Cognition 276 (2026) 106663

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/cognit

Distinct developmental trajectories shape human sensitivity to rhythms in the environment

Antoine Guinamard [a,b,c,d,*], Nicholas E.V. Foster [a,b,c], Sylvain Clément [d], Valentin Bégel [e], Sonja A. Kotz [f,g], Séverine Samson [d,h], Simone Dalla Bella [a,b,c,i,1,*], Delphine Dellacherie [d,j,1,*]

[a] International Laboratory for Brain, Music and Sound Research (BRAMS), Montreal, Canada
[b] Department of Psychology, University of Montreal, Pavillon Marie-Victorin CP 6128 Succursale Centre-Ville, Montréal, QC H3C 3J7, Canada
[c] Centre for Research on Brain, Language and Music (CRBLM), Montreal, Canada
[d] Univ. Lille, ULR 4072 - PSITEC - Psychology : Interactions, Time, Emotions, Cognition, F-59000 Lille, France
[e] Institut des Sciences du Sport Santé de Paris (I3SP), Université Paris Cité, Paris, France
[f] Department of Neuropsychology & Psychopharmacology, University of Maastricht, Maastricht, the Netherlands
[g] Department of Neurology, Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany
[h] Université Paris Cité, Institut Pasteur, AP-HP, INSERM, CNRS, Fondation Pour l'Audition, Institut de l'Audition, IHU reConnect, F-75012 Paris, France
[i] VIZJA University, Warsaw, Poland
[j] CHU Lille, Centre de Référence Malformations et Maladies Congénitales du Cervelet, F-59000 Lille, France

ARTICLE INFO

Keywords:
Rhythm
Implicit
Explicit
Timing
Development
Children

ABSTRACT

Rhythm is an omnipresent feature of our environment. Repetitive temporal patterns in sound and vision influence how we pay attention to the world, move, and speak. Grasping these regularities is critical for development. Humans can track surrounding rhythms explicitly—like dancing to the beat of music—or implicitly, when rhythms guide perception and behavior without deliberate attention. Whether these abilities follow different developmental trajectories remains unknown. Here, we tested 98 children aged 7–13 using a novel gamified task measuring implicit rhythm processing, alongside assessments of explicit rhythmic abilities and cognition. We show that explicit and implicit rhythmic abilities follow distinct developmental trajectories: whereas explicit rhythmic abilities improve with age and formal musical experience, implicit rhythmic sensitivity remains remarkably stable throughout childhood. Implicit and explicit rhythm processing also showed distinct associations with executive functioning. In addition, the relation between these two forms of rhythm processing appeared to depend on cognitive flexibility. These findings provide new insights into the development of rhythmic abilities and may inform future work on neurodevelopmental disorders and rhythm-based rehabilitation.

1. Introduction

Rhythmic patterns are a ubiquitous feature of our environment. Temporal regularities occur in music and speech, in bodily movements, and across many everyday activities (Doelling et al., 2023). From the repetitive pulse of an ambulance siren to the complex temporal structure of language or music, humans display remarkable sensitivity to rhythm. The ability to detect and track such temporal regularities -broadly referred to as rhythmic abilities - is partly rooted in our genetics (Alagöz et al., 2025; de Hoyos et al., 2025; Niarchou et al., 2022). Far beyond musicality, these abilities support the prediction of future events and help optimize perception and action in a constantly changing environment (Haegens & Zion Golumbic, 2018; Nobre & van Ede, 2018). In childhood, rhythmic abilities contribute to core developmental domains (Frischen et al., 2022), such as language (Fiveash et al., 2021), social interaction (Kirschner & Tomasello, 2010; Trainor & Cirelli, 2015) and

* Corresponding authors at: BRAMS, Université de Montréal, Département de psychologie, C.P. 6128, succ. Centre-ville, Montréal, QC H3C 3J7, Canada; and Laboratoire PSITEC, Université de Lille, Domaine Universitaire du Pont de Bois, Rue du Barreau, BP 60149, 59653 Villeneuve-d'Ascq Cedex, France.

E-mail addresses: antoine.guinamard@umontreal.ca, antoine.guinamard@univ-lille.fr (A. Guinamard), simone.dalla.bella@umontreal.ca (S. Dalla Bella), delphine.dellacherie@univ-lille.fr (D. Dellacherie).

[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.cognition.2026.106663
Received 14 August 2025; Received in revised form 12 July 2026; Accepted 13 July 2026

literacy (Tierney et al., 2021). In turn, poor rhythmic abilities have been linked to developmental conditions like dyslexia (Bégel, Dalla Bella, et al., 2022) or ADHD (Puyjarinet et al., 2017), and are considered potential precursors of broader learning and developmental disorders (Ladányi et al., 2020; Lense et al., 2021).

Understanding how rhythmic abilities develop is therefore essential, both for identifying early signs of learning difficulties and informing targeted interventions. However, most developmental studies have focused on explicit rhythm processing (i.e., deliberate engagement with rhythmic patterns, typically involved when we dance or sing along with music). In everyday life, though, rhythm more often shapes perception and action implicitly. Whether reacting to traffic or engaging in conversation, we routinely benefit from temporal regularities without deliberately attending to them. This study addresses a critical gap by examining, for the first time, the joint development of explicit and implicit rhythmic abilities, and their relation to cognitive functions in children.

Explicit rhythm processing is typically assessed using tasks that directly involve rhythmic structure, such as beat perception (e.g., judging whether a sound aligns with the underlying pulse of music) and beat synchronization (e.g., tapping in time with the beat). In contrast, implicit rhythm processing is evaluated through tasks where rhythm is not the focus, such as pitch discrimination, but where temporal regularity can still enhance performance, for example by speeding up reaction times (Bégel et al., 2017; Bouwer et al., 2021; Coull & Nobre, 2008). The distinction between implicit and explicit processing has been extensively studied in domains such as memory (Graf, 1990; Rugg et al., 1998; Voss & Paller, 2008) or single duration processing (Capizzi et al., 2022; Droit-Volet et al., 2019; Droit-Volet & Coull, 2016), but has received much less attention in rhythm and beat processing research. Emerging evidence in adults suggests that implicit and explicit rhythm processing may rely on distinct mechanisms. Evidence comes from disorders in rhythm perception (beat deafness; Palmer et al., 2014; Phillips-Silver et al., 2011). In a multiple case-study, three individuals with poor explicit rhythm perception nonetheless showed faster responses to temporally regular sequences in a pitch detection task (Bégel et al., 2017). Similarly, implicit rhythm processing appears more resilient to age-related decline than explicit perception (Hiroyasu & Yotsumoto, 2020). However, to our knowledge, no study has examined this distinction in children, and it remains unknown whether implicit and explicit rhythmic abilities follow separate developmental trajectories or emerge in tandem during childhood.

There is compelling evidence that explicit rhythmic abilities, such as beat perception and synchronization, improve steadily throughout childhood and adolescence (Drake et al., 2000; Hannon et al., 2018; McAuley et al., 2006; Nave-Blodgett et al., 2021; Thompson et al., 2015). Most individuals, regardless of musical education, eventually acquire the ability to perceive and move to a beat (Sowiński & Dalla Bella, 2013; Tranchant et al., 2016). Still, substantial individual differences exist (Dalla Bella, Janaqi, et al., 2024; Fiveash et al., 2022), partly shaped by musical experience (Dalla Bella, Janaqi, et al., 2024; Nave-Blodgett et al., 2021) and broader cognitive factors including cognitive control (Löser et al., 2024; Slater et al., 2018). In contrast, very little is known about the development of implicit rhythm processing. Implicit processes more broadly are often assumed to emerge early and to be largely mature by childhood (Coull & Droit-Volet, 2018; Karmiloff-Smith, 1994; Reber, 1992). However, the only developmental study of implicit rhythmic abilities, conducted in the visual modality, reported increasing reaction time benefits from rhythm regularity between ages 5 and 12 (Debrabant et al., 2012). Whether similar patterns hold in the auditory domain remains unclear, given that studies in adults suggest that auditory and visual implicit rhythm processing rely on distinct mechanisms and show uncorrelated performance (Attout et al., 2024; Capizzi et al., 2024).

A key to understanding how explicit and implicit rhythmic abilities develop may lie in their relationship to executive functions, a set of higher-order cognitive control processes supporting goal-directed behavior, concentration, learning, and self-regulation (Diamond, 2013). These functions develop substantially during school years (Brocki & Bohlin, 2004; Buttelmann & Karbach, 2017; Diamond, 2013), in parallel with improvements in explicit rhythmic abilities. Significant associations have been reported between explicit rhythmic abilities and various executive components, including controlled attention (Tierney & Kraus, 2013), inhibition (Puyjarinet et al., 2017), working memory (Colley et al., 2018; Kim et al., 2022), and cognitive flexibility (Bégel, Dalla Bella, et al., 2022). By contrast, implicit rhythmic abilities are thought to rely less on executive functions, operating largely automatically (Breska & Deouell, 2014a). Evidence from adult studies suggests implicit rhythm processing can occur independently of cognitive control (Cutanda et al., 2015, 2019), but whether this is also true in children remains unknown. Moreover, the cognitive predictors of implicit rhythmic abilities remain largely unexplored. To summarize, it remains unclear whether implicit and explicit rhythmic abilities follow shared or distinct developmental trajectories in childhood, and whether they relate similarly to executive functions. Clarifying these relationships is essential for refining theoretical models of rhythm processing and informing interventions targeting rhythm-related difficulties.

For this purpose, we examined the developmental trajectories of both implicit and explicit rhythmic abilities and their links to executive functions in school-aged children, a key developmental window for cognitive control and the emergence of learning difficulties. To evaluate implicit rhythm processing, we developed a novel gamified task in which children detected pitch changes presented after regular or irregular tone sequences to help a small astronaut navigate through space. Crucially, neither the task goals nor instructions required attention to rhythmic regularity. Reaction time benefits from regularity indexed implicit rhythm processing. To assess explicit abilities, we used beat perception and synchronization tasks from a standardized rhythm battery (Dalla Bella et al., 2017; Dalla Bella, Janaqi, et al., 2024). Finally, we evaluated executive functions using established tasks of auditory controlled attention, inhibitory control, working memory, and cognitive flexibility (Manly et al., 2001; Roy et al., 2020; Wechsler, 2014). According to our predictions, explicit rhythmic abilities would be more closely linked to age, formal musical experience, and executive functions than implicit abilities.

2. Methods

2.1. Participants

One hundred and six French-speaking children aged 7 to 13 participated in the study; 98 were included in the final analysis. They were recruited in Lille (France) and Montréal (Canada). All children's main language was French; four children also spoke fluently a second language (e.g., English, Spanish, Arabic). Language background was not a variable of interest in the present study, thus it was not included in the analyses. The following non-inclusion criteria were applied: 1) a reported diagnosis of a neurodevelopmental or psychiatric disorder, 2) a history of neurological events, 3) reported hearing impairments, and 4) uncorrected vision deficits. To control for general intellectual and sensori-motor functioning, we assessed fluid reasoning and processing speed using the Matrix Reasoning and Coding subtests of the Wechsler Intelligence Scale for Children - 5th edition (Wechsler, 2014). A below-threshold score (i.e., standard score < 5) on either subtest was defined as an exclusion criterion. Additionally, a data quality check was performed on the implicit rhythmic task to ensure that children adequately understood and performed the task. A high number of invalid trials or performance close to chance level was considered an exclusion criterion (see section **2.4.1**.).

In total, eight children were excluded: two due to a low score on one of the control tests, four because they did not meet the quality criteria for the implicit rhythmic task, and two due to behavioral issues or technical problems during testing.

The final sample consisted of 98 children aged 7 to 13 ($M = 10.1$, $SD = 1.6$), including 62 children from France and 36 from Canada, with 58% being female. Among them, 35 had at least one year of formal musical experience (for the whole group: $M = 0.95$ years, $SD = 1.5$, range = [0; 5]). The occupational categories reported by the children's parents were professionals and managers (41%), office and service workers (45%), skilled and unskilled manual workers (6%), and unemployed (6%).

Mean standard scores on the control tests were as follows: Matrix Reasoning ($M = 10.5$, $SD = 2.53$) and Coding ($M = 11.5$, $SD = 2.31$). Spontaneous motor tempo was also assessed using an unpaced tapping task administered prior to the rhythmic tasks. As this measure was not central to our hypotheses and did not show any significant association with age and implicit or explicit rhythmic performance, it is not included in the main analysis. For completeness, we report in **Appendix A** the distribution of mean inter-tap interval ($M = 549$ ms, $SD = 186$) and its coefficient of variation (**Fig. A1**), along with scatterplots showing no relationship with age (**Fig. A2**).

Written informed consent was obtained from all participants' parents, in accordance with the Declaration of Helsinki. Children also gave assent prior to testing. The study was approved by the ethics committees of the University of Montreal (CEREP-22-052-D) and the University of Lille (CER-2021-563-S101).

2.2. Materials and tasks

2.2.1. Implicit rhythmic task

In the implicit rhythmic task, children listened to sequences of tones (standard sounds of identical pitch), each followed by a target sound that was either identical in pitch (non-deviant) or higher in pitch (deviant) (Fig. 1). Children were instructed to respond as quickly as possible only if the target sound was deviant.

2.2.1.1. Stimulus materials. Each sequence consisted of eight standard sounds (600 Hz), followed by a target sound, which was either higher in pitch than the standard sounds (deviant, 2/3 of target sounds) or identical in pitch (non-deviant, 1/3 of target sounds). The pitch deviation of the target sounds was individually adjusted to each child's pitch detection ability (see 2.2.1.2.). All the sounds were pure tones (duration: 150 ms, including 10 ms rise and fall times) and were computer-generated using the *scipy.signal* python library (Virtanen et al., 2020) in Python 3.10.

2.2.1.2. Adaptation of task difficulty. An adaptive procedure was implemented to tailor task difficulty to each child's pitch discrimination ability and learning speed. At the beginning of the experiment, a brief staircase method (1 up, 1 down) was used to estimate each child's pitch discrimination threshold and define the initial pitch difference for deviant tones, setting the starting difficulty level. Throughout the experiment, task difficulty was adjusted after each block based on the child's performance: if accuracy exceeded 85%, the pitch difference was decreased to increase difficulty; if accuracy fell below 70%, the pitch difference was increased to make the task easier; and if accuracy remained between 70% and 84%, the pitch difference was left unchanged. These threshold values were determined in a pilot phase to ensure smooth progression of the task. This adaptive design aimed to maintain an optimal challenge, ensuring sustained engagement of the children throughout the task.

2.2.1.3. Task description and procedure. We manipulated the temporal regularity of the standard sound sequences. In regular trials (50%), standard sounds occurred at a fixed inter-onset interval (IOI) of 600 ms (i.e., isochronously). In irregular trials (50%), IOIs varied randomly between 300 and 900 ms (flat distribution). In both cases, the target sound followed the last standard sound after 600 ms. The task consisted of six blocks, each containing 20 deviant target trials and 10 non-deviant target trials. Each block contained 15 regular and 15 irregular trials presented in a randomized order.

To enhance the child's engagement and motivation, the task was gamified (Fig. 2). The game featured *Marius*, a lost astronaut navigating his way back to Earth using sound cues. Higher-pitched sounds indicated that Marius was moving away from Earth, prompting children to redirect him by pressing a button. Each level represented the discovery of a new planet. During a trial, children viewed a black screen and were instructed to fixate on a central red rocket while listening to the sequences. They were asked to press a button only if the final sound in a sequence was higher in pitch than the preceding tones. As a warning signal, the red rocket turned green on the 8th sound, indicating that the target sound was about to be presented. Instructions emphasized

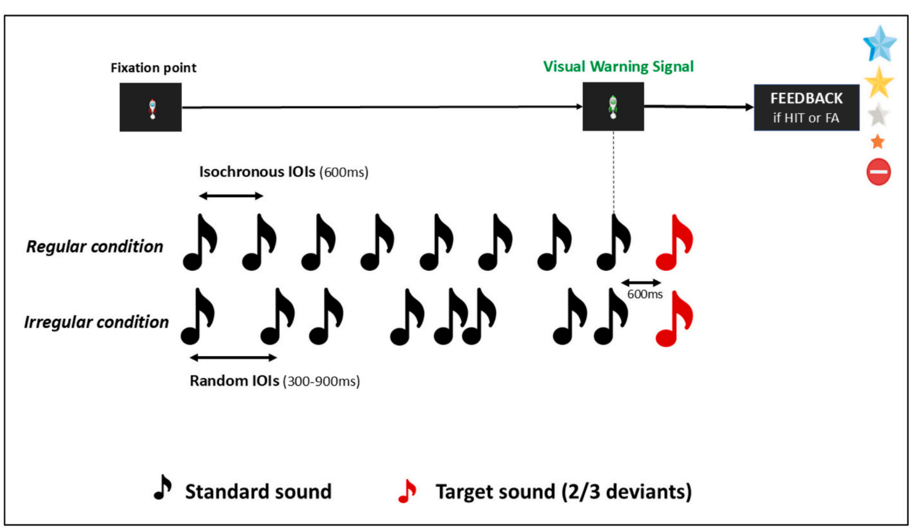

Fig. 1. Schematic representation of the implicit rhythmic task. In this task, children were instructed to press a button when they detected a deviant pitch following an 8-tone sequence, which could be either temporally regular or irregular. During each trial, children viewed a black screen and were asked to fixate on a red rocket at the center, which turned green on the last standard tone before the target appeared. Star-shaped feedback was provided after correct responses, with faster reaction times earning higher-level stars (from bronze to diamond). A “no-go” sign appeared following false alarms. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

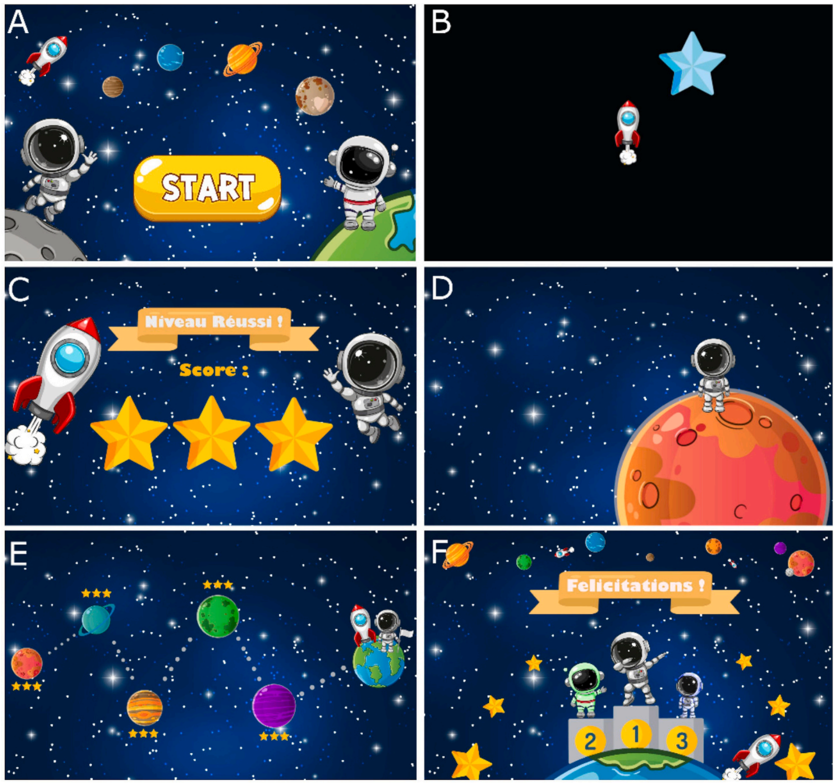

Fig. 2. Screenshots of the gamified implicit rhythmic task: **(A)** introduction screen; **(B)** screen during a trial, with a fixation point (the rocket) and positive feedback (the star); **(C)** feedback on overall performance during a block; **(D)** transition screen between blocks showing the discovery of a new planet; **(E)** transition screen between blocks showing end of the sixth block; **(F)** end of the task. In this game, children helped a small astronaut return to Earth by detecting deviant sounds. Each block corresponded to a game level, at the end of which a new planet was discovered. To sustain motivation, performance at each level was rewarded with one, two, or three stars based on overall accuracy.

responding exclusively to deviant target sounds while ignoring non-deviant targets and standard sounds. As the task focused on pitch discrimination, it did not require explicit attention to the temporal regularity of the sequences, and the child was not informed that rhythm was manipulated.

The main dependent measure was reaction time (RT) on deviant targets. Additionally, response types were recorded: Hits (button presses on deviant targets), False Alarms (FA; button presses on non-deviant targets), Correct Rejections (CR; correctly withholding a response to a non-deviant target), and Misses (failure to respond to a deviant target). To maintain engagement, visual feedback encouraged rapid and accurate responses: quick reactions were rewarded with a diamond star (RT $<$ 450 ms), gold star (RT between 450 and 549 ms), silver star (RT between 550 and 649 ms), or bronze star (slower RTs). False alarms triggered a no-go sign to discourage random button presses. At the end of each block, the child received feedback on their overall accuracy, represented by 1, 2, or 3 stars. Regardless of performance, all children successfully "reached Earth" at the end of the game to ensure a positive and engaging experience.

The implicit rhythmic task was developed using PsychoPy (Peirce et al., 2019). Game images were sourced from Shutterstock.com (freely available for non-commercial use) and edited using GIMP software (https://www.gimp.org/). The experiment took place in a quiet room, with the child being seated in front of a computer next to the experimenter. The child responded using their dominant hand via a response button (Buddy Button). The entire task, including instructions, training, and short breaks between blocks, lasted approximately 30 min.

2.2.2. *Explicit rhythmic tasks*

Explicit rhythmic tasks were selected from the mobile version of the Battery for the Assessment of Auditory and Sensorimotor Timing Abilities (BAASTA; Dalla Bella et al., 2017; Dalla Bella, Foster, et al., 2024) and administered using a tablet with headphones. BAASTA includes various tests designed to evaluate both perceptual and sensorimotor explicit rhythmic abilities. All sensorimotor tests were performed using the index finger of the participants' dominant hand. Instructions explicitly emphasized temporal regularity, and all auditory stimuli were computer-generated with a piano timbre. This battery was previously used in studies involving both typically and atypically developing children within this age range (Bégel, Bachrach, et al., 2022; Bégel, Dalla Bella, et al., 2022; Puyjarinet et al., 2017).

Beat perception was assessed using the *Beat Alignment Test (BAT)*. In this task, children judged whether a metronome was correctly aligned with the beat of a musical excerpt or not. Musical excerpts were presented at a tempo of 600 ms per beat. After seven beats, a metronome was superimposed on the music, either aligned or misaligned to the beat. The test contained two-thirds of misaligned trials and one-third of aligned trials, including both phase errors (the tones preceded or followed the beats while keeping the same tempo of the musical stimulus) and period errors (the tones were presented at a tempo which was slower or faster than the tempo of the musical stimulus).

Beat synchronization was evaluated through four *paced tapping tasks*, in which children tapped along with either isochronous sequences (two conditions: 450 ms and 600 ms IOIs) or musical excerpts (two pieces: *Badinerie* by Bach (music 1) and the *William Tell Overture* by Rossini (music 2), both featuring an inter-beat interval of 600 ms). Each task consisted of two trials.

2.2.3. *Executive functions tests*

The tests were selected from the Wechsler Intelligence Scale for Children - 5th edition (WISC-V; Wechsler, 2014), the Test of Everyday Attention for Children (TEA-ch; Manly et al., 2001), and the FÉE battery for executive function in children (Roy et al., 2020).

Auditory controlled attention was assessed using the *Coups de Fusil* task from the French version of the TEA-Ch battery. Children listened to ten series of sounds presented in a temporally irregular sequence. Their task was to silently count the number of sounds in each series (ranging from 9 to 15) without using their fingers. This multicomponent task taps into both sustained attention and executive functioning, notably auditory working memory and cognitive control.

Inhibitory control was assessed using the *Tapping Enfant* task from the FÉE. In this test, children were instructed to tap on the table with their index finger, either once or twice, depending on the experimenter's actions. The task consisted of three parts with increasing difficulty. In the first part, children simply had to reproduce the experimenter's gestures: tapping once when the experimenter tapped once and tapping twice when the experimenter tapped twice. The second part introduced a go/no-go paradigm, where children still had to tap once when the experimenter tapped once but were required to refrain from tapping if the experimenter tapped twice. In the third and most complex part, the rules were reversed: children had to tap twice when the experimenter tapped once and tap once when the experimenter tapped twice. Additionally, if the experimenter used two fingers instead of just the index finger - regardless of whether they tapped once or twice - children had to withhold their response.

Working memory was assessed using the *Mémoire des Chiffres* test from the WISC-V. In this digit-span task, children were asked to repeat sequences of numbers presented aloud by the examiner. The task consisted of three conditions: in the forward digit span, children repeated the numbers in the same order as presented; in the backward digit span, they repeated them in reverse order; and in the ascending digit span, they reordered the numbers in ascending order.

Cognitive flexibility was evaluated with the task *Les petits Hommes Verts* from the French version TEA-Ch. In this task, children counted small green monsters appearing along burrows. Arrows placed between the creatures indicated the counting direction: children started by counting forward one by one, but whenever they encountered an arrow pointing downward, they had to switch directions and count backward until reaching the final creature.

2.2.4. *Demographic questionnaires*

Parents completed a demographic questionnaire including basic information about the child and family (e.g., school grade, language background and formal musical experience). Parents were asked whether their child had received any formal musical training outside of school and, if so, for how many years. The number of years of formal musical training was used in the following analyses to quantify children's formal musical training.

2.3. *Procedure*

Children participated in two sessions, conducted either at the BRAMS laboratory in Montreal, Canada or in a quiet room at their school in Lille, France. All tasks were administered in French, by a French-speaking experimenter. One session focused on rhythmic abilities (implicit and explicit, ~1h15), while the other session assessed cognitive abilities (~45 min). During the rhythm session, children first completed a spontaneous motor tempo assessment, followed by the implicit rhythmic task and the perceptual and paced tapping tasks from BAASTA. In the cognitive session, they began with subtests from the WISC-V battery evaluating reasoning and processing speed, used as control measures of intellectual and sensory-motor efficiency, before completing tests from the WISC-V, TEA-CH and FÉE batteries assessing auditory controlled attention, inhibitory control, working memory, and cognitive flexibility. To minimize fatigue, sessions were scheduled on two different half-days, either on separate days or with one in the morning and the other in the afternoon. The order of the sessions was randomized, with 40% of the children starting with the cognitive session and 60% beginning with the rhythm session. No significant effect of session order was found for any of the variables of interest (all $p > .05$, lowest $p = .55$).

2.4. *Data pre-processing and analysis*

2.4.1. *Implicit rhythmic task data pre-processing*

The following steps outline the data pre-processing procedure (Lönneker et al., 2024). A quality check was performed to ensure data reliability. For each participant, trials were classified as valid or invalid. A trial was considered valid if no button press occurred before target onset, in line with the instruction to respond only to the target sound. Although a small number of invalid trials can reflect impulsive or anticipatory responses, a high proportion may indicate poor task compliance. The percentage of valid trials was computed for each participant (mean = 95.2%), with no significant difference between conditions ($p = .401$). Participants with fewer than 60% valid trials were excluded, which applied to only one participant. For the remaining participants, invalid trials were removed from further analyses. We then computed the proportion of correct responses. Participants performing near chance level (accuracy <60%) were excluded from the analysis ($n = 3$).

In a second step, trials with outlier RTs were removed. Outliers were defined as RTs falling more than ±3 SD from the participant's mean RT (Berger & Kiefer, 2021). Outlier identification was conducted independently of conditions and included both correct responses and false alarms (André, 2022). Overall, 1.69% of trials were classified as outliers. Condition differences were examined post hoc (see Section 3.4). While no significant difference was found for early outliers (i.e., fast responses; $p = .308$), a slightly higher proportion of late outliers was observed in the irregular condition than in the regular condition (regular: 1.25%, irregular: 1.96%, $p = .002$).

Finally, for each participant and each condition (regular and irregular), we computed the mean correct RT, keeping only the RTs from Hit trials (on average, 52.9/60 Hits and 7.3/30 FA per condition). As a secondary measure, accuracy was assessed using a sensitivity index (d'), calculated as the difference between the z-transformed Hits and FA rates. In accordance with Macmillan and Kaplan's correction (Macmillan & Kaplan, 1985), Hit and FA rates of 0 or 1 were adjusted to l/(2 N) and 1–l/(2 N), respectively, where N corresponds to the number of signal (for Hits) or noise (for FA) trials.

Implicit rhythmic ability was quantified as the difference in mean reaction time (ΔRT) between the two conditions, with positive values indicating better performance (i.e., smaller RT) in the regular condition than the irregular one ($\Delta RT = RT_{irregular} - RT_{regular}$). It is noteworthy that this difference did not depend on baseline reaction times, as ΔRT was not correlated with reaction time collapsed across conditions ($r = -0.006$, $p = .950$), nor with reaction times in the irregular condition ($r = 0.14$, $p = .159$). As a secondary measure, we computed the mean difference in accuracy ($\Delta d'$), where positive values also indicated better performance in the regular condition ($\Delta d' = d'_{regular} - d'_{irregular}$).

2.4.2. *Explicit rhythmic tasks: calculation of the Beat Tracking Index*

To obtain a composite score expressing rhythm perception and synchronization abilities, we computed the Beat Tracking Index, which combined beat perception and beat synchronization scores (Dalla Bella, Foster, et al., 2024; Puyjarinet et al., 2017).

The beat perception score was derived from the sensitivity index (d') in the BAT, calculated based on Hits (correct detections of misaligned metronomes) and FA rates (incorrect detections of misalignment in aligned metronomes). Individual d' values were converted to z-scores based on the full sample distribution.

The beat synchronization score was based on synchronization consistency across the four paced tapping tasks. Consistency reflects the temporal regularity of tapping intervals relative to the beat within a trial - that is, how stably participants maintained a periodic response pattern. It was computed using circular statistics (Dalla Bella et al., 2017; Dalla

Bella, Foster, et al., 2024) yielding values from 0 (no consistency) to 1 (perfect consistency). To correct for the typical skewness of synchronization data, consistency scores were logit-transformed (Dalla Bella, Foster, et al., 2024; Sowiński & Dalla Bella, 2013) producing values theoretically ranging from -∞ (logit(0)) to +∞ (logit(1)). These transformed scores were then converted into *z*-scores for each task and averaged to obtain a composite beat synchronization score.

The Beat Tracking Index was computed as the mean of each participant's beat perception and beat synchronization *z*-scores. For one participant, synchronization could not be computed due to insufficient tapping signal in the music trials; as such, Beat Tracking Index analyses include 97 participants.

We also computed synchronization accuracy using the angle of the resultant vector *R*, computed from the circular distribution of tap times relative to the pacing event (defined as 0). Accuracy corresponds to the angular deviation from 0, such that taps occurring closer in time to the pacing event are associated with smaller angular values and therefore greater accuracy. The sign of the angle indicates whether taps occurred before (negative values) or after (positive values) the pacing event and is not interpreted as reflecting better or worse performance. Accuracy was computed only when synchronization performance exceeded chance level, as determined by the Rayleigh test for circular uniformity as done in previous studies (Dalla Bella et al., 2017; Dalla Bella, Foster, et al., 2024; Sowiński & Dalla Bella, 2013). As tapping accuracy was not a primary outcome of the present study, it was not included in the main analyses and is reported in the Supplementary Material for completeness.

2.4.3. Executive function tests

The auditory controlled attention score was derived from the raw score of the *Coups de Fusil* test, representing the number of correctly counted sound sequences. For the inhibition task, a raw performance score was computed by summing the number of correct responses across the three parts of the *Tapping Enfant* test. The auditory working memory score corresponded to the total raw score obtained on the *Digit* test, reflecting the number of correctly recalled sequences across all three conditions (forward, backward, and ascending). Finally, cognitive flexibility was measured using the raw accuracy score from the *Les petits Hommes Verts* test, which corresponded to the number of sequences correctly completed despite changes in counting direction. Executive function scores were then converted to *z*-scores for each task based on the distribution of the full sample. The correlations between executive function *z*-scores and age are provided in Appendix A, **Fig. A3**.

2.5. Statistical analyses

Data processing and statistical analyses were conducted using R version 4.4.0 (R Core Team, 2024). Implicit rhythmic abilities were assessed through pairwise comparisons of mean reaction times between the temporally regular and irregular conditions. Additional comparisons were performed on mean accuracy, measured by the sensitivity index (d'). Prior to analysis, variable distributions were tested for normality using the *jmv* package (Selker et al., 2023); a variable was considered normally distributed if both skewness and excess kurtosis fell within the [−1,1] range. For normally distributed variables, two-sided paired-sample *t*-tests were used; otherwise, two-sided Wilcoxon signed-rank tests were applied. Effect sizes were computed using the R *effectsize* package (Ben-Shachar et al., 2020): Cohen's *d* for t-tests, rank-biserial correlation (*r*) for Wilcoxon tests, and partial omega squared (ω^2_p) for F-tests in regressions analyses. Effect sizes were interpreted following established guidelines: Funder and Ozer (2019) for rank biserial *r*, Sawilowsky (2009) for Cohen's d, and Field (2013) for ω^2_p.

To further explore reaction time differences in the implicit rhythmic task, we conducted mixed-effects model analysese. These analyses were implemented using the *lmerTest* (Kuznetsova et al., 2017) and *lme4* (Bates et al., 2015) R packages. The models included log10-transformed correct RTs per trial as the dependent variable to better normalize residuals. Fixed effects comprised condition (with the irregular condition as the reference level) and either age or the accuracy difference between conditions ($\Delta d'$). To account for the hierarchical structure of the data, we included random intercepts for participants and random slopes for the condition effect. Omnibus tests for main effects and interactions were performed using type III sum of squares, with *F* and *p*-values computed via the Kenward-Roger approximation for degrees of freedom (Halekoh & Højsgaard, 2014; Luke, 2017).

Finally, relationships between rhythmic abilities (both implicit and explicit) and variables such as age, formal musical experience, and executive functions were explored using simple and multiple linear regressions. Models were fitted using the *lm* function in R, with ΔRT (from the implicit task) serving as the primary measure of implicit rhythmic abilities and $\Delta d'$ included as additional information on accuracy differences. The Beat Tracking Index was used as a measure of explicit rhythmic abilities. In models including measures of executive functioning, age was included as a covariate. All predictors were standardized prior to inclusion in the models, except for $\Delta d'$, which was left unstandardized so that a value of 0 represented no difference in accuracy between conditions. Model diagnostics were performed using the *performance* package (Lüdecke et al., 2021), and all models showed good fit. Because large inter-individual variability is commonly reported in both implicit and explicit rhythmic abilities (Capizzi et al., 2024; Criscuolo et al., 2023; Criscuolo et al., 2025; Dalla Bella, Janaqi, et al., 2024; Zagala et al., 2024), the presence of outliers is expected, particularly in children. As an additional robustness check, rank-based regression analyses were therefore conducted using *rfit* package (Kloke, 2024) to ensure that potential extreme scores did not drive the observed differences between implicit and explicit rhythm processing (**Appendix B**).

3. Results

3.1. Children's performance in the implicit rhythmic task

To test whether children implicitly track rhythmic regularities in sound sequences, i.e., even when rhythm is not directly task-relevant, we examined whether they responded faster to auditory targets (detecting a pitch difference) following regular (isochronous) versus irregular (temporally random) tone sequences. Fig. 3A shows RTs for trials with correct responses, per condition. RTs were significantly faster in the regular condition than in the irregular one ($RT_{regular}$: $M = 518.7$ ms, $SD = 78.1$ ms; $RT_{irregular}$: $M = 538.7$ ms, $SD = 89.0$ ms; two-sided Wilcoxon signed rank test: $V = 1083$, $p < .001$). The very large effect size (rank biserial correlation, $r = -0.55$) indicates a consistent influence of temporal regularity on children's RTs.

To further probe this effect, we examined whether regularity also influenced accuracy in detecting pitch changes. Children were slightly less accurate in the regular condition than in the irregular condition, as reflected by a drop in the sensitivity index ($d'_{regular}$: M = 2.43, SD = 1.16; $d'_{irregular}$: $M = 2.61$, $SD = 1.13$; d'; $t_{(97)} = -3.32$, $p = .001$) with a very small effect size ($d = -0.16$). This difference was primarily driven by an increase in the false alarm rate (i.e., responses to non-deviant targets, $V = 2883.5$, $p < .001$, $r = 0.47$), while the Hit rate (i.e., correct responses to pitch changes, $V = 1929$, $p = .658$, $r = 0.47$) did not differ between conditions. This suggests that children were more biased toward target detection in regular sequences ($Hit_{regular}$: $M = 0.930$, $SD = 0.09$; $Hit_{irregular}$: $M = 0.927$, $SD = 0.10$; $FA_{regular}$: $M = 0.23$, $SD = 0.24$; $FA_{irregular}$: $M = 0.19$, $SD = 0.23$).

To determine whether RT benefits were robust after accounting for individual differences in accuracy, we fitted a linear mixed-effects model including condition, accuracy benefits ($\Delta d' = d'_{regular} - d'_{irregular}$), and their interaction as predictors (see **Appendix B for more details**). While the model revealed a positive Condition × $\Delta d'$ interaction ($\beta = 0.0162$, $F_{(1,96.5)} = 5.49$, $p = .02$) with a small effect size ($\omega^2_p = 0.05$), it confirmed

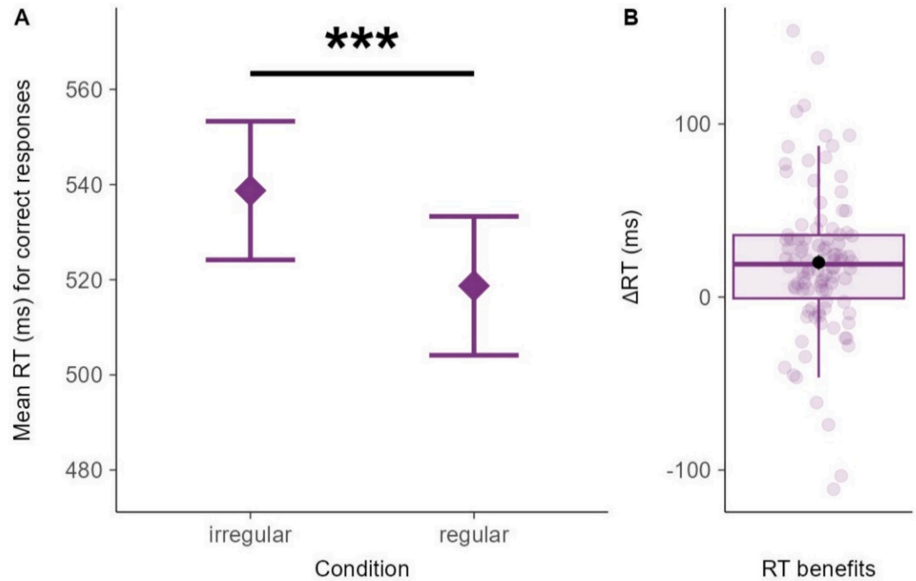

Fig. 3. Reaction times for correct responses in the implicit rhythmic task. (A): Mean RT for correctly detected auditory targets following temporally regular or irregular tone sequences. Central diamonds indicate the mean RT; error bars represent the standard error of the mean (s.e.m.). ***$p < .001$ (two-tailed Wilcoxon signed-rank test). **(B)**: Distribution of RT benefits from temporal regularity ($\Delta RT = RT_{irregular}$ - $RT_{regular}$). Boxes show the interquartile range (IQR; 25th–75th percentiles) with the median as the central line; whiskers extend to 1.5 × IQR. Black dots indicate the mean with error bars representing the s.e.m.; purple dots represent individual observations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

a main effect of condition ($\beta = -0.0125$, $F_{(1,95.0)} = 10.29$, $p = .002$) with a moderate effect size ($\omega_p^2 = 0.09$). The effect of $\Delta d'$ on RT was not significant ($F_{(1,96)} = 0.72$, $p = .40$, $\omega_p^2 = 0.00$). Thus, the main benefit of temporal regularity is apparent in terms of response preparation and speed, while being accompanied by a modest cost in accuracy. Importantly, RT benefits remained significant when taking into account for accuracy in the model, indicating a genuine facilitation of response speed beyond a mere speed–accuracy trade-off.

We then computed mean RT benefits from regularity on correct responses ($\Delta RT = RT_{irregular}$ - $RT_{regular}$) for each participant as the main measure of implicit rhythmic processing for the following analyses. The ΔRT ($M = 20.0$ ms, $SD = 43.1$ ms) ranged from -111 ms (i.e., slowing of RT with regular stimuli) to +154 ms (i.e., speeding of RT with regular stimuli) reflecting wide interindividual variability in implicit influence of rhythm among children (Fig. 3B).

3.2. Children's performance in explicit rhythmic tasks

To assess children's explicit rhythmic abilities, we measured accuracy in beat perception, i.e., the ability to detect beat misalignments in the BAT, as well as accuracy and consistency in a series of audio-motor beat synchronization tasks from the BAASTA. **Appendix A** presents descriptive statistics for raw task scores in **Table A1**, with score distributions in **Fig. A4 and A5**, and inter-task correlations in **Fig. A6**.

In the beat perception task, children were generally proficient at identifying beat misalignments, as reflected by a mean sensitivity index (d') of 1.77 ($SD = 1.19$). Given that $d' = 0$ reflects chance-level performance and values above 2 are typically considered good, this suggests moderately accurate beat perception, albeit with substantial individual variability. For beat synchronization, children were overall able to reliably align their movements to the beat, with a mean consistency score across tasks of 0.79 ($SD = 0.30$) (note: 0 = poor synchronization; to 1 = perfect synchronization). Accuracy scores further revealed a tendency to anticipate the beat, as shown by a negative mean vector angle ($M = -21.9°$, $SD = 39.4$), indicating early taps relative to the beat onset.

As expected, beat perception and synchronization performance were strongly related: standardized BAT performance significantly predicted synchronization consistency scores ($\beta = 0.64$, $p < .001$), with a large effect size ($\omega_p^2 = 0.4$) accounting for 41% of the variance ($R^2 = 0.41$; Fig. 4A).

To capture individual differences in explicit rhythmic ability, we computed the Beat Tracking Index combining standardized performance in both BAT and synchronization tasks (Dalla Bella, Foster, et al., 2024; Puyjarinet et al., 2017). The Beat Tracking Index scores ranged from −1.86 to 1.60 ($M = 0.001$, $SD = 0.88$; Fig. 4B). Note that the Beat Tracking Index is computed from z-scores but it is not itself a z-score; therefore, its mean is not exactly zero and its standard deviation is not exactly one. The Beat Tracking Index was used as the main index of explicit rhythmic abilities.

3.3. Relation between rhythmic abilities, age and formal musical experience

We first examined the effect of age on implicit rhythm processing using a mixed-effects model fitted to trial-level reaction times for correct responses, including condition (regular vs. irregular), age, and their interaction as fixed effects (Fig. 5). The model included a random intercept for participants and a random slope for condition, and RTs were log-transformed to better normalize residuals (*log_{10}(RT) ~ condition × age + (condition | participant)*). Results revealed a main effect of condition ($\beta = -0.015$, $p < .001$, $\omega^2{}_p = 0.14$), as well as a main effect of age ($\beta = -0.029$, $p = .008$, $\omega^2{}_p = 0.07$) on reaction times, but no interaction between condition and age ($\beta < 0.01$, $p = .479$, $\omega^2{}_p < 0.01$), indicating that the effect of temporal regularity remained stable across the age range:

In a second step, to test whether implicit and explicit rhythmic abilities follow distinct developmental trajectories, we examined how ΔRT in the implicit task and the Beat Tracking Index derived from explicit tasks varied with age and formal musical experience (Fig. 6), using multiple linear regression models including both variables as predictors.

ΔRT showed no significant association with either age ($\beta = -0.01$, $p = .902$; $\omega_p^2 < 0.01$) or formal musical experience ($\beta = 0.05$, $p = .603$; $\omega_p^2 < 0.01$), both entered as predictors in the same regression model ($R^2 = 0.003$, $F_{(2,\ 95)} = 0.14$, $p = .868$). We also examined whether these variables predicted accuracy differences between conditions ($\Delta d'$), but we

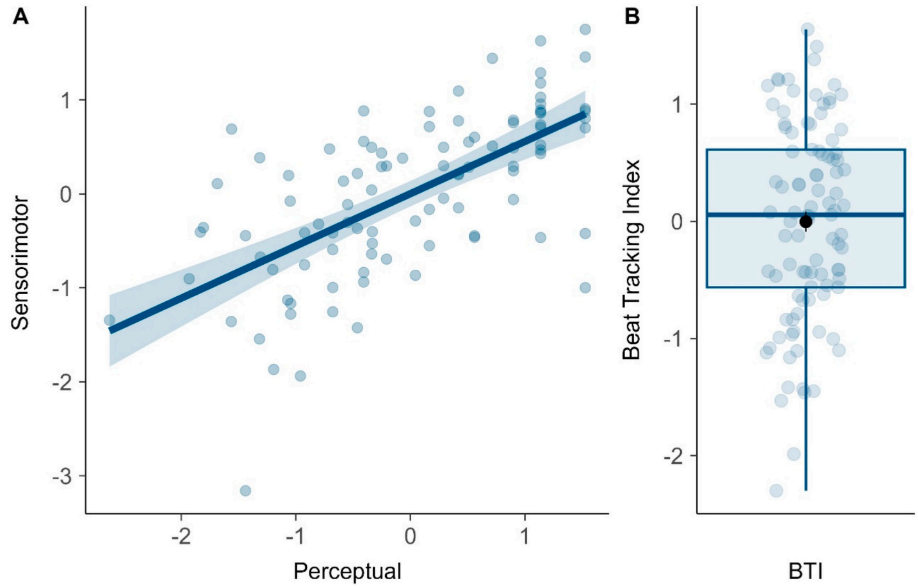

Fig. 4. Explicit rhythmic abilities summarized in the Beat Tracking index. (A): Relationship between perceptual (BAT *z*-score) and sensorimotor (synchronization consistency *z*-score) in explicit rhythmic tasks. The regression line is shown with its shaded areas representing 95% confidence intervals. **(B)**: Distribution of Beat Tracking Index scores, obtained by averaging the perceptual and sensorimotor scores. Boxes show the interquartile range (IQR; 25th–75th percentiles) with the median as the central line; whiskers extend to 1.5 × IQR. Black dots indicate the mean with error bars representing the s.e.m.; blue dots represent individual observations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

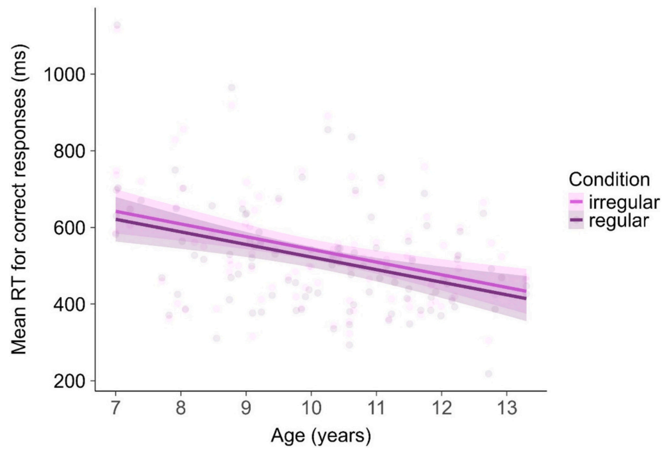

Fig. 5. Mean correct reaction times per condition in the implicit rhythmic task, as a function of age. Regression lines are displayed separately for each condition, with shaded areas representing 95% confidence intervals. Analyses confirmed a main effect of regularity on RTs. While a main effect of age was also observed, no age × condition interaction was found, indicating that the regularity effect remained stable across this age range.

found no effect of age ($\beta = 0.14$, $p = .177$; $\omega_p^2 = 0.01$) or formal musical experience ($\beta = -0.10$, $p = .348$; $\omega_p^2 < 0.01$; $R^2 = 0.027$; $F_{(2, 95)} = 1.32$, $p = .272$). Together, these findings suggest that implicit rhythmic benefits remain stable across this age range and are not modulated by formal musical experience.

In contrast, the Beat Tracking Index increased with both age ($\beta = 0.32$, $p = .001$, $\omega_p^2 = 0.13$) and formal musical experience ($\beta = 0.42$, $p < .001$; $\omega_p^2 = 0.19$), corresponding to medium and large effect sizes, respectively ($R^2 = 0.30$; $F_{(2, 94)} = 19.36$, $p < .001$). This pattern was also observed when examining the perceptual and sensorimotor components of the Beat Tracking Index separately, indicating that the positive associations were not driven by the motor demands of the tasks (see Appendix A, **Fig. A**7).

3.4. Relation between rhythmic abilities and executive functions

We next examined how rhythmic abilities relate to executive functions. First, we computed Pearson correlations between executive function raw scores and either ΔRT or the Beat Tracking Index. Interestingly, RT benefits in the implicit task (ΔRT) showed an overall negative association pattern with executive functions, with significant correlations observed across all executive functions (auditory controlled attention: $r = -0.35$, $p < .001$; inhibitory control: $r = -0.20$, $p = .049$, working memory: $r = -0.25$, $p = .013$; cognitive flexibility: $r = -0.23$, $p = .019$).

In contrast, correlations with explicit rhythmic abilities were positive but less consistent across executive functions. The Beat Tracking Index was positively correlated with inhibitory control ($r = 0.28$, $p = .004$) and working memory ($r = 0.26$, $p = .010$), but not with cognitive flexibility ($r = -0.01$, $p = .922$) or auditory controlled attention ($r = 0.09$, $p = .382$). Correlation plots are displayed in Appendix A (**Fig. A**8).

Because executive function measures were intercorrelated and positively associated with age (Appendix A, **Fig. A3),** we then ran separate multiple regression models for implicit and explicit rhythmic abilities, including the four executive functions components and age as predictors, to identify the strongest contributors to each index.

For implicit rhythmic abilities, the overall model was significant ($R^2 = 0.17$; $F_{(5,\ 92)} = 3.79$, $p = .003$), and auditory controlled attention emerged as the strongest predictor ($\beta = -0.27$, $p = .018$, $\omega^2{}_p = 0.12$). The effects of age ($\beta = 0.15$, $p = .156$, $\omega^2{}_p = 0.01$), inhibitory control ($\beta = -0.07$, $p = .553$, $\omega^2{}_p < 0.01$), working memory ($\beta = -0.15$, $p = .196$, $\omega^2{}_p < 0.01$), and cognitive flexibility ($\beta = -0.12$, $p = .254$, $\omega^2{}_p = 0.01$) were not significant (Fig. 7).

For explicit rhythmic abilities, the regression model was also significant ($R^2 = 0.19$; $F_{(5,\ 91)} = 4.25$, $p = .002$). Inhibitory control emerged as the strongest predictor ($\beta = 0.26$, $p = .024$, $\omega^2{}_p = 0.07$), whereas the effects of age ($\beta = 0.21$, $p = .059$, $\omega^2{}_p = 0.03$), auditory controlled attention $\beta = -0.08$, $p = .459$, $\omega^2{}_p < 0.01$), working memory ($\beta = 0.20$, $p = .099$, $\omega^2{}_p = 0.07$), and cognitive flexibility ($\beta = -0.20$, $p = .061$, $\omega^2{}_p < 0.01$) did not reach significance **(**Fig. 7).

To determine whether the negative association between executive functioning and RT benefits could be explained by a speed–accuracy

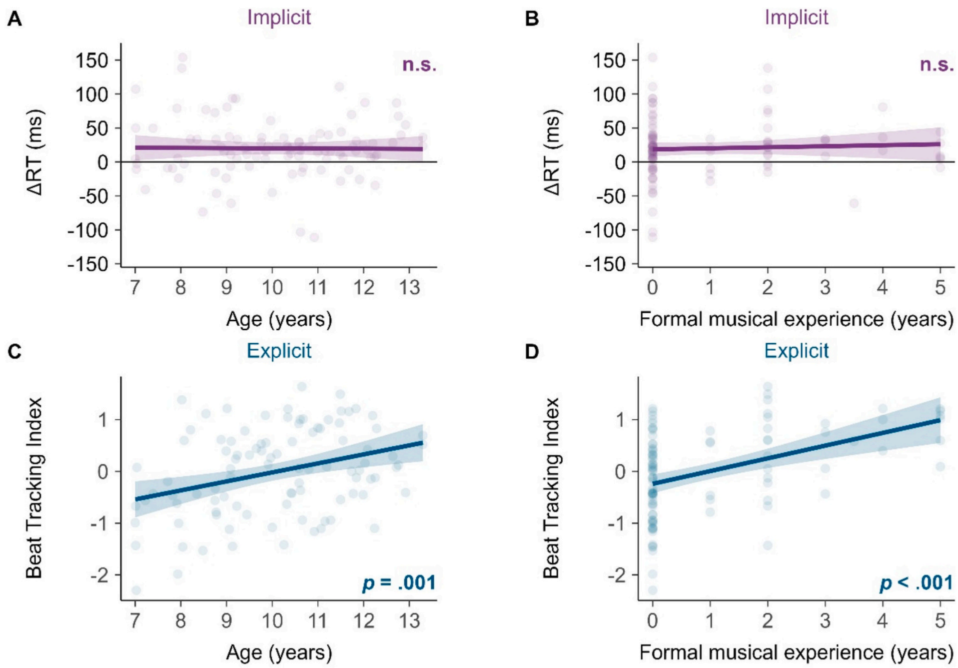

Fig. 6. Indices of implicit and explicit rhythmic processing and their relationship with age and formal musical experience. Panels **(A)** and **(B):** RT benefits in the implicit task ($\Delta RT = RT_{irregular} - RT_{regular}$) as a function of participants' age **(A)** and formal musical experience **(B)**. Panels **(C)** and **(D)**: Explicit rhythmic abilities (Beat Tracking Index) as a function of age **(C)** and formal musical experience **(D)**. Regression lines are shown with shaded areas representing 95% confidence intervals. *p*-values are derived from multiple linear regressions including both age and formal musical experience as predictors. 'n.s.' indicates non-significant relationships ($p > .05$).

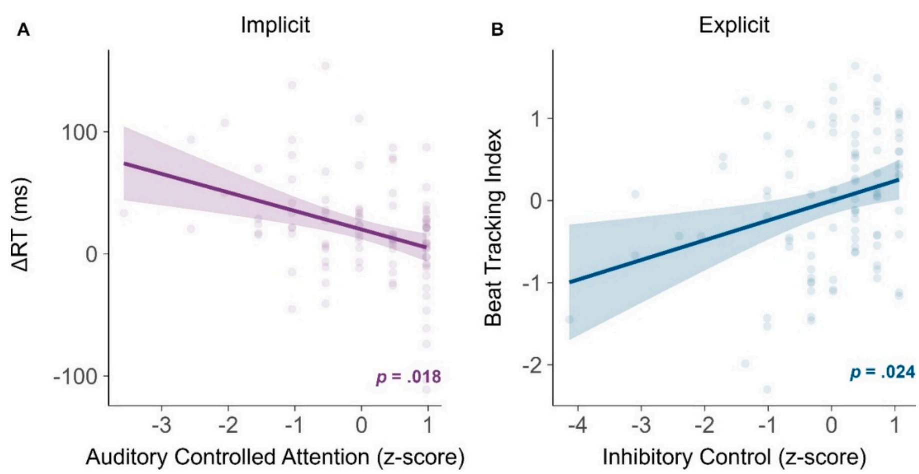

Fig. 7. Indices of implicit and explicit rhythmic processing and their relationship with executive functions. (A) RT benefits in the implicit task ($\Delta RT = RT_{irregular} - RT_{regular}$) plotted as a function of auditory controlled attention scores, showing a significant negative association. (B) Explicit rhythmic abilities (Beat Tracking Index) plotted as a function of inhibitory control scores. Regression lines are displayed with shaded areas representing 95% confidence intervals. *p*-values were derived from multiple linear regressions including auditory controlled attention, inhibitory control, working memory, cognitive flexibility, and age as predictors.

trade-off, we conducted a multiple regression analysis predicting ΔRT from accuracy differences ($\Delta d'$) in the implicit task, the four executive-function measures, and age. While accuracy differences were not a significant predictor of RT benefits, auditory controlled attention remained the only significant predictor of ΔRT (see Appendix C). These results indicate that the negative association between executive functioning and RT benefits cannot be fully explained by a speed–accuracy trade-off and further support the role of auditory controlled attention in individual differences in implicit rhythmic benefits. To further investigate the possible role of attention in the implicit task, we analyzed the proportion of late RT outliers across conditions. This analysis revealed a slightly higher proportion of late responses in the irregular condition than in the regular (regular: $M = 1.25\%$, $SD = 1.54$; irregular: $M = 1.96\%$, $SD = 1.54$; $V = 2312.5$, $p = .002$).

3.5. Relation between implicit and explicit rhythmic abilities

To first assess the independence between implicit and explicit rhythmic abilities, we tested whether RT benefits from regularity in the implicit task (ΔRT) were related to explicit rhythmic abilities. A simple regression analysis showed that ΔRT was not significantly related to the Beat Tracking Index ($\beta = 0.14$, $p = .185$, $\omega_p^2 = 0.01$; $R^2 = 0.02$; see scatterplots in Appendix A, **Fig. A**9), suggesting a relative independence between implicit and explicit rhythmic abilities.

We then conducted exploratory analyses to examine whether the relationship between implicit and explicit rhythmic abilities varied depending on executive functioning. Because the primary goal of this section was to better understand interindividual variability in implicit rhythmic processing, we focused specifically on predictors of ΔRT. Separate regression models were run for each executive-function measure (auditory controlled attention, inhibitory control, working memory, and cognitive flexibility). In each model, ΔRT was predicted from Beat Tracking Index scores, the executive-function measure, their interaction, and age.

Beat Tracking Index scores significantly predicted ΔRT in models controlling for inhibitory control and working memory. The effect was marginal when controlling for auditory controlled attention (Table 1). In addition, the relationship between Beat Tracking Index scores and ΔRT significantly varied as a function of cognitive flexibility, as revealed by a positive interaction (Table 1). These results suggest that links between implicit and explicit rhythmic abilities emerge when executive functioning is taken into account. The positive interaction further suggests that these links may become stronger as cognitive flexibility increases.

4. Discussion

Understanding how rhythmic abilities develop and shape sensitivity to environmental regularities requires disentangling their implicit and explicit components. In this study, we directly compared implicit and explicit rhythmic processing in 98 children aged 7 to 13, a critical window for cognitive maturation and learning (Brocki & Bohlin, 2004; Diamond, 2013). We found that explicit, deliberate rhythm processing improves markedly with age and formal musical experience, whereas implicit rhythm sensitivity remains remarkably stable across development. Although implicit and explicit rhythmic abilities were not directly associated, exploratory analyses suggested that links between the two processes may emerge when accounting for executive functioning. Together, these findings provide new insights into the boundaries and potential interactions between implicit and explicit cognition during development.

This study examined the development of both implicit and explicit rhythm processing, shedding new light on how rhythmic abilities emerge and interact during childhood. Previous developmental studies have primarily focused on explicit, deliberate rhythm processing, which relies on cognitive control to direct attention toward rhythm, maintain an internal beat, and align actions accordingly. However, rhythm often influences behavior in more subtle ways (Nobre & van Ede, 2018). In everyday contexts, rhythm per se is rarely the focus of attention, yet it can implicitly shape perception, prediction, and response to events (Haegens & Zion Golumbic, 2018; Saberi & Hickok, 2022; Schwartze & Kotz, 2013). Unlike explicit tasks, our novel implicit task did not require participants to attend to rhythm. Instead, children played a gamified task in which they had to detect pitch changes to help a small astronaut navigate through space. Crucially, children were faster to detect pitch targets when these followed temporally regular sequences, revealing implicit sensitivity to rhythm, even when rhythm was not directly relevant to the task.

A pivotal finding of this study is the clear dissociation in developmental trajectories. Explicit rhythmic abilities improved with age and formal musical experience, consistent with previous findings (Drake et al., 2000; McAuley et al., 2006; Nave-Blodgett et al., 2021; Thompson et al., 2015), whereas implicit rhythm sensitivity remained remarkably stable between ages 7 and 13. This lack of age or training effects was observed in a relatively large sample size for this developmental window. It suggests that the ability to process environmental rhythmic regularities is already well established by early childhood, much earlier than is typically reported in developmental studies of rhythm. Thus, the prolonged developmental trajectory of rhythmic abilities reported across childhood and adolescence may largely reflect the reliance of most tasks on explicit rhythm processing. Explicit tasks, similar to those commonly used in adults, require sufficient cognitive control and conscious access to temporal regularities in order to voluntarily attend to them, judge them, or produce movements synchronized with them. In contrast, implicit rhythm processing does not require voluntary engagement or explicit awareness of temporal regularities and can capture attention in a more automatic manner. In this sense, this more basic form of temporal processing may be closer to the behavioral or physiological measures typically used in early infancy, which often rely on passive listening paradigms without an explicit temporal goal. Consistent with this view, EEG work in preterm infants suggests that neural markers of rhythmic entrainment emerge during gestation (Edalati et al., 2023) and are already comparable to those observed in adults at term (Saadatmehr et al., 2025). Implicit rhythmic abilities may thus be functional from birth, potentially supporting early learning processes such as language acquisition.

Our results contrast with prior work reporting age-related increases in visual implicit rhythmic effects (Debrabant et al., 2012). A likely explanation lies in the used modality: humans show greater sensitivity to rhythmic regularity in the auditory modality (Attout et al., 2024), and auditory rhythms engage stronger auditory-motor coupling than visual rhythms (Comstock & Balasubramaniam, 2018; Grahn, 2012; Repp & Penel, 2004). Notably, auditory beat perception is already observable in premature newborns (Edalati et al., 2023; Saadatmehr et al., 2025). Infants are then exposed to the rhythmic structure of lullabies, nursery rhymes, and speech prosody (Cirelli et al., 2016; Trehub, 2003), which may accelerate implicit auditory rhythm processing relative to visual rhythms, contributing to the auditory advantage reported in adults (Attout et al., 2024). Future research directly comparing auditory and visual modalities using matched paradigms will be needed to test this hypothesis. Nevertheless, our findings echo results from other domains such as memory (Graf, 1990) or auditory single-duration processing (Droit-Volet & Coull, 2016), where implicit processes appear more stable across development than explicit ones.

Another intriguing finding is that implicit and explicit rhythmic abilities, despite following distinct developmental trajectories, appeared to be associated when executive functioning was taken into account. Exploratory analyses further suggested that this relationship was modulated by cognitive flexibility. Such findings raise questions about a strict dichotomy between implicit sensitivity to temporal regularities and voluntary, explicit rhythm processing. Instead, they are consistent with a more dynamic framework in which the two systems partly rely on shared mechanisms and may interact depending on individual cognitive profiles. These findings suggest the possibility that, at least during childhood, individuals with higher cognitive flexibility may be more

Table 1
Regression models predicting implicit rhythmic benefits (ΔRT) from explicit rhythmic abilities (Beat Tracking Index) and executive functions.

	Beat Tracking Index		Executive Function		Interaction		R^2
	β	p	β	p	β	p	
Auditory controlled attention	*0.19*	*0.065*	−0.36	< 0.001	0.13	0.199	0.17
Inhibitory control	**0.22**	**0.041**	−0.23	0.047	0.13	0.190	0.10
Working memory	**0.21**	**0.041**	−0.34	0.003	*0.19*	*0.056*	0.14
Cognitive flexibility	0.09	0.403	−0.22	0.030	**0.23**	**0.026**	0.12

Note. Separate regression models were conducted for each executive-function measure. Each model included age as a covariate; age was not a significant predictor in any model. Interaction refers to the Beat Tracking Index × Executive Function interaction term. Bold values highlight significant effects involving Beat Tracking Index scores (main effects or interactions). Italic values highlight marginal effects.

likely to recruit strategies or mechanisms typically associated with explicit rhythm processing, even when rhythmic processing is not explicitly required to perform the task. Dynamic links between implicit and explicit abilities have also been reported in the processing of single durations, with the nature of these associations differing between younger and older adults (Otsuka et al., 2023), although these links have not yet been related to executive functioning. Given the exploratory nature of our findings, future studies should test this possibility directly and clarify the mechanisms linking cognitive flexibility to implicit-explicit rhythm interactions.

Perhaps most intriguingly, executive functions showed distinct patterns of association with implicit and explicit rhythm processing. Analyses revealed that inhibitory control positively predicted explicit rhythmic abilities when age and the other executive-function measures were taken into account. This finding is consistent with previous work showing that inhibition is associated with explicit rhythmic abilities in both children and adults (Jamey et al., 2025; Löser et al., 2024; Puyjarinet et al., 2017), and supports the view that explicit rhythm processing relies on high level, goal-directed mechanisms engaging executive resources. In contrast, implicit reaction-time benefits showed broadly negative correlations across executive-function measures. In particular, auditory controlled attention emerged as the strongest predictor of RT benefits in the implicit task when the four executive-function measures and age were considered simultaneously. These findings suggest that implicit rhythmic processing may not operate entirely independently of higher-level cognitive functions, as is often suggested in adult studies describing it as largely automatic and bottom-up (Cutanda et al., 2015; de la Rosa et al., 2012). Taken together, these results highlight distinct relationships between executive functioning and implicit versus explicit rhythmic abilities, and raise important questions regarding how executive control interacts with the development of implicit rhythm processing.

One possible explanation for the broad pattern of negative associations with executive functioning is that, when rhythm is incidental as in our implicit task, stronger executive functioning may reduce reliance on implicit temporal regularities. According to entrainment models (Lakatos et al., 2019; Saberi & Hickok, 2022), particularly the Dynamic Attending Theory (Jones, 1976; Jones et al., 2002; Large & Jones, 1999), rhythmic temporal regularity facilitates perception by aligning internal neural oscillations with external periodicities (Fujioka et al., 2012; Nozaradan, 2014; Nozaradan et al., 2015). Although typically mainly automatic and bottom-up (Breska & Deouell, 2014a), entrainment can be modulated by top-down control depending on task demand (Farahbod et al., 2020; Haegens & Zion Golumbic, 2018). One possibility is that children with higher executive functions rely less on spontaneous entrainment or actively override it in favor of more controlled strategies. In our task, they may have selectively focused on pitch changes, resisting the influence of the preceding rhythmic sequence, whereas children with lower executive functioning may have been more readily entrained, leading to greater RT benefits in the regular condition. Such top-down modulation may be relevant in everyday environments, where rhythm-based cues are not always informative (Breska & Deouell, 2016).

Alternatively, the broad pattern of negative associations with executive functioning may reflect a relationship with a more central executive process, given that executive functions are highly interrelated and build upon one another during development (Diamond, 2013). Supporting this account, auditory controlled attention emerged as the strongest negative predictor of RT benefits. This pattern may suggest that auditory rhythmic regularity exerts a more general, non-specific effect on attentional engagement, without necessarily relying exclusively on entrainment mechanisms (Pomper et al., 2023; Román-Caballero et al., 2024). Supporting this interpretation, irregular trials elicited more late outlier responses, suggesting possible greater attentional disengagement under temporal uncertainty. These findings are consistent with the idea that unpredictability imposes a higher cognitive cost (Román-Caballero et al., 2024). Such mechanisms could partly explain why larger RT differences were observed in children with weaker executive functioning, a possibility that future studies should investigate further.

Another contributing factor may be a strategic shift toward speed over accuracy in children with weaker executive functions. Overall, children produced more false alarms following regular sequences, suggesting that temporal regularity may promote a greater tendency to respond rapidly at the expense of accuracy. Recent studies have similarly suggested that temporal regularity may increase impulsivity (Cannon et al., 2023; Korolczuk et al., 2018). However, the negative link between executive functions and RT benefits remained significant after controlling for accuracy differences, suggesting that impulsivity alone does not fully explain this relationship. Further studies should nevertheless investigate whether these negative associations are specific to certain types of implicit rhythmic paradigms or task demands. Taken together, these explanations are not mutually exclusive. The variability in RT benefits likely reflects a dynamic interplay between cognitive control, individual strategies, and sensitivity to temporal regularities. Substantial inter-individual variability has also been reported in adults (Capizzi et al., 2024; Criscuolo et al., 2023; Criscuolo et al., 2025; Henry et al., 2025), and our findings extend this perspective developmentally.

Variability is a hallmark of the human sense of rhythm (Criscuolo et al., 2023; Dalla Bella, Janaqi, et al., 2024; Grahn & Schuit, 2012), and understanding why and how individuals do or do not rely on rhythmic regularities in their environment is a compelling avenue for future research (Zagala et al., 2024). A limitation in this field is that implicit and explicit paradigms have historically developed along partly independent methodological traditions, often relying on different behavioral indices. As a result, implicit and explicit tasks, such as those used in the present study, differ not only in their cognitive demands but also in the type of measures they involve. A promising direction for future research would be to compare implicit and explicit rhythmic processing using closely matched paradigms and materials, varying only task instructions (Herbst et al., 2022). Such an approach would help disentangle potentially distinct yet complementary roles of implicit and explicit rhythmic abilities in development and learning, particularly given evidence linking implicit rhythmic processing to learning outcomes (Schultz et al., 2013; Selchenkova et al., 2014).

Other promising directions include the development of paradigms that dissociate general attentional benefits from entrainment-specific effects, as well as the use of neurophysiological methods to probe the temporal dynamics of rhythm-related facilitation across development (Breska & Deouell, 2014b; Criscuolo et al., 2023; Criscuolo et al., 2025). Critically, extending this work to neurodevelopmental conditions such as ADHD or speech and language disorders known to involve explicit rhythm deficits (Bégel, Dalla Bella, et al., 2022; Guinamard et al., 2022; Ladányi et al., 2020; Lense et al., 2021; Puyjarinet et al., 2017) could help determine whether implicit rhythm processing is similarly affected, and how such impairments impact everyday functioning. These questions are not only theoretically important but hold translational promise. Some studies suggest that training explicit rhythmic abilities may lead to transfer effects on executive functioning in children (Bégel, Bachrach, et al., 2022; Frischen et al., 2019; Jamey et al., 2025; Jamey et al., 2026). Whether implicit rhythmic abilities can also be trained remains an open question, but video games embedding rhythmic regularities without explicitly directing attention to time may represent a promising tool (Foerster et al., 2022). Investigating whether such training can yield broader cognitive benefits constitutes an exciting direction for future research.

5. Conclusions

In this study, we show that explicit and implicit rhythmic abilities follow distinct developmental trajectories. Explicit rhythmic skills improve with age and formal musical training, whereas behavioral benefits from implicit rhythm processing remain remarkably stable throughout childhood. Nonetheless, these two forms of rhythm processing may not be entirely independent: their relationship appears to be modulated by executive functions. Notably, implicit and explicit rhythmic abilities showed distinct patterns of association with executive functioning, pointing to partially dissociable underlying cognitive mechanisms. Together, these findings provide a new perspective on rhythm processing in childhood, highlighting potential links between controlled and more automatic forms of rhythmic behavior. They further suggest that cognitive control may shape the implicit tracking of temporal regularities in the environment. These insights have both theoretical and applied implications, particularly for understanding the interplay between rhythm and cognition in typical and atypical development. More broadly, the dissociation between implicit and explicit rhythmic processing may open new avenues for investigating the origins of human musicality.

Studies in human

This study was performed in compliance with relevant laws, regulatory frameworks and guidelines where the research took place.

This study was conducted in accordance with Declaration of Helsinki.

This study was approved by the Comité d'Ethique de la Recherche (CER), University of Lille and Comité d'éthique de la recherche en éducation et en psychologie (CEREP), University of Montreal.

(Approval No. CER-2021-563-S101 and CEREP-22-052-D)

CRediT authorship contribution statement

Antoine Guinamard: Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Nicholas E.V. Foster:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Sylvain Clément:** Writing – review & editing, Software, Methodology. **Valentin Bégel:** Writing – review & editing, Software. **Sonja A. Kotz:** Writing – review & editing, Methodology. **Séverine Samson:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Simone Dalla Bella:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Delphine Dellacherie:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Informed consent and patient details

Written informed consent to take part in the study and to publish the article has been obtained from all participants or their legal representatives. The privacy rights of participants have been observed.

Declaration of competing interest

SDB is on the board of the BeatHealth company dedicated to the design and commercialization of technological tools for assessing rhythmic abilities such as BAASTA tablet and implementing rhythm-based interventions. All other authors declare they have no competing interests.

Acknowledgements

The study was supported by a Discovery Grant from Natural Sciences and Engineering Research Council of Canada (NSERC; RGPIN-2019-05453) and by the Canada Research Chair program (CRC in Music Auditory-Motor Skill Learning and New Technologies) awarded to S.D. B.; by the University of Lille and grants from the Académie Française and ISITE-ULNE awarded to A.G.; by a grant from the Institut National Supérieur du Professorat et de l'Éducation (INSPE) awarded to D.D.; and has benefited from a French government grant managed by the Agence Nationale de la Recherche under the France 2030 program (reference ANR-23-IAHU-0003) awarded to S.S. We are also grateful to the children and their families for their participation, and to Océane Martin, Margaux Dos Santos, Célina Zenag, and Noémie Beauduin for their assistance with recruitment and data collection.

Appendix. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2026.106663.

Data availability

The dataset and R code used to reproduce the analyses reported in this article are available at: https://github.com/agnmrd/Developmental-trajectories-rhythm-sensitivity

References

Alagöz, G., Eising, E., Mekki, Y., Bignardi, G., Fontanillas, P., Nivard, M. G., … Gordon, R. L. (2025). The shared genetic architecture and evolution of human language and musical rhythm. *Nature Human Behaviour, 9*(2), 376–390. https://doi.org/10.1038/s41562-024-02051-y

André, Q. (2022). Outlier exclusion procedures must be blind to the researcher's hypothesis. *Journal of Experimental Psychology. General, 151*(1), 213–223. https://doi.org/10.1037/xge0001069

Attout, L., Capizzi, M., & Charras, P. (2024). Enhancing rhythmic temporal expectations : The dominance of auditory modality under spatial uncertainty. *Attention, Perception & Psychophysics, 86*(5), 1681–1693. https://doi.org/10.3758/s13414-024-02898-3

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software, 67*, 1–48. https://doi.org/10.18637/jss.v067.i01

Bégel, V., Bachrach, A., Dalla Bella, S., Laroche, J., Clément, S., Riquet, A., & Dellacherie, D. (2022). Dance improves motor, cognitive, and social skills in children with developmental cerebellar anomalies. *Cerebellum, 21*(2), 264–279. https://doi.org/10.1007/s12311-021-01291-2

Bégel, V., Benoit, C.-E., Correa, A., Cutanda, D., Kotz, S. A., & Dalla Bella, S. (2017). "Lost in time" but still moving to the beat. *Neuropsychologia, 94*, 129–138. https://doi.org/10.1016/j.neuropsychologia.2016.11.022

Bégel, V., Dalla Bella, S., Devignes, Q., Vandenbergue, M., Lemaître, M.-P., & Dellacherie, D. (2022). Rhythm as an independent determinant of developmental dyslexia. *Developmental Psychology, 58*(2), 339–358. https://doi.org/10.1037/dev0001293

Ben-Shachar, M. S., Lüdecke, D., & Makowski, D. (2020). Effectsize: Estimation of effect size indices and standardized parameters. *The Journal of Open Source Software, 5*(56), 2815. https://doi.org/10.21105/joss.02815

Berger, A., & Kiefer, M. (2021). Comparison of different response time outlier exclusion methods: A simulation study. *Frontiers in Psychology, 12*. https://doi.org/10.3389/fpsyg.2021.675558

Bouwer, F. L., Nityananda, V., Rouse, A. A., & ten Cate, C. (2021). Rhythmic abilities in humans and non-human animals: A review and recommendations from a methodological perspective. *Philosophical Transactions of the Royal Society, B: Biological Sciences, 376*(1835), Article 20200335. https://doi.org/10.1098/rstb.2020.0335

Breska, A., & Deouell, L. Y. (2014a). Automatic Bias of temporal expectations following temporally regular input independently of high-level temporal expectation. *Journal of Cognitive Neuroscience, 26*(7), 1555–1571. https://doi.org/10.1162/jocn_a_00564

Breska, A., & Deouell, L. Y. (2014b). Mechanisms of implicit timing: Cognitive and electrophysiological manifestations of temporal expectations following rhythmic visual input. In *, Vol. 126. Procedia - social and behavioral sciences, international conference on timing and time perception, 31 March – 3 April 2014, Corfu, Greece* (pp. 45–46). https://doi.org/10.1016/j.sbspro.2014.02.312

Breska, A., & Deouell, L. Y. (2016). When synchronizing to rhythms is not a good thing: Modulations of preparatory and post-target neural activity when shifting attention away from on-beat times of a distracting rhythm. *Journal of Neuroscience, 36*(27), 7154–7166. https://doi.org/10.1523/JNEUROSCI.4619-15.2016

Brocki, K. C., & Bohlin, G. (2004). Executive functions in children aged 6 to 13: A dimensional and developmental study. *Developmental Neuropsychology, 26*(2), 571–593. https://doi.org/10.1207/s15326942dn2602_3

Buttelmann, F., & Karbach, J. (2017). Development and plasticity of cognitive flexibility in early and middle childhood. *Frontiers in Psychology, 8*. https://doi.org/10.3389/fpsyg.2017.01040

Cannon, J., Eldracher, E., Cardinaux, A., Irfan, F., Bungert, L., Li, C., O'Brien, A., Treves, I., Diamond, S., & Sinha, P. (2023). Rhythmic and interval-based temporal orienting in autism. *Autism Research, 16*(4), 772–782. https://doi.org/10.1002/aur.2892

Capizzi, M., Attout, L., Mioni, G., & Charras, P. (2024). *Unifying temporal preparation: The temporal preparation task (TEP-task)*. OSF. https://doi.org/10.31234/osf.io/xdp9s

Capizzi, M., Visalli, A., Faralli, A., & Mioni, G. (2022). Explicit and implicit timing in older adults: Dissociable associations with age and cognitive decline. *PLoS One*. https://doi.org/10.1371/journal.pone.0264999
Cirelli, L. K., Spinelli, C., Nozaradan, S., & Trainor, L. J. (2016). Measuring neural entrainment to beat and meter in infants: Effects of music background. *Frontiers in Neuroscience, 10*. https://doi.org/10.3389/fnins.2016.00229
Colley, I. D., Keller, P. E., & Halpern, A. R. (2018). Working memory and auditory imagery predict sensorimotor synchronisation with expressively timed music. *Quarterly Journal of Experimental Psychology, 71*(8), 1781–1796. https://doi.org/10.1080/17470218.2017.1366531
Comstock, D. C., & Balasubramaniam, R. (2018). Neural responses to perturbations in visual and auditory metronomes during sensorimotor synchronization. *Neuropsychologia, 117*, 55–66. https://doi.org/10.1016/j.neuropsychologia.2018.05.013
Coull, J. T., & Droit-Volet, S. (2018). Explicit understanding of duration develops implicitly through action. *Trends in Cognitive Sciences, Special Issue: Time in the Brain, 22*(10), 923–937. https://doi.org/10.1016/j.tics.2018.07.011
Coull, J. T., & Nobre, A. C. (2008). Dissociating explicit timing from temporal expectation with fMRI. *Current Opinion in Neurobiology, Cognitive Neuroscience, 18*(2), 137–144. https://doi.org/10.1016/j.conb.2008.07.011
Criscuolo, A., Schwartze, M., Bonetti, L., & Kotz, S. A. (2025). Aging impacts basic auditory and timing processes. *European Journal of Neuroscience, 61*(5), Article e70031. https://doi.org/10.1111/ejn.70031
Criscuolo, A., Schwartze, M., Henry, M. J., Obermeier, C., & Kotz, S. A. (2023). Individual neurophysiological signatures of spontaneous rhythm processing. *NeuroImage, 273*, Article 120090. https://doi.org/10.1016/j.neuroimage.2023.120090
Cutanda, D., Correa, Á., & Sanabria, D. (2015). Auditory temporal preparation induced by rhythmic cues during concurrent auditory working memory tasks. *Journal of Experimental Psychology. Human Perception and Performance, 41*(3), 790–797. https://doi.org/10.1037/a0039167
Cutanda, D., Sanabria, D., & Correa, Á. (2019). Cognitive entrainment to isochronous rhythms is independent of both sensory modality and top-down attention. *Psicológica Journal, 40*(2), 62–84. https://doi.org/10.2478/psicolj-2019-0005
Dalla Bella, S., Farrugia, N., Benoit, C.-E., Begel, V., Verga, L., Harding, E., & Kotz, S. A. (2017). BAASTA: Battery for the assessment of auditory sensorimotor and timing abilities. *Behavior Research Methods, 49*(3), 1128–1145. https://doi.org/10.3758/s13428-016-0773-6
Dalla Bella, S., Foster, N., Laflamme, H., Zagala, A., Melissa, K., Komeilipoor, N., Blais, M., Rigoulot, S., & Kotz, S. (2024). Mobile version of the battery for the assessment of auditory sensorimotor and timing abilities (BAASTA): Implementation and adult norms. *Behavior Research Methods*. https://doi.org/10.3758/s13428-024-02363-x
Dalla Bella, S., Janaqi, S., Benoit, C.-E., Farrugia, N., Bégel, V., Verga, L., … Kotz, S. A. (2024). Unravelling individual rhythmic abilities using machine learning. *Scientific Reports, 14*(1), Article 1. https://doi.org/10.1038/s41598-024-51257-7
Debrabant, J., Gheysen, F., Vingerhoets, G., & Van Waelvelde, H. (2012). Age-related differences in predictive response timing in children: Evidence from regularly relative to irregularly paced reaction time performance. *Human Movement Science, 31*(4), 801–810. https://doi.org/10.1016/j.humov.2011.09.006
Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*(1), 135–168. https://doi.org/10.1146/annurev-psych-113011-143750
Doelling, K. B., Herbst, S., Arnal, L., & van Wassenhove, V. (2023). Psychological and neuroscientific foundations of rhythms and timing. In C. Wöllner, & J. London (Eds.), *Performing time: Synchrony and temporal flow in music and dance*. Oxford University Press. https://doi.org/10.1093/oso/9780192896254.003.0005.
Drake, C., Jones, M. R., & Baruch, C. (2000). The development of rhythmic attending in auditory sequences: Attunement, referent period, focal attending. *Cognition, 77*(3), 251–288. https://doi.org/10.1016/s0010-0277(00)00106-2
Droit-Volet, S., & Coull, J. T. (2016). Distinct developmental trajectories for explicit and implicit timing. *Journal of Experimental Child Psychology, 150*, 141–154. https://doi.org/10.1016/j.jecp.2016.05.010
Droit-Volet, S., Lorandi, F., & Coull, J. T. (2019). Explicit and implicit timing in aging. *Acta Psychologica, 193*, 180–189. https://doi.org/10.1016/j.actpsy.2019.01.004
Edalati, M., Wallois, F., Safaie, J., Ghostine, G., Kongolo, G., Trainor, L. J., & Moghimi, S. (2023). Rhythm in the premature neonate brain: Very early processing of auditory beat and meter. *Journal of Neuroscience, 43*(15), 2794–2802. https://doi.org/10.1523/JNEUROSCI.1100-22.2023
Farahbod, H., Saberi, K., & Hickok, G. (2020). The rhythm of attention: Perceptual modulation via rhythmic entrainment is lowpass and attention mediated. *Attention, Perception, & Psychophysics, 82*(7), 3558–3570. https://doi.org/10.3758/s13414-020-02095-y
Field, A. (2013). *Discovering statistics using IBM SPSS statistics*. SAGE.
Fiveash, A., Bedoin, N., Gordon, R. L., & Tillmann, B. (2021). Processing rhythm in speech and music: Shared mechanisms and implications for developmental speech and language disorders. *Neuropsychology*. https://doi.org/10.1037/neu0000766 (2021–77811-001).
Fiveash, A., Dalla Bella, S., Bigand, E., Gordon, R. L., & Tillmann, B. (2022). You got rhythm, or more : The multidimensionality of rhythmic abilities. *Attention, Perception & Psychophysics, 84*(4), 1370–1392. https://doi.org/10.3758/s13414-022-02487-2
Foerster, F. R., Chidharom, M., Bonnefond, A., & Giersch, A. (2022). Neurocognitive analyses reveal that video game players exhibit enhanced implicit temporal processing. *Communications Biology, 5*(1), 1082. https://doi.org/10.1038/s42003-022-04033-0
Frischen, U., Degé, F., & Schwarzer, G. (2022). The relation between rhythm processing and cognitive abilities during child development: The role of prediction. *Frontiers in Psychology, 13*. https://doi.org/10.3389/fpsyg.2022.920513
Frischen, U., Schwarzer, G., & Degé, F. (2019). Comparing the effects of rhythm-based music training and pitch-based music training on executive functions in preschoolers. *Frontiers in Integrative Neuroscience, 13*. https://doi.org/10.3389/fnint.2019.00041
Fujioka, T., Trainor, L. J., Large, E. W., & Ross, B. (2012). Internalized timing of isochronous sounds is represented in neuromagnetic β oscillations. *The Journal of Neuroscience, 32*(5), 1791–1802. https://doi.org/10.1523/JNEUROSCI.4107-11.2012
Funder, D. C., & Ozer, D. J. (2019). Evaluating effect size in psychological research: Sense and nonsense. *Advances in Methods and Practices in Psychological Science, 2*(2), 156–168. https://doi.org/10.1177/2515245919847202
Graf, P. (1990). Life-span changes in implicit and explicit memory. *Bulletin of the Psychonomic Society, 28*(4), 353–358. https://doi.org/10.3758/BF03334041
Grahn, J. A. (2012). See what I hear? Beat perception in auditory and visual rhythms. *Experimental Brain Research, 220*(1), 51–61. https://doi.org/10.1007/s00221-012-3114-8
Grahn, J. A., & Schuit, D. (2012). Individual differences in rhythmic ability : Behavioral and neuroimaging investigations. *Psychomusicology, 22*(2), 105–121. https://doi.org/10.1037/a0031188
Guinamard, A., Clément, S., Goemaere, S., Mary, A., Riquet, A., & Dellacherie, D. (2022). Musical abilities in children with developmental cerebellar anomalies. *Frontiers in Systems Neuroscience, 16*. https://doi.org/10.3389/fnsys.2022.886427
Haegens, S., & Zion Golumbic, E. (2018). Rhythmic facilitation of sensory processing: A critical review. *Neuroscience & Biobehavioral Reviews, 86*, 150–165. https://doi.org/10.1016/j.neubiorev.2017.12.002
Halekoh, U., & Højsgaard, S. (2014). A Kenward-Roger approximation and parametric bootstrap methods for tests in linear mixed models – The R package pbkrtest. *Journal of Statistical Software, 59*, 1–32. https://doi.org/10.18637/jss.v059.i09
Hannon, E. E., Nave-Blodgett, J. E., & Nave, K. M. (2018). The developmental origins of the perception and production of musical rhythm. *Child Development Perspectives, 12*(3), 194–198. https://doi.org/10.1111/cdep.12285
Henry, M. J., Obleser, J., Crusey, M., Fuller, E., Lee, Y., Meyer, M., … Peelle, J. (2025). How strong is the rhythm of perception? A registered replication of Hickok et al. (2015). *Royal Society Open Science, 12*. https://doi.org/10.1098/rsos.220497
Herbst, S. K., Obleser, J., & van Wassenhove, V. (2022). Implicit versus explicit timing-separate or shared mechanisms? *Journal of Cognitive Neuroscience, 34*(8), 1447–1466. https://doi.org/10.1162/jocn_a_01866
Hiroyasu, E. M. G., & Yotsumoto, Y. (2020). Older adults preserve accuracy but not precision in explicit and implicit rhythmic timing. *PLoS One*. https://doi.org/10.1371/journal.pone.0240863
de Hoyos, L., Verhoef, E., Okbay, A., Vermeulen, J., Figaroa, C., Lense, M., Fisher, S., Gordon, R., & St. Pourcain, B. (2025). Preschool musicality is associated with school-age communication abilities through genes related to rhythmicity. *npj Science of Learning, 10*, Article 39. https://doi.org/10.1038/s41539-025-00329-y
Jamey, K., Finlay, S., Foster, N. E. V., Dalla Bella, S., & Falk, S. (2026). A Proof-of-Concept Study of Gamified Rhythmic Training in Preadolescents Who Stutter. *Annals of the New York Academy of Sciences, 1557*(1), Article e70188. https://doi.org/10.1111/nyas.70188
Jamey, K., Laflamme, H., Foster, N. E. V., Rigoulot, S., Lippé, S., Kotz, S. A., & Dalla Bella, S. (2025). Can you beat the music? Validation of a gamified rhythmic training in children with ADHD. *Behavior Research Methods, 57*(11), 303. https://doi.org/10.3758/s13428-025-02802-3
Jones, M. R. (1976). Time, our lost dimension: Toward a new theory of perception, attention, and memory. *Psychological Review, 83*(5), 323–355. https://doi.org/10.1037/0033-295X.83.5.323
Jones, M. R., Moynihan, H., MacKenzie, N., & Puente, J. (2002). Temporal aspects of stimulus-driven attending in dynamic arrays. *Psychological Science, 13*(4), 313–319. https://doi.org/10.1111/1467-9280.00458
Karmiloff-Smith, A. (1994). Précis of beyond modularity: A developmental perspective on cognitive science. *Behavioral and Brain Sciences, 17*(4), 693–707. https://doi.org/10.1017/S0140525X00036621
Kim, H.-W., Lee, K. M., & Lee, Y. (2022). Sensorimotor and working memory systems jointly support development of perceptual rhythm processing. *Developmental Science*. https://doi.org/10.1111/desc.13261
Kirschner, S., & Tomasello, M. (2010). Joint music making promotes prosocial behavior in 4-year-old children. *Evolution and Human Behavior, 31*, 354–364. https://doi.org/10.1016/j.evolhumbehav.2010.04.004
Kloke, J. (2024). Rfit: Rank-based estimation for linear models. https://github.com/kloke/Rfit.
Korolczuk, I., Burle, B., & Coull, J. T. (2018). The costs and benefits of temporal predictability: Impaired inhibition of prepotent responses accompanies increased activation of task-relevant responses. *Cognition, 179*, 102–110. https://doi.org/10.1016/j.cognition.2018.06.006
Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest package: Tests in linear mixed effects models. *Journal of Statistical Software, 82*, 1–26. https://doi.org/10.18637/jss.v082.i13
Ladányi, E., Persici, V., Fiveash, A., Tillmann, B., & Gordon, R. L. (2020). Is atypical rhythm a risk factor for developmental speech and language disorders? *WIREs Cognitive Science, 11*(5), Article e1528. https://doi.org/10.1002/wcs.1528
Lakatos, P., Gross, J., & Thut, G. (2019). A new unifying account of the roles of neuronal entrainment. *Current Biology, 29*(18), R890–R905. https://doi.org/10.1016/j.cub.2019.07.075

Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How people track time-varying events. *Psychological Review, 106*(1), 119–159. https://doi.org/10.1037/0033-295X.106.1.119

Lense, M. D., Ladányi, E., Rabinowitch, T.-C., Trainor, L., & Gordon, R. (2021). Rhythm and timing as vulnerabilities in neurodevelopmental disorders. *Philosophical Transactions of the Royal Society, B: Biological Sciences*. https://doi.org/10.1098/rstb.2020.0327

Lönneker, H., Buchanan, E., Martinovici, A., Primbs, M., Elsherif, M., Baker, B., Dudda, L., Filipovic Durdevic, D., Mišić, K., Peetz, H., Röer, J., Schulze, L., Wagner, L., Wolska, J., Kührt, C., & Pronizius, E. (2024). We Don't know what you did last summer. On the importance of transparent reporting of reaction time data pre-processing. *Cortex, 172*, 14–37. https://doi.org/10.1016/j.cortex.2023.11.012

Löser, A. S., Dalla Bella, S., Keller, P. E., Villringer, A., Obrig, H., & Engel, A. (2024). Inhibitory control and working memory predict rhythm production abilities in patients with neurocognitive deficits. *Neuropsychologia, 204*, Article 109009. https://doi.org/10.1016/j.neuropsychologia.2024.109009

Lüdecke, D., Ben-Shachar, M. S., Patil, I., Waggoner, P., & Makowski, D. (2021). Performance: An R package for assessment, comparison and testing of statistical models. *The Journal of Open Source Software, 6*(60), 3139. https://doi.org/10.21105/joss.03139

Luke, S. G. (2017). Evaluating significance in linear mixed-effects models in R. *Behavior Research Methods, 49*(4), 1494–1502. https://doi.org/10.3758/s13428-016-0809-y

Macmillan, N. A., & Kaplan, H. L. (1985). Detection theory analysis of group data: Estimating sensitivity from average hit and false-alarm rates. *Psychological Bulletin, 98*(1), 185–199.

Manly, T., Anderson, V., Nimmo-Smith, I., Turner, A., Watson, P., & Robertson, I. H. (2001). The differential assessment of children's attention: The test of everyday attention for children (TEA-Ch), normative sample and ADHD performance. *Journal of Child Psychology and Psychiatry, and Allied Disciplines, 42*(8), 1065–1081. https://doi.org/10.1111/1469-7610.00806

McAuley, J. D., Jones, M. R., Holub, S., Johnston, H. M., & Miller, N. S. (2006). The time of our lives: Life span development of timing and event tracking. *Journal of Experimental Psychology. General, 135*(3), 348–367. https://doi.org/10.1037/0096-3445.135.3.348

Nave-Blodgett, J. E., Snyder, J. S., & Hannon, E. E. (2021). Hierarchical beat perception develops throughout childhood and adolescence and is enhanced in those with musical training. *Journal of Experimental Psychology. General, 150*(2), 314–339. https://doi.org/10.1037/xge0000903

Niarchou, M., Gustavson, D. E., Sathirapongsasuti, J. F., Anglada-Tort, M., Eising, E., Bell, E., … Gordon, R. L. (2022). Genome-wide association study of musical beat synchronization demonstrates high polygenicity. *Nature Human Behaviour, 6*(9), 1292–1309. https://doi.org/10.1038/s41562-022-01359-x

Nobre, A. C., & van Ede, F. (2018). Anticipated moments: Temporal structure in attention. *Nature Reviews Neuroscience, 19*(1), 34–48. https://doi.org/10.1038/nrn.2017.141

Nozaradan, S. (2014). Exploring how musical rhythm entrains brain activity with electroencephalogram frequency-tagging. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 369*(1658), Article 20130393. https://doi.org/10.1098/rstb.2013.0393

Nozaradan, S., Zerouali, Y., Peretz, I., & Mouraux, A. (2015). Capturing with EEG the neural entrainment and coupling underlying sensorimotor synchronization to the beat. *Cerebral Cortex, 25*(3), 736–747. https://doi.org/10.1093/cercor/bht261

Otsuka, T., Yotsumoto, Y., & Mioni, G. (2023). Explicit Timing Differently Predicts Implicit Timing Performance in Younger and Older Adults. *Timing & Time Perception, 13*(1), 46–64. https://doi.org/10.1163/22134468-bja10101

Palmer, C., Lidji, P., & Peretz, I. (2014). Losing the beat: Deficits in temporal coordination. *Philosophical Transactions of the Royal Society, B: Biological Sciences, 369*(1658), Article 20130405. https://doi.org/10.1098/rstb.2013.0405

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., … Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods, 51*(1), 195–203. https://doi.org/10.3758/s13428-018-01193-y

Phillips-Silver, J., Toiviainen, P., Gosselin, N., Piché, O., Nozaradan, S., Palmer, C., & Peretz, I. (2011). Born to dance but beat deaf: A new form of congenital amusia. *Neuropsychologia, 49*, 961–969. https://doi.org/10.1016/j.neuropsychologia.2011.02.002

Pomper, U., Szaszkó, B., Pfister, S., & Ansorge, U. (2023). Cross-modal attentional effects of rhythmic sensory stimulation. *Attention, Perception, & Psychophysics, 85*(3), 863–878. https://doi.org/10.3758/s13414-022-02611-2

Puyjarinet, F., Bégel, V., Lopez, R., Dellacherie, D., & Dalla Bella, S. (2017). Children and adults with attention-deficit/hyperactivity disorder cannot move to the beat. *Scientific Reports, 7*(1), Article 11550. https://doi.org/10.1038/s41598-017-11295-w

R Core Team. (2024). *R: A language and environment for statistical computing [computer software]*. Vienna, Austria: R Foundation for Statistical Computing. https://www.r-project.org/.

Reber, A. S. (1992). The cognitive unconscious: An evolutionary perspective. *Consciousness and Cognition, 1*(2), 93–133. https://doi.org/10.1016/1053-8100(92)90051-B

Repp, B. H., & Penel, A. (2004). Rhythmic movement is attracted more strongly to auditory than to visual rhythms. *Psychological Research, 68*(4), 252–270. https://doi.org/10.1007/s00426-003-0143-8

de la Rosa, M., Sanabria, D., Capizzi, M., & Correa, Á. (2012). Temporal preparation driven by rhythms is resistant to working memory interference. *Frontiers in Psychology, 3*. https://doi.org/10.3389/fpsyg.2012.00308

Román-Caballero, R., Martín-Arévalo, E., Martín-Sánchez, P., del, C., Lupiáñez, J., & Capizzi, M. (2024). Influence of rhythmic contexts on perception: No behavioral and eye-tracker evidence for rhythmic entrainment. *Consciousness and Cognition, 126*, 103789. https://doi.org/10.1016/j.concog.2024.103789

Roy, A., Fournet, N., Gall, D., & Roulin, J.-L. (2020). Un nouveau dispositif des fonctions exécutives chez l'enfant: La batterie FÉE. *ANAE - Approche Neuropsychologique Des Apprentissages Chez l'Enfant, 167*, 393–402.

Rugg, M. D., Mark, R. E., Walla, P., Schloerscheidt, A. M., Birch, C. S., & Allan, K. (1998). Dissociation of the neural correlates of implicit and explicit memory. *Nature, 392*(6676), 595–598. https://doi.org/10.1038/33396

Saadatmehr, B., Edalati, M., Wallois, F., Ghostine, G., Kongolo, G., Flaten, E., … Moghimi, S. (2025). Auditory Rhythm Encoding during the Last Trimester of Human Gestation : From Tracking the Basic Beat to Tracking Hierarchical Nested Temporal Structures. *The Journal of Neuroscience, 45*(4), Article e0398242024. https://doi.org/10.1523/JNEUROSCI.0398-24.2024

Saberi, K., & Hickok, G. (2022). Forward entrainment: Psychophysics, neural correlates, and function. *Psychonomic Bulletin & Review*. https://doi.org/10.3758/s13423-022-02220-y

Sawilowsky, S. S. (2009). New effect size rules of thumb. *Journal of Modern Applied Statistical Methods, 8*, 597–599. https://doi.org/10.56801/v8.i.452

Schultz, B. G., Stevens, C. J., Keller, P. E., & Tillmann, B. (2013). The implicit learning of metrical and nonmetrical temporal patterns. *Quarterly Journal of Experimental Psychology, 66*(2), 360–380. https://doi.org/10.1080/17470218.2012.712146

Schwartze, M., & Kotz, S. A. (2013). A dual-pathway neural architecture for specific temporal prediction. *Neuroscience & Biobehavioral Reviews, 37*(10), 2587–2596. https://doi.org/10.1016/j.neubiorev.2013.08.005

Selchenkova, T., Jones, M. R., & Tillmann, B. (2014). The influence of temporal regularities on the implicit learning of pitch structures. *Quarterly Journal of Experimental Psychology, 67*(12), 2360–2380. https://doi.org/10.1080/17470218.2014.929155

Selker, R., Love, J., Dropmann, D., Moreno, V., & Agosti, M. (2023). *Jmv: The "jamovi" analyses* (version 2.4.11) [computer software]. https://cran.r-project.org/web/packages/jmv/index.html.

Slater, J. L., Ashley, R., Tierney, A., & Kraus, N. (2018). Got rhythm? Better inhibitory control is linked with more consistent drumming and enhanced neural tracking of the musical beat in adult percussionists and nonpercussionists. *Journal of Cognitive Neuroscience, 30*(1), 14–24. https://doi.org/10.1162/jocn_a_01189

Sowiński, J., & Dalla Bella, S. (2013). Poor synchronization to the beat may result from deficient auditory-motor mapping. *Neuropsychologia, 51*(10), 1952–1963. https://doi.org/10.1016/j.neuropsychologia.2013.06.027

Thompson, E. C., White-Schwoch, T., Tierney, A., & Kraus, N. (2015). Beat synchronization across the lifespan: Intersection of development and musical experience. *PLoS One, 10*(6), Article e0128839. https://doi.org/10.1371/journal.pone.0128839

Tierney, A., Gomez, J. C., Fedele, O., & Kirkham, N. Z. (2021). Reading ability in children relates to rhythm perception across modalities. *Journal of Experimental Child Psychology, 210*, Article 105196. https://doi.org/10.1016/j.jecp.2021.105196

Tierney, A., & Kraus, N. (2013). The ability to tap to a beat relates to cognitive, linguistic, and perceptual skills. *Brain and Language, 124*(3), 225–231. https://doi.org/10.1016/j.bandl.2012.12.014

Trainor, L. J., & Cirelli, L. (2015). Rhythm and interpersonal synchrony in early social development. *Annals of the New York Academy of Sciences, 1337*, 45–52. https://doi.org/10.1111/nyas.12649

Tranchant, P., Vuvan, D. T., & Peretz, I. (2016). Keeping the beat: A Large sample study of bouncing and clapping to music. *PLoS One, 11*(7), Article e0160178. https://doi.org/10.1371/journal.pone.0160178

Trehub, S. E. (2003). The developmental origins of musicality. *Nature Neuroscience, 6*(7), 669–673. https://doi.org/10.1038/nn1084

Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D., … SciPy 1.0 Contributors. (2020). SciPy 1.0: Fundamental algorithms for scientific computing in Python. *Nature Methods, 17*(3), 261–272. https://doi.org/10.1038/s41592-019-0686-2

Voss, J. L., & Paller, K. A. (2008). Brain substrates of implicit and explicit memory: The importance of concurrently acquired neural signals of both memory types. *Neuropsychologia, 46*(13), 3021–3029. https://doi.org/10.1016/j.neuropsychologia.2008.07.010

Wechsler, D. (2014). *WISC-V: Wechsler intelligence scale for children* (5th ed.). MN: Pearson.

Zagala, A., Foster, N. E. V., van Vugt, F. T., Dal Maso, F., & Dalla Bella, S. (2024). The ramp protocol: Uncovering individual differences in walking to an auditory beat using TeensyStep. *Scientific Reports, 14*(1), Article 23779. https://doi.org/10.1038/s41598-024-72508-7