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Auditory-motor synchronization in developmental coordination disorder: Effects on interlimb coordination during walking and running

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Abstract

Developmental coordination disorder (DCD) presents challenges in motor control. DCD affects tasks such as walking and running and is characterized by poor interlimb coordination and increased spatiotemporal variability compared to typically developing children (TDC). While auditory rhythm synchronization has shown to have benefits for gait performance in adults, its impact on children with DCD during walking and running remains unclear. This study investigated auditory-motor synchronization and interlimb coordination during walking and running in children with and without DCD. Twenty-one DCD and 23 TDC participants aged 8-12 years walked and ran to two different auditory metronomes (discrete and continuous). Synchronization consistency was the primary outcome, with interlimb coordination and spatiotemporal variability as secondary outcomes. Results showed that children with DCD exhibited significantly lower synchronization consistency than TDC, particularly during running. The metronome structure did not influence synchronization ability. Additionally, interlimb coordination differed significantly between DCD and TDC during running and was not impacted by auditory-motor synchronization. Spatiotemporal variability was higher in DCD during both walking and running than in TDC, and accentuated during running. Variability of cadence was influenced by the use of continuous metronomes, which may offer potential benefits in reducing cadence variability.

KEYWORDS

auditory-motor synchronization, developmental coordination disorder, interlimb coordination, running, walking

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Developmental coordination disorder (DCD) is a neurodevelopmental disorder affecting around 6% of school-aged children.¹ It is characterized by deficiencies in various aspects of motor coordination, predictive motor control, skill automatization, and postural control.^{2,3} The manifestation and severity of DCD are heterogeneous⁴ and present without underlying neurological, intellectual, or visual deficits.¹ These motor challenges negatively impact children's daily activities, academic achievement, and participating in sports. Previous studies have documented lower levels of physical activity and, consequently, lower physical fitness levels in DCD.^{5,6} Children with DCD typically exhibit slower running speeds and lower physical function, including reduced cardiorespiratory fitness and anaerobic capacity.^{6,7} Consequently, individuals with DCD may be less inclined to participate in play and sports, including walking or running, thereby limiting their opportunities to develop proficient motor skills and achieve adequate fitness levels.⁸ The reduced physical activity is believed to be linked to difficulties in mastering fundamental motor skills, such as running, jumping, and hopping, which are particularly challenging for children with DCD.⁸ Specifically, the gait pattern of children with DCD is often described as clumsy, with frequent reports of falls.⁹

As the diagnostic term suggests, the primary characteristic of children with DCD is impaired coordination. Coordination can be defined as the effective control of different degrees of freedom into a kinematic coupling or synergy formation, organizing a movement pattern to ensure stability under environmental demands to achieve a specific goal.^{10,11} Although the underlying mechanisms and etiology of coordination deficits in DCD are still unclear, previous research has proposed several hypotheses.^{3,12–14} From a fundamental cognitive neuroscience approach, coordination deficits are mainly related to impairments in the internal model.¹³ In contrast, the ecological dynamical system approach views motor coordination within a dynamical relationship between task demands, environmental context, and characteristics of the individual.¹⁵ The hybrid model combines both the cognitive neuroscience approach and the dynamical system theory.¹² At the individual level, interactions between deficits in internal modeling, perceptionmotor coupling, motor learning, and executive functions can constrain the child's movement performance. At the task level, factors such as task type, movement complexity, and level of precision are suggested to influence motor performance. Finally, at the environmental level, factors like the support surface, background noise, or crowded surroundings may shape the movement performance. For instance, under simple task conditions, such as walking in a quiet environment at a comfortable pace, deficits in internal modeling might not significantly impact walking performance, as slower feedback-based control might suffice for skilled performance. However, tasks with increased complexity, like walking at higher speeds or running, may stress these deficits. Running, in particular, presents unique challenges compared to walking, including the absence of a double support phase and the presence of a flight phase, necessitating higher demands on dynamical postural control and a faster timing to prevent falls.¹⁶ Consequently, predictive control becomes crucial, and slower feedback control may

prove insufficient for mastering skilled running performance. In DCD, this concept is supported by observations of a significantly higher spatiotemporal variability and worse interlimb coordination during running compared to walking.¹⁷

The dynamic interplay among the individual, the task, and the environment can either impede or enhance motor performance. Sportsrelated research in adults has shown that optimizing running performance is achievable through the use of tempo-matched auditory rhythms, thereby altering the environmental factors.¹⁸⁻²⁰ Specifically, a more consistent running cadence is achieved when synchronizing running steps to auditory metronomes compared to running without auditory rhythms.¹⁸ In this context, auditory-motor synchronization refers to the consistent sensorimotor coupling between the auditory rhythm (beat) and the motor rhythm (footfall) over time. Both synchronization and motor performance appear to be influenced by the dynamical interaction between the type of movement (discrete or continuous) and the temporal structure of sensory rhythms (discrete or continuous).²¹⁻²³ It is suggested that discrete movements, like finger tapping, synchronize better with discrete auditory rhythms, 23-25 while continuous movements, like walking and running, may benefit from continuous auditory rhythms.^{21,24,26} The former auditory rhythm involves clear changes in sound amplitude, like an isochronous discrete metronome, while the latter thrives with smoother, gradual changes, such as in continuous metronomes or music.

Until now, synchronization research in DCD has predominantly focused on discrete motor tasks, such as finger tapping, marching, or clapping to auditory metronomes with a discrete temporal structure to assess auditory-motor synchronization.²⁷ Findings from these studies indicate that children with DCD exhibit lower auditory-motor synchronization consistency compared to their typically developing peers.²⁷⁻²⁹ Auditory-motor consistency can be quantified as the coherence or stability of the relative phase angles (e.g., timing of the finger tap relative to the closest beat) over time. If the relative phase angle stays stable over time, this is referred to as phase coherence, or high synchronization consistency. In contrast, when the relative phase angle deviates over time, and the distribution is more multimodal or broad, synchronization consistency is lower.³⁰⁻³² To our knowledge, only one study has focused on auditory-motor synchronization during a continuous task of daily life, namely walking.³³ The results confirmed that children with DCD exhibit lower auditory-motor synchronization consistency during walking compared to their typically developing peers, particularly when walking to metronomes at a slower than preferred pace. Although previous studies consistently report lower auditory-motor synchronization consistency in children with DCD compared to typically developing children (TDC), none have examined the impact of auditory-motor synchronization on motor coordination during walking or running.

Given the significance of walking and running as a crucial daily skill, combined with evidence of a more stable walking and running pattern when synchronizing steps to auditory rhythms in adult research, this study addressed auditory-motor synchronization, interlimb coordination, and spatiotemporal variability of children with and without DCD during walking and running to metronomes with different temporal structures (discrete and continuous). Accordingly, the first research goal was to examine the level of synchronization to auditory metronomes with different temporal structures during walking and running in children with and without DCD. We hypothesized that children with DCD would have a lower synchronization consistency than their typically developing peers,³⁴ irrespective of the temporal structure of the metronome. The second research goal was to determine whether synchronization would impact interlimb coordination and spatiotemporal variability compared to walking or running without metronomes. In addition, we hypothesized that implementing metronomes with a continuous temporal structure would enhance interlimb coordination and spatiotemporal variability in both groups.^{21,22} This study's significant contribution is providing empirical evidence to support underlying theoretical frameworks related to the internal model deficit hypothesis and the dynamical systems approach within the context of auditory-motor synchronization. Thereafter, the study is of clinical relevance as the use of auditory rhythms in DCD can be introduced as targeted task-specific interventions in DCD.

METHODS

Participants

Participants were recruited through flyers, sport centers, and schools with children with DCD additionally recruited through physiotherapists. Inclusion criteria were: (a) aged between 8 and 12 years old; (b) absence of physical impairments hindering independent walking; and (c) either typically developing or diagnosed/likely to have DCD. Group assignment, either DCD or TDC, was determined based on the criteria outlined in the fifth edition of the Diagnostic and Statistical Manual of Mental Disorders (DSM-V).^{1,35} Specifically, children were included in the DCD group if they met the following four criteria: (1) their execution of coordinated motor skills was substantially below the expected level for their chronological age and their opportunity for skill learning, confirmed by a total percentile score ≤ 16 or a subdomain score of ≤5 on the Movement Assessment Battery for Children, second edition (m-ABC2)^{1,36}; (2) motor skill difficulties significantly interfered with activities of daily living and impacted school, leisure, and play, confirmed by the Dutch translation of the DCD-questionnaire (DCD-Q, Dutch translation Coördinatievragenlijst voor ouders)³⁷; (3) the symptom onset was in the early developmental period, validated through a parent-reported health questionnaire; and (4) the motor difficulties were not attributed to a neurological, neuromuscular, intellectual, psychological, or visual impairment, verified using a parent-reported health questionnaire. Children were included in the TDC group if (1) they had a total percentile score of ≥ 25 on the m-ABC2; (2) the parents did not report significant motor difficulties in daily life, based on the DCD-Q; (3) they had no motor difficulties in the early developmental period; and (4) the child had no neurological, neuromuscular, intellectual, psychological, visual, or other impairment or diagnosis confirmed by a parent-reported questionnaire.

Individuals were excluded if (a) they had behavioral difficulties that significantly interfered with reliable testing and (b) their char-

acteristics did not align with the above-mentioned DSM-V criteria, thus preventing clear categorization into either the DCD or TDC groups. Therefore, they could not be categorized in the DCD or the TDC group. Participants were age-matched within a 3 months' time range.

Study design and procedure

This case-control observational study was approved by the Medical Ethical Committee (B115202000009) at Hasselt University and registered on clinical trials.gov (NCT04891562). Children and parents were informed about the study through an informed-consent form, which was verbally explained during recruitment, allowing them to ask questions. At the start of the first session, this information was briefly restated, emphasizing that participation was voluntary, and could be withdrawn at any time. After discussing the study with their child, parents provided signed consent. The child participants provided verbally informed assent to participate.

The study consisted of two sessions conducted on two separate days. Both sessions took place in a sports hall and lasted 90 and 120 min, respectively, including rest time to minimize the effect of testing fatigue. The time interval between the two sessions was dependent on the availability of the participants with a minimum time interval of 24 h. The time between the two sessions ranged from 1 to 7 days. All assessments were conducted by M.G., a researcher with a clinical physiotherapy background with a specialty in pediatrics.

Sampling descriptive measures

A broad descriptive assessment was conducted to give a comprehensive view of the study population in terms of motor and cognitive abilities. Specifically, during the first session, demographic information, including age, early motor developmental period, medical history, and participation in organized sports was collected by using a parentreported questionnaire. Additionally, gross and fine motor functioning were assessed using the m-ABC2, a standardized and norm-referenced test compromising three subdomains (manual dexterity, aiming and catching, static and dynamic balance) in children aged 3-16 years. A total percentile score equal to or less than 16 or a percentile score in any specific subdomain equal to or less than five is indicative of "likely to experience motor problems."36 The m-ABC2 demonstrates good to excellent interrater and test-retest reliability, along with fair to good validity.³⁸ The age-adapted KidsBESTest was used to assess postural control, taking into account the normal development of postural control (Verbecque et al., Reliability of age-adapted Kids BESTest, in progress). The Kids-BESTest comprises 36 items distributed across six domains, each addressing a specific postural control system^{39,40}: biomechanical constraints (5 items), stability limits and verticality (7 items), transitions/anticipatory (6 items), reactive (6 items), sensory orientation (5 items), and stability in gait (7 items). Each item is assessed using a 4-point ordinal rating scale ranging from 0 (unable to perform independently) to 3 (normal performance). Performance

can be expressed through domain and total scores using percentages, where higher percentages indicate better performance.^{39,41}

Rhythm and melody perception were also assessed by the rhythm and melody task of the short version of the Montreal Battery of Evaluation of Musical Abilities (MBEMA-s).⁴² Both the melody and rhythm parts of the MBEMA-s comprise two practice trials and 20 test trials. Each trial consists of two pairs of melodies or rhythms. Participants were asked to make perceptual judgments regarding whether the two rhythms or melodies were similar or distinct from each other. A higher score on the MBEMA-s indicates a better performance, with a maximum score of 20 on every subtest. Afterward, a global score (% correct answers) that combines the two subtest scores can be calculated, of which a higher global score indicates more correct answers. The total test lasts around 15 min. Psychometric properties have been tested in children aged 4-6 and 6-8 years, and have been shown to have a good sensitivity^{42,43} and test-retest reliability.⁴³ Lastly, executive functioning was evaluated through the digit span (forwards and backwards) and an auditory Go/No-go task, specifically targeting working memory⁴⁴ and behavioral inhibition,⁴⁵ respectively.

During the digit span task, children were asked to listen to a digit span, consisting of random digits ranging from 1 to 9, and repeat the digit span forwards or backwards. A standardized form of digit strings was used. Two practice trials of a digit span of two digits preceded the test to ensure that the child understood the instruction. If the span was recalled correctly twice, the digit span was increased with an extra digit. Testing was discontinued as soon as the participant did not perfectly recall both same-length trials. For both the backwards and forwards digit span, the score was the total amount of correct recalled digit spans. Therefore, a higher score indicates a better performance.⁴⁶ Psychometric properties of the digit span task are dependent on administration and scoring.⁴⁷ The Go/No-go task paradigm was developed to assess behavioral inhibition in children with limited working memory demands.^{44,45} The used Go/No-go paradigm was based on previous research methodologies to assess behavioral inhibition in children.⁴⁴ The test contained 60 trials, of which 75% of the trials were Go trials (sound of a dog) and 25% No-go trials (sound of a ringing bell). Children needed to press the spacebar of a laptop when a Go stimulus appeared, but not when a Go/No-go stimulus appeared. They were instructed to perform the task as accurately and as quickly as possible. The inter-trial interval was kept constant at 2250 ms during the test. The mean reaction time, commission errors, and omission errors were captured. Five practice items were administered to ensure that the children understood the task instruction.

A computer-generated number generator was used to randomize the descriptive measures for each individual. Rest time was included between the assessments in order to reduce testing fatigue.

Experimental paradigm

During the second session, the experimental auditory-motor (AM) paradigm was implemented. The paradigm started with a familiarization trial where children walked or ran comfortably along a 20 by 15-

meter oval trajectory to get familiar with it. Following this, a baseline trial was conducted during which participants walked or ran at their preferred comfortable pace for 3 min without auditory stimuli to establish their comfortable cadence. Subsequently, participants engaged in the auditory-motor conditions, wherein they were instructed to synchronize their steps with the metronome beats. Specifically, the AM-conditions involved 3-min walks or runs to metronomes with discrete or continuous temporal structures, while other auditory features remained consistent. Metronome tempo matched the individual's preferred comfortable cadence from the baseline trial, applying an individualized tempo of the metronomes for both the walking and running trials. The task and metronome conditions were randomized. Figure 1 illustrates the experimental paradigm.

Equipment

The D-jogger was utilized to deliver auditory rhythms with precise metronome structure and tempo (beats per minute) in real-time.⁴⁸ It consisted of a software installed on a laptop, Sennheiser RS 127-8 headphones (Sennheiser electronic SE & Co. KG), and two NGIMU sensors (x-io Technologies Limited) affixed to the ankles for instantaneous cadence detection. Both the assessor and the child were equipped with Sennheiser RS 127-8 headphones connected to the output of the D-jogger. Before the start of each trial, the assessor tested the auditory input of the headphones for the child to ensure that the headphone was tuned correctly. The volume was individually adjusted in order to have a clear sound for the participant. During the testing, the assessor could hear in real-time the same auditory input as the participant to ensure the quality of the auditory input.

Additionally, two Physilog®5 (Physilog) wearable sensors were positioned on the dorsum of each foot to capture interlimb coordination and spatiotemporal gait parameters. The use of Physilog®5 inertial sensors has been validated for capturing gait parameters in adolescents.^{49,50}

Outcome measures

Primary outcome measures

Tempo matching, relative phase angle, and resultant vector length were calculated to assess auditory–motor synchronization during the AM-paradigm. 32

Tempo matching

Tempo matching evaluates participants' ability to match their average walking cadence with the metronome tempo throughout the entire trial. It is computed using the formula: *tempo matching* (%) = (average steps per minute/ beats per minute) * 100. A tempo matching value of 100% indicates that the participant's average cadence matches the preset metronome tempo throughout the trial. Values above or below 100% indicate a faster or slower mean cadence compared to the metronome tempo, respectively.



FIGURE 1 Visualization of the experimental auditory-motor paradigm. During the baseline trial, participants walked or ran at their comfortable pace for 3 min to collect their comfortable cadence. Afterward, participants were instructed to synchronize their steps with the beat of a metronome with either a discrete or continuous temporal structure in a randomized order. The metronome tempo was set at their comfortable tempo collected during the baseline trial.

The relative phase angle (rPA)

The rPA reflects the timing of the footfall relative to the closest beat calculated using circular statistics. The rPA gives an indication of synchronization accuracy. A positive rPA indicates a footfall occurring after the beat (reacting or lagging), while a negative rPA suggests a footfall before the beat (anticipating). The average of the rPA throughout the trial is reported in the results.

The resultant vector length (RVL)

RVL measures the consistency of relative phase angles over time.³⁰ RVL ranges from 0 to 1, where a value closer to 1 signifies high consistency and strict phase locking over time, while a value closer to 0 implies less coherent phase synchronization. Studies on auditory-motor coupling in healthy adults proposed an RVL value of 0.75 or higher to reflect high synchronization consistency, whereas lower values would indicate a less consistent phase synchronization.³¹ This reference value of synchronization consistency has also been applied in other populations such as in persons with neurological impairments.²⁴

Secondary measures

Interlimb coordination was assessed using the Phase Coordination Index (PCI), a measure that quantifies the accuracy (P ϕ ABS) and consistency (ϕ CV) of the temporal coordination between left and right steps.⁵¹

Mean accuracy of the relative phases ($P\varphi ABS$)

PφABS reflects precision in generating antiphase stepping. The relative phase (φ) indicates the timing relationship between contralateral footsteps, with accurate antiphase interlimb coordination reflected by a φ of 180°. PφABS represents the absolute difference between each φ and 180°. This is calculated using the formula: PφABS = |(mean φ - 180°)/180°)| * 100.

Coefficient of variation of the relative phases (φ CV)

 φ CV reflects the consistency of φ over time and is computed as: φ CV = 100 * ((*standard deviation* φ /*mean* φ)).

PCI (%)

PCI assesses the average accuracy and consistency of interlimb coordination throughout the trial, calculated by the sum of φ CV and P φ ABS. A lower PCI indicates higher phase control and coordination. For further details, we refer to the comprehensive description by Plotnik et al.⁵¹

Gait variability

Gait variability was quantified by the coefficient of variance (CoV) of cadence, step length, and gait speed using the following formula: $CoV = 100 * ((standard deviation \varphi/mean \varphi)).$

Statistical analysis

Descriptive measures were compared between groups using an independent *t*-test when the data exhibited a normal distribution as determined by the Shapiro–Wilk test. For non-normally distributed data, a Wilcoxon-signed rank test was employed. Categorical descriptive measures were compared between groups using a Fisher exact test.

Primary outcomes, which pertained to auditory-motor synchronization, were analyzed by using a mixed model analysis of variance with backward modeling. This included fixed effects of group (DCD, TDC), task (walking, running), and metronome structure (discrete, continuous), along with their interactions. Secondary outcomes, which focused on interlimb coordination and spatiotemporal variability, were analyzed using a mixed model analysis of variance with backward modeling. This involved fixed effects of group (DCD, TDC), task (walking, running), and condition (baseline, discrete metronome, continuous metronome), along with their interactions. Participants were considered as random effects in both models. For both primary and secondary outcomes, the normal distribution of the final model was checked using conditional residual plots. If a main or interaction effect was significant (at a significance level of $\alpha = 0.05$), a post-hoc Tukey test was performed, accounting for multiple comparisons using Tukey-Kramer adjustment. All analyses were conducted using JMP Pro 17.0.0.

During one baseline running trial, an outlier was identified for the CoV gait speed and CoV step length using quantile range outlier detection. Consequently, data from this trial for these particular measures were omitted from the analysis for this participant (DCD group). Additionally, due to a technical error with the Physilog®5 sensors during the auditory-motor trial involving discrete metronomes for one participant (TDC group), that trial was excluded from the secondary outcome analysis.

RESULTS

Participants

Fifty-two children aged between 8 and 12 years old were recruited. Among them, 22 were referred as either diagnosed with DCD (n = 19) or likely to have DCD (n = 3), while the remaining 30 were referred as TDC. Following the application of the specific inclusion and exclusion criteria, which included the DSM-V criteria for DCD, 21 children were included in the DCD group and 23 were categorized as TDC. A flow chart of the participants can be found in Figure 2.

The DCD and TDC group showed similarities in terms of age, working memory (digit span), melody and rhythm perception, years of music lessons, and auditory Go/No-go commission errors and reaction time. However, significant differences were evident in gender distribution, with 81% boys in the DCD group compared to 41% in the TDC group. Moreover, children with DCD significantly and markedly participated less in organized sports than TDC. Additionally, they exhibited significantly lower motor performance than TDC, as evidenced by lower scores on m-ABC2, KidsBESTest, and DCD-Q. Furthermore, on the auditory Go/No-go task, children with DCD made significantly more omission errors than TDC, resulting in fewer correct answers compared to TDC. Table 1 presents the sample descriptive information and the between-group results.

Primary outcome measures

Table 2 summarizes the mean and standard deviation of the primary outcomes during the AM-paradigm, including the statistical results.

Tempo matching (%)

A significant task effect was present (F(1,131) = 6.17, p = 0.0142) for tempo matching. Both groups exhibited adequate tempo matching during walking (100.24%) and running (99.78%). Post-hoc test indicated a small, but significant between-task difference of 0.46% (t(adjusted df = 131) = -2.48, p = 0.0142). No significant effects of group or metronome structure were found for tempo matching.

Relative phase angle (°)

There were no significant main effects of task, group, or condition, nor any interaction effect between task, group, or metronome structure for the mean relative phase angle.

RVL

A Group*Task interaction effect was present (F(1,130) = 7.82, p = 0.006) for the RVL. Post-hoc multiple comparison revealed that children with DCD had a significantly lower RVL than TDC, both during walking (t = -3.25(adjusted df = 130), p = 0.0079) and running (t = -4.79(adjusted df = 130), p<0.0001). Within the DCD group, the RVL was significantly lower during running compared to walking (t = -5.36(adjusted df = 130), p<0.0001). Metronome structure did not significantly impact RVL. Figure 3 visualizes the results of synchronization consistency, expressed by the RVL during walking and running for both groups.

Secondary outcome measures

Table 3 gives an overview of the secondary outcomes, including the statistical results.

Interlimb coordination

A Group*Task interaction effect was present for the PCI (*F*(1,217) = 18.58, p<0.0001), P φ ABS (*F*(1,217) = 14.30, p = 0.0002), and CV φ (*F*(1,217) = 20.20, p<0.0001). Post-hoc multiple comparison revealed that children with DCD have a significantly higher PCI (t =

TABLE 1 Sample descriptive characteristics and between-group results.

		DCD (n=21)	TDC (n=23)	p-value
Age (years)		10.27 (1.53)	10.37 (1.25)	ns ^a
Body weight (kilograms)		36.85 (10.60)	36.00 (6.89)	ns ^b
Body length (centimeters)		143.16 (14.45)	144.60 (9.68)	ns ^c
Leg length (centimeters)		74.90 (8.49)	77.53 (6.64)	ns ^c
Participation sports (hours/week)		1.05 (1.45)	4.51 (2.40)	<0.001 ^b
Gender (boys)	n (%)	17 (81%)	9 (39%)	<0.01 ^d
Comorbidity diagnosis	Total %	35%	0%	
	AD(H)D (n)	3		
	ASD (n)	3		
	CVI (n)	1		
	Learning disorder (n)	2		
DCDQ (/75)		35.14 (9.92)	70.44 (3.34)	<0.0001 ^b
m-ABC-2 (percentile 0–100)	Total	7.34 (10.20)	62.96 (19.82)	<0.0001 ^b
	Manual dexterity	11.00 (17.33)	58.43 (32.61)	<0.0001 ^b
	Aiming and catching	9.47 (13.31)	49.35 (24.54)	<0.0001 ^b
	Balance	19.85 (25.86)	62.04 (18.62)	<0.0001ª
Kids BESTest (0–100%)	Total	79.66 (8.15)	94.02 (3.83)	<0.0001 ^b
	Domain I	88.89 (11.80)	97.97 (3.73)	<0.0001ª
	Domain II	68.48 (11.71)	84.06 (10.80)	0.0001ª
	Domain III	75.13 (16.63)	96.14 (6.58)	<0.0001 ^b
	Domain IV	84.39 (10.34)	95.41 (6.19)	<0.001ª
	Domain V	91.75 (8.14)	99.13 (2.30)	<0.001 ^b
	Domain VI	69.31 (17.37)	91.44 (9.47)	<0.0001 ^b
Digit span forwards (0–18)		7.52 (1.99)	6.77 (1.34)	0.3314ª
Digit span backwards (0–16)		4.24 (1.41)	4.77 (1.38)	0.1783ª
Auditory Go/No-go	Correct (0–60)	54.67 (6.92)	58.59 (2.09)	0.0202 ^b
	Omission errors (0–60)	3.05 (6.15)	0.18 (0.50)	0.0458 ^b
	Commission errors (0–60)	2.29 (2.78)	1.23 (1.77)	0.2582ª
	Reaction time (ms)	817.14 (214.37)	803.68 (134.40)	0.8077 ^c
Music lessons (years)		0.76 (1.48)	0.70 (1.29)	0.8690 ^a

(Continues)

TABLE 1 (Continued)

	DCD (n=21)	TDC (n=23)	p-value
MBEMA-s total %	75.92 (13.08)	78.18 (12.75)	0.5798 ^c
(0-100%)			

Note: Data represent mean (standard deviation). Between-group differences are reported with the corresponding *p*-value. Bold *p*-values are considered as significant using two-sided *p*-values <0.05.

Abbreviations: AD(H)D, attentional deficit (hyperactivity) disorder; ASD, autism spectrum disorder; CVI, cerebral visual impairment; DCD, developmental coordination disorder; DCDQ, Developmental Coordination Disorder Questionnaire; m-ABC-2, Movement Assessment Battery—second edition; TDC, typically developing children.

^aWilcoxon signed rank test.

^bWelch's test.

^cIndependent *t*-test.

^dFisher's exact test.

		Metronome	Group		Backwards	Post-hoc multiple comparison, Tukey–Kramer adjustment						
Outcome Task	structure	DCD (n=21)	TDC (n=23)	analysis of variances	Comparison	Adjusted df	Difference	SE	t-ratio	p-value		
Tempo matching (%)	Walk	Discrete	100.75 (2.21)	100.20 (1.25)	Task: (F(1,131)=6.17, p=0.0142)	Run versus walk	131	-0.46	0.18	-2.48	0.0142	
		Continuous	100.09 (1.87)	99.96 (1.06)								
	Run	Discrete	99.82 (1.45)	99.54 (0.93)								
		Continuous	100.01 (1.17)	99.80 (0.67)								
Relative phase angle (°)	Walk	Discrete	–24.57 (69.39)	-16.31 (36.51)	Not significant							
		Continuous	1.55 (53.03)	-7.13 (34.86)								
	Run	Discrete	-10.9 (57.73)	-20.45 (51.61)								
		Continuous	2.42 (71.38)	–20.84 (59.84)								
Resultant vector length (0–1)	Walk	Discrete	0.49 (0.27)	0.75 (0.23)) Group*Task: (F(1,130)=7.82, p=0.006)	DCD: run versus walk	130	-0.15	0.028	-5.36	<0.0001	
		Continuous	0.55 (0.30)	0.75 (0.25))	DCD versus TDC: run		-0.34	0.070	-4.79	<0.0001	
	Run	Discrete	0.38 (0.25)	0.73 (0.20))	DCD versus TDC: walk		-0.23	0.070	-3.25	0.0079	
		Continuous	0.36 (0.26)	0.68 (0.23))							

TABLE 2 Results of auditory-motor synchronization during the auditory-motor synchronization paradigm.

Note: Data are represented as mean (standard deviation). Results of the backward repeated mixed model analyses are reported by F(df) = F-value, p-value. Significant results, after post-hoc multiple comparison with Tukey–Kramer test, are reported. Bold indicates significance at p<0.05. Abbreviations: DCD, developmental coordination disorder; SE, standard error; TDC, typically developing children.

5.45(adjusted df = 217), p<0.0001), $P\varphi$ ABS (t = 4.98(adjusted df = 217), p<0.0001), and CV φ (t = 5.55(adjusted df = 217), p<0.0001) than TDC during running. In addition, within the DCD group, a significantly higher PCI (t = 6.73(adjusted df = 217), p<0.0001), $P\varphi$ ABS (t

= 5.95(adjusted df = 217), p<0.0001), and CV φ (t = 6.98(adjusted df = 217), p<0.0001) was observed during running compared to walking. The condition (baseline, metronome discrete, metronome continuous) did not significantly impact interlimb coordination.



FIGURE 2 Flow chart of the participants. After the inclusion and exclusion criteria, 21 children were included in the DCD group and 23 in the TDC group. Abbreviations: DCD, developmental coordination disorder; m-ABC2, Movement Assessment Battery for Children, second edition; TDC, typically developing children.



FIGURE 3 The resultant vector length during walking and running in (A) typically developing children (TDC) and (B) developmental coordination disorder (DCD). Children with DCD show a significantly lower RVL than TDC, both during walking (green striped bar, **TDC-DCD W) and running (blue filled bar, **TDC-DCD R), regardless of the metronome structure. Within the DCD group, the RVL was significantly lower during running than walking (*DCD W-R). Metronome structures are grouped within each task for the visualization. Bars represent mean and standard error. Abbreviations: R, running; TDC-DCD, TDC compared to DCD; W, walking; W-R, walking compared to running.

Variability in spatiotemporal gait parameters

A Group*Task interaction effect was found for the CoV of cadence (F(1,215) = 13.72, p = 0.0003), CoV step length (F(1,216) = 21.41, p<0.0001), and CoV gait speed (F(1,216) = 24.97, p<0.0001). Posthoc multiple comparison revealed a significantly higher CoV of cadence

(t = 3.30(adjusted df = 215), p = 0.0063), CoV of step length (t = 3.12(adjusted df = 216), p = 0.0110), and CoV of gait speed (t = 2.90(adjusted df = 216), p = 0.0211) in DCD than TDC during walking. During running, this between-group difference became even more prominent. Specifically, children with DCD ran with a significantly higher CoV of cadence (t = 6.13(adjusted df = 215), p < 0.0001), CoV

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TABLE 3	Results of interlimb	coordination and	spatiotemporal	variability dur	ring the auditory	 motor synchronization 	paradigm.
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			Group		Backwards	Post-hoc multiple comparison Tukey test, Tukey–Kramer adjustment					
Outcome	Task	Condition	DCD (n=21)	TDC (n=23)	- mixed model analysis of variances	Comparison	Adjusted df	Difference	SE	t-ratio	p-value
Phase coordination index (%)	Walk	Baseline	7.00 (1.53)	6.09 (1.29)	Group*Task: (F(1,217) =18.58, p<0.0001)	DCD: run versus walk	217	2.98	0.44	6.73	<0.0001
		Discrete	6.72 (1.40)	5.85 (1.49)							
		Continuous	6.73 (1.35)	5.79 (1.26)							
	Run	Baseline	10.13 (5.33)	5.68 (2.13)		DCD versus TDC: run		3.55	0.65	5.45	<0.0001
		Discrete ^T	9.77 (4.91)	6.67 (3.27)							
		Continuous	9.49 (4.48)	6.46 (3.06)							
Mean accuracy of relative phases (PφABS, %)	Walk	Baseline	3.26 (0.80)	2.78 (0.70)	Group*Task: (F(1,217) =14.30, p=0.0002)	DCD: run versus walk	217	1.20	0.20	5.95	<0.0001
		Discrete	3.11 (0.65)	2.71 (0.80)							
		Continuous	3.09 (0.63)	2.69 (0.73)							
	Run	Baseline	4.47 (2.37)	2.63 (1.03)		DCD versus TDC: run		1.48	0.30	4.98	<0.0001
		Discrete ^T	4.24 (2.15)	3.08 (1.34)							
		Continuous	4.35 (2.22)	2.94 (1.26)							
Coefficient of variance of relative phases (CVφ, %)	Walk	Baseline	3.74 (0.75)	3.32 (0.65)	Group*Task: (F(1,217) =20.20, p<0.0001)	DCD: run versus walk	217	1.77	0.25	6.98	<0.0001
		Discrete	3.62 (0.76)	3.14 (0.72)							
		Continuous	3.64 (0.75)	3.10 (0.63)							
	Run	Baseline	5.66 (3.11)	3.05 (1.25)		DCD versus TDC: run		2.06	0.37	5.55	<0.0001
		Discrete ^T	5.52 (2.83)	3.58 (2.05)							
		Continuous	5.13 (2.36)	3.53 (1.89)							
CoV cadence (%)	Walk	Baseline	3.16 (0.81)	2.44 (0.65)	Group*Task: (F(1,215) =13.72, p=0.0003)	DCD: run versus walk	215	0.31	0.11	2.89	0.0218
		Discrete	2.80 (0.62)	2.21 (0.45)		DCD versus TDC: run		1.18	0.19	6.13	<0.0001

(Continues)

TABLE 3 (Continued)

			Group		Backwards	Post-hoc multiple comparison Tukey test, Tukey–Kramer adjustment					
Outcome	Task	Condition	DCD (n=21)	TDC (n=23)	analysis of variances	Comparison	Adjusted df	Difference	SE	t-ratio	p-value
		Continuous	2.72 (0.66)	2.13 (0.53)		DCD versus TDC: walk		0.63	0.19	3.30	0.0063
	Run	Baseline	3.35 (1.31)	1.97 (0.52)	Condition: (F(2,215)=3.7 p=0.0255)	Continuous Versus baseline		-0.24	0.090	-2.67	0.0221
		Discrete ^T	3.20 (1.20)	2.05 (0.64)							
		Continuous	3.05 (1.13)	2.05 (0.59)							
CoV step length (%)	Walk	Baseline	5.81 (1.20)	4.58 (0.84)	Group*Task: (F(1,216) =21.41, p<0.0001)	DCD: run versus walk	216	3.20	0.25	12.78	<0.0001
		Discrete	5.84 (1.29)	4.64 (1.35)		DCD versus TDC: run		2.92	0.42	6.89	<0.0001
		Continuous	5.99 (1.46)	4.47 (0.99)		DCD versus TDC: walk		1.32	0.42	3.12	0.0110
	Run	Baseline ⁰	9.08 (2.74)	5.77 (1.17)		TDC: run versus walk		1.60	0.24	6.68	<0.0001
		Discrete ^T	9.05 (2.53)	6.28 (1.57)							
		Continuous	9.10 (2.98)	6.48 (2.28)							
CoV speed (%)	Walk	Baseline	5.27 (1.54)	4.01 (1.01)	Group*Task: (F(1,216) =24.97, p<0.0001)	DCD: run versus walk	216	4.06	0.25	16.18	<0.0001
		Discrete	5.02 (1.25)	3.87 (1.39)		DCD versus TDC: run		3.04	0.45	6.73	<0.0001
		Continuous	5.09 (1.56)	3.58 (0.98)		DCD versus TDC: walk		1.31	0.45	2.90	0.0211
	Run	Baseline ⁰	9.33 (2.92)	5.81 (1.32)		TDC: run versus walk		2.33	0.24	9.71	<0.0001
		Discrete ^T	8.99 (2.46)	6.24 (1.62)							
		Continuous	9.21 (3.01)	6.42 (2.33)							

Note: Data are mean (standard deviation). Results of the backward repeated mixed model analyses are reported by F(df) = F-value, *p*-value. Significant results, after post-hoc multiple comparison with Tukey–Kramer test, are reported. Discrete^T, due to a technical error, data of one child were excluded from analysis within the running condition to discrete metronomes. Baseline^O, one participant was detected as an outlier for the CoV step length and CoV speed during baseline running and was, therefore, excluded from this analysis. Bold indicates statistical significance.

Abbreviations: CoV, coefficient of variance (CoV); $CV\phi$, coefficient of variance of relative phases; DCD, developmental coordination disorder; $P\phi$ ABS, absolute error of the relative phase; PCI, phase coordination index; SE, standard error; TDC, typically developing children.

of step length (t = 6.89(adjusted df = 216), p<0.0001), and CoV of gait speed (t = 6.73(adjusted df = 216), p<0.0001) than TDC. Within both groups, a significantly higher CoV of step length and CoV of gait speed was present during running compared to walking. Only within the DCD group was there a significantly higher CoV of cadence during running compared to walking (t = 2.89(adjusted df = 215), p<0.0001). Figure 4 visualizes the variability of cadence—expressed as the CoV of cadence. Besides the Group*Task interaction effect, a significant condition effect was present for the CoV of cadence (F(2,215) = 3.73, p = 0.0255). Post-hoc multiple comparison tests indicated that, regardless of the task or group, the CoV of cadence was significantly higher during the baseline silence trial compared to the metronomes with a continuous structure (t = -2.67(adjusted df = 215), p = 0.00221). Figure 5 visualizes the main effect of condition for the CoV of cadence.



FIGURE 4 The coefficient of variance (CoV) of cadence. The CoV is visualized when walking and running during baseline silence (blue filled bar), metronome discrete (green striped bar), and metronome continuous (orange dotted bars) trials of (A) typically developing children and (B) children with developmental coordination disorder. Mean and standard errors are shown.



FIGURE 5 The main effect of metronome condition for the coefficient of variation of cadence (CoV of cadence). The CoV is significantly lower during the metronome continuous condition compared to the baseline silence condition. *indicates significant difference at *p*<0.05 for condition.

DISCUSSION

In this study, our primary aim was to understand the level of synchronization to auditory metronomes with different temporal structures (discrete, continuous) during walking and running in children with and without DCD. Second, we aimed to examine whether auditory-motor coupling would impact interlimb coordination and spatiotemporal variability compared to walking or running in silence. Below, we discuss the results within the framework of the hybrid multicomponent model of motor coordination in DCD, encompassing both dynamical system theory and the internal-model deficit hypothesis.

The findings revealed that children with DCD exhibited lower synchronization consistency, expressed as a lower RVL, than typically developing peers during both walking and running. However, tempo matching and average relative phase angle did not significantly differ between groups. Our results align with previous studies investigating auditory-motor coupling in DCD.^{27,33} However, this study is the first to specifically examine synchronization to a rhythmical auditory stimulus during walking and running. It is important to note that both tempo matching and relative phase angle are averaged values across the trial. Therefore, even if the cadence fluctuates around the metronome tempo, the average cadence may still match with the preset metronome tempo, resulting in a tempo matching value of 100%. However, the degree of consistency in synchronizing steps with the metronome beat would be relatively low, as reflected in our findings of the RVL within the DCD group, indicating that children with DCD synchronized significantly less consistently than TDC. Additionally, our results show that within the DCD group, synchronization consistency is influenced by task complexity, with lower consistency observed during running compared to walking to metronomes. Studies on auditorymotor coupling in healthy adults and neurological populations have suggested that an RVL value of 0.75 or higher indicates high synchronization consistency, whereas lower values signify less consistent phase synchronization.^{24,31} Research on the impact of development on synchronization consistency, particularly during finger tapping, suggests that synchronization consistency improves with age and reaches adult-like levels in TDC around 8–10 years old.⁵²⁻⁵⁴ Thus, given the age group of our study sample, we anticipated the synchronization consistency of TDC aged 8–12 years to be adult-like. Our results confirm this expectation: the TDC group achieved, on average, high synchronization consistency (RVL = 0.75) while walking to metronomes and nearly reached this level while running to metronomes. In contrast, the DCD group did not reach the reference value of 0.75, indicating lower consistent synchronization on average.

From a theoretical standpoint, auditory-motor synchronization is governed by the dynamic process of entrainment, which involves coupling a motor rhythm to auditory beats to achieve consistent and stable synchronization in both phase and period.⁵⁵ Entrainment can be explained through an error-prediction minimization process^{25,55} or as a dynamical process.²⁰ The error-prediction minimization process describes entrainment as minimizing timing differences between the steps and the auditory beats so that the motor rhythm becomes aligned with the auditory rhythm. According to this process, the lower synchronization consistency observed in DCD may stem from an internal modeling deficit, or a deficiency in generating or implementing predictive models, which hampers the error-prediction minimization process. Internal models play a vital role in anticipating motor outcomes before the slower sensorimotor feedback is accessible, thereby facilitating rapid real-time adjustments.^{56,57}

Running to metronomes may exacerbate challenges to internal modeling by necessitating faster timing within the motor system to maintain balance and prevent falls.¹⁶ Additionally, the shorter interbeat intervals within the high metronome tempo during running require precise beat prediction and demand accurate predictive con-

trol for consistent step-to-beat alignment.⁵⁸ If children with DCD rely more on slower feedback control mechanisms, they may struggle to achieve consistent synchronization under these conditions. Alternatively, from the perspective of dynamical systems theory, the motor and auditory systems are viewed as two oscillatory systems that exert mutual forces to achieve coupled dynamics. Thus, this perspective attributes difficulties in auditory-motor synchronization to the interaction between internal and external forces, with reduced temporal motor stability reflecting challenges in dynamic movement control.⁵⁹

The secondary objective of the study was to investigate whether the synchronization of steps to auditory metronomes would influence interlimb coordination and spatiotemporal variability as compared to walking or running in silence. This objective was guided by previously reported higher spatiotemporal variability during over-ground walking and running in silence in DCD compared to TDC.^{17,60} Notably. higher variability is not always a deficit. According to the internal model deficit hypothesis in DCD, increased variability is seen as noise that impacts sensorimotor control, motor output, and predictive control, thus creating predictive uncertainty.⁶¹ Conversely, the dynamical model views variability as a necessary adaptation to changing environments marking skilled performance. This aligns with Bernstein's definition of coordination, which involves organizing movement patterns to ensure stability under environmental demands.^{10,62} During the metronome conditions, children were instructed to synchronize their steps with isochronous metronomes with an individualized tempo that matched their comfortable cadence. In addition, the metronomes had no changes in phase or tempo, thus requiring no continuous adaptations.

To elaborate, once coupling in phase and/or tempo was reached, children needed to maintain a consistent rhythm throughout the trial. It was hypothesized that using metronomes would assist children with DCD in improving interlimb coordination and maintaining a consistent cadence, reflecting the within-trial variability of cadence seen in the TDC group. This hypothesis was partially supported. Metronomes neither facilitated nor hindered interlimb coordination. However, as hypothesized, the spatiotemporal variability of cadence decreased with the introduction of metronomes, although higher variability remained in the DCD group compared to the TDC group. Therefore, we propose that children with DCD have more difficulties than TDC with consistently timing their motor coordination within a well-controlled environment (silence condition) as task complexity increases, such as during running, and that isochronous metronomes (with a continuous temporal structure) may guide or help them with consistently timing their motor actions. The differential effect on interlimb coordination and spatiotemporal variability may be explained by a different level of phase matching and tempo matching. To elaborate, children with DCD exhibited limited phase matching consistency, as indicated by a relatively low RVL. This reduced phase synchronization consistency may have limited the impact on interlimb coordination, which was assessed by the PCI-a measure of phase timing between the left and right steps. Notably, interlimb coordination did not deteriorate with the addition of metronomes, suggesting that their incorporation was not perceived as a distraction or an additional task. However, the

incorporation of metronomes with a continuous temporal structure positively influenced cadence variability. Both groups demonstrated an adequate tempo matching ability, indicating that children could match their average cadence with the preset metronome tempo. In other populations, it has been proposed that incorporating metronomes with a continuous structure or music optimizes a consistent walking or running cadence.^{18,21,22,63} These effects may be explained by the dynamical interaction between the type of movement (discrete or continuous) and the temporal structure of the auditory rhythms (discrete or continuous), and the underlying temporal processing frameworks of event-based and emergent timing.^{23,64}

Several methodological considerations should be noted. We acknowledge that children in our study were not matched based on their physical activity level. While sports experience and practice may influence running performance, our study did not aim to explore the impact of participation in sports on interlimb coordination. As a result, we observed that children with DCD reported lower participation in organized sports compared to TDC. It is important to note that this self-reported participation in organized sports did not include regular physical activity (e.g., playing outside with friends or walking or cycling to school) or a quantitative measure of physical fitness. Previous research has reported similar findings of lower activity levels in DCD than in TDC.⁵ The lower self-reported levels of physical activity in DCD may limit their opportunities to develop proficient motor skills and may be linked to difficulties in mastering fundamental motor skills, such as running.⁸ Therefore, the observed differences in interlimb coordination during running might be driven by the fact that TDC tend to be more active in sports, including running. However, previous research has shown that even in a novel coordination task, the coordination pattern of children with and without DCD differs.⁶⁵ Hence, we suggest that further studies explore the impact of practice and physical activity, preferably guantitatively measured, on interlimb coordination.

Additionally, a large within-group heterogeneity was present in interlimb coordination and auditory-motor synchronization in the DCD group. This aligns with the known heterogeneity in impairments among children with DCD⁶⁶ and the frequent presence of comorbidities.¹ Deficits in postural control and executive functions are also commonly reported in DCD.^{3,66} Our broad descriptive assessment aimed to provide a comprehensive view of the study population (see Table 1). Between-group differences were identified in postural control (Kids BESTest) and behavioral inhibition (auditory Go/No-go test correct and omission errors), confirming difficulties in these areas. However, no difference in working memory as assessed by the digit span was found. This lack of differences may be attributed to the scoring and administration of the digit span.⁴⁷

Additionally, no between-group differences were observed in MBEMA-s score, a task designed to assess rhythm and melody perception.^{42,43} Although previous research suggests auditory perception difficulties in DCD,⁶⁷ we did not observe such differences in our study. For future studies, we recommend using a broader assessment tool, such as the Battery for the Assessment of Auditory Sensorimo-

tor and Timing Abilities, which encompasses a wide range of timing skills.⁶⁸ This would help to explore the extent to which auditory perceptual deficits contribute to auditory-motor synchronization. Individual factors such as dynamical postural control, musical experience,^{69,70} auditory perception,⁷¹ presence of comorbidities,^{72,73} and executive functioning^{74,75} may impact auditory-motor synchronization. For example, previous research suggests that executive control plays a role in rhythm perception and auditory-motor synchronization, especially when the tempo of the metronomes is sufficiently slow or fast.^{74,75} In our study, metronomes were individually set at the child's preferred comfortable cadence without changes in phase or tempo-eliminating the need for continuous adaptations. Thus, we assumed a limited impact of executive function and postural control on auditory-motor synchronization. However, due to the relatively small sample size and limitations of some descriptive assessments used, we could not apply robust statistical methods to examine the impact of individual factors on our results. Further research with a sufficient sample size and sensitive and reliable tests is recommended to explore the impact of executive functions and other individual factors on synchronization, incorporating challenging higher and lower auditory tempi or including phase and tempo shifts.

Additionally, regarding methodological aspects, it is worth considering the envelope utilized to establish a continuous temporal framework within the metronome rhythm. Although our intention was to emulate the rhythmic structure of music, it is plausible that the temporal envelope employed in our study might not have accurately represented the intricate structure of music. While the metronome structure did not significantly impact synchronization outcomes in our study, unlike findings from studies comparing music to metronomes in adults and persons with multiple sclerosis,^{23,24} we did observe an effect of the continuous metronome structure on reducing movement variability, which is consistent with existing literature. Further studies could explore the incorporation of music given its added motivational influences and decreased perceived fatigue.⁷⁶ Moreover, further research is recommended to investigate how metronomes or music can be integrated into rehabilitation strategies for children with DCD to address increased movement variability and coordination deficits while walking and running. Additionally, the development of new technologies aimed at promoting auditory-motor synchronization consistency in DCD could assist in enhancing phase coupling between left and right steps, thereby facilitating interlimb coordination.

CONCLUSION

Our findings revealed lower synchronization consistency, higher spatiotemporal variability, and inferior interlimb coordination in DCD, which is particularly accentuated during running. The results indicate that metronomes with continuous temporal structures might decrease spatiotemporal variability of cadence in DCD while walking and running. Overall, this research offers valuable insights for the development of effective interventions aimed at improving coordination during walking and running in DCD. These interventions should consider the individual, task, and environmental influences outlined in a hybrid multicomponent model.

AUTHOR CONTRIBUTIONS

M.G.: Conceptualization, methodology, formal analysis, investigation, data curation, writing—original draft, visualization, project administration, funding acquisition. P.F.: Conceptualization, methodology, resources, writing—review and editing, supervision. E.R.: Conceptualization, methodology, resources, writing—review and editing, supervision. B.M.: Methodology, software, validation, resources, writing review and editing. M.L.: Methodology, software, validation, resources, writing—review and editing. L.M.: Conceptualization, methodology, resources, writing—review and editing, supervision, funding acquisition.

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COMPETING INTERESTS

The authors declare no competing interests.

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