limiting factor in motor rehabilitation.

4.5 Limitations and Future Directions

As data for the present study was collected entirely online, poor data quality, low sample rates, and unknown synchronization between audio and video presented challenges for applying measurements common to auditory-motor synchronization research, such as using circular statistics to measure synchronization between the auditory beat and the movements at salient moments (i.e. steps or claps). As well, although the rDCD group all fell below the cutoff for DCD, the mean was toward the higher end of this category, so our findings may in fact be underestimating the deficits that may be present in children with a diagnosis of DCD. Follow-up research investigating the performance of the step-clap movement should be conducted with motion capture to enable more precise analysis of timing information, including circular statistical measures such as phase alignment and consistency. There would also be a benefit in conducting this research in-person, to increase proper adherence to the task and to standardize the setup and background for data collection. This would also help researchers ensure that videos were not mirrored, a possible issue with some webcams, allowing hand dominance to be examined as a factor in effector differences under more controlled conditions. Finally, risk for DCD among recruited children was based on parent reports on the DCD questionnaire and not on clinical tests. The groups were also highly imbalanced, due to the nature of the participant recruitment methods, and not enough information on music experience was collected to include it in the analysis. Future research including participants identified as at risk for DCD using the Movement Assessment Battery for Children would lead to more reliable conclusions, as well as more controlled measures of music experience. Additionally, though our sample size was too small to include participants that were both at risk for DCD as well as ASD, including a group of participants in future studies with ASD would benefit our understanding of motor coordination deficits in both DCD and ASD.

5. Conclusion

Children at risk for DCD were able to perform a step-clap dance step. They were significantly slower compared to age-matched typically developing children. At faster tempi, children with rDCD were also less coordinated to the auditory beat. However, similar performance between groups at slower tempi suggests that children with rDCD have the ability to perform auditory-motor coordination tasks at the right level of difficulty. This underlines the importance of choosing appropriate tempi when designing interventions for this population. Overall, the results indicate that dance interventions, including at-home designs, involving rhythmic auditory cuing for children with DCD are promising and should be further investigated.

Data Availability: The data that has been used is confidential.

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Supplementary Material

Beat Locations in Music Excerpts

The beat locations of the music excerpts were obtained by having two expert drummers tap along to their perceived beat of the music for nine trials per song (6 from Drummer 1, and 3 from Drummer 2). Coefficient of variation (CV) within a trial was calculated as the standard deviation of inter-tap intervals (ITIs) divided by the mean ITI. Standard deviation across trials was calculated to determine how consistent the mean ITI was within a song. The drummers were remarkably consistent across trials (average standard deviation = 0.003). Mean ITI, CV within a trial, and standard deviation between trials for each of the three songs are summarized in Table S1. For each song, the mean tempo (ITI in ms) was then used to calculate the beat locations using an isochronous pulse, which was aligned with the song using a best-fit model.

Table S1
Summary of Inter-Tap Intervals for Expert Drummers

Song	Drummer	Mean ITI (ms)	CV (Within Trial)	Standard Deviation (Between Trials)
Fast	1	374.99	0.038	0.005
	2	374.87	0.034	0.003
Medium	1	521.87	0.028	0.003
	2	522.24	0.032	<0.001
Slow	1	638.36	0.022	<0.001
	2	638.33	0.030	0.003

Detailed ANOVA and GLMM Results

Repeated measures analyses of variance (ANOVA) were conducted for all conditions where assumptions of normality were met. If assumptions were violated, generalized linear mixed models (GLMM) were conducted, and fixed effects were estimated using likelihood-ratio tests. For movement frequency data, ANOVAs were used in all conditions (Table S2). For coefficient of variation of power, a repeated measures ANOVA was conducted in the metronome and continuation condition, while a GLMM was used in the music condition (Table S3). In coordination of movement to music, GLMMs were used in all conditions (Table S4).

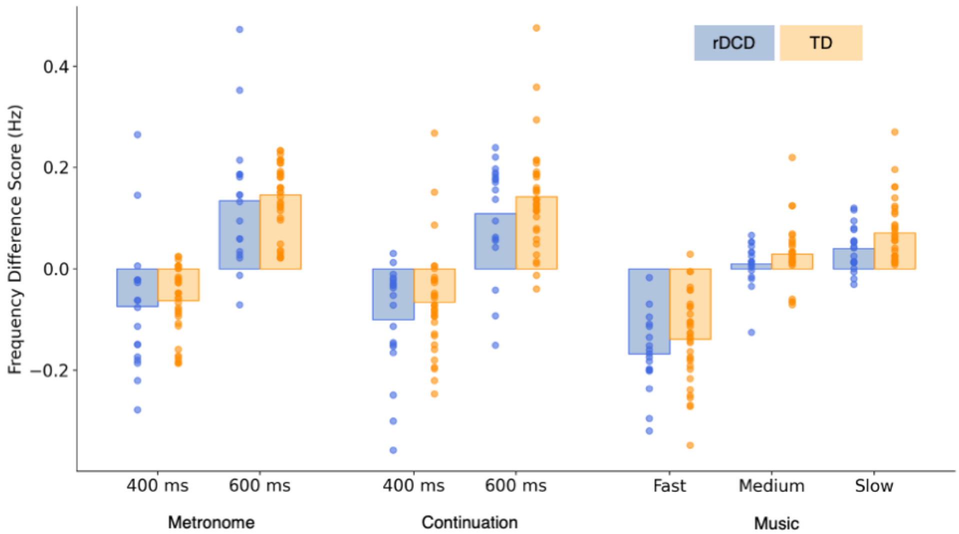
Table S2
Movement Frequency

Condition	Factor	DF[1]	*F*	*p*-value	η^2
SMT	Group	1,49	0.21	.651	.004
	Effector	1.6,77.9	1.09	.329	.020
	Group:Effector	1.6,77.9	0.89	.392	.020
Metronome and Continuation	Group	1, 44	4.63	.037	.100
	Effector	3,132	2.82	.042	.008
	Group:Effector	3,132	0.60	.616	.002
	Condition	1, 44	2.14	.151	.020
	Group:Condition	1, 44	0.18	.675	.002
	Tempo	1, 44	63.51	<.001	.540
	Group:Tempo	1, 44	0.00	.949	<.001
	Effector:Condition	2.7,119.9	0.81	.479	.009
	Group:Effector:Condition	2.7,119.9	0.57	.619	.004
	Effector:Tempo	2.5,108	0.79	.478	.090
	Group:Effector:Tempo	2.5,108	0.75	.498	<.001
	Condition:Tempo	1, 44	4.16	.048	.020
	Group:Condition:Tempo	1, 44	0.44	.512	.020
	Effector:Condition:Tempo	3,135	0.4	.757	.020
	Group:Effector:Condition:Tempo	3,135	0.19	.910	.010
Music	Group	1, 45	3.64	.063	.070
	Effector	2.4, 109.7	4.01	.015	.080
	Group:Effector	2.44, 109.7	1.67	.186	.040
	Song	1.3, 60	19.46	<.001	.300
	Group:Song	1.3, 60	0.86	.387	.020
	Effector:Song	3, 132.5	0.98	.401	.020
	Group:Effector:Song	3, 132.5	1.23	.302	.030

[1]DF = degrees of freedom.

Figure S1

Difference Scores of Movement Frequency Compared to Target Frequency



Difference scores calculated by subtracting the target frequency from the actual frequency (Hz), averaged across effectors. Negative values represent moving slower than the target frequency.

Table S3

Coefficient of Variation of Power

Condition	Factor	DF[1]	Test Statistic[2]	*p*-value	η^2
Metronome and Continuation	Group	1,52	0.72	.399	.010
	Condition	1,52	8.35	.006	.140
	Group:Condition	1,52	2.02	.161	.040
	Tempo	1,52	23.98	<.001	.320
	Group:Tempo	1,52	1.17	.285	.020
	Condition:Tempo	1,52	1.08	.304	.020
	Group:Condition:Tempo	1,52	0.01	.937	<.001
Music	Group	1	1.22	.269	
	Song	2	12.62	.002	
	Group:Song	2	4.67	.097	

[1]DF = degrees of freedom.

[2]In the metronome and continuation condition, this test statistic is an *F*-statistic from an ANOVA. In the music condition, this column represents a Chi-square statistic from a likelihood-ratio test comparing nested GLMMs.

Table S4

Coordination to Auditory Stimuli

Condition	Factor	DF[1]	χ^2	*p*-value
Metronome and Continuation	Group	1	0.37	.545
	Condition	1	1.80	.179
	Tempo	1	4.91	.027
	Group:Condition	1	2.21	.137
	Group:Tempo	1	1.69	.194
	Condition:Tempo	1	1.21	.272
	Group:Condition:Tempo	1	6.37	.012
Music	Group	1	3.04	.081
	Song	2	24.40	<.001
	Group:Song	2	9.45	.009

[1]DF = degrees of freedom.

Chapter 4: The role of synchrony in expert hip hop dance competitions

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Preface

In this chapter, I shift the focus from children with coordination difficulties to expert performers for whom movement synchrony is central to success. Chapter 4 investigates the role of interpersonal synchrony in professional hip hop dance competitions. While previous studies have shown that synchrony enhances social bonding and aesthetic judgments, it remained unclear whether it plays a decisive role in performance evaluations within live, culturally significant contexts. Using motion capture during a live dance competition, I quantified interpersonal group synchrony and related it to judges' and audience members' ratings. I found that the objective measure of interpersonal synchrony was indeed a significant predictor of both expert judges' and lay audiences' scores. This chapter shows the importance of interpersonal synchrony in ecologically valid performance environments.

Abstract

Hip hop dance competitions have grown in popularity in recent years, but there is minimal research assessing the reliability of hip hop judging and whether certain elements of dance routines impact scoring more than others. Considering the aesthetic appeal of synchrony in dance, we investigated whether the winning group can be predicted by how objectively synchronized the dancers were, hypothesizing that the most synchronized routine will win. We held an in-person hip hop dance competition, with six groups of five experienced dancers wearing motion capture markers. Five paid expert judges determined the winner by assessing the routines on choreography, execution (including synchrony), and overall cohesion. Simultaneously, audience members provided their own scores. Synchrony was a significant predictor of scores for both judges and audience members. The judges were highly consistent in their scoring, with an intra-class correlation coefficient of 0.94. Audience members with hip hop dance training were significantly more likely to correctly predict the winning group compared to those without. The results emphasize the importance of synchrony in hip hop competition judging, but suggest that judges' expertise led them to incorporate additional important factors in their assessments.

Introduction

Hip hop dance is one of many street dance disciplines, with others including house, locking, popping, and breaking [1]. Like other street dance styles, hip hop can foster community by uniting dancers locally, nationally, and globally to participate in a wide range of events. As hip hop and street dance have risen in popularity from the streets of the Bronx all the way to the Summer 2024 Olympics, an increasing number of hip hop competitions are being held worldwide. However, scoring criteria are often not clearly defined and very little research has focused on judging reliability [2]. In the present study, we focus on how consistent professional judges and audience members are in judging hip hop competitions, with a particular interest in the importance of synchrony between dancers in determining ratings.

In the context of the aesthetic appeal of dance, movement synchrony refers to the ability of two or more dancers to execute movements together in both space and in time [3]. Several studies have found that synchrony influences the aesthetic enjoyment of watching dance performance. When people observed a 30-minute dance performance where movement synchrony between performers varied over time, functional magnetic resonance imaging (fMRI) revealed that movement synchrony among performers was the strongest predictor of neural similarity between observers, supporting theories that movement synchrony is a crucial component of aesthetics in dance performance [4]. In another study, observers of dyads moving either synchronously or asynchronously rated synchronous movement as more enjoyable [3]. Similarly, audiences rated pairs of dancers performing simple hip hop dance steps higher in aesthetic appeal when the dancers moved in synchrony compared to asynchrony [5]. This study also found that observing synchronous dance elicited greater pupil dilation compared to asynchronous dance [5]. In a contemporary dance performance presented to four different audiences, where movement synchrony was manipulated to vary over the course of the choreography, movement synchrony was a significant predictor of both heart rate and continuous enjoyment ratings of the audience [6]. However, some audience members showed no relationship between synchrony and enjoyment ratings, or even a reverse relationship, suggesting factors other than performers' dynamic movement synchrony influenced audience enjoyment [6].

The appeal of synchrony across many dance and musical practices [5,6] may relate to the general finding that moving in synchrony with other people, that is, coordinating movements in time, has been shown to increase trust, cooperation, empathy, and positive associations within groups [7–10], even promoting prosocial behaviour in infants [11–13]. From a physiological perspective, dancing in synchrony with others leads to increased pain thresholds, a commonly-used proxy for increased endorphin release [14]. Increased endorphin release is found both in synchronous activity with higher exertion, as well as shared musical experiences, both of which occur when people dance together [15]. Generalizing from participation in synchrony to *observation* of synchrony, the coalition-signaling hypothesis states that synchronized music-dance performances communicate group cohesion, signaling to observers they can form a cooperative alliance [5,6,16]. This hypothesis is supported by research showing observers expect synchronous dyads to affiliate more and work better together than asynchronous dyads [17]. In other words, synchrony in dance may signal group cohesion and cooperation among the dancers [8] and create an environment of social bonding that includes the audience.

Despite findings on preference for synchrony in dance performance, it remains unclear how large a role it plays in hip hop dance competitions, and whether preference for synchrony interacts with other factors. For example, cultural familiarity with a dance style appears to play a role in the preference for synchrony in dance [18]. Hip hop was originally performed at parties and battles [19]. One study found that dance battle competitors tended to synchronize in anti-phase with one another [20], but it is unclear what impact anti-phase synchrony has on observers. Further, as hip hop was historically often improvised, synchrony between dancers may not have been a very important factor considered by judges choosing winners of competitions or battles during its early development. However, as hip hop dance has become more mainstream, commercialized, presented to wider audiences, integrated with other styles of dance, and more planned and choreographed, synchrony may have become more important, and therefore more heavily weighted during judging and audience appreciation.

Although there is evidence supporting a preference for synchrony in the observation of dance performance, effects of the experience and expertise of the observers have been less studied. Research suggests dance expertise leads to increased perceptual efficiency; when expert and novice observers watched a contemporary dance film, the expert dancers had significantly faster saccades and shorter eye fixations for dance movements and configurations [21], indicating dance expertise enhances visual processing speed and the ability to anticipate and quickly process choreographic movements. In general, dancers create stronger mental representations of observed dance movements than novices, as reflected by stronger within-brain theta-band synchrony in electroencephalography (EEG) recordings while observing dance, whether from videos [22] or live performances [23]. Stronger theta-band synchrony is associated with memory and multisensory processing [24,25], as well as shifting spatial attention [26]. Further, fMRI studies showed higher neural similarity between the brains of trained ballroom dancers than between the brains of novices when watching dance performance videos [27], and higher neural similarity between the choreographer of a contemporary dance and trained versus novice observers [4]. While the studies reviewed above suggest expert and novice dancers differ in their neural responses to dance, few studies have examined whether their judgements are influenced by the same or different factors. Novice observers have been shown to prefer dance routines with symmetrical movement, continuous movement transitions, body postures that maximize spatial symmetry, higher movement amplitudes, faster turning velocities, and movements that involve the entire body such as jumps [28–31], but it is not clear whether they weight these factors similarly to expert dancers or, indeed, if expert dancers are consistent among themselves in their preferences.

Within dance competition judging, little research has investigated how consistent judges are in their ratings, the factors that influence their ratings, or how to implement objective judging measures. One study examined past score sheets of hip hop dance competitions held in Japan between 2014 and 2019 to determine judges' consistency and reliability [2]. Of the categories (technical quality, synchronization, impression, creativity, expression and interpretation), technical quality showed the highest reliability, and impression (whether the performance evoked emotional responses from audience) the poorest. Consistency scores were variable, ranging from fair to excellent across different categories. Synchronization showed good reliability but only moderate consistency. However, as this study only investigated past competitions, the authors were not able to compare any of the findings to objective measures of the performance [2].

The present study aimed to investigate: (1) the importance of movement synchrony, measured objectively using motion capture, in evaluation of hip hop dance quality, (2) the consistency of expert judges' scoring, including subjective synchrony scores, and (3) the role of dance experience in judgements of audience members during a high-level hip hop dance competition. We hosted an in-person hip hop competition in the McMaster LIVELab and collected motion capture data of the dancers during their performances. The judges determined the winner of the competition using a provided set of criteria, and audience members provided their own ratings of the performances. We hypothesized that given its aesthetic appeal, motion capture synchrony of the dancers would be a strong predictor of the competition winner, such that the routine with the highest level of synchronization would win the competition. We also predicted that audience members with hip hop dance training would be more similar to the judges in their scoring compared to non-hip hop trained audience members.

Methods

Participants

Participants included competing dancer groups (6 groups of 5 dancers for a total n = 30), audience members (n = 74), and judges (n = 5). Dancers and audience members were recruited via public social media posts. Judges were paid and selected based on extensive hip hop dance backgrounds and judging expertise. The five judges ranged in age from 28-39 years (*M* = 30.8, *SD* = 4.9). To compete, choreographers had to submit a sample piece of choreography and be approved by experimenters to ensure they had the requisite dance experience. All dancers paid a $10 registration fee. Competing dancers ranged from ages 16-27 years (*M* = 20.7, *SD* = 2.6). Audience members bought tickets and were invited to participate. They ranged from ages 17-56 years (*M* = 31, *SD* = 12.2). Prior to the competition, all participants (competing dancers, judges, and audience members) completed consent forms and demographic surveys, which included questions about their music and dance experience. For compensation, the winning group of the dance competition was given the dancer registration fees, totalling $300. This study was conducted in accordance with the McMaster Research Ethics Board (MREB #1975) and informed consent was obtained from all participants.

Stimuli

Each dance group provided their own musical selections, which were presented through the Meyer Constellation speaker system in the LIVELab. The average amplitude levels were matched across group. For consistency, simple white stage lighting was used during all competing performances.

Procedure

Each dancer could only compete in one group. Each group performed one routine between 2:20 - 2:40 min in length that contained only one song. To facilitate synchrony analyses, each routine was required to have a minimum of 15-20 seconds of choreography in which all dancers performed identical movements, including no level changes, formation changes, or differences in direction of movement. Competing groups chose their own costumes. Prior to the competition, dancers were sent an information packet containing the rules and regulations of the competition, along with a schedule for the competition day and the judges' score sheet (Table 1). Performance order was random. The choreographer(s) of each group choreographed their own dance routine and rehearsed it with their group prior to the competition day.

All competing groups had a 10-min technical run on the LIVELab stage in the afternoon of the competition to acclimatize to the motion capture markers. Only LIVELab staff and experimenters were permitted in the theatre at the time of technical runs. Motion capture was collected during the technical runs and the competition, but only the latter was analyzed.

The evening competition began with an emcee explaining to the audience how the research study would integrate into the competition. Each competing group performed once. The judges were given time to fill out their score sheets after each performance (Judge Score 1). All competing groups performed before intermission, at which point each judge was allowed to independently adjust their scores (Judge Score 2). Judges were then allowed to discuss amongst themselves the merits of the performances before providing their final scores (Judge Score 3), while the audience watched a showcase of three non-competing teams. Finally, the 1st and 2nd place winners were announced based on the judges' final scores. All winning groups were presented with a certificate, and the first-place winner was awarded the $300 prize.

Audience participants were recruited on site from those who purchased tickets for the event. They also rated the performances after each routine according to a simplified rating sheet (Audience Ratings). Post-performance questionnaires were given to the performers after their own group's performance (Dancer Post-Performance Questionnaire).

Data Collection

The competition took place at McMaster's LIVELab research-based performance theatre in November 2023. There were 106 seats, with five reserved for the judges. Stage dimensions were adjusted to 132 x 254 inches by tape, to assure the movements of the dancers were fully captured by the motion capture system.

i. Motion Capture

The dancers' movements were tracked using the Qualisys motion capture system with 13 cameras at a sample rate of 100 samples per second. Dancers wore ankle bands and wrist bands containing one marker each, and a headband with two markers (six markers in total per dancer). The head markers were averaged together for data analysis. Only data during the performances were analyzed.

ii. Judges' Evaluations

Judges evaluated the performances using a score sheet created by the experimenters (Table 1), based on commonly used criteria at competitions [2]. The three main criteria categories were *Choreography* (with 2 subsections), *Execution* (3 subsections), and *Overall Cohesion*. Experimenters discussed the score sheet with the judges prior to the start of the competition. Each judge's overall score was the sum of the subsection scores, and each group's final score was calculated as the mean of the five judges' overall scores. Dancers were provided with copies of their own score sheet after the competition. Judges were also asked to provide their own suggested weights for each section. These weights were not used for the calculation of the top scoring group.

iii. Audience Ratings

After each performance, audience participants rated two questions on a scale of 1 to 10: 1) "Overall, what score would you give the performance?" and 2) "How well do you know the dancers in this piece?". After all six performances, they were asked to provide a ranking for first, second, and third place: "Please rank who you believe should win the top three places overall. This ranking does not need to line up exactly with your scores." Audience ratings had no influence in determining the competition winner.

iv. Demographics Questionnaire

All participants filled out a demographics questionnaire including questions on their dance and music background prior to the beginning of the competition.

v. Video and Audio Recordings

Performances were recorded using a Sony PXW-Z90V Version 2.01 camera to serve as a reference for cleaning the motion capture data and to investigate the intensity of audience cheering.

vi. Dancer Post-performance Questionnaire

The post-performance questionnaire asked the dancers to rate the following aspects of their routine, each out of 10. *Overall Performance*: "How well did you feel your performance went overall?"; *Synchrony*: "How synchronized did you feel your performance was?"; *Complexity*: "How complex did you feel the choreography of this dance piece was?"; *Creativity*: "How creative did you feel the choreography of this dance piece was?"; and *Execution*: "How well do you think your group executed the dance?".

Table 1

Judges Score Sheet

Category	Subsection	Description	Comments	Score[1]
Choreography	Complexity	Difficulty Musicality of choreography Staging/transitions		/20
	Creativity	Creativity Originality		/20
Execution	Technique	Technique/skill		/10
	Timing	Musicality of execution Synchronization Cleanliness		/15
	Stage Presence	Stage presence Facials Expression		/15
Overall Cohesion		Costume Music Overall flow of set		/20
Total				/100

[1]Judges were provided three columns for each sub-score: (1) immediately after watching the performance, (2) adjusted score after seeing all competing groups, and (3) adjusted score after discussion with other judges. Score 3 was used to determine the winner of the competition.

Data Preprocessing

i. *Intra-Class Correlation Coefficients (ICC)*

To assess the reliability of ratings provided by judges and audience members, Intraclass Correlation Coefficients (ICC) were calculated using the ICC(3,k) model. This model is appropriate for situations where the same fixed set of raters evaluates all subjects. A two-way mixed-effects model was used where rater effects were fixed, and the reliability was based on the mean ratings. The ICC(3,k) provides an estimate of the consistency of ratings, and was calculated for judges as well as audience members.

ii. *Motion Capture Synchrony*

For each marker, missing data was interpolated using linear interpolation for sections of time less than three seconds. An average of 5.4% of the data included in the analysis was interpolated (*SD* = 2.1% across groups). Sections with more than three seconds of missing data were not included in the analysis for that marker. An average of 1.7% of the data was not included (*SD* = 2.8% across groups). Spline smoothing was applied to each coordinate axis (X, Y, Z) of the position data before calculating the magnitude of velocity as the sum of the absolute value of each coordinate axis. Velocity magnitude was normalized across time for each marker within a participant. Sections of the routines were identified as identical movement if all dancers were performing the same movement at the same time (for at least three consecutive seconds), as determined by inspection of the videos by the experimenters. The total amount of identical movement time ranged from 41.6 s to 79.4 s (*M* = 63.6 s, *SD* = 15.1) across groups; the number of separate sections of identical movement ranged from 7-9 across groups. Synchrony was calculated as an average of the Pearson's correlation coefficients (lag = 0) of the velocities between each pair of dancers. To equate the amount of data analyzed across groups, a nested bootstrap procedure was used such that, for each identical movement section, 300 data points (the minimum number of data points in a section of identical movement) were randomly selected to calculate motion capture synchrony [32]. This procedure was repeated with 1000 resamples based on bootstrapping guidelines [33]. The synchrony of each section of identical movement was estimated as the average of the 1000 resamples. Synchrony was calculated separately for the head, wrist, and ankle markers between each pair of dancers (averaged across all possible pairs of dancers) for each section of identical movement within each group.

iii. Intensity of Audience Cheering

Music pieces were matched in intensity prior to the competition. Thus, differences in sound intensity during the performances largely reflected differences in the intensity of audience cheering. Average intensity was analyzed from the beginning of the music to the time at which the audience naturally stopped cheering (M = 10.08 s, SD = 1.26 s of cheering after music ended). The two stereo channels of the audio recordings were averaged together, and the intensity (volume) of each performance was calculated as the root mean square (RMS) amplitude.

Results

Demographics

Demographic information for the dancers, audience members and expert judges is summarized in Table 2.

Competing Dancers

Competing dancers (n = 30) had 2-21 years of dance training experience (*M* = 9.48, *SD* = 6.8). A 1x6 analysis of variance (ANOVA) with group as a factor found no significant differences between groups for years of dance training ($F(5,22) = 1.21$, $p = .335$). Music training experience ranged from 0-16 years of experience (*M* = 3.89, *SD* = 4.8), and a 1x6 ANOVA with group as a factor found no significant differences between groups ($F(5,22) = 0.56$, $p = .728$). Of the dancers, three identified as Black, four as White, fourteen as Asian, five as South Asian, one as First Nations, two as Latina, and one as mixed.

Audience Members

Audience members (n = 74) ranged from 0-38 years of dance training (*M* = 5.6, *SD* = 7.48). There were 32 hip hop dancers (HH), 15 non-hip hop dancers (NH) who indicated training in a dance style other than hip hop (or street dance), and 27 non-dancers (ND). The music training of the audience ranged from 0-15 years of experience (*M* = 4.8, *SD* = 4.52). Of the audience participants, 42 people identified as Asian, 6 as Black, 2 as Latina, 4 as mixed/biracial, 16 as White, and 4 participants did not report their ethnicity.

Judges

The five judges' years of training in hip hop and other street dance styles (including but not limited to popping, locking, and breaking) ranged from 9-24 years (*M* = 17.0, *SD* = 5.6). The judges had a range of 1-7 years of music training (*M* = 3.5, *SD* = 3.0). Two judges identified as Filipino, two as Black, and one as South Korean.

Table 2

Demographics for all participants

	Dancers	Judges	Audience
Sample Size	30	5	74
Female:Male:NB[1]	26:4:0	2:3:0	49:21:3
Age	20.7 ± 2.6	32.6 ± 6.3	31.0 ± 12.2
Years of Dance Training	9.48 ± 6.8	17.0 ± 5.6	5.6 ± 7.5
Years of Music Training	3.89 ± 4.8	3.5 ± 3.0	4.8 ± 4.5

[1]NB = non-binary.

Overall Scores and Questionnaire Responses

Judges Scores

The winner of the competition as assessed by the judges' scores (Fig. 1A-C) had the highest overall mean score of 86.80 (SD = 9.47) out of 100. Judges demonstrated high levels of consistency across competing groups, with an ICC of 0.94 (95% CI[0.845, 0.99], $p < .001$). A breakdown for each scoring subsection can be found in Table 3 and supplementary material (Fig. S1) based on their final scores. On average, judges changed their total scores by 1.75 points (SD = 1.65) at the first adjustment period and 0.63 points (SD = 0.79) at the second adjustment period. Changes are presented visually in supplementary material (Fig. S2). Their scoring consistency was high even with the initial scores provided immediately after each performance, ICC = 0.90 (95% CI[0.73, 0.98], $p < .001$).

ICC was calculated for scores for each subsection using the final score (Score 3). Under Choreography, Complexity showed an ICC of 0.88 (95% CI[0.68, 0.97], p < .001) and Creativity an ICC of 0.90 (95% CI[0.72, 0.98], p < .001). In the Execution section, Technique showed an ICC of 0.81 (95% CI[0.49, 0.96], p = .003), Timing an ICC of 0.86 (95% CI[0.63, 0.97], p <

.001), and Stage Presence an ICC of 0.80 (95% CI[0.46, 0.96], p = .004). Finally, Overall Cohesion had an ICC of 0.92 (95% CI[0.78, 0.98], p < .001).

Judges' suggested weights for the subsections of the score sheet indicated fewer points be allocated to the complexity of choreography ($M_{points} = 18.6 \pm 0.9$), creativity of choreography ($M_{points} = 16.6 \pm 0.9$), and overall cohesion ($M_{points} = 14 \pm 1.7$) and more points allocated to technique ($M_{points} = 16.1 \pm 0.6$), timing ($M_{points} = 18.1 \pm 1.6$), and stage presence ($M_{points} = 16.6 \pm 3.3$). In recalculating the scores with the mean suggested weights, the order of groups' final scores do not change ($M_{Group\ 1} = 77.5$, $M_{Group\ 2} = 65.2$, $M_{Group\ 3} = 73.4$, $M_{Group\ 4} = 86.7$, $M_{Group\ 5} = 73.2$, $M_{Group\ 6} = 62.9$). Mean suggested weights are shown compared to actual weights in supplementary material (Fig. S3).

Table 3

Means and Standard Deviations (SD) of Judges and Audience Scores

			Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
Judges[1]	**Total (/100)**	**Mean**	**78.00**	**65.60**	**74.00**	**86.80**	**73.70**	**64.00**
		SD	**10.22**	**7.13**	**14.00**	**9.47**	**4.44**	**11.77**
	Complexity (/20)	Mean	15.60	12.80	14.40	17.00	15.10	13.40
		SD	2.61	2.05	3.36	2.35	2.25	3.29
	Creativity (/20)	Mean	15.20	12.40	14.20	16.40	15.00	12.60
		SD	3.03	2.61	3.11	2.70	1.58	3.44
	Technique (/10)	Mean	7.40	6.00	6.20	8.20	7.40	5.20
		SD	0.55	1.73	2.39	1.10	0.89	1.64
	Synchrony (/15)	Mean	11.80	9.80	11.60	13.80	10.00	9.20
		SD	1.10	1.48	2.30	0.84	1.87	1.10
	Stage Presence (/15)	Mean	11.40	10.60	12.20	13.40	10.80	10.20
		SD	2.07	1.52	1.30	1.14	0.84	1.92
	Cohesion (/20)	Mean	16.60	14.00	15.40	18.00	15.40	13.20
		SD	2.88	1.87	2.88	2.00	1.67	2.05
Audience[2]	**Score (/10)**	**Mean**	**8.24**	**6.85**	**9.12**	**8.91**	**8.45**	**6.96**
		SD	**1.05**	**1.07**	**0.71**	**0.95**	**1.26**	**1.23**
	Familiarity (/10)	Mean	2.34	2.91	2.74	2.39	3.01	2.34
		SD	2.58	3.03	2.69	2.92	3.16	2.65
	HH Score (/10)	Mean	8.11	6.78	9.02	9.07	7.98	6.46
		SD	1.26	1.10	0.75	0.88	1.15	1.15
	NH Score (/10)	Mean	8.12	6.33	9.27	8.77	8.98	7.20
		SD	0.75	1.11	0.68	0.96	1.00	1.15
	ND Score (/10)	Mean	8.46	7.23	9.15	8.80	8.70	7.41
		SD	0.89	0.90	0.70	1.02	1.35	1.19

[1]Judges (averaged across the five judges) scores reflect responses from their score sheets. Total scores are the sum of all subsections. Only their final scores are reported.

[2]Audience (averaged across the 74 audience members) scores reflect responses from their score sheets. Scores are then broken down by dance training of the audience members. HH = hip hop trained (n = 32), NH = non-hip hop trained (n = 15), ND = non-dancer (n = 27).

Audience Scores

Fig. 1D shows audience members' overall mean scores across competing groups, with a highest overall mean score of 9.12 (SD = 0.71) out of 10. All audience scores are summarized in Table 3. It can be noted that audience members rated a different group as having the top score than the judges. Audience members' familiarity with dancers did not differ significantly across groups ($F(5,444) = 0.84$, $p = .523$). Overall, audience members showed a moderate consistency in scoring across pieces with an ICC of 0.67 (95% CI[0.57, 0.76], $p < .001$). To investigate the impact of hip hop training on these scores, ICCs were calculated separately for the three different audience groups. The hip hop trained group showed an ICC of 0.74 (95% CI[0.60, 0.84, $p < .001$), the non-hip hop trained group an ICC of 0.73 (95% CI[0.50, 0.88], $p < .001$), and the non-dancer group an ICC of 0.53 (95% CI[0.26, 0.73], $p = .003$).

The overall audience scores (averaged across audience members) were then correlated to each subsection of the judges' score sheets (averaged across judges) to investigate which subsections of the judges' scoring related most strongly to the audience overall scores (Table 4). Note that these presented p-values are not corrected for multiple comparisons and should be considered as exploratory. After correcting for multiple comparisons using Bonferroni correction, no correlations reached significance ($p > .05$).

Table 4

Pearson's Correlations between Judges' Subsection Scores and Audience Total Scores

Judges' Subsection Score	Audience Total Score	
	Coefficient[1]	P-Value[2]
Complexity	.79	.060
Creativity	.85	.031
Technique	.70	.122
Timing	.76	.080
Stage Presence	.80	.055
Overall Cohesion	.80	.058

[1]Correlations were performed between judges' total scores (averaged across the five judges) and audience total scores (averaged across the 74 audience members).

[2]P-Values are not corrected for multiple comparisons. Degrees of freedom = 4 for all tests, representing the six groups included in the analysis.

Finally, audience scores were correlated with the intensity of audience cheering (RMS) for each competing group to investigate whether there was a relationship between how loud the audience cheered for each piece with how highly they scored them (Fig. 1E). Results show a moderate positive correlation, though it did not reach significance, $r(4) = 0.53$, $p = .279$.

Dancer Post-Performance Questionnaires

All post-performance questionnaire results are summarized in Table 5, averaged across all members of the group. Statistical correlations were not conducted between the dancers' responses with the judges scores, as the judges saw all groups perform whereas the dancers did not see other performances and therefore did not complete their responses in relation to other groups.

Table 5

Mean and standard deviations (SD) of Dancers' Ratings of their own performances

		Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
Overall	**Mean**	**9.00**	**6.80**	**9.00**	**8.20**	**9.00**	**7.80**
	SD	**0.00**	**0.84**	**1.41**	**0.45**	**1.22**	**1.92**
Complexity	Mean	8.80	5.80	8.20	9.40	6.00	8.60
	SD	0.84	2.17	0.84	0.55	2.55	0.89
Creativity	Mean	9.20	6.20	8.80	9.20	7.00	8.20
	SD	0.84	1.92	1.10	1.10	2.00	0.84
Synchrony	Mean	9.00	5.80	9.00	7.00	8.60	7.00
	SD	0.00	1.48	1.22	1.22	1.14	2.00
Execution	Mean	9.00	7.00	9.00	8.20	9.00	8.00
	SD	0.71	1.22	0.71	0.84	1.00	1.58

Motion Capture Synchrony of Competing Groups

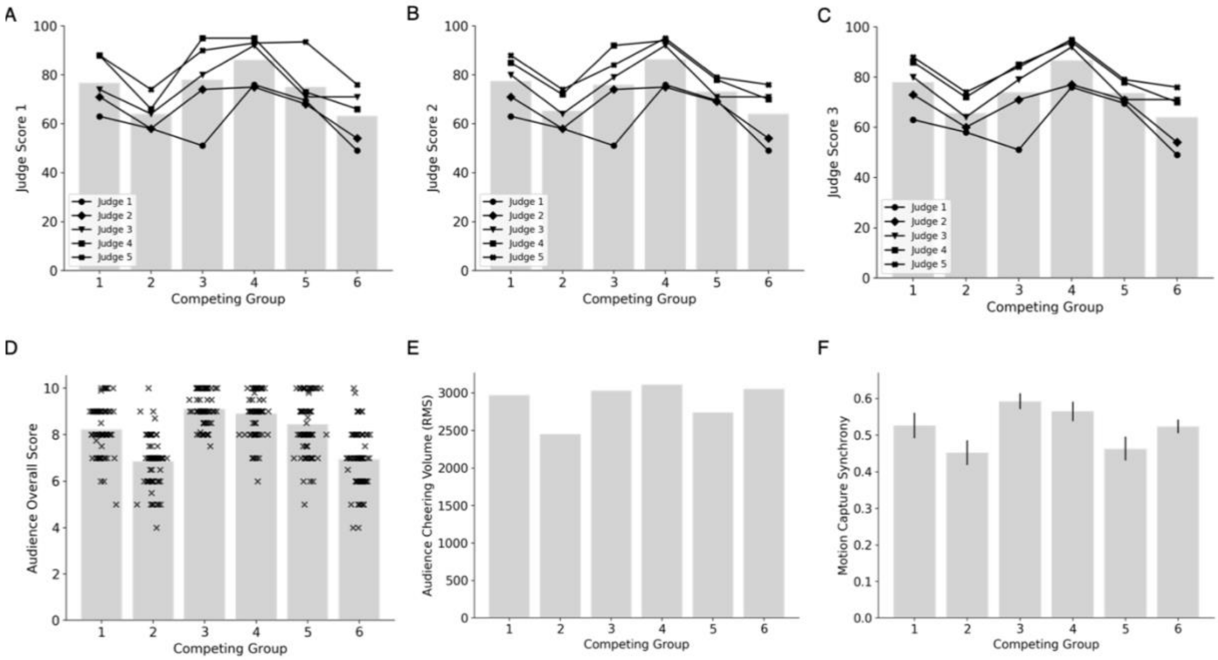
Mean motion capture synchrony scores of the competing groups were calculated only during sections of time where dancers were performing identical movements. A linear regression analysis was conducted to predict judges' overall scores based on motion capture synchrony, length of identical movement section (in s), and the interactions between markers and motion capture synchrony. The model accounted for 10.3% of the variance in judge scores, $R^2 = .103$, adjusted $R^2 = .064$, $F(10,229) = 2.62$, $p = .005$. The intercept was significant, $\beta = 71.06$, SE = 1.97, $t(229) = 36.08$, $p < .001$. Among the main effects, motion capture synchrony was a significant predictor of judge scores, $\beta = 11.48$, SE = 3.50, $t(229) = 3.28$, $p = .001$. Length of identical movement section also significantly predicted judge scores, $\beta = -0.40$, SE = 0.10, $t(229) = -4.06$, $p < .001$, indicating that longer identical movement sections were associated with lower overall scores. None of the interactions between motion capture synchrony and marker reached significance.

A similar linear regression investigated the prediction of audience scores based on motion capture synchrony, length of identical movement section (in s), and the interactions between markers and motion capture synchrony. The model accounted for 11.6% of the variance in audience scores, $R^2 = .116$, adjusted $R^2 = .08$, $F(10,229) = 3.02$, $p = .001$. The intercept was significant, $\beta = 7.66$, SE = 0.22, $t(229) = 35.22$, $p < .001$. Among the main effects, motion capture synchrony was a significant predictor of audience scores, $\beta = 1.50$, SE = 0.39, $t(229) = 3.89$, $p < .001$. Length of identical movement section also significantly predicted audience scores, $\beta = -0.05$, SE = 0.01, $t(229) = -4.11$, $p < .001$, indicating that longer identical movement sections were associated with lower scores. None of the interactions between motion capture synchrony and marker reached significance.

As shown in Fig. 1, the group with the highest motion capture synchrony (averaged across markers), Group 3 (Fig. 1F), corresponded with the audience's highest scoring group (Fig 1D), but not the judges' highest score (Fig. 1C). Spearman's rank correlation coefficients show a smaller association between motion capture synchrony (averaged across markers) and judges' scores (averaged across judges), $r(4) = 0.66$, $p = .175$, compared to the association between motion capture synchrony and audience's scores (averaged across audience members), $r(4) = 0.83$, $p = .058$.

Figure 1

Scores, volume of cheering, and motion capture synchrony across all competing groups



(A-D) Scores for each competing group, scored by (A) Judges immediately after watching the performance, (B) Judges after seeing all competing pieces, (C) Judges after discussing with one another, and (D) Audience members immediately after watching the performance, such that each X represents one audience member participant. (E) Amplitude of audience cheering for each competing group. (F) Motion capture synchrony of each competing group's movement velocity. Error bars represent standard error of the mean across markers.

To investigate which factors of the judges' scoring were related to synchrony, motion capture synchrony (averaged across markers) was correlated with the individual subsections of the judges score sheet (averaged across judges). Results showed the strongest correlations with motion capture synchrony were judges' ratings of Timing (r = .65) and Stage Presence (r = .71). The weakest relation was between motion capture synchrony and ratings of Technique (r = .12). All Pearson's correlations are summarized in Table 6.

Table 6

Pearson's Correlations between Judges' Subsection Scores and Motion Capture Synchrony

Judges' Subsection Scores	Motion Capture Synchrony	
	Coefficient[1]	P-Value[2]
Complexity	.45	.370
Creativity	.41	.420
Technique	.12	.815
Timing	.65	.160
Stage Presence	.71	.116
Overall Cohesion	.44	.378

[1]Correlations were performed between judges' subsection scores (averaged across the five judges) and motion capture synchrony (averaged across markers).

[2]P-Values are not corrected for multiple comparisons. Degrees of freedom = 4 for all tests, representing the six groups included in the analysis.

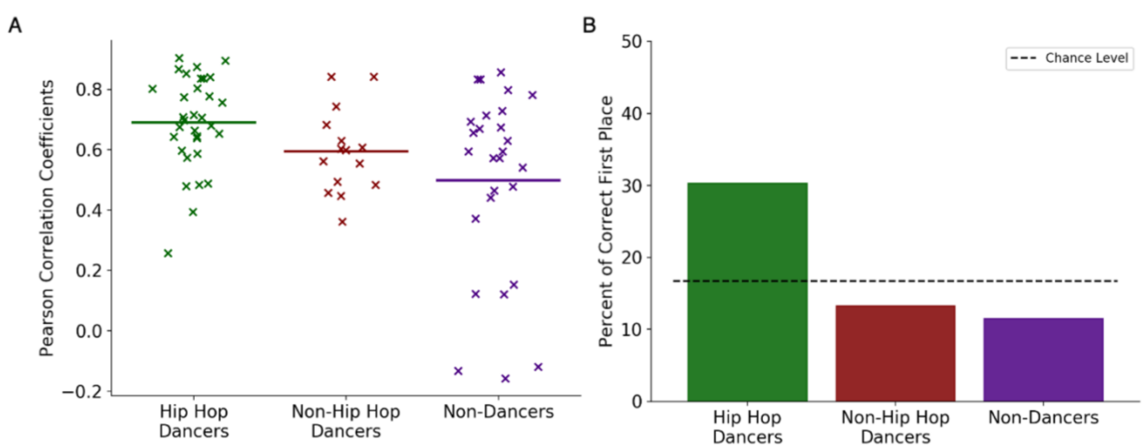
Audience Similarity to Judges

To investigate the influence of hip hop dance training on the audience's ability to score the dances, similarity was evaluated as the Pearson's correlation coefficient between each audience member's overall score with the judges' final scores (averaged across judges). All Pearson correlation coefficient calculations had four degrees of freedom, representing the six groups included in the measure. To investigate the effect of dance experience, similarity scores were then separated by the three groups of dance training: hip hop (HH), non-hip hop (NH), and no dance training (ND). Results are summarized in Fig. 2A. A 1x3 ANOVA was conducted on similarity (Pearson's coefficients) with the between-subject factor of dance training (HH, NH, and ND). Results showed a significant effect of dance training ($F(2, 71) = 5.55$, $p = .006$). Post-hoc Welch's t-tests (Bonferroni corrected) between training groups found that hip hop dancers were significantly more similar to judges than non-dancers ($t(36.9) = 2.95$, $p = .005$, $p_{bonf} = .016$). Hip hop dancers were more similar to judges than non-hip hop dancers, but this did not reach significance after correcting for multiple comparisons ($t(30.1) = 2.14$, $p = .040$, $p_{bonf} = .121$). Non-hip hop dancers and non-dancers did not differ significantly ($t(39) = 1.37$, $p = 1.78$, $p_{bonf} = .534$).

Fig. 2B shows the percentage of audience members who correctly predicted the judge's choice of winner, separated by dance training, based on audience members' final choice of winner after having seen all of the performances. The hip hop dance trained group had the highest proportion of participants (30.3%) who correctly predicted the winner, while 13.3% of non-hip hop dancers and 11.5% of non-dancers correctly predicted the winner, both below chance level. A chi-square test examining the effect of dance training on the proportion of participants who predicted the correct winner revealed a significant effect of dance training, $\chi^2(2) = 371.76$, $p < .001$.

Figure 2

Audience Similarity to the Judges Separated by Dance Training



(A) Audience similarity to judges scores, such that each X represents the Pearson's correlation coefficient for one audience member compared to the judges scores. (B) Percentage of audience members who correctly predicted the winner for each group of training.

Discussion

The present study was the first to investigate an in-person, high-level hip hop dance competition using multiple simultaneous modes of data collection. This experiment was novel in its methodological design, ecological validity, and use of motion capture during a real hip hop dance competition with expert-level dancers and professional judges. The results showed that an objective measure of synchrony via motion capture analyses was a significant predictor of scores from both the highly experienced judges as well as audience members. At the same time, the first-place winning group as assessed by the judges was not the one with highest motion capture synchrony. However, objective synchrony may play a stronger role in the audience member's impression of the dance performances, as the highest overall score aligned with the most objectively synchronized group. Audience members with hip hop dance training were twice as likely as non-hip hop trained participants to choose the same winning group as the judges. Further, the dance training of the audience members was a significant factor in how similar their scores were overall to those of the judges. Finally, judges' scores were highly correlated, suggesting that they used similar metrics for evaluation.

Judges are Highly Consistent in their Scoring Across Groups

Although the judges were not identical in their scoring and differed in the range of scores used, they were highly consistent in their relative scoring across groups. This remained true for their initial scores, first adjustment scores, and final adjustment scores. In fact, most of the scoring adjustment occurred at the first adjustment period, at which point judges had seen all the groups but not each other's scores.

The consistency of judges' scores across subsections differed from the reliability scores found in a previous study [2]. In our study, technique had the lowest consistency (ICC = 0.81), and overall cohesion the highest (ICC = 0.92). The previous study found technique to be the most reliably judged subsection and overall impression to be lower [2]. Thus, how subsections are described to judges, and the context of the competition may affect how reliably certain factors are judged.

To gain insight into the judges' expert opinions on the provided score sheets, they were asked to give their preferred weighting for each subsection. On average, the judges indicated they would put more weight (points allocated) for execution, which included more points for technique, timing, and stage presence. They indicated they would allocate fewer points for choreography (creativity and complexity), as well as overall cohesion. This helps inform the design of score sheets for future competitions and calls for a greater emphasis on execution of dance performance in competition settings. It should be noted that the order of the groups' scores did not change when recalculated using these suggested weights.

Audience Members Chose a Different Winner than Judges

Interestingly, audience members' highest mean score did not align with the highest mean score from the judges, suggesting audience members may have weighted (valued) the factors differently compared to judges. Understanding street dance technique, the intricacies of timing and musicality, and the complexity of movement and choreography are likely to be scored more appropriately by judges with high levels of expertise. It is also important to note that the audience members scored the pieces on an overall scale of 1-10, while the judges scored individual subsections, which likely enhanced their ability to take multiple factors into account.

Another explanation for why the judges and audience members evaluated the competing routines differently could relate to differences in intentions. Audience members likely came to enjoy watching the performances, and therefore were influenced more by the aesthetic appeal of synchrony. The judges were there to evaluate the performances and determine a winner. As a result, they may have been less influenced by personal enjoyment and more focussed on the subsections of the score sheets to ensure fairness.

What Factors Might be Influencing Audience's Members Scoring?

While the judges were provided a detailed score sheet with six different subsections, audience members were asked simply to provide a score from 1-10. Correlations between the audience members' overall score with the subsections of the judges' scores can provide insight into what factors may be related to the audience's perception of the performances. Higher correlation coefficients were found between audience members' scores and judges' scores for creativity of the choreography, overall cohesion of the performance, and stage presence. Compared to more technical aspects of the performances, these may be more subjective, require less training to evaluate, and relate more to overall enjoyment of the performance than objective quality.

The Role of Synchrony

Motion capture synchrony was a significant predictor of scores from both judges and audience members, emphasizing the importance of movement synchrony in dance observation, aligning with research showing the aesthetic appeal of synchrony in dance performance [3–6]. However, contrary to our hypothesis, the winning routine of the competition did not have the highest level of objective synchronization. Interestingly, the audience members rated the objectively most synchronized group highest, suggesting the audience may have valued routines higher in synchrony more than the judges. Spearman's rank correlations showed higher coefficients for motion capture synchrony to the audience rankings compared to the judges. Though these correlations did not reach significance, likely due to low power from having only six dance groups, they indicate a complex relationship between synchrony and scoring, since the routines' synchronization levels did not predict the exact rankings for either the audience or the judges. The length of the sections containing identical movement in all five dancers varied across groups, and was also a significant predictor of judges and audience scores, such that choreographies with longer identical sections had lower scores. This may be because with longer sections of the same movement, observers are more easily able to identify lower amounts of synchrony. It may also reflect less interesting or creative choreography if the observers felt the dancers were doing the same movement for too long.

It is also possible that our objective measure of synchrony did not capture all aspects of what makes a performance be perceived as synchronized. One limitation with our approach is that the entire dance was not included in the analysis of motion capture synchrony, as we only analyzed the sections when the dancers were performing identical movement. The observers (both judges and audience members) of the performance, on the other hand, would have considering the entire performances in their scoring. A second possible limitation is that we calculated motion capture synchrony using only velocity. Velocity takes into account movement timing information but not necessarily positional information that might also influence synchrony perception. As synchrony research strives towards accounting for both timing and positional synchrony [34–36], incorporating these features in synchrony measures should be a focus of future experimental designs. Additional research on what objective measures of synchrony best capture viewers' perceptions of synchrony during highly complex movement such as hip hop dance would benefit the fields of dance, movement, and synchrony research.

The objective measure of motion capture synchrony was not only strong correlated with judges' ratings of how synchronized the dancers' movements were, but stage presence was also strongly correlated with motion capture synchrony. This may reflect an interaction between stage presence and timing, such that expression and energy of a dance performance can be appreciated more, and therefore scored higher, when the movements are also synchronized. Interestingly, the technique subsection was the least related to synchrony, indicating that hip hop technique comprises important factors other than synchrony.

Audiences Make Their Voices Heard in Hip Hop Dance

The audience has been historically very important in hip hop culture. The winners of dance battles were typically decided by the cheering level of the audience, which likely caused the audience to be more engaged and vocal while watching competitions [2,37]. Although it is less common now for audience members to be the sole deciding factor, this history likely contributes to audience members continuing to be highly engaged and vocal about what they like. Thus, it is unsurprising that we saw a trend for a correlation between the audience scores and the intensity of their cheering. This emphasizes the social nature of hip hop dance and highlights the robust relationship between audience members and performers that exists in hip hop culture.

Hip Hop Training Makes Audience Members More Similar to the Judges

As hypothesized, scores from the hip hop trained audience members were significantly more correlated with the judges' scores compared to the non-dancers. Additionally, the overall first place winner provided by each audience member, which was not required to align with their total scores, revealed that audience members with hip hop training were twice as likely to correctly guess the first place winner (compared to the non-hip hop dancers and non-dancers, both of whom performed below chance). This aligns with previous research showing trained dancers to be more similar to choreographers in their continuous ratings [4], as well as research showing increased efficiency in perceiving dance in dancers compared to novice observers [4,21,22,27]. The fact that the non-hip hop dance trained participants performed below chance level for predicting the winner suggests that general training in dance does not transfer to a nuanced understanding of street dance, highlighting the need for judges trained specifically in hip hop for hip hop competitions.

Limitations and Future Directions

Our study's strengths include its high ecological validity, live data collection, comparison of judges and audience ratings, and objective measurement of synchrony. However, the trade-off with ecological validity was a relatively low number of competing groups, leading to low powered statistical analyses. This study required a large amount of preparation from the experimenters as well as the dancers, as they needed to choreograph and rehearse their dance routines. We required competing groups to have exactly five dancers to control this factor and to simplify the data analysis. However, it is common in hip hop dance competitions to have much larger competing groups. Future research allowing larger groups to compete would help generalize these findings on the importance of synchrony in group dance.

As this study was the first of its kind, many of the analyses were exploratory and correlational. Additionally, our method of calculating synchrony only included the sections of the dances where dancers were performing identical movement, and only used the dimension of velocity. Future work examining the role that synchrony in space (i.e. position across all three axes), the synchrony of movement to music, and an objective measure of synchrony during non-identical movement would contribute to our understanding of the role synchrony plays in the perception of dance.

Conclusion

In a hip hop dance competition, the synchrony of the dancers plays a significant role in the perception of the performance, but motion capture synchrony alone is not able to predict the winner of the competition. Motion capture synchrony does, however, appear to align more strongly with the audience than judges' ratings, and synchrony alone was enough to predict the audience members' mean top score. When developing objective judging criteria, synchrony should be considered important, but not the determining factor of a winning routine, as we found other factors influence judges' scores. These findings contribute to standardization of hip hop judging criteria and inform dancers to focus beyond synchrony when preparing for competitions. Audience members with hip hop training were significantly more similar to the judges in their scoring, emphasizing the role of expertise and familiarity with a style of dance, and highlighting the need for specifically hip hop and street dance trained judges in competition settings. Judges were found to be highly consistent in their scoring, providing evidence that experienced and trained judges are capable of providing reliable scoring in hip hop dance competitions. Overall, this novel and highly ecologically valid study investigating the role of synchrony in hip hop dance competitions showed that there are multiple factors in addition to synchrony that influence the scoring of the highly complex art of hip hop.

Data Availability: The data that support the findings of this study are available upon request from the corresponding author.

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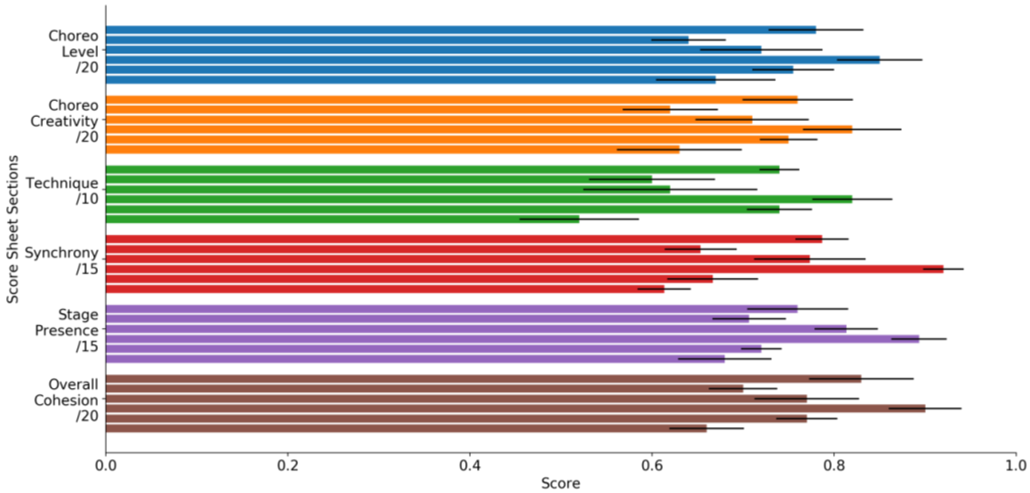
Supplementary Material

Figure S1

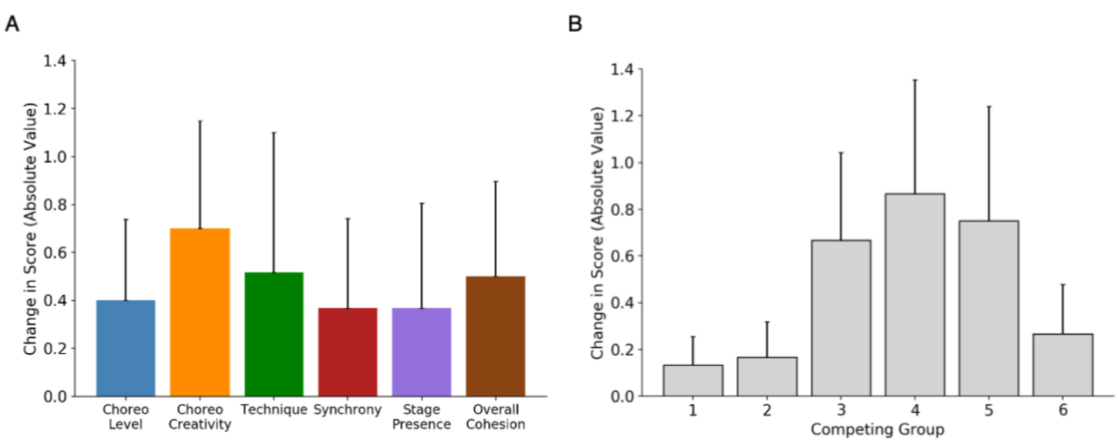
Breakdown of subsections of judges score sheet by competing group



These scores are written as proportions of the raw score divided by the maximum possible points, as labelled on the y-axis. Within each subsection, each bar represents a competing group, with the highest bar on the y-axis corresponding to the first competing group. Error bars represent standard error of the mean across judges.

Figure S2

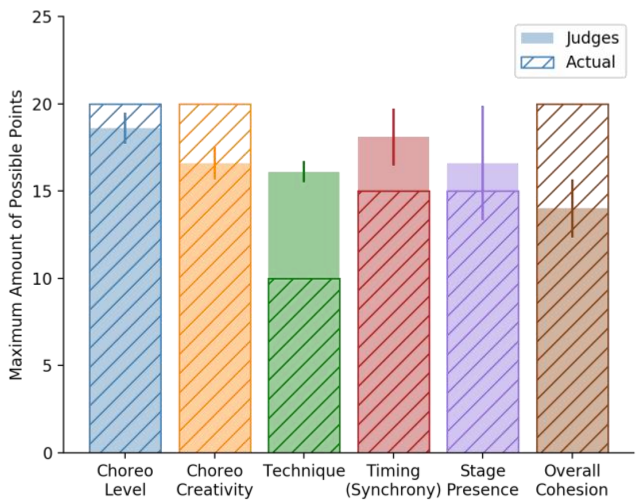
Changes in judges scores by subsection and competing group



Mean amount of change in judges scores from Score 1 to 3, separated by (A) Subsection of the score sheet, and (B) Competing group. Error bars represent standard error of the mean across judges.

Figure S3

Judges suggested weights for the score sheet



Suggested weights (shaded) are compared to hashed weights (actual). Each bar represents a subsection of the score sheet.

Chapter 5: Individual Differences in Hip Hop Dancers' Motor Synchrony

Preface

Chapter 5 links the two strands of this dissertation by examining the relationship between basic auditory-motor timing skills and interpersonal synchrony in dancers. While Chapter 4 established that group synchrony strongly predicts performance evaluations in competition, there was variability in how well individual dancers were able to synchronize their movements with other dancers. The individual-level skills that influence these differences in interpersonal synchrony remain understudied. To address this, the same dancers who participated in the competition completed a series of tasks measuring auditory timing perception and auditory-motor synchronization, similar to those used in Chapters 2 and 3 with children at risk for DCD. I found that tapping consistency was a significant predictor of individual interpersonal synchrony, suggesting that the skills impaired in DCD are the same skills that were associated with complex group synchrony in expert dancers. This chapter identifies which individual differences in auditory- and auditory-motor timing predict successful interpersonal synchrony.

Abstract

The ability to synchronize movements with others is a fundamental skill in everyday life, yet it varies widely both within and across populations. Interpersonal movement synchrony emerges in infancy, develops through adulthood, and has been shown to promote trust and cooperation in groups. Despite its developmental and social importance, little is known about the factors that affect individual differences in movement synchrony skills. In this study, we examined potential factors influencing movement synchrony in a population of expert dancers. Using motion capture, we quantified interpersonal synchrony in hip hop dancers performing in groups of five and compared these outcomes to individual auditory timing perception and auditory-motor synchronization measures. We found that tapping consistency predicted individuals' ability to synchronize with others. This finding suggests that underlying auditory timing skills are related to complex interpersonal synchrony, highlighting mechanisms that may explain variability in this fundamental aspect of social coordination.

1. Introduction

Movement synchrony, defined as the matching of movements in both space and time (Cross et al., 2024), is a skill that begins to develop very early in life and continues into adulthood (McAuley et al., 2006; Phillips-Silver et al., 2024). Movements can be synchronized to other people (interpersonal movement synchrony) and/or to music (auditory-motor synchrony). There are substantial individual differences in how well people can synchronize their movements to one another (e.g. Fujiwara et al., 2019; Miles et al., 2009), even among trained professionals, such as dance performers (e.g. Carrillo et al., 2025; Woolhouse & Lai, 2014; Cross et al., 2024; Orgs et al., 2024), but very little is known about what factors may lead to this variability. This study aims to investigate some factors that may contribute to why people differ in their ability to synchronize movement.

Moving in synchrony with others is a fundamental skill necessary for everyday activities like walking together, dancing, or singing in unison. Further, it has become a focus in social and developmental research for its role in fostering connection and trust. From birth, infants experience moving in sync with a caregiver when they are rocked or bounced. Infants begin to spontaneously coordinate movements to music as early as five months, for example, moving faster to faster music (Zentner & Eerola, 2010). By 2.5 years, children can begin to synchronize their movements (e.g. hand tapping) with other people (Kirschner & Tomasello, 2009), and this ability strengthens throughout childhood, with improvements continuing to occur after age 11 (Phillips-Silver et al., 2024). Importantly, moving in sync with others promotes interpersonal relationships, as seen by an increase in trust and cooperation within groups who coordinate their movements (e.g., Wiltermuth & Heath, 2009; Jackson et al., 2018; Tomashin et al., 2022; Behrends et al., 2012; Good et al., 2017). As young as 14 months, bouncing a baby in synchrony with an adult has been shown to increase the infant's prosocial behaviours towards that person (Cirelli et al., 2014; 2016). At age 4 years, children are more likely to help and cooperate with one another after a joint dancing and music-making task compared to playing together in a non-musical setting (Kirschner & Tomasello, 2010). Together, these findings highlight that synchronizing with others fosters social connection and that this ability continues to improve throughout development, from infancy to adulthood. Understanding what drives individual differences and potential difficulties in synchronizing movements with others is therefore important given the role this skill plays in social development and connection across the lifespan.

Interpersonal movement synchrony is often examined in pairs or in groups in settings such as dance performance, but rarely studied on an individual level despite the impact an individual's skills may have on group synchrony. Dance requires both auditory-motor and interpersonal synchrony, making it an optimal context for investigating synchrony. Choreographed routines are specifically designed to align movements with music and between dancers, and repeated rehearsal tends to strengthen synchrony (Krug, 2022). Because of its structured yet naturalistic nature, dance offers a unique opportunity to examine synchronized movement in both controlled and ecologically valid settings. Moreover, dance is a familiar, everyday activity that many people engage in across cultures and regardless of formal training. Investigating individual abilities in a population of expert dancers can give valuable insight into individual differences in movement synchrony as they can be studied under well-controlled, rehearsed conditions. Further, individual differences in the ability to synchronize movement exist even in highly trained dancers (e.g., Carrillo et al., 2025; Orgs et al., 2024; Cross et al., 2024). Thus, if dance training alone is insufficient to maximize movement synchrony, additional factors or underlying skills must contribute to these individual differences. Uncovering what these factors are may suggest skills that could be trained to potentially improve interpersonal synchrony in dance.

Some perceptual-motor skills are better in dancers compared to non-dancers, such as beat perception (Nguyen et al., 2022), auditory-motor synchronization (Nam et al., 2024), and auditory timing perception (Skoe et al., 2021). However, the ability to synchronize with other dancers is rarely studied, and dancers are typically studied as a group in comparison to novice control groups, such that within-group variability is rarely investigated. Thus, little is known about how these perceptual-motor skills contribute to complex real-world synchrony, such as coordinating with others in dance. Given the high demand for auditory-motor synchronization and auditory timing perception during group dance performance, these skills are strong candidates for explaining individual differences in interpersonal movement synchrony.

In the current study, expert hip hop dancers completed a set of auditory timing perception and auditory-motor synchronization tasks. These participants had previously participated in a hip hop dance competition study in which each group of five dancers choreographed their own dance, which they performed while wearing motion capture markers (Carrillo et al., 2025). These dancers returned to the lab at a later date to individually complete a set of tasks, including rhythm discrimination, duration discrimination, and tapping production to music. Results were then compared to each individual's ability to synchronize to the other dancers in their group during the hip hop dance competition, as assessed through the previously collected motion capture data. We hypothesized that there would be positive associations between individual movement synchrony ability and performance on the current tasks. This study takes a novel approach by investigating the link between interpersonal movement synchrony in complex dance performance and basic auditory and auditory-motor timing skills. Demonstrating an association would not only deepen our understanding of individual differences in interpersonal synchrony, but also inform how these skills might be trained to enhance coordinated movement with others.

2. Methods

2.1 Participants

Participants were recruited from the group of 30 competing dancers who previously participated in a hip hop dance competition in the McMaster LIVELab. Participants were contacted via email and social media after previously consenting to be contacted for any follow-up studies. This study was conducted in accordance with the McMaster Research Ethics Board #2164. Participants visited the lab individually, and data was collected one year after the original experiment.

2.2 Rhythm and Duration Discrimination

2.2.1 Stimuli

Auditory stimuli were computer generated complex tones 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 (Chang et al., 2021). Stimuli were presented through a speaker located approximately 1 m in from of the participant, in a sound attenuated room at 75.5 dB SPL(A) on average over a noise floor of approximately 28 dB SPL(A). Stimuli were presented through Presentation version 20.0.

2.2.2 Procedure

Duration and rhythm discrimination thresholds were measured using a two-alternative forced choice (2AFC) method (Kingdom & Prins, 2010), with procedures following those of Chang et al. (2021). On each trial, standard and target stimuli were presented sequentially (randomly ordered), separated by 1120 ms, and participants were asked to click on the target stimulus (Fig. 1A). An adaptive 2-up-1-down psychophysical procedure was used, such that two correct responses were required for the task to increase in difficulty, and one incorrect response led to a decrease in difficulty (Levitt, 1971). Both tasks had 43 trials, and the 70.7% discrimination threshold was then measured for both duration and rhythm discrimination by averaging the reversal points (Chang et al., 2021). The order of the two tasks were counterbalanced across participants.

For the duration discrimination task, each of the two stimuli on each trial consisted of a pair of tones. Participants were instructed to identify the stimulus with a shorter interval between the pairs of tones. The standard stimulus had an inter-onset interval (IOI) of 500 ms between tones, and the IOI in the target stimulus ranged from 260 and 500 ms in 15 ms step sizes, beginning at 260 ms and adapting as per the 2-up-1-down procedure. Participants were given five training trials with target stimuli at 250 ms IOIs to ensure an understanding of the task. All five practice trials needed to be answered correctly to proceed to the test trials, but practice trials were not included in the threshold calculation.

For the rhythm discrimination task, each of the two stimuli on each trial consisted of a sequence of five tones, and participants were asked to identify the stimulus that was non-isochronous (had an off-beat tone). The standard stimulus had IOIs of 500ms between successive tones, whereas the target stimulus also had IOIs of 500 ms except for the last IOI of the sequence, which ranged from 335 to 500 ms with a 15 ms step size. The IOI adapted across the task according to the 2-up-1-down procedure. Participants were given five training trials with target stimuli ending with a 250 ms IOI to ensure an understanding of the task. All five practice trials needed to be answered correctly to proceed to the test trials, but practice trials were not included in the threshold calculation.

For more details on the methodology, see Chang et al. (2021).

2.3 Tapping Production

2.3.1 Stimuli

All music stimuli were 30 s in length, selected from pop and hip hop genres (Table 1). IOIs between beats ranged from 375 to 690 ms, and the amplitude was ramped up and down over 500 ms at the beginning and end of each excerpt. The true beat onsets for each musical excerpt were determined by averaging the tapping data of two adult semi-professional drummers (for each excerpt, taps from nine trials were averaged, six trials from one drummer and three trials from the other), and the tempo of each excerpt was determined by the mean interval of beat onsets. The stimuli were presented to the participants through a speaker located approximately 1 m in from of the participant, in a sound attenuated room on average at 75.5 dB SPL(A) over a noise floor of approximately 28 dB SPL(A). A drum was placed on a table at a comfortable distance in front of the participant, and audio recordings of tapping data were collected through Audacity (version 2.1.0) at a sample rate of 8000 Hz.

Table 1

Songs Used for Tapping Production Task

Song Name	Artist	IOI (ms)
Superstition	Stevie Wonder	602
Love On Top	Beyonce	640
Hey Ya	Outkast	377
Happy	Pharrell Williams	375
Umbrella	Rihanna ft. Jay-Z	690
Uptown Funk	Bruno Mars	522

2.3.2 Procedure

Participants began by tapping a 30-second trial at their preferred tapping rate (spontaneous motor tempo), with instructions to tap at a consistent pace that felt not too fast, not too slow, but just right. Participants were given the opportunity to try out a couple different rates of tapping before data collection began. Participants then tapped along to the beat of six different 30 s musical excerpts. Each excerpt was presented twice, and excerpts were randomized within the 6-excerpt blocks for each participant. Participants were instructed to tap the beat of the music, described as the consistent pace to which they would naturally nod their head or tap their foot.

2.3.3 Data Analysis

Tapping accuracy and consistency were calculated using circular statistics, following the procedure of Carrillo et al. (2024). Taps were identified using an amplitude threshold calculated individually for each participant, based on the intensity of their tapping. Each tap was then paired with the closest stimulus beat in time, and the distances from each tap to its associated beat were used as input for circular (or directional) statistical analyses, which were used to calculate the phase and consistency of tapping. Taps can be represented on a 360° polar scale, plotted by their relative angles from the stimulus beat onsets. The stimulus beat onsets are represented at angle 0, and the differences from 0 in tap times are measured in radians. A mean vector R was calculated by circularly averaging all taps from a single trial. The angle of vector R represents the mean phase, or the accuracy with which the participant tapped relative to the stimulus beat. Positive angles represent tapping after the onset of the stimulus beat, and negative angles tapping before. The length of R represents consistency, which can be thought of as the reciprocal of variability. Values range between 0 and 1, where 1 represents perfect consistency (i.e., the asynchrony between every tap and stimulus beat onset is identical across every tap in the trial), and 0 represents a circular-uniform random distribution of tap times relative to the beat. Consistency data was submitted to a logit transformation before further analysis to reduce data skewness, as is common in tapping synchronization research (Dalla Bella et al., 2017; Falk et al., 2015).

2.4 Previously Collected Movement Synchrony Scores

Individual movement synchrony scores for each participant in the present study were previously calculated in the original the hip hop dance competition study, conducted in the LIVELab (Carrillo et al., 2025). Synchrony was calculated as the cross-correlation of motion velocity between each possible pair of dancers within a group of five. The individual movement synchrony score for a particular dancer is represented by the average of that dancer's cross-correlation scores with each of the other four dancers in their group, averaged all motion capture markers. See Carrillo et al., (2025) for more detail on methodology and data processing.

2.5 Statistical Analyses

Performance on each of the tasks of the present study was correlated with individual movement synchrony scores from in our previous study. All correlations were corrected for multiple comparisons using Bonferroni correction. A linear mixed effects model was used to predict individual movement synchrony, with fixed factors chosen from the tasks with the highest correlation coefficients to movement synchrony. Group (i.e., the groups of 5 dancers from the original study) was used as a random variable to account for the fact that individual synchrony was dependent on the particular choreography and the other members of the group, as not all groups had equally good overall movement synchrony.

3. Results

3.1 Demographics

Of the 30 competing dancers who previously participated in the hip hop dance competition study, 20 participated in this follow-up study. Three participants were removed as outliers for tapping consistency scores more than two standard deviations from the mean. A total of 17 participants were included in the final analyses.

3.2 Duration and Rhythm Discrimination

For duration discrimination, participants had a mean threshold of 70.12 ms (SD = 28.8 ms; Fig. 1B). Pearson correlation coefficients showed no relation between duration thresholds and dance movement synchrony scores, $r(15) = -0.10$, $p_{bonf} > .999$ (Fig. 2A). For rhythm discrimination, participants had a mean threshold of 29.32 ms (SD = 7.24 ms; Fig. 1C). Pearson correlation coefficients showed a moderate negative association between rhythm thresholds and dance movement synchrony scores that approached significance before Bonferroni correction ($r(15) = -0.47$, $p = .055$) but did not approach significance after correction for multiple comparisons, $r(15) = -0.47$, $p_{bonf} = .220$ (Fig. 2B).

3.3 Tapping Production

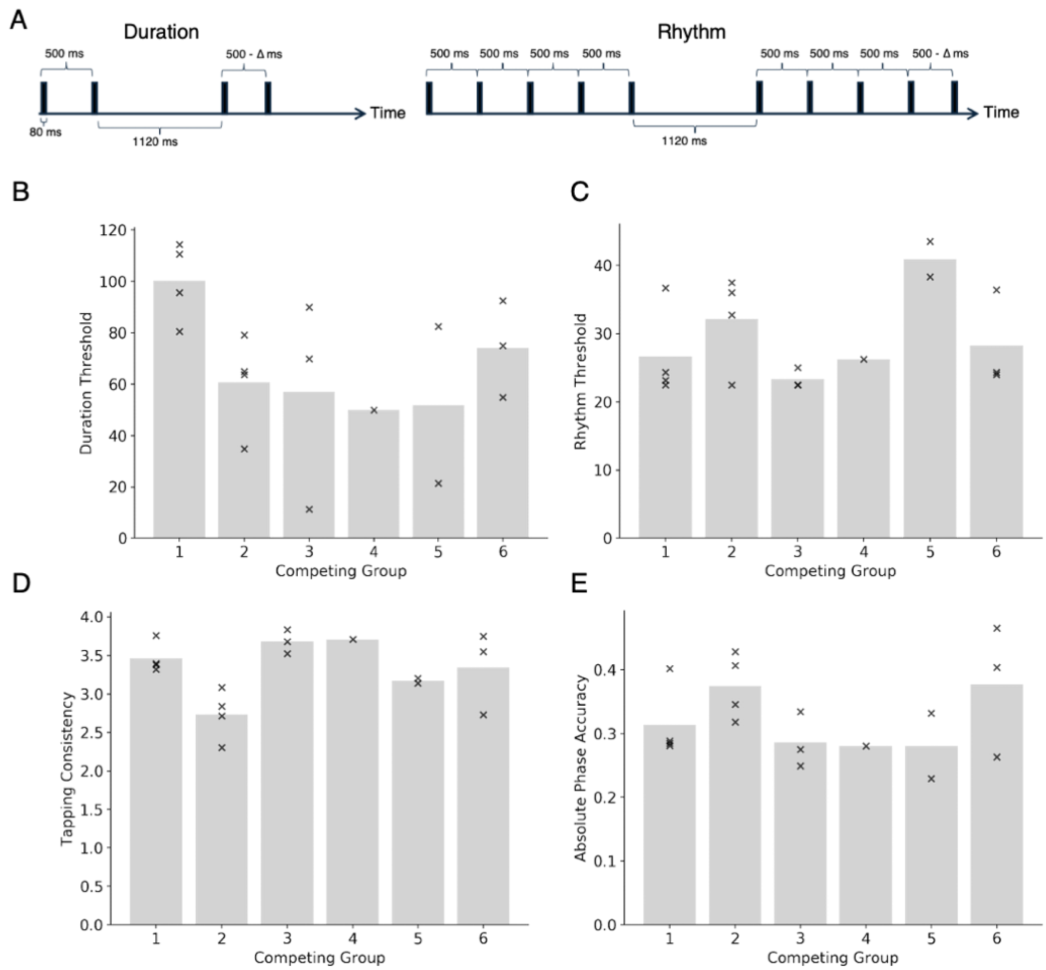
Participants had a mean tapping consistency of 0.96 (SD = 0.02; Fig. 1C). Consistency scores were submitted to a logit transform prior to any further analysis (Carrillo et al., 2024). Pearson correlation coefficients between tapping consistency and dance movement synchrony scores showed a significant positive correlation, $r(15) = 0.68$, $p_{bonf} = .012$ (Fig. 2C). Participants tapped on average slightly before the beat with a mean accuracy of -0.03 radians (SD = 0.122 radians; Fig. 1D). There was no relation between tapping accuracy and dance movement synchrony scores, $r(15) = -0.10$, $p_{bonf} > .999$ (Fig. 2D). For spontaneous motor tempo, participants tapped on average at a rate of 631.26 ms intervals between taps (SD = 181.32 ms), with a mean coefficient of variation (standard deviation of intervals divided by mean tapping interval, calculated for each participant) of 0.25 (SD = 0.33). Spontaneous motor tempo rates did not correlate with any of the other tasks, including dance movement synchrony ($p > .05$).

3.4 Synchrony Model

To investigate whether tapping consistency and rhythm discrimination thresholds could predict the ability to synchronize movements with others, a linear mixed effects model was conducted with dance movement synchrony scores as the outcome measure. Consistency and rhythm discrimination thresholds were chosen, as they correlated most strongly with the dance movement synchrony scores. Group was used as a random variable to account for the fact that other members of an individual's group would have impacted their synchrony score. The model revealed a significant positive effect of tapping consistency, $b = 0.07$, $SE = 0.02$, $t(14) = 2.94$, $p = .011$, indicating that higher consistency was associated with higher movement synchrony scores. In contrast, rhythm was not a significant predictor, $b = –0.002$, $SE = 0.001$, $t(14) = –1.37$, $p = .193$. The intercept was significant, $b = 0.34$, $SE = 0.10$, $t(14) = 3.29$, $p = .005$, indicating the predicted level of dance movement synchrony if tapping consistency scores and rhythm discrimination thresholds were both at zero.

Figure 1

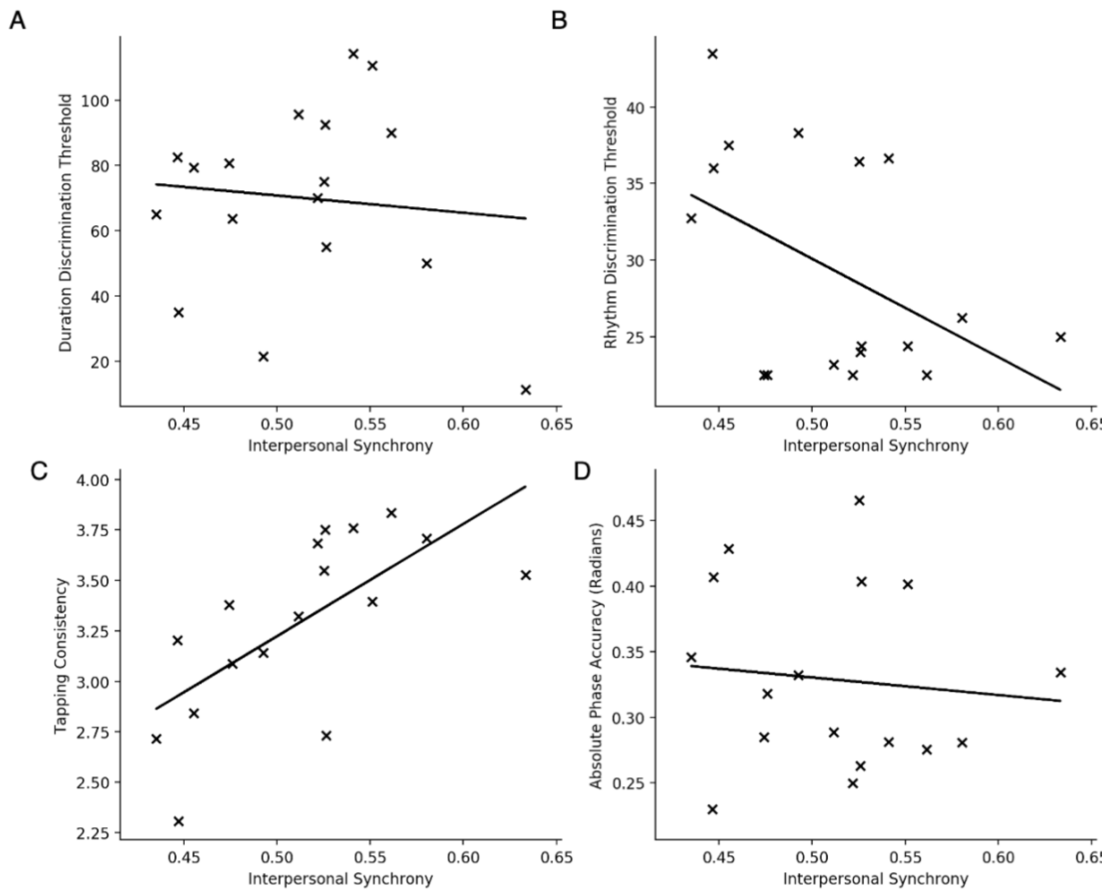
Task Schematic and mean scores separated by competing group



(A) Task schematic for duration and rhythm discrimination tasks. In these two-alternative forced choice tasks, participants heard two stimuli and were asked to judge which was shorter (duration discrimination) and which had an offbeat tone (rhythm discrimination). The difference (Δ) represents the temporal difference between target and standard stimuli, which varied across trials according to a one-up-two-down adaptive procedure. (B) Duration discrimination thresholds separated by group. (C) Rhythm discrimination thresholds separated by group. (D) Tapping consistency scores (logit transformed) separated by group. (E) Tapping phase accuracy (absolute value) separated by group. Individual scores for dancers in each group are shown with ‘x’s.

Figure 2

Correlation of dance movement synchrony to tapping production and duration and rhythm discrimination thresholds



Correlation of individual dance movement synchrony scores with (A) duration discrimination thresholds, (B) rhythm discrimination thresholds, (C) tapping consistency scores (logit transformed), and (D) tapping phase accuracy (absolute value).

4. Discussion

This study investigated the relation between complex interpersonal dance synchrony in expert hip hop dancers and their auditory timing perception and simple auditory-motor (tapping) synchronization abilities. Tapping consistency was significantly positively related to interpersonal dance synchrony, as well as a significant factor in predicting interpersonal synchrony. This is unsurprising given both tasks are related to the ability to synchronize a motor movement with an external stimulus, whether it be an auditory cue such as music or the movements of another dancer. Phase accuracy in tapping was not found to be related to interpersonal dance synchrony, which is somewhat surprising given that aligning the phase of movements is an important aspect of motor synchrony in complex dance. It is possible that phase accuracy in hand tapping is a separate skill that is not highly related to gross motor interpersonal synchrony.

Rhythm discrimination thresholds showed a trend towards a negative relation with interpersonal synchrony, aligned with our prediction that better rhythm discrimination would relate to better interpersonal synchrony. On the other hand, duration discrimination thresholds did not show any association with interpersonal synchrony. Rhythm discrimination is more related to beat-based timing, while duration discrimination is a more related to absolute timing (Chang et al., 2021), which are two distinct timing mechanisms associated with different neural networks (Teki et al., 2012; McAuley & Jones, 2003). The trend in the current data is consistent with the idea that hip hop dancing requires synchronization to beat-timed music. Future studies should continue to explore the individual differences in rhythm and duration discrimination and their associations with movement synchrony, particularly with larger sample sizes.

The present study examined individual differences in a highly skilled population of hip hop dancers. However, examining individual differences could also be important in other populations. Children with a variety of neurodevelopmental disorders show deficits in auditory-motor synchronization tasks (see Lense et al., 2021 for a review), including children with developmental coordination disorder (DCD) (Carrillo et al., 2024; Pranjic et al., 2023), attention deficit hyperactivity disorder (Puyjarinet et al., 2017), dyslexia (Thomson & Goswami, 2008), developmental language disorder (Cumming et al., 2015), and autism spectrum disorder (ASD) (Vishne et al., 2021; Morimoto et al., 2017). Of these disorders, there appears to be research into the relationship between social skills and movement synchrony only for ASD, perhaps because ASD is defined as a social disorder. Studies show that in children with ASD aged 5-12 there are significant correlations between simple synchrony task performance (i.e. stepping or clapping to music or with another person) and both general ASD severity as well as the social aspect of ASD (Kaur et al., 2018). Further, movement synchrony during social interactions and conversations has been found to be negatively correlated with both ASD severity and standardized ratings of social and communication skills in ASD (Zampella et al., 2020). Although not a developmental disorder, in patients with Schizophrenia, one study found correlations between movement synchrony and symptom severity and social impairments (Kupper et al., 2015).

Impairments in auditory-motor synchronization and auditory timing perception are seen in other neurodevelopmental disorders (Lense et al., 2021), but the association between interpersonal movement synchrony and symptom severity has not been investigated in these disorders. Children with DCD have been shown to have impairments in tapping consistency and rhythm discrimination (Carrillo et al., 2024; Chang et al, 2021), but it remains unknown as to whether these deficits relate to interpersonal movement synchrony ability. Taking into account individual differences in the ability to synchronize with others may both explain disorder symptom severity and suggest interventions involving interpersonal movement training. Knowing individual performance on underlying skills may be important for determining interventions. For example, one study found that patients with Parkinson's disease responded well to interventions involving rhythmic cueing only if the patients had intact rhythmic abilities, as assessed using the Beat Alignment Test (Dalla Bella et al., 2018). This highlights the need for an individualistic approach to intervention, especially as many neurodevelopmental disorders such as DCD are highly heterogeneous.

This study did have some limitations. Low sample sizes likely led to underpowered statistics, particularly with uneven numbers across groups. The individual movement synchrony measure was also limited by its dependence on other group members, which makes the correlation values more difficult to interpret. Future studies investigating the association between movement synchrony and basic auditory timing perception should ensure to include a measure of movement synchrony that is independent of the skills of other dancers, as well as a measure of motor synchrony to the music. Nonetheless, the present study was an important step in understanding how different skills involving auditory and motor timing are related at an individual level, and opens many future questions on how these skills interact and whether such association can be used to the benefit of training or interventions.

5. Conclusion

Expert hip hop dancers were found to have significant correlations between their interpersonal synchrony performance during a complex hip hop dance performance and their tapping production consistency. Tapping consistency was also a significant predictor of interpersonal synchrony during the dance performance. This study was highly novel as the first investigation into such individual differences in auditory and motor timing performance. The results lay the groundwork for understanding the factors that lead to individual differences in how well highly trained dancers can coordinate their movements with one another, and suggest that underlying skills in auditory timing perception likely impact this ability.

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Chapter 6: General Discussion

In this thesis I investigated the role of movement synchrony in motor skills and performance art, examining the nature of auditory-motor synchronization in children at risk for developmental coordination disorder (DCD) and individual differences in interpersonal synchrony in expert dancers. By examining populations at both ends of the skill spectrum, we can better understand the importance of movement synchrony in both everyday motor skills and high-level artistic performance.

A defining feature of DCD is a deficit in coordinating and executing movements (Wilson et al., 2013). While motor difficulties are the diagnostic hallmark of DCD, recent evidence suggested that this population also has impairments in auditory timing perception (Chang et al., 2021). However, it remained unclear whether these timing difficulties extended to auditory-motor synchronization, particularly in ecologically valid tasks, and how these impairments related to general motor skills. I examined both simple hand-tapping tasks and full-body coordinated dance steps in children with rDCD, showing that auditory-motor synchrony impairments extend to both fine- and gross-motor domains. Importantly, I also found that external rhythmic auditory cues enhanced motor performance in both typical and rDCD populations, suggesting potential for rhythm-based interventions.

At the other end of the spectrum, expert dancers provide a uniquely informative case for understanding synchrony when it is highly refined. Despite years of training, dancers still exhibit individual differences in their ability to synchronize movement with others (Orgs et al., 2024). Synchrony in dance is a critical marker of group coordination: observers reliably perceive highly synchronized groups as more cohesive, aesthetically pleasing, and technically skilled (Cross et al., 2024; Vicary et al., 2017). Yet, despite its central role in performance, little was known about how differences in interpersonal synchrony impact the perception of dance in competitive performance settings, or how basic auditory-motor timing skills may underlie the ability to synchronize with others. To investigate this, I used motion capture during live performances of expert dancers to demonstrate that interpersonal synchrony between dancers predicts both judges' and audience members' evaluations in real-world competitions. Furthermore, I found that individual differences in auditory timing perception and auditory-motor synchrony significantly predict the ability of dancers to synchronize with their peers, directly linking measures of sensorimotor timing to complex group performance.

Together, these findings provide new evidence that movement synchrony both constrains development when impaired and enhances performance when refined. By connecting basic auditory-motor and interpersonal timing skills to real-world social and artistic outcomes, this work bridged developmental and expert perspectives, offering a comprehensive account of how movement synchrony shapes human interaction and expression.

Main Findings and Unique Contributions

Auditory-Motor Synchrony in rDCD

The research in Chapter 2 was the first investigation of both auditory-motor synchrony and speech recognition with distorted timing in children at risk for DCD (rDCD). Previous research showed children with rDCD show impairments in auditory timing perception including rhythm and duration discrimination (Chang et al., 2021). Further, it had been predicted that children with DCD would have auditory-motor synchronization deficits in addition to their motor timing impairments given that auditory timing relies on motor planning brain regions (Trainor et al., 2018). In Chapter 2 I had three main goals: First, to replicate the findings of impaired auditory timing perception in children with rDCD, but during a non-beat based task. Second, to investigate whether children with rDCD have impaired auditory-motor synchronization. And, finally, to examine whether the motor performance of children with rDCD can benefit from the presence of an auditory cue.

To test these questions, I compared children with rDCD to a typically developing (TD) control group. For the auditory timing perception task, children identified target words while listening to sentences with either intact or distorted rhythms. I found that children with rDCD were more negatively impacted by the distorted rhythms compared to the TD group. This was the first study to use a speech recognition with distorted rhythms paradigm in DCD. The results suggest a strong reliance on auditory rhythmic cues in rDCD during speech perception, which is interesting given the previous findings of impaired rhythm discrimination in rDCD (Chang et al., 2021). This finding likely reflects less flexible adaptation to changes in a stimulus, which fits in well with previous work showing slower adaptability to changes in a visual stimulus during visual-motor synchrony (P. H. Wilson et al., 2013). This study was the first to find impaired adaptation to change in rDCD in a task without a motor component.

For auditory-motor synchronization, I measured tapping consistency in a task where participants tapped along to metronomes, continuation (tapping the same tempo after the metronome is removed), and music. I found that children with rDCD were significantly less consistent in their tapping compared to TD children, but that both groups were significantly more consistent with the presence of an auditory cue (metronome or music) compared to without (continuation). The research of Chapter 2 was the first to show auditory-motor synchronization deficits in children with rDCD. A previous study had found impairments in tapping consistency in children with both DCD and ADHD (Puyjarinet et al., 2017), but they had not tested a DCD-alone group. My findings were in line with this study and provided evidence for auditory-motor synchronization deficits in children with rDCD alone.

This research also investigated whether participants could use auditory rhythmic cueing to their benefit, and I found that motor performance in both rDCD and TD groups benefited from the presence of an auditory rhythm. In the perception task, both groups showed improved recognition of target words when the speech rhythms were intact and predictable compared to distorted. In the production tasks, both groups tapped significantly more consistently when an auditory cue was present (metronome or music) compared to when the auditory cue was removed (continuation). While previous research has shown impaired beat and rhythm perception in DCD (Chang et al., 2021), this study was the first to show that children with rDCD are still able to perceive and benefit from auditory cueing. The findings align well with a recent study that also found tapping production benefits in children with DCD with the presence of an auditory cue (Pranjić et al., 2025).

Another novel contribution of this study was the finding of a positive correlation between motor assessment scores (MABC-2) and both tapping consistency and speech recognition performance. This is the first evidence linking standardized motor skills with auditory timing skills in rDCD, supporting theories of the motor system's involvement in auditory timing perception (e.g. Cannon & Patel, 2021; Fujioka et al., 2012; Patel & Iversen, 2014). I did not find a significant relationship between the perception (speech recognition) and production (tapping) tasks, contrary to a previous study showing positive correlations in typically developing populations (Dalla Bella et al., 2017). This suggests that perception and production may rely on partly distinct mechanisms, particularly when tasks differ in their reliance on beat-based timing.

The results of Chapter 2 were crucial for furthering our understanding of the impairments associated with rDCD, and how these impairments relate to general motor skills. By demonstrating difficulties in both auditory timing perception and auditory-motor synchronization, this study provides converging evidence that timing deficits in rDCD extend beyond the motor domain. At the same time, the finding that children with rDCD can still benefit from external auditory cues highlights an important avenue for potential intervention, suggesting that auditory rhythms could be used to structure motor practice and improve motor performance.

Chapter 3 extended the investigation of auditory-motor synchrony in rDCD to more ecologically valid, full-body movement. I used an online data platform to collect data from children coordinating a step-clap dance step to auditory stimuli. In this chapter I found that children with rDCD moved overall slower during the movement compared to TD children, regardless of the tempo of the stimuli. I also found that their movements were significantly less coordinated with auditory stimuli (metronome or music) compared to TD children, particularly at faster tempi, fitting in well with previous research showing increased motor variability in DCD (e.g. Adams et al., 2014; Wilson et al., 2013), but contrary to the lack of tempo effects found in Chapter 2. It is possible that tempo effects that emerged in Chapter 3 were a result of the increased complexity of this task compared to the simple hand tapping in Chapter 2 – as the demands of the task increased, the ability of children to adapt their movement to a tempo outside of their comfort zone may have decreased. This study was the first to find effects of tempo in children with DCD during a full-body movement task, and importantly shows that consideration of both task complexity and tempo is important in clinical settings.

Chapter 3 also showed that at slower tempi, children with rDCD performed very similarly to TD children. This highlights the ability of both groups to properly execute this task and shows that children with rDCD are capable of coordinating their movements with auditory cues in specific circumstances. From a clinical perspective, this provides evidence that including auditory cueing during motor intervention is feasible. Further, parents reported that their children enjoyed the task, which is a crucial aspect of designing any intervention, as compliance often dictates the effectiveness of the intervention. While this study did not aim to improve motor performance with auditory cueing, it does show that children with rDCD are not so impaired in their auditory-motor synchronization (as shown in Chapter 2) or auditory timing perception (Chang et al., 2021) that they cannot coordinate with music or metronomes at all. Therefore, this study was an important first step in investigating whether motor interventions that include auditory cueing, such as dance intervention, could be a viable option for DCD in addition to physical therapy. Additionally, this study was unique it its use of online data collection, which opens the possibility of using this same paradigm with other special populations.

Together, Chapters 2 and 3 provide strong evidence for impairments in auditory-motor synchronization in children with rDCD. Importantly, both chapters highlight the ability of both the rDCD and TD groups to perform motor synchronization tasks, whether it be simple hand tapping or a more complex dance step. Chapter 2 also showed evidence that children with rDCD benefit from the presence of an auditory cue, both in perception and production tasks. Given this potential benefit of an auditory cue during motor tasks, as well as reports from parents of children with DCD expressing a need for more accessible and enjoyable options for motor intervention (Maciver et al., 2011), this raises the question of whether a dance intervention is a potential option for children with DCD. The only study to date to investigate dance as therapy for children with rDCD found an improvement in MABC-2 scores in children who participated in the intervention, and no significant change in scores in the group that did not receive any intervention (Díaz-Pérez et al., 2021). My results suggest in turn that more research should be conducted on the potential of dance intervention for DCD.

Interpersonal Synchrony in Expert Dancers

Chapter 4 shifted the focus from a clinical population to expert performers, examining how movement synchrony contributes to the evaluation of professional hip hop dancers. In a highly novel experiment of a live hip hop dance competition, dancers performed self-choreographed routines in groups of five while I collected motion capture data of their movements. Expert judges and lay audience members scored each performance immediately after watching them, and I investigated whether the interpersonal synchrony between dancers (objectively measured by motion capture) would predict the audience members' and judges' scores. I found that interpersonal synchrony was indeed a significant predictor of both audience and expert judges' ratings. These results fit well with previous research finding audience members prefer to watch videos containing synchronous movement between dancers compared to asynchronous movement (Tang Poy & Woolhouse, 2020; Vicary et al., 2017). My research in Chapter 4 provides the first objective evidence that interpersonal synchrony directly influences aesthetic judgments in live, high-level dance performance. I also found that audience members were significantly more similar in their scoring to the judges if they were trained in hip hop dance. This is similar to previous research showing that audience members with dance training rate enjoyment of dance performances more similarly to choreographers of the dances, compared to novice audience members (Orgs et al., 2024). Complimenting this work, my study is the first to find higher similarity of scoring related to the specific type of dance training (hip hop compared to other styles of dance).

A major strength of this study is its ecological validity: synchrony was assessed in a real performance context, under competition conditions, with complex, self-choreographed routines. There is a strong cultural significance of the relationship between performers and audience members in hip hop dance: in its early development, audience members would loudly cheer to decide the winners of battles and competitions, leading to highly engaged and vocal performer-audience interactions (Sato, 2022). Given this, it was important to move beyond laboratory tasks and capture interpersonal synchrony when performing for a live audience, as it naturally occurs in performance art. I also showed that expert judges were very consistent in their ratings, and that their perception of movement synchrony aligned with our objective motion capture measures, validating both the reliability of expert evaluation and the relevance of the synchrony metric itself.

Together, these findings highlight that interpersonal synchrony is a defining feature of expert dance, shaping how performances are evaluated by both experts and lay audiences. Chapter 4 therefore established interpersonal synchrony as a marker of expertise in complex group performance. However, while Chapter 4 provides clear evidence of the importance of moving in synchrony between dancers, there were still distinct individual differences in how well dancers aligned their movements with one another. The factors driving these differences are not well understood. The earlier chapters of this thesis (Chapters 2 and 3) demonstrated that auditory-motor synchrony skills can vary widely, particularly in children with motor coordination challenges. This raised the question of whether similar underlying auditory-motor skills might explain variability in expert dancers' ability to synchronize their dance movements. By linking the more controlled measures from Chapters 2 with the ecologically valid performance data from Chapter 4, I then aimed to bridge laboratory-based assessments of synchrony with real-world, high-level performance, providing a more complete picture of the factors that contribute to movement synchrony across different populations and contexts.

Chapter 5 investigated whether expert dancers' ability to synchronize their movements with others is related to auditory-motor synchronization and auditory timing perception. To test this, the same dancers who participated in the hip hop dance competition were brought back into the lab to perform a set of auditory-motor synchronization and auditory timing perception tasks previously shown to reveal deficits in children with rDCD, including hand tapping along to music (Chapter 2) and rhythm and duration discrimination tasks (Chang et al., 2021). I found a significant positive correlation between interpersonal synchrony with tapping consistency and a negative correlation between rhythm discrimination thresholds with interpersonal synchrony (as expected, given that higher thresholds represent poorer performance). I also found tapping consistency to be a significant predictor of interpersonal synchrony in a linear mixed model.

Chapter 5 was the first study to investigate the relationship between commonly studied basic abilities such as tapping consistency and auditory timing perception and a more complex measure of movement synchrony during dance. The findings suggest that stronger basic auditory timing skills affect interpersonal synchrony in a demanding dance context. While I cannot show a causal relationship from these correlational results, this does suggest that certain basic skills may impact the ability to synchronize complex movement.

Collectively, this thesis is the first to provide evidence of auditory-motor synchronization impairments in children with rDCD while also demonstrating the importance of movement synchrony in high-level dance performance. These findings suggest that while movement synchrony manifests differently across populations and contexts, underlying auditory-motor synchrony skills play a consistent role: weaknesses limit performance in children with rDCD, and strengths set apart top performers in dance.

Limitations of Thesis Research

The present thesis is the first to present evidence for the important role of movement synchrony from children with motor disabilities to expert dancers with years of training. However, the research has some limitations as discussed below.

To define our DCD groups, I used validated motor assessments (MABC-2 in Chapter 2, DCD Questionnaire in Chapter 3) to assess DCD risk. Different research groups use different percentile cutoffs on the MABC-2 to define DCD. For example, some studies use a stringent 5^{th} percentile cutoff to differentiate 'high-risk DCD' from 6^{th}-16^{th} percentile 'mild-risk DCD' (e.g. Cairney et al., 2015; Lee et al., 2019) whereas my research used a 16^{th} percentile cutoff, following the methods of Cairney et al. (2019). The DCD Questionnaire also relied exclusively on parent reports of motor skills (Wilson et al., 2009). Thus, it is possible that my rDCD group included participants who would not be considered to actually have DCD by a medical doctor. It would be beneficial for future studies in which the DCD group solely includes those with a formal diagnosis to ensure the findings are representative of the disorder. However, if a more stringent definition of DCD was used than in my research, it is likely that the differences between those defined as rDCD and those who were typically developing would be much larger than found in my analyses.

The group of participants identified as being at risk for DCD may also have presented with additional neurodevelopmental disorders that were either undisclosed or undiagnosed. In Chapter 2, for instance, a small subset of participants were additionally identified as being at risk for ADHD. In contrast, in Chapter 3, insufficient parental reporting in the online study led to an absence of assessment of ADHD risk. Given the high rates of comorbidity between DCD and other neurodevelopmental disorders, such as ADHD and dyslexia (American Psychiatric Association, 2013), diagnostic overlap is highly probable. Consequently, attempts to delineate groups of participants with “pure” DCD are unlikely to reflect the true heterogeneity of the disorder. As outlined previously, future research would be strengthened by the inclusion of participants with formal DCD diagnoses who have also been comprehensively assessed for other co-occurring conditions, thereby providing a more accurate account of the impairments associated with DCD.

Another limitation of this research is inconsistencies in how movement synchrony was measured across the different studies. In Chapter 2, I investigated auditory-motor synchronization using circular statistics to obtain a measure of how consistently children could tap along to an auditory beat. This measure is very temporally sensitive, and appropriate for the data collected under controlled laboratory conditions. In Chapter 3, the data was collected from each participant’s home webcam; thus I had to pivot to a different measure of synchrony due to the low video sample rates and concerns with whether there were any audio-visual asynchronies. I chose to use a measure of ‘coordination’ that compared the continuous movement data to a simulated continuous cosine wave representing the auditory beat. I calculated the cross-correlation between the x-axis of the movement data with the simulated auditory wave, using a range of possible time lags between them. While this measure of coordination did not have the same temporal sensitivity that circular statistics provides, it did allow me to investigate how similar the children’s movements were relative to the expected trajectory if they were coordinating with the music. Unfortunately, this limited our ability to compare synchrony directly between Chapters 2 and 3, as the measures were quite different. Moving on to Chapter 4, the movements of the expert dancers were much too complex to use circular statistics or to simulate expected movement. Additionally, I focused on interpersonal synchrony as opposed to auditory-motor synchrony (as investigated in Chapters 2 and 3). To measure interpersonal synchrony, I used cross-correlation of the velocity with no time lag between each dancers' movements. This worked well for investigating how well the dancers synchronized the timing of their movements with one another, but it may not have accounted for the spatial dimension of their movements. Future work on interpersonal synchrony of dancers would benefit from including both the spatial and temporal dimensions of movement. In Chapter 5 I looked at the relationship between my measure of interpersonal movement synchrony and tapping consistency (using circular statistics), and I did find a significant positive correlation. While these differences in the measures used to investigate movement synchrony makes the results of each of my first three data chapters more difficult to compare, it does highlight how complex movement synchrony is, and how there is not one single way to calculate or conceptualize it.

Finally, this thesis aimed to investigate the role that movement synchrony plays in a wide range of contexts, with a focus on the consequences of impaired movement synchrony. My experiments were not able to show whether training in movement synchrony would improve outcomes in either context. I did not conduct any randomized clinical control trials, nor did I specifically train any population in dance and measure the outcomes, as these experiments were outside the scope of my thesis. Instead, my research focused on first understanding how the deficits associated with movement synchrony present themselves in children with rDCD in order to provide evidence that training these skills is an important aspect of intervention. I also investigated how important movement synchrony is in performance art, but did not conduct research comparing dancers with and without enriched training in movement synchrony. Thus, it is crucial not to interpret the findings of my studies, which highlight the important role movement synchrony plays in multiple aspects of motor production and perception, as evidence that training in dance and movement synchrony is an intervention that leads to improved motor performance quality. Instead, my findings should be interpreted as supporting the idea that future research should focus on the potential of dance intervention for children with motor disabilities, and that focusing training on interpersonal synchrony may improve performance quality in high level dancers.

Clinical Implications and Future Directions

The results of this thesis lead to considerations of whether dance intervention should be considered as an option for children with DCD. Many of the key impairments associated with DCD relate to processes involved in dance and thus potentially could be strengthened by dance training, including prediction, anticipation and error correction, automatization of movement, and action observation. The motivation to synchronize movement to auditory stimuli is thought to be related to prediction of upcoming events (Foster Vander Elst et al., 2021; Matthews et al., 2023; Repp, 2005), which is a crucial component of beat perception. According to predictive coding models, during beat perception, the brain is constantly predicting upcoming auditory events based on an internal model (Vuust & Witek, 2014). Similar to motor planning prediction, this predictive model is then compared to sensory input of the beat, and adjusts the model in order to minimize errors (Proksch et al., 2020; Vuust et al., 2009; Vuust & Witek, 2014). Despite this research focusing on music perception, a recent review of dance from a neuroscientific perspective highlighted the necessity of predictive coding during dance (Foster Vander Elst et al., 2023). Further, in dance, predictions for one's own movements, as well as those of fellow dancers, are highly multisensory, involving visual and haptic domains in addition to auditory and motor domains (Foster Vander Elst et al., 2023). Anticipation and error correction of movements are important components of dance, and they are also key areas of impairment in DCD according to the internal model deficit theory (Adams et al., 2014). Dance also focuses on the automatization of movement, as it is repetitive and rhythmic in nature. Automatizing movements has been shown to be impaired in DCD (Biotteau et al., 2015; Schott et al., 2016), so an intervention program focusing on repetition of movements could be of benefit. In a dance class or intervention setting, action observation and motor imagery are also used as children observe and learn from the teacher and other students (Bläsing et al., 2012). Children with DCD have been found to have impairments in motor imagery (Baiano et al., 2023; Wilson et al., 2013) and action observation (Bieber et al., 2023), which thus may be strengthened by dance training. In sum, dance training has the potential to improve many of the perceptual areas in which children with DCD have deficits.

Dance has many benefits that extend beyond auditory-motor integration and motor skill training. Importantly, dance is a fun and engaging activity for children, which is a significant factor for intervention compliance. Finding engaging activities that younger children enjoy can be challenging but crucial for a child to be motivated to continue with an intervention. Young children appear intrinsically motivated to dance. Studies investigating the potential of dance as an intervention report high enjoyment and engagement in both children and adults (Schroeder et al., 2017) and adolescent girls (King et al., 2019), and a meta-analysis of dance movement therapy found it to significantly decrease depression and anxiety, and increase quality of life, in both children and adults (Koch et al., 2019). The inclusion of music enhances engagement, as the act of listening to music is inherently rewarding and has been linked to dopamine release (Salimpoor et al., 2011). Studies find that music with higher levels of syncopation and groove make participants report wanting to dance more to the music (Witek et al., 2014), even in children (Cameron et al., 2023), and studies have shown activation of reward pathways in the brain relating to the motivation to move in synchrony to music (Foster Vander Elst et al., 2021; Matthews et al., 2020). In music interventions, the type or style of music participants dance to can be catered to their needs, not just in preference, but also in tempo and beat salience. Thus, the musical aspect of dance intervention helps make it adaptable to individual participants. A review of interventions for DCD found that the most effective interventions had a common feature of being tailored to the individual and the particular interests of the child (Preston et al., 2017).

Dance is very accessible – it relies on almost no equipment, can easily be delivered in varying settings, and can occur during school hours. Another potential benefit of dance as an intervention is that it can be done as group therapy. This not only helps parents by lowering expenses, but children can benefit from the social aspects of dance. Indeed, dance is most typically done with others in a group, which promotes increased body awareness and error correction through coordination with others (Dhami et al., 2015). Synchronizing movements with others also has social benefits, increasing trust, cooperation, and positive associations among those synchronizing together (Jackson et al., 2018; Tomashin et al., 2022; Wiltermuth & Heath, 2009). In adults, participating in dance classes has been associated with an improved social wellness (Zafeiroudi, 2023), and participating in traditional dance styles of one's culture was shown to foster community and strengthen the connection to identity and culture (Smith, 2018). Participation in dance classes has been shown to improve wellbeing, emphasizing the benefits of dance beyond auditory and motor skills (Du et al., 2025; Sheppard & and Broughton, 2020). Given the social impairments associated with DCD (Smits-Engelsman & Verbecque, 2022), dance interventions are a strong alternative or additional candidate to more traditional physical therapies because synchronizing movements to music is intrinsically rewarding, and dancing in a group setting has social benefits and increases a sense of community.

Conclusion

In my thesis, I examined movement synchrony in a variety of populations, specifically in children with motor disorders and expert dancers. I found that children with rDCD have impairments in auditory-motor synchronization but can use an auditory cue to improve their rhythmic motor skills. I also found these impairments extend to full-body movements, and that tempo plays a large role in the success of children with rDCD to synchronize a dance step to music. Furthermore, I found that interpersonal synchrony plays an important role in how observers score expert level hip hop dancers during a performance. I then found that the ability of hip hop dancers to synchronize their dancing to one another is related to the same auditory-motor synchronization skills that are impaired in children with rDCD. My thesis shows that movement synchrony is a crucial skill for all movement, whether it be the everyday movements of children with motor impairments, or the complex movement performances of expert dancers. Taken together, these findings revealing that movement synchrony is a core skill that both constrains everyday motor skills in populations with coordination difficulties and distinguishes high-level performance in expert contexts. By examining synchrony across this spectrum, my thesis highlights not only its central role in human movement, but also its potential as a target for intervention and a marker of expertise.

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