



Can you beat the music? Validation of a gamified rhythmic training in children with ADHD

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Received: 18 March 2024 / Accepted: 8 August 2025
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Abstract

Neurodevelopmental disorders like ADHD can affect rhythm perception and production, impacting performance in attention and sensorimotor tasks. Improving rhythmic abilities through targeted training might compensate for these cognitive functions. We introduce a novel protocol for training rhythmic skills via a tablet-based, serious game called Rhythm Workers (RW). This proof-of-concept study tested the feasibility of using RW in children with ADHD. We administered an at-home longitudinal protocol across Canada. A total of 27 children (7 to 13 years) were randomly assigned to either a finger-tapping rhythmic game (RW) or a control game with comparable auditory-motor demands but without beat synchronization (active control condition). Participants played the game for 300 min over 2 weeks. We collected data (self-reported and logged onto the device) on game compliance and acceptance. Further, we measured rhythmic abilities using the Battery for the Assessment of Auditory Sensorimotor and Timing Abilities (BAASTA). The current findings show that both games were equally played in duration, rated similarly for overall enjoyment, and relied on similar motor activity (finger taps). The children who played RW showed improved general rhythmic abilities compared to the controls; these improvements were also positively correlated with the playing duration. We also present evidence that executive functioning improved in those who played RW, but not in the controls. These findings indicate that both games are well matched. RW demonstrates efficacy in enhancing sensorimotor skills in children with ADHD, which may benefit their executive functioning. A future RCT with extended training and sample size could further validate these skill transfer effects.

Keywords Rhythmic training · Serious games · ADHD · Executive functioning · Children

The use of music as a therapeutic tool has shown considerable potential in addressing neurodevelopmental and neurological conditions, exploiting the brain's sensitivity to musical stimuli. In particular, research indicates that rhythmic

training through musical activities – such as tapping fingers to a melody, walking in sync with a beat, or clapping to rhythmic patterns – can improve sensorimotor synchronization, the skill of aligning movements with external rhythmic cues like a musical beat, as well as enhance cognitive functions. Such benefits have been observed in both typically developing children (Frischen et al., 2019; Zanto

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et al., 2024) and in clinical conditions such as Parkinson's disease (Béget et al., 2018; Dauvergne et al., 2018; Puyjariet et al., 2022). In recent years, digital health innovations – such as interactive games and mobile apps – have made these interventions more engaging and accessible (Agres et al., 2021). Emerging research highlights the potential of gamified, rhythm-based digital training to enhance cognitive functioning in neurotypical populations (Zanto et al., 2024), while non-rhythmic gamified digital interventions have also demonstrated success in improving attention performance in children with ADHD (Kollins et al., 2020). However, no studies to date have examined the efficacy of rhythm-based gamified digital training specifically in children with ADHD. By incorporating rhythm training into digital formats, these therapies offer a modern, scalable approach to improving motor and cognitive skills, especially for those with neurodevelopmental disorders, creating new possibilities for rehabilitation and mental health support.

Music training and sensorimotor functioning

Playing an instrument requires a tight coordination between focusing on sounds and controlling motor actions. This ongoing process incorporates various sensory inputs – such as auditory cues – that are integrated by the brain to accomplish complex sensorimotor tasks. Although visual and tactile inputs play supporting roles, auditory perception is central to this integration, a process termed auditory-motor integration (Alho et al., 2014; Liu et al., 2020). Musical training strengthens brain pathways that link the auditory and motor systems (Dalla Bella, 2016; Dalla Bella, Janaqi et al., 2024b; Herholz & Zatorre, 2012; Hyde et al., 2009; Merrett et al., 2013). Depending on these intricate connections, music education offers a rich, multimodal experience that requires substantial cognitive effort. The process of learning music involves various interdependent mechanisms that can support both auditory-motor skills and cognitive functions like attention and communication during child development. These mechanisms are underpinned by broader sensorimotor networks involving superior temporal regions (Karpati et al., 2017; Li et al., 2018) and executive functioning such as pathways in the corpus callosum connecting superior frontal sensory and motor segments (Habibi et al., 2018) and the right inferior frontal gyrus (Hennessy et al., 2019; Sachs et al., 2017).

Music and executive functioning

An integrated theory of executive functioning by Diamond (2013) offers a comprehensive framework for examining the role of core executive functions, particularly inhibitory control and cognitive flexibility, in musical contexts. According

to this theory, executive functions are interdependent processes that operate synergistically to facilitate complex cognitive and behavioral tasks. The present study focuses on three key subcomponents: interference control, response inhibition, and cognitive flexibility. In musical activities, these processes often function together – for instance, interference control helps suppress competing auditory or motor responses, response inhibition allows for withholding habitual actions, and cognitive flexibility supports shifting between rhythmic or melodic patterns. Together, these capacities enable individuals to adapt effectively to the dynamic demands of performing, practicing, and learning to play a musical instrument.

Inhibition control, in particular, is crucial for musicians, enabling them to suppress automatic responses and maintain concentration during performances. It helps regulate timing to facilitate synchronization with a beat or rhythm, and is particularly vital in ensemble settings to prevent misalignments (Medina & Barraza, 2019; Zuk et al., 2014). Musicians exhibit faster behavioral response times on executive functioning tasks and possess more efficient executive attentional networks compared to non-musicians, with improvements linked to years of musical training and a transfer effect to inhibitory attentional control (Medina & Barraza, 2019). Improved performance monitoring, as evidenced by stronger neural responses to errors (e.g., error-related negativity and N200 amplitude), has been observed in amateur instrumental musicians, particularly those with more training, suggesting better cognitive control and error correction that may enhance overall performance abilities (Jentschke & Koelsch, 2009). Recent research by Jamey et al. (2024) highlights how music training particularly strengthens inhibitory control, and these effects are reflected in functional and structural neural activity (Habibi et al., 2018; Hennessy et al., 2019; Sachs et al., 2017). Training that involves moving to a musical beat, such as clapping or drumming, relies on inhibition control by enhancing the ability to suppress irrelevant responses (response inhibition) and maintain focus on rhythmic cues (interference control), helping to minimize reactions to distractions (Frischen et al., 2019; Slater et al., 2018). This type of training is particularly beneficial in tasks requiring precise timing and attentional control, such as complex musical performances or real-life situations that demand managing responses to distractions or errors (Vazou et al., 2020). Rhythmic training provides a unique lens through which to explore the relationship between music and cognitive functioning. Theories of rhythm perception offer valuable insights into how attention and motor coordination are intertwined with rhythmic processing. This connection sets the stage for understanding rhythmic training and its potential to enhance executive functioning.

Rhythmic training rationale

The rationale underlying the effect of rhythmic training on cognitive functioning is inspired by theories of rhythm perception. Dynamic attending theory (DAT) suggests that attention is modulated in synchrony with periodic events in music, providing a temporal structure that facilitates the regulation of attention (Jones, 2019; Large & Jones, 1999). Recent research links DAT to neural oscillations, demonstrating that brain activity synchronizes with external rhythms like musical beats but also speech patterns (Falk et al., 2017; Morillon et al., 2015; Nozaradan, 2014; Rimele et al., 2018). Building on DAT, active sensing theory (Morillon et al., 2015; Schmid, 2024) emphasizes the brain's predictive role in perceiving rhythms, involving both sensory and motor coordination. This approach suggests a bidirectional interaction: while rhythmic entrainment can influence sensorimotor synchronization by aligning motor actions with external rhythms, the process of synchronization itself might enhance the brain's ability to entrain to future rhythmic cues. In this dynamic interaction, both the perception of rhythm and the execution of motor responses become more efficient over time through reciprocal influence. Rhythmic entrainment, as described in a “cognitive-motor entrainment” model, improves executive functioning by aligning motor and cognitive processes, reducing cognitive load in dual-task scenarios, and enhancing attentional control, as evidenced by EEG data showing increased neural synchronization (Conradi et al., 2016; Schmidt-Kassow et al., 2009, 2013; Schmidt-Kassow & Kaiser, 2023).

By enhancing sensory-motor coordination and attention, rhythmic entrainment helps establish more predictable and structured engagement with the environment (Balasubramaniam et al., 2021; Dalla Bella, 2020; Patel & Iversen, 2014). Rhythmic interventions have gained recognition as effective tools for rehabilitation in neurological and neurodevelopmental conditions, drawing on the brain's natural responsiveness to rhythm. Synchronizing actions to a beat such as finger-tapping to musical sequences and mentally tracking a beat involves brain areas linked to motor control, such as the premotor and supplementary motor areas, basal ganglia, cerebellum, and also engages executive functions (Chen et al., 2008; Coull et al., 2011; Fujii & Wan, 2014; Grahn & Brett, 2007; Grahn & Rowe, 2009). Rhythmic synchronization tasks require participants to align their actions with a steady beat, relying on executive function skills like inhibitory control to avoid off-beat distractions, as well as cognitive flexibility when shifting between different rhythmic patterns (Vuust et al., 2006, 2011; Zuk et al., 2014). A recent study in preschoolers indicates that rhythmic training may improve inhibitory control more effectively than pitch-based training (Frischen et al., 2019).

Building on the role of rhythmic entrainment in enhancing sensory-motor coordination and executive functions, the link between timing abilities and executive functioning becomes particularly relevant in understanding how these skills interact in the context of ADHD, where deficits in both areas are often observed.

Timing abilities, attention, and ADHD

ADHD, a neurodevelopmental disorder affecting 2 to 7% of school-aged children, manifests core symptoms such as hyperactivity, impulsivity, and inattention (Erskine et al., 2013; Polanczyk et al., 2014; Willcutt et al., 2012). Notably, these symptoms are frequently associated with timing-related issues (Gustafsson et al., 2023). Evidence collected over the past two decades shows that ADHD is associated with poor treatment of single durations as well as difficulties in tracking rhythmic sequences (Noreika et al., 2013; Puyjarinet et al., 2017). The concurrent rhythmic and attentional deficits observed in ADHD suggest that there may be a strict relation between timing and executive functioning impairments in ADHD, notably for inhibition control and cognitive flexibility, pointing to potentially shared mechanisms. Impulsiveness is a timing and motor-based impairment whereby response styles are premature, impatient, delay-averse, and non-reflected (Puyjarinet et al., 2017; Rubia, 2002; Rubia et al., 2009). Timing abilities and executive functioning are closely linked as both rely on overlapping neural circuits, particularly in the prefrontal cortex, basal ganglia, and cerebellum (Piras & Coull, 2011; Rubia et al., 2009). Timing tasks often engage core components of executive functioning, such as inhibitory control, which is critical for suppressing inappropriate responses or distractions during precise timing tasks (Buhusi & Meck, 2009; Schwartze & Kotz, 2013). Enhancing rhythmic abilities through timing-based training – like the one employed in this protocol – may positively affect both sensorimotor and attentional executive functions, offering initial evidence of a causal link between rhythm and broader cognitive improvements. These connections between timing abilities, executive functioning, and ADHD provide a compelling framework for exploring innovative interventions that can simultaneously address rhythmic and cognitive deficits.

“Serious games” and mental health

One promising approach to bridging these domains is the use of “serious games”, which combine engaging gameplay with targeted cognitive and motor training to address specific challenges, such as those faced by children with ADHD. Designed with goals beyond simple entertainment, serious

games have become increasingly relevant in fields such as education and healthcare. These games use the captivating nature of gameplay to promote learning, training, therapy, and behavioral change (Agres et al., 2021; Michael & Chen, 2006; Susi et al., 2007). In educational environments, serious games are used to teach complex concepts, enhance problem-solving, and encourage collaboration (Deterding et al., 2011; Gee, 2003). In the healthcare sector, they assist in cognitive rehabilitation and physical therapy, helping patients enhance both motor and cognitive skills (Agres et al., 2021; Lau et al., 2017; McCallum, 2012). For children with ADHD, serious games designed for cognitive training can enhance executive functioning by promoting sustained attention in a complex and stimulating environment (Kollins et al., 2020). While the interactive nature of these games offers great potential for improving engagement and learning outcomes, their effectiveness can differ based on factors such as design, execution, and the specific learning mechanisms they are built to target. The success of serious games depends not only on user engagement but also on their alignment with targeted learning goals and the rigorous validation of their impact (Connolly et al., 2012). Despite their promise, there is a need for robust research to develop standardized approaches for evaluating their effects and addressing challenges like appropriate control group comparisons and randomization (Connolly et al., 2012; Girard et al., 2013). Evidence suggests cognitive training games often fail to produce lasting, transferable cognitive improvements beyond practiced tasks (Melby-Lervåg et al., 2016; Simons et al., 2016). In contrast, music-based games may be less limited due to music training's multi-dimensional, multisensory nature (Russo, 2019). Music training simultaneously engages auditory perception, motor coordination, memory, and attention, integrating these processes to mirror real-world cognitive demands (Kraus et al., 2014) and promoting brain plasticity (Dalla Bella, 2016). Unlike traditional cognitive training games, which focus on specific tasks, music-based games offer a holistic approach, fostering broader cognitive gains.

Rhythmic serious games

The past decade has seen growing interest in using rhythmic training and new technologies to improve motor and attentional functions, with studies linking multisensory rhythm processing to brain maturation and cognitive skills in ADHD (Park & Choi, 2017; Shaffer et al., 2001). Rhythm-based serious games have gained attention as promising training tools for strengthening auditory and motor functions in Parkinson's disease (Bégl et al., 2017; Dalla Bella, 2022), and more recently, for enhancing reading and inhibition control in typically developing children (Zanto et al., 2024). By incorporating beat-synchronization tasks, these games likely

engage similar neural circuits as auditory-motor tapping and tracking tasks like motor control, temporal processing, sensorimotor synchronization, executive functions (Chen et al., 2008; Coull et al., 2011; Fujii & Wan, 2014; Grahm & Brett, 2007; Grahm & Rowe, 2009). Such games are versatile and can be tailored to various populations, including those with developmental and neurological disorders. The combination of structured rhythmic exercises and the engaging nature of games provides a motivational alternative to conventional therapies, creating an environment that fosters both cognitive and motor development.

Rhythm workers (RW)

Although many rhythm-based games are available, few are designed with the specific objectives required for a "serious game" focused on rhythmic training. A review by Bégl et al. (2017) evaluated 27 rhythm-based games and found none ideally suited for structured rhythmic training protocols. Most of these games manipulate task difficulty by adding distracting stimuli rather than manipulating rhythmic characteristics, and they typically fail to focus player actions on explicit rhythmic elements or incorporate controlled movement training. To address this gap, our laboratory developed a game called "Rhythm Workers" (RW), which is specifically designed to train explicit rhythmic skills using auditory stimuli and audio-visual targets (Bégl et al., 2018).

In the RW game, participants tap their fingers to the beat of auditory stimuli (e.g., music) on a tablet. The goal is to construct a building within a specific time limit, with construction progress, aesthetics, and scores determined by how accurately and consistently the player's tapping aligns with the beat. The game's initial prototype featured progressively challenging levels linked to the beat saliency of chosen auditory stimuli (Bégl et al., 2018). It was tested with healthy adults and in an intervention study with patients with Parkinson's disease, where RW was compared to an active control game (Puyjarinet et al., 2022). The aim was to improve rhythmic abilities through finger tapping. The study involved three groups: one playing RW, one playing Tetris as a control, and one with no training. The rhythmic game significantly reduced motor variability and improved rhythm perception, with these effects not observed in the control group. Additionally, rhythmic training benefits extended to other motor tasks, supporting the notion of general timing impairments in Parkinson's disease.

The RW game has not yet been validated in neurodevelopmental populations. To that goal, the current prototype has been significantly improved and adapted for children with both typical and atypical development. In adults with Parkinson's, four weeks of training were possible. To ensure that this protocol was feasible to undertake in children with ADHD we administered 300 min of training. Based on a

review in typically developing children, this dosage may even be enough to observe changes in inhibition control (Jamey et al., 2024). The results from this feasibility study will inform a larger randomized controlled trial.

This study introduces a new, accessible protocol for evaluating a serious game in a home setting (RW) using a randomized control trial approach with an active control condition. The RW game aims to train rhythmic skills through complex integrated sequences that engage various executive functioning demands: a) Sustaining and focusing attention when synchronizing fine-motor movement to a musical beat; b) Starting and stopping repetitive actions like tapping a precise moving visual target in time with the beat instead of tapping anywhere on the screen; c) Filtering out rhythmic distractions within the music, such as off-beat instrumental sounds; d) Regulating perceptual-motor coordination by mentally tracking the beat at all times; e) Adapting dynamically when rhythmic patterns change within a song.

Main objectives

The RW game is designed with the primary goal of improving rhythmic abilities, making rhythmic performance enhancement an intended practice effect across various populations. Previous research has established a link between rhythmic abilities and executive functioning, suggesting the potential for executive functioning improvement through transfer by training rhythmic skills. While the direction of the causal relationship between rhythm and executive functioning remains an open question, there is a well-established, tight connection between the two. In our study, we specifically test the possibility that rhythm training may positively influence executive functioning. Given that executive functioning is often impaired in individuals with ADHD, this study aims to investigate whether rhythmic training can provide a pathway to remediate executive functioning. A key objective of this pilot study is to validate the effectiveness of RW training in enhancing rhythmic performance, specifically in children with ADHD, as this forms a critical part of the rationale for a larger randomized controlled trial (RCT). While improvements in executive functioning are not necessarily anticipated in this pilot due to the reduced duration of training, any observed gains in executive functioning would further validate the approach and offer additional insights into its therapeutic potential.

Specific aims and hypotheses

The study aimed to examine the feasibility and effectiveness of using the RW game in children with ADHD, compared to a relevant active control condition, the non-rhythmic digital control game Frozen Bubble (FB). The first objective was

to assess adherence to the training protocol and the level of acceptance of the games. It was expected that both measures would show adequate and comparable levels across the training groups. The second aim was to evaluate the effectiveness of RW in improving rhythmic abilities, with the hypothesis that participants would show superior auditory-motor synchronization performance after playing RW compared to FB, as measured by a normalized rhythmic assessment battery. Additionally, it was expected that longer training duration would be associated with greater sensorimotor improvement. Finally, on an exploratory note, we investigated whether RW had a positive effect on executive functioning, particularly inhibitory control and cognitive flexibility.

Methods

Participants

Thirty-one children were enrolled in this study, of whom 26 completed it with valid data, resulting in a completion rate of 84%. Five participants were excluded from the analyses: data from one participant were lost during the protocol, while four withdrew due to lack of interest. The study involved children aged 7–13 years with ADHD (three females, one non-binary) recruited through announcements, advertisements, and targeted social media outreach within the ADHD community. We included participants fluent in either French or English, with 60% of participants choosing to participate in French. All participants had an ADHD diagnosis based on a written declaration from a parent; however, we did not ask for an official clinical report. We also excluded participants if parents reported comorbid neuropsychological, psychiatric, or developmental disorders related to ADHD or more than 2 years of formal musical training. Overall, 96% of the parents provided information on their child's video gaming history and socio-economic status. The previous video game was assessed using parent-reported weekly playing duration. Socio-economic status was determined by converting household income and education level into Z-scores, which were then combined. Measuring video gaming habits and socio-economic status (SES) helps control for prior exposure and skill levels, as previous gaming experience may influence adaptation to the game (Green & Bavelier, 2012; Staiano et al., 2013). SES is important because it correlates with cognitive development resources, stress levels, and mental health, potentially affecting a child's ability to benefit from the intervention (Hackman & Farah, 2009; Noble et al., 2015). Accounting for these variables ensures more accurate and generalizable findings across diverse populations (Bradley & Corwyn, 2002). Participants received \$50 upon completing the protocol. Due to the small sample size in this proof-of-concept study, non-parametric statistical analyses

Table 1 Participant background and performance baselines

Characteristic	Rhythm Workers					Frozen Bubble					<i>p</i> value
	<i>N</i>	Mean	SD	Min	Max	<i>N</i>	Mean	SD	Min	Max	
Age (years)	13	10.6	2.0	7.4	13.4	13	10.7	2.1	7.3	13.7	0.9
BTI Baseline	13	0.1	1.0	− 1.2	1.9	12	0.1	0.7	− 0.8	1.3	0.7
EF Baseline	13	0.1	0.3	− 0.2	0.8	13	− 0.1	0.6	− 1.3	0.9	0.8
Video Game History ¹	9	490.0	452.5	0	1200	11	518.2	406.5	60	1200	0.9
Socio-Economic Status	12	0.2	0.5	− 0.4	0.7	12	− 0.2	1.1	− 2.4	1.2	0.7

¹Parent reports of minutes spent video-gaming each week prior to training

(Wilcoxon rank sum tests) were employed for group comparisons related to the participants' backgrounds (see Table 1 for demographic and background characteristics).

General procedure

This single-blind, two-arm, parallel-group randomized control study assigned participants to the experimental group (playing the rhythmic game, RW) or the active control group (playing the non-rhythmic game, FB). The general procedure comprised a screening phase, remote testing and training, and a final debriefing interview with parents.

Screening

A Zoom teleconferencing interview was conducted to ensure understanding and compliance with inclusion and exclusion criteria. Eligible participants were enrolled in the study once they consented via e-mail.

Remote testing and training

The experiment was conducted between October 2021 and March 2022 across Canada. The entire research protocol was conducted remotely from the participants' homes, using the BRAMS Online Testing Platform, teleconferencing video meetings (Zoom), and testing equipment mailed to the participants. The equipment was shipped to the participants who were considered eligible for the study. Rhythmic and cognitive abilities of each participant were assessed before and after the 2-week training program via four video meetings. This 2-week training duration was selected for practical reasons to prioritize the feasibility of the pilot study in children with ADHD. Upon reception of the equipment, two video meetings (separated by at least 90 min) were scheduled with the participant. During the first meeting, participants completed four online executive functioning tasks on the BRAMS Online Testing Platform ([https://](https://brams.org/online-testing-platform-training/)

brams.org/online-testing-platform-training/), comprising Go/No-Go, flanker, and set-shifting (see below for details), and an N-back working memory task (not included in the present analyses). During the second meeting, participants completed tablet-based rhythmic tests from the Battery for the Assessment of Auditory Sensorimotor and Timing Abilities (BAASTA; (Dalla Bella, Farrugia et al., 2017b, Dalla Bella, Foster et al., 2024a); see below for details). Participants were instructed not to reveal which game they had been assigned to the experimenter and not to use the tablet before the rhythmic task session. The researchers conducting executive functioning and rhythmic tests were blinded to the participants' group assignments. At the end of the second meeting, a research assistant (non-blinded) presented and explained to participants how to play the game they received. Participants were instructed to begin playing the game once they understood the instructions explained by the research assistant. The third and fourth video meetings, comparable to the first two meetings, were scheduled after the end of the training period. At the end of the fourth meeting, the research assistant scheduled a debriefing meeting to collect general comments and feedback about the game. Given the age range of 7–13 years and the varying degrees of support required based on symptom severity, parents were instructed to ensure children adhered to the protocol by playing the required amount of time and completing the handwritten reports before and after each session. Parents also recorded the level of support provided, if necessary. They were instructed not to play the game on behalf of the child and had a follow-up call with our team every 3 days.

Sampling and randomization

We employed simple random sampling to recruit participants. We targeted any Canadian parent with a child with ADHD using social media advertising. This approach included anyone with a Facebook or Instagram account in Canada (~30 million users) and an interest in ADHD. Being not confined to a single community, institution, city or province is a unique strength of our novel remote RCT

study design. Participants were randomized using covariate adaptive randomization with the “minimization” approach (Lin et al., 2015) by an experimenter who was not involved in any other task during the protocol execution. The first six participants were assigned via block randomization (random permutation of three in the experimental group and three in the control group) without regard to covariates. The seventh and eighth participants received purely random assignments. The remaining participants were then assigned using “biased coin” randomization with $p = .8$ (Pocock & Simon, 1975) to minimize group imbalance in the number of participants, gender, age, language (English/French), and music experience. These variables were group-matched at $p > .89$ in the final sample. Biased coin randomization is a technique used in clinical trials to balance participant allocation across treatment groups by increasing the likelihood of assigning participants to the smaller group when imbalances arise, ensuring more even group sizes and reliable comparisons, especially in smaller trials.

Equipment and calibration

A Samsung Galaxy Tab A 8.0” 2019 Android tablet (model SM-T290) was sent to participants for use in the experiment. The tablet had a 2-GHz processor, 1280 × 800 pixels display resolution, and 32 GB of RAM. Participants used the touch screen to navigate and play the applications. JBL Tune 500 Wired On-Ear Headphones with One-Button Remote/Mic were used to play music and sounds from the applications. All materials required to complete the study were mailed using postal and courier services. This material included the tablet (the game assigned to the participant, and the rhythmic assessment application BAASTA), a gooseneck phone holder, headphones, paper questionnaires, game-specific instructions, and sanitizing kits. The game’s scoring system is based on a combination of touch and audio, with synchronization consistency calculated via touch input. Tablet devices typically present touch-to-audio latency resulting from hardware factors that need to be corrected via a calibration procedure to ensure proper sound-tap alignment. We measured the mean latency from audio-based testing of five tablets, which was 274 milliseconds ($SD = 16$ ms). This latency was estimated by subtracting the impulse peak of the metronome sound from the amplitude peak of the tapping sound in the recorded audio when playing the game to a metronome. The latency was then subtracted from the tapping time to ensure that taps were correctly aligned with the musical beats, providing accurate scores. This procedure ensured that tap timing was properly aligned with the musical beat when synchronization was perfect. For BAASTA, the online tablet-based application calculates synchronization consistency scores using audio.

Training protocol

Participants were instructed to play their assigned game 30 min a day, 5 days a week, for 2 weeks (300 minutes of gameplay). They were allowed to combine two 30-min sessions into a 1-h session to provide more flexibility in planning. Participants received the following instructions: “*I would like you to play it for about 30 minutes a day, five days a week, for 2.5 hours a week. You can play more if you want, but don’t play more than an hour a day*”. No child reported playing more than 1 h a day. During the two weeks of playing the game, participants were asked to complete a questionnaire before and after each session. The questionnaire included nine yes or no questions about their mood taken from a children’s mood questionnaire (Derbaix & Pecheux, 1999). Participants also indicated their progress in the game (level number), as well as the perceived difficulty of the game on a five-item Likert scale (1 = very easy; 5 = very hard) and how much they enjoyed the game on a scale of (1 = very boring; 5 = very fun).

Stimulus selection

Before the training, we conducted a pilot study in typically developing children to select the musical stimuli for the rhythmic game. Fifty-eight musical excerpts (30 s each) were chosen to be appealing to children between the ages of 7–13 years, with tempi ranging from 78 to 135 bpm, and including an equal proportion of electronic, classical, pop rock, jazz funk, and traditional genres. All musical excerpts were instrumental and did not include vocals. Half of the excerpts were composed by musicians for the commercial release of RW (BeatWorkers, commissioned by BeatHealth Company). The other half of the stimuli were selected from a royalty-free music archive composed by Kevin MacLeod (<https://incompetech.com/music/royalty-free/faq.html>). In an online experiment run on the BRAMS Online Testing Platform, we asked 25 typically developing children aged 7–13 years (mean age = 10.23, $SD = 2.11$; 54% females) to tap to the beat of each stimulus, using the space bar of a keyboard or by tapping on the green button on a touch screen. At the end of each excerpt, children rated the stimuli on a five-point Likert scale in terms of enjoyment (1 = very boring; 5 = very fun; $M = 2.72$; $SD = 1.11$; range = 2.3–3.3) and tapping difficulty (1 = very easy; 5 = very hard; $M = 2.89$; $SD = 0.96$; range = 2.5–3.23). We computed the synchronization consistency of tapping performance using circular statistics (i.e., vector length; see Dalla Bella, Benoit et al. 2017a, Dalla Bella, Farrugia et al., 2017b; Sowiński & Dalla Bella, 2013). Synchronization consistency was measured using vector length and was logit-transformed to reduce data skewness, a common practice for synchronization data (e.g., Kirschner & Tomasello, 2009; Sowiński &

Dalla Bella, 2013). Scores and ratings of each of the 58 musical stimuli are presented in Table 1.

To select songs for the 32 levels of RW, we primarily relied on the synchronization consistency rankings shown in Table 1. Music by Kevin MacLeod was prioritized because synchronization consistency varied within a broader range (0.07–1.51) than the commercial music of BeatHealth company (0.45–1.54) and thus provided greater margin to manipulate rhythmic difficulty. Moreover, royalty-free licenses enhance accessibility, transparency, and openness for future research. Music from the BeatHealth company was selected in specific situations to avoid songs that received low ratings for stimulus appreciation or extremely high ratings of perceived difficulty, as well as to diversify tempo and genre during level progression. In total, 25 musical stimuli by Kevin MacLeod and seven by the BeatHealth company were used. We rated syncopation (the displacement of the normal musical accent from a strong beat to a weak one; Scholes & Nagley, 2011) scores based on expert judgment on a scale between 0% (no syncopation) and 100% (full syncopation). These syncopation scores were not used for stimuli selection but to evaluate relationships with enjoyment, difficulty and synchronization consistency. The final order of the 32 selected songs across game levels was adjusted by KJ and NF based on their expert judgment Table 2.

Rhythmic “serious game”

The RW “serious game” used in this proof-of-concept study was initially developed for adults (Bégel et al., 2018). The scoring method and synchronization condition of the game were similar, but significant improvements were made in terms of the visual interface, the gameplay, difficulty, and musical stimuli to suit children. First, we replaced the musical stimuli from simple MIDI-generated music (Bégel et al., 2018) with complex and layered instrumentations performed, recorded, and designed by professional musicians. The objective of this modification was to make the musical stimuli more engaging for children. Second, we added spatial moving targets that fit the motor level and cognitive functioning of 7–13-year-old children. Third, the game’s scoring system was also altered so fewer points were required to build a complete building within each level’s timeframe. Finally, the graphics and interface were also improved, giving the game a finished feel like an online commercial game (for a version of the game for the public, see <https://www.beatworkers.com>).

In this version of RW, players were asked to synchronize their finger taps to the beat of musical excerpts. The goal of the game was to construct a building by aligning the taps to the musical beat. Circular statistics were employed using data from the most recent eight taps to evaluate real-time

tapping performance. To derive a comprehensive score, the assessment measured synchronization consistency (expressed as vector length) and accuracy (expressed as a vector angle representing the extent to which tapping tended to lead or follow the stimulus beat). The scoring process involved multiplying synchronization consistency (ranging from 0 to 1) by 100, yielding a score within the 0 to 100 range. Note that achieving maximum consistency (1.0) is unattainable in human performance. Three points were automatically added, resulting in a perfect score of 100 for outstanding players. Scores were then adjusted based on synchronization accuracy. For vector angles exceeding 60 degrees, deductions were made every 10 degrees, with decreasing accuracy. For instance, between 60 and 70 degrees, five points were deducted from the final score, and between 70 and 80 degrees, ten points were subtracted, following a similar pattern. Players sometimes tapped in antiphase (i.e., midway between the beats), which was considered an erroneous performance. Antiphase tapping was identified during the level assessment when the player’s synchronization accuracy deviated by at least 120 degrees from the beat, given that the antiphase corresponds to 180 degrees.

Players received feedback while playing at the end of each 8-bar sequence. If the score was above 90, the expression “ACE!” showed on the screen (see Fig. 1); the building story was constructed faster, and players scored the most points. For a score between 70 and 90, players saw “BIG!”; the building was constructed normally, and players scored points. Scores below 70 showed the words “Err!”; no progress was achieved on building the stories, and no additional points were given. Players could receive medals at the end of each level based on their total points, and this unlocked more game levels to play. Successive levels each required a greater number of accumulated medals to be unlocked. Accordingly, during their progression through the game, players usually had a range of 2–4 new levels ahead that they could access.

Prior to the start of this proof-of-concept study, the child-friendly, adapted version of RW was tested in another in-person laboratory survey in 13 typically developing children between 6 and 13 years of age to ensure that the music selection, gameplay interface, and graphics were suitable for that age range. Feedback from these participants allowed us to improve the game and adaptation for children further. RW included 32 levels, each corresponding to one of the songs selected in the stimulus pilot study. The game’s progression was designed by increasing rhythmic difficulty using the synchronization consistency scores (vector length logit transform) obtained during the validation of the musical stimuli. Each level involved two repetitions of the same excerpt. The first repetition, a standard rhythmic task in which the participant taps to the beat of music without spatial moving targets, served as practice. The second repetition

Table 2 Ranking of musical excerpts (in descending order with regard to synchronization consistency), genre, tempo (beats per minute; BPM), synchronization consistency (logit-transformed vector length), syncopation, and participants' ratings perceived difficulty and of enjoyment (provided on a five-point scale), as well as selection choice, are also reported

Stimulus ID	Genre	BPM	Syncop.	Vector length	Perceived difficulty	Enjoyment	selected
cheery_monday	Pop Rock	102	0%	0.76	2.87	2.93	Yes
np_4_rouen_1	Pop Rock	100	0%	0.76	3.00	2.93	
np_15_tou_loose_2	Jazz Funk	100	0%	0.76	3.33	3.27	Yes
crusade_heavy_industry	Classical	90	25%	0.75	2.87	2.80	
np_8_lis_le_1	Pop Rock	120	0%	0.75	3.00	3.20	
tech_live	Electronic	124	0%	0.75	3.00	3.07	Yes
np_19_mont-pele_3	Reggae	105	0%	0.75	3.07	2.93	
np_5_roulant_2	Pop Rock	110	0%	0.74	3.27	3.07	
np_3_en_g_2	Electronic	105	0%	0.74	3.13	3.13	
np_9_lis_le_2	Pop Rock	125	0%	0.73	3.20	3.40	Yes
the_complex	Electronic	104	0%	0.73	3.40	2.87	Yes
np_11_strass_bourge_1	Traditional	105	0%	0.73	3.33	3.00	
radio_martini	Classical	118	0%	0.73	3.13	2.93	
kool_kats	Electronic	113	25%	0.73	3.00	2.60	Yes
np_1_kaysenberg	Electronic	100	0%	0.73	2.93	2.93	
np_16_tou_loose_3	Jazz Funk	120	0%	0.72	2.87	2.87	
bass_walker	Jazz Funk	113	0%	0.71	2.87	3.07	Yes
funkorama	Jazz Funk	101	25%	0.71	3.00	2.20	Yes
funin_and_sunnin	Pop Rock	108	0%	0.70	2.93	3.00	Yes
np_7_bille_a_rixe_2	Jazz Funk	110	6.25%	0.70	3.33	2.87	
galway	Traditional	110	75%	0.70	3.13	2.60	Yes
np_26_tigre_3_135bpm	Pop Rock	135	0%	0.70	3.07	2.93	
the_builder	Jazz Funk	123	18.75%	0.70	2.87	2.80	Yes
np_22_marcel_3	Jazz Funk	100	0%	0.70	2.20	2.33	
np_25_tigre_2	Pop Rock	120	50%	0.70	2.87	3.00	
mischief_maker	Traditional	125	0%	0.70	2.93	2.87	Yes
industrial_cinematic	Classical	110	25%	0.70	2.93	3.07	
np_20_marcel_1	Reggae	95	0%	0.69	3.07	3.20	
master_of_the_feast	Traditional	122	100%	0.69	2.60	2.87	Yes
np_12_strasse_bourge_2	Traditional	105	75%	0.69	3.20	2.87	
np_2_en_g_1	Electronic	100	0%	0.69	3.13	3.33	Yes
motherlode	Pop Rock	90	25%	0.69	2.67	3.20	Yes
np_14_tou_loose_1	Jazz Funk	90	0%	0.69	3.00	2.93	
chee_zee_lab	Electronic	120	25%	0.68	2.93	2.73	Yes
np_21_marcel_2	Jazz Funk	89	50%	0.68	2.87	2.53	
disco_medusae	Jazz Funk	115	0%	0.68	3.13	3.07	Yes
np_24_tigre_1	Pop Rock	120	50%	0.67	2.87	3.13	
rolling_at_five	Jazz Funk	105	0%	0.67	2.63	2.90	Yes
industrious_ferret	Classical	95	25%	0.66	3.00	2.67	Yes
pixellan	Electronic	115	0%	0.66	2.87	3.00	Yes
np_6_bille_a_rixe_1	Jazz Funk	90	0%	0.65	3.07	2.73	
np_28_par_ici_1	Electronic	130	50%	0.65	3.00	3.13	
shaving_mirror	Jazz Funk	78	0%	0.64	3.07	2.80	Yes
five_armies	Classical	114	100%	0.64	2.93	2.73	
doobly_doo	Jazz Funk	85	0%	0.64	2.73	3.00	Yes
hyperfun	Jazz Funk	100	100%	0.63	3.07	2.73	Yes
edm_detection_mode	Electronic	128	0%	0.63	2.93	3.00	Yes

Table 2 (continued)

Stimulus ID	Genre	BPM	Syncop.	Vector length	Perceived difficulty	Enjoyment	selected
np_17_mont_pele_2	Reggae	95	50%	0.62	3.13	2.80	Yes
danger_storm	Electronic	80	0%	0.62	3.00	3.13	Yes
np_27_tigre_4	Electronic	130	25%	0.62	3.07	2.60	Yes
zazie	Pop Rock	90	0%	0.61	3.07	3.07	Yes
np_23_marcel_4	Pop Rock	80	50%	0.58	3.13	2.87	Yes
np_17_mont_pele_1	Reggae	80	50%	0.56	3.20	3.07	Yes
surf_shimmy	Pop Rock	85	50%	0.55	2.80	2.87	Yes
evil_incoming	Classical	132	50%	0.50	2.47	2.73	Yes
call_to_adventure	Classical	85.5	100%	0.37	2.40	2.33	
mega_hyper_ultrastorm	Electronic	110	75%	0.31	2.60	2.60	
cool_rock	Pop Rock	129	0%	0.22	3.00	2.93	

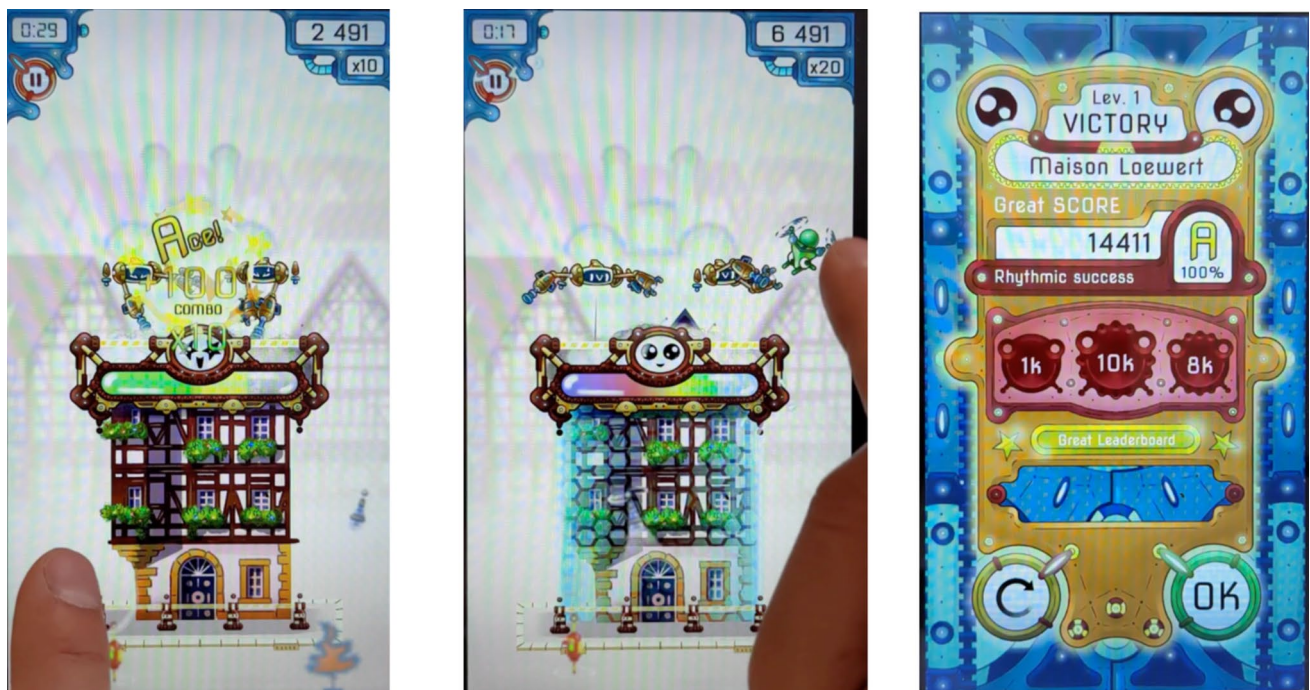


Fig. 1 Example of Rhythm Workers gameplay (experimental training condition) used in this proof-of-concept study. On the **left**, a building was constructed, and the player scored maximum points and received

visual feedback. In the center, the player tapped on a spatial moving target on the beat. On the **right**, the player saw their scoreboard once the level was completed

added spatial moving targets that could be eliminated by tapping them on the beat. We varied spatial moving target difficulty by increasing the speed (three different speeds) at which they moved on the screen and how many taps were required to eliminate the enemy (one or two taps). If the player did not destroy the spatial moving target, the spatial moving target attacked the building, reducing the player's score. Spatial moving target difficulty was introduced progressively in the game, and spatial moving targets appeared only in a sequence. During the first six levels, 1–2 spatial

moving targets appear, requiring one or two taps on the beat to eliminate them. The first six levels were limited to a maximum of two spatial moving targets so participants could familiarize themselves with the spatial moving targets. For the following levels, between four and eight spatial moving targets appeared, requiring one or two taps on the beat to make them disappear. The number of spatial moving targets was added for variety and to guarantee sustained attention throughout the training sessions. For this reason, we did not increase the number of spatial moving targets



Fig. 2 Example of Frozen Bubble gameplay (control training condition). On the *left*, the black bubble was released in the direction of the arrow by two finger taps (the first to arm, and the second to aim

toward the higher two black bubbles and shoot). On the *right*, at a different moment in the game, a bubble has hit its target and freed bubbles

with increasing level progression but instead attributed the 4–8 spatial moving targets randomly per level. We verified after training that the amount of spatial moving targets presented was not related to improvement in rhythmic abilities or executive functioning ($p > .32$). A sample of the musical stimuli of the game and examples of the gameplay can be found at the following link: https://osf.io/gykjd/?view_only=26be79399f1e48fe838107df437e0ceb.

Non-rhythmic active control game

The control game, Frozen Bubble (FB) was based on a publicly available version of the game on GitHub (<https://github.com/videogameboy76/frozenbubbleandroid>) and is a puzzle arcade shooting game in which the goal is to clear the screen of descending bubbles using finger tapping. The arrangement of bubbles progressively moved down the screen, and the player lost if they reached the bottom of the screen. To make the bubbles fall, players had to arrange them by color. When three or more bubbles of the same color were stuck together, they fell off the screen, and any bubbles attached below became free (see Fig. 2).

The game played background instrumental music with a beat similar to RW, except players did not synchronize their motor movements to the beat. To make motor demands comparable with RW, we modified the FB game

to double the number of taps (one to arm and one to launch the bubble gun), as described below. Players had a choice of three play modes: “Puzzle Mode”, “Arcade Mode, and “Player vs. Computer”. In “Puzzle Mode” an arrangement of bubbles of different colors was presented on the screen for each of the 100 levels. To launch a bubble, players had to tap twice on the place where they wanted to send the bubble: Once to load the gun and a second time to launch the bubble. This principle of shooting and connecting bubbles to clear them from the screen was the same across the three modes. In “Arcade Mode”, the bubble arrangement descended gradually on the screen, with new rows emerging from the top edge, and the player’s goal was to clear bubbles from the screen to survive as long as possible. In this mode, levels were not presented. In “Player vs. Computer” mode, an arrangement of colored bubbles was presented on the screen, and players played against the computer, which also had a screen with bubbles to eliminate; cleared bubbles were sent from the player to the computer and vice-versa, adding to the counterpart’s arrangement of bubbles to be cleared. The game’s goal was to clear all bubbles from the screen before the computer cleared all bubbles from its screen. This was the most challenging mode.

Evaluation of game compliance and acceptance

The first aim of this proof-of-concept study was to evaluate if participants adequately followed the study protocol and played the experimental and the control games in comparable ways.

Compliance

The compliance levels in this study refer to the degree to which participants fulfilled the requested protocol targets. Complete compliance entailed using the assigned game for the requested time while respecting a 2-week playing time distribution. We assessed participant compliance with protocol targets by comparing the cumulative training duration (i.e., of training sessions; self-reported and logged on the device) and continuous playing time in minutes (i.e., time spent in active gameplay in game levels; logged on the device). Participant self-reports of session times and dates were cross-checked manually with logfiles for overall coherence.

Game acceptance

In the context of this research, game acceptance refers to the degree to which participants felt engaged when playing the game. We measured game acceptance by the level of enjoyment and frustration expressed after a gaming session and an overall game recommendation. At the end of each gaming session, participants were asked to use a five-scale smiley-face Likert scale and circle their enjoyment level (1 = very boring; 5 = very fun) and perceived difficulty (1 = very easy; 5 = very hard). The means of all sessions for enjoyment and perceived difficulty were calculated as a cumulative measure of appraisal of the game participants played. At the end of the 2 weeks, during the debriefing session, participants were asked if they would recommend the game on a three-point scale ranging from “Yes”, “Maybe with changes” to “No”.

Assessment of rhythmic abilities

Rhythmic abilities were assessed with selected tests from BAASTA. We selected tasks well suited to capture rhythmic abilities' perceptual and sensorimotor dimensions (Dalla Bella, Foster et al., 2024a) while being feasible for children (Bégl et al., 2022; Puyjarinet et al., 2017). The tasks involved the Beat Alignment Test (BAT), paced tapping to a metronome, and paced tapping to music.

The BAT was initially designed by Iversen and Patel, 2008 to assess participants' ability to perceive the beat inherent to a musical stimulus. The participants were submitted

to the abbreviated version of the BAT (24 trials, with a 600-ms inter-beat interval, instead of the full 72-stimuli version; Dalla Bella, Benoit et al. 2017a, Dalla Bella, Farrugia et al., 2017b). Excerpts counting 20 beats each, taken from Bach's “Badinerie” and Rossini's “William Tell Overture”, were presented. An isochronous sequence (metronome) superimposed on the music was either aligned or not with the beat. Out of 24 trials, 16 were not aligned to the beat. The non-alignment was initiated either by a phase shift or a period shift. Participants were asked whether the sequence aligned with the music's beat. They were given two examples of aligned and non-aligned trials, followed by four training trials. The duration of the test was approximately 8 min.

In paced tapping to a metronome and music, participants were asked to tap their finger in synchrony with an isochronous sequence of piano tones and with short musical excerpts taken from Bach's “Badinerie” and Rossini's “William Tell Overture” (for details, see Dalla Bella, Benoit et al., 2017a, Dalla Bella, Farrugia et al., 2017b, Dalla Bella, Foster et al., 2024a, Dalla Bella, Janaqi et al., 2024b for the tablet version). The participants repeated the test twice for each metronome or musical stimulus. The participant was given a short training before each different tempo or excerpt. The overall duration of these tests was approximately 10 min.

Assessment of executive functions

We administered set-switching, Eriksen flanker, and Go/No-go tests to assess executive functioning.

Set-switching test

This test was organized into three different blocks (48 trials per block): “location”, “direction” and “mixed”. In the “location” block, participants had to identify where a red arrow appeared on the screen while ignoring the direction it was pointing. Conversely, in the “direction” block, participants were asked to respond only to the direction a blue arrow was pointing, regardless of which side of the screen it appeared on. The “mixed” block presented red and blue arrows in a predetermined pseudo-random order. When participants saw red arrows, they were asked to abide by the “location” rule, and when blue arrows appeared, they had to switch to the “direction” rule. Participants were invited to respond as fast as possible in all blocks. In all trials, a white fixation cross was shown for 500 ms; then the arrow was displayed until the participant responded (up to a maximum of 4500 ms), and between trials, a blank screen was shown for 750 ms. This task took approximately 6–8 min for each participant to complete.

Eriksen flanker fish task

Participants were presented with graphics of one or five fish of the same size arranged in a horizontal line on the screen. The participants were asked to respond as quickly as possible by pressing one of two keys to indicate the direction in which the middle fish was swimming (either left or right) while ignoring any other fish surrounding (flanking) the middle fish. In one-third of the trials, only one fish was presented without any flanking fish (neutral); one-third of trials contained flanking fish that were oriented in the same direction as the middle fish (congruent trials); and one-third of the trials contained flanking fish oriented in the opposite direction as the middle fish (incongruent trials). Participants had a 2000 ms (ISI) to respond, including a 500-ms stimulus and 1500-ms fixation duration. In between all trials, a white fixation cross was shown for 750 ms; then, the stimulus was shown until the participant responded. This test had 96 trials and took approximately 3–5 min for participants to complete.

Go/No-Go task

In this test, participants were shown two different stimuli: an orange circle or a blue circle. The participant was asked to press the space bar on a physical keyboard as soon as possible when a blue circle appeared (Go-trial) and to refrain from pressing any key when an orange circle appeared (No-Go trial). Blue circles were shown in 70% of the trials, and orange circles in the remaining 30%. After a 1500-ms white fixation cross, the stimulus was shown on screen for 500 ms, for a total inter-onset interval of 2000 ms. Late responses (i.e., during the following fixation period) were accepted during the task, and then a response timing criterion was applied during analysis. This task used 100 trials and took approximately 4–5 min for each participant to complete. A minimum of ten trials was required for inclusion in the analysis. Responses shorter than 100 ms were not considered valid inhibition control responses and, therefore, were excluded from analysis.

Measures and statistical analyses

All statistical analyses were performed using R Studio (R Core Team, 2022).

Compliance and acceptance

To compare the means of both games on measures related to compliance and acceptance, we utilized the Wilcoxon rank sum test because we did not expect data for these measures to be normally distributed.

BAASTA

We computed d-prime (d') scores for the BAT task to obtain a measure of perceptual beat tracking sensitivity while accounting for response bias. For the paced tapping tasks, logit-transformed vector length values were used to measure synchronization consistency, as described above (see “[Stimulus selection](#)”). The synchronization consistency scores for each subtask (three metronome tempos and two music excerpts) were then each converted to z -scores according to the entire sample’s pre-training mean and standard deviation for the subtask. These scores were then averaged per participant and timepoint at the task level, yielding standardized scores (i.e., derived from z -scores) of synchronization consistency for paced tapping to metronome and paced tapping to music.

Subsequently, to obtain a measure that reflects both perceptual and sensorimotor rhythmic abilities, we computed the Beat Tracking Index (BTI). The BTI was used because it has a high test-retest reliability in adults (Dalla Bella, Foster, et al., 2024a; Puyjarinet et al., 2017) and has successfully captured individual differences in children and adults with neurodevelopmental disorders (ADHD; Puyjarinet et al., 2017). The BTI was calculated by averaging z -scores of the perceptual performance (BAT d') with the average of the scores of tapping to metronome and music.

To assess changes in rhythmic performance (post-minus pre-training) of participants in each game, we estimated linear models using the `lm()` function in R for each of the four rhythmic performance scores (BTI, paced tapping to music, paced tapping to metronome, and BAT d'). The dependent value for each model was the difference scores between time points, i.e., post-training performance minus pre-training on the corresponding score. Due to the inherent difference in continuous playing time (between RW and FB arising from navigation through map levels and score screens, these models included a mean-centered term for continuous playing time to account for this variation between the games. Moreover, previous research on RW in adults with Parkinson’s disease indicated that individuals may benefit differently from playing the game based on their pre-training rhythmic abilities (Dalla Bella et al. 2018), so the models also included a term for the baseline pre-training performance score. The linear models thus contained these predictors as main effects, as well as all interactions (two-way and three-way):

$$\text{Difference score} = 1 + \text{game} \times \text{continuous playing time} \times \text{baseline}$$

Additionally, the effect of individual differences in training dose was assessed within each game by testing the Pearson correlations between rhythm scores and training duration (total training duration and continuous playing time,

separately. Effect size interpretations of eta squared for linear regression are based on (Miles & Shevlin, 2001).

Executive functioning tasks

In the flanker and set-shifting tasks, response time (RT) values were calculated after removing trials with incorrect responses, and after removing trials with early or late responses. For both the flanker and set-shifting tasks, RT values shorter than 200 ms were discarded. Additionally, for the flanker task, RT values greater than 1300 ms were discarded, whereas for the set-shifting task, longer RT values were expected due to the higher complexity task and no maximum criterion was applied. For the set-shifting task, we then subtracted the mean RT of non-mixed blocks of the task (i.e., when only the “location” or “direction” rule was applied) from the mean RT of the mixed section (when the “location” or “direction” rule alternates pseudo-randomly). For the flanker task, we subtracted the mean RT of congruent trials from the mean RT of the incongruent trials.

Following the approach of previous studies using the trail-making test, which is a similar task involving simultaneous executive functioning processes (i.e., processing speed, inhibition, and cognitive flexibility), we calculated a proportional score based on RT values. Such proportional scores are used as a sensitive index of change in executive functioning following an intervention (Periáñez et al., 2007; Stuss et al., 2001). The mean RT of the incongruent trials was subtracted from the mean RT of the congruent trials, and this difference was divided by the RT of the congruent trials, i.e., $(\text{congruent RT} - \text{incongruent RT}) / (\text{congruent RT})$, where higher (less negative) scores represent higher attentional functioning. It should be noted that this formula differs from typical use of proportional scores in that the order of terms in the numerator is reversed (i.e., a typical approach would use incongruent RT minus congruent RT); this change allowed for higher values to represent better performance, and for higher difference scores (of proportional scores between time points) to indicate improvement after training.

We opted to merge these tasks into one comprehensive executive functioning index. This approach aligns with Diamond's integrated theory of executive functioning (Diamond, 2013), which highlights the interdependence of executive functions. Effective interference control, which involves filtering out distractions and maintaining task-relevant focus, depends on response inhibition to suppress irrelevant information. Cognitive flexibility, in turn, relies on both interference control and response inhibition to disengage from one mental set and shift to another without interference from previous task rules. RW offers a naturalistic way to engage and improve these cognitive processes:

Response inhibition – players must suppress premature motor responses and adapt to correct timing;

Interference control – as musical stimuli become more complex (e.g., with increasingly emphasized off-beat sounds), participants must resist interference from competing rhythmic patterns;

Cognitive flexibility – adapting to rhythmic modulations, coordination demands for moving visual targets and change of tempo between levels requires shifting between response strategies.

To measure the impact of RW training on executive functions, we used task-based assessments that correspond to the targeted cognitive processes:

- 1) The **flanker task (interference control)** requires participants to suppress distractor stimuli and focus on the relevant target. Since RW training involves filtering out irrelevant rhythmic elements, it may primarily enhance interference control, explaining the strongest effects being observed in this task.
- 2) The **Go/No-Go task (response inhibition)** measures the ability to inhibit prepotent responses, which is trained in RW through precise motor timing and suppression of premature movements.
- 3) The **set-shifting task (cognitive flexibility)** measures the ability to switch between different rules or task sets.

Performance is assessed through reaction times and error rates, reflecting the ability to inhibit previous rules and adapt to new ones efficiently. RW training requires adapting to changing musical patterns, which may translate to improved cognitive flexibility performance on a set-shifting task. On the Go/No-Go task, scoring was based on signal detection theory in order to measure the sensitivity to correctly detect “go” stimuli, while accounting for response bias or the general tendency to respond. We calculated A' , the non-parametric equivalent of d' , to avoid score approximations in the case of ceiling hit rates or zero false alarm rates, which were common in this task. An A' near 1.0 indicates high discrimination sensitivity, while a value near 0.5 means chance performance (Makowski, 2018).

Scores from the Go/No-Go, flanker, and set-shifting tasks were combined into a single index for accuracy. For the combined reaction time score, only the flanker and set-shifting tasks were considered appropriate because the no-go condition of the Go/No-Go is correct only in the absence of a reaction time score. Proportional scores from both tasks at pre- and post-training were converted into z-scores based on the task means and standard deviations of all participants at pre-training. These z-scores were then averaged at each time point for each participant. Improvement was calculated by subtracting the pre-training scores from the post-training

Table 3 Compliance with protocol targets and acceptance for the two games

Characteristic	Rhythm Workers					Frozen Bubble						
	<i>N</i>	Mean	SD	Min	Max	<i>N</i>	Mean	SD	Min	Max	<i>p</i> value	
Continuous playing time	13	141.0	60	30	244	13	275	83	103	367	< .001	
Taps per minute ¹	13	61.2	9.1	44.9	78.8	13	56.6	12.5	39.3	83.9	0.3	
Game enjoyment	12	3.5	0.6	2.3	4.5	13	3.5	1.0	1.6	5.0	0.9	
Perceived difficulty	13	3.7	0.7	1.9	4.8	12	2.8	0.8	1.6	4.2	0.03*	
Recommendation	13					13					0.9	
“Yes”		<i>n</i> = 6 (55%)						<i>n</i> = 6 (75%)				
“Maybe with changes”		<i>n</i> = 2 (27%)						<i>n</i> = 1 (13%)				
“No”		<i>n</i> = 2 (18%)						<i>n</i> = 1 (13%)				
Did not answer		<i>n</i> = 3						<i>n</i> = 5				

¹Total number of logged finger-taps by game divided by training duration in minutes

scores, and the resulting changes in executive functioning were assessed. After graphically and statistically verifying that the scores were normally distributed between groups, we performed *t* tests to assess whether the difference scores from the RW group were greater than those from the FB group. We then tested if the within-group change was significantly greater than 0 using a one-sample *t* test.

Results

We begin by presenting the results of compliance and the acceptance of both games in children with ADHD, followed by the effects of RW training on rhythmic and executive functioning.

Compliance and acceptance

A total of 87.1% (27 out of 31) of the children with ADHD completed the study protocol. Four children, two from the RW group and two from the FB group, did not complete the study due to time management issues or severe ADHD symptom manifestations, and are not included in analyses. Additionally, one participant was excluded from all analyses due to a technical problem where the participant accidentally changed the tablet's settings, affecting the game's progression and invalidating their training progress. One participant had unreliable logged data regarding training compliance, so their self-reported training duration was used instead of their logged training duration. All remaining participants completed seven to ten (the maximum) self-reported questionnaires about each gaming session and returned the tablet data.

Total training duration progress was comparable between RW (88% completion, *M* = 267.0, *SD* = 96.3, range = 90–420) and FB (100% completion, *M* = 321.8, *SD* = 94.4,

range = 136–455), *p* = .22), meeting the target of 300 min of training over 2 weeks. Despite these similarities, we found that the amount of continuous playing time in the RW group was significantly lower than the amount of continuous playing time in the FB group as shown in Table 3, $W_A = 19$, *p* < 0.001). The continuous playing time was 54% of the logged training duration in RW and 86% in FB. Training duration was strongly and positively correlated with the continuous playing time, $r(24) = .73$, *p* < .0001, suggesting both variables reliably measure training dose.

Comparable amounts of motor movement (number of taps) were observed between games as shown by similar tapping rates per minute of training between games (*p* = .29). Participants expressed above-average levels of enjoyment, comparable for both games (*p* = .98). When participants were asked if they would recommend the game, more than half of the participants in each group responded positively, and the distribution of responses was similar between games (*p* = .90). Participants in the RW group perceived the game as significantly more difficult than FB ($W_A = 119$, *p* = .03); however, perceived difficulty did not correlate significantly with enjoyment in RW (*p* = .80) or FB (*p* = .09).

Figure 3 shows a correlation matrix with the relations between vector length (1 = perfect sync; 0 = no sync), perceived difficulty (5 = very difficult; 1 = very easy), stimuli appreciation (1 = Don't like the music; 5 = Really like the music) and syncopation (1 = no clear beat; 0 = all beats pronounced isochronously).

As shown in Fig. 3, stimuli with lower vector lengths, which were harder to tap to, were perceived as more difficult and less appreciated, while easier-to-tap stimuli were more appreciated. Syncopation may play an intermediate role, as some level of syncopation is enjoyable (Matthews et al., 2019; Vuust & Witek, 2014). More syncopated stimuli, though perceived as more difficult, scored high on both vector length and appreciation, suggesting that factors such

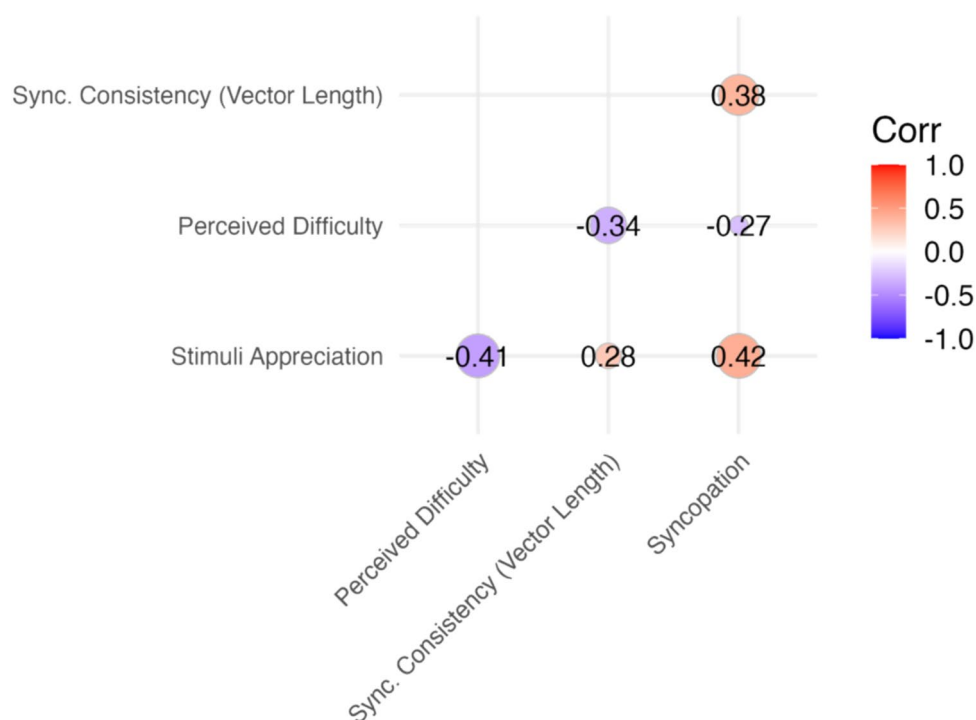


Fig. 3 Correlation matrix showing relations between rhythmic aspects and game acceptance (all $p < .05$)

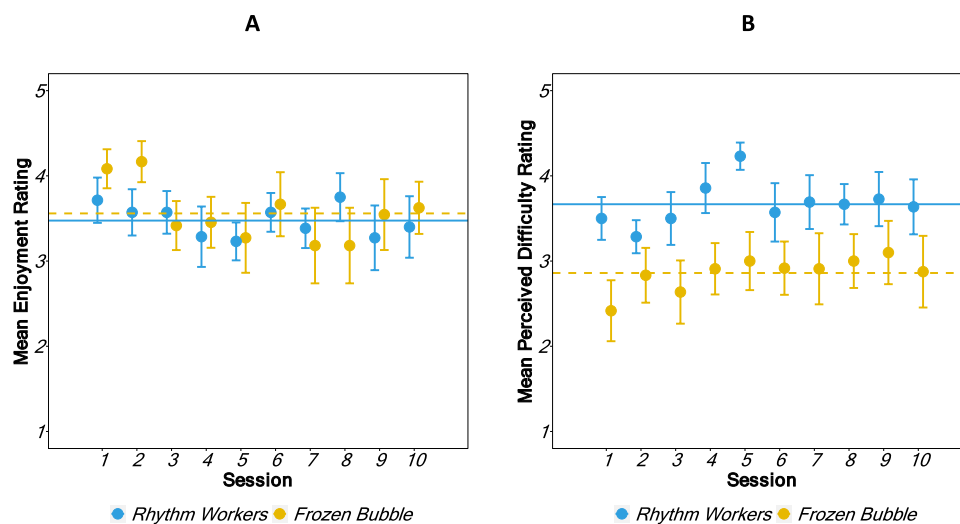


Fig. 4 Time series of mean enjoyment **A** and mean perceived difficulty over the sessions **B** between Rhythm Workers and Frozen Bubble. Error bars indicate the standard error, and horizontal lines represent the means across sessions

as pulse clarity or rhythmic pattern may also influence variability in vector length. Both groups played a comparable number of sessions, averaging five per week per game. Figure 4 shows the evolution of enjoyment and perceived difficulty over the sessions for both games.

Rhythmic performance

Table 4 shows the rhythmic performance at both time points between games on individual tasks of BAASTA and the BTI.

In the BTI, which captures the general capacity to track a beat, a positive effect of the training condition, $t(17) = -2.46$, $p = .025$, was found for those who played the RW

Table 4 Rhythmic performance of children with ADHD after training

Rhythmic Domain		Rhythm Workers					Frozen Bubble					p^5
		N ²	Mean	SD	Min	Max	N ²	Mean	SD	Min	Max	
BTI	Pre	13	0.05	1.01	− 1.17	1.79	12	0.02	0.76	− 0.99	1.15	.89
	Post	13	0.19	0.84	− 1.33	1.45	12	− 0.07	0.84	− 1.19	1.17	.41
	Δ^3	13	0.14	0.48	− 0.60	1.11	12	− 0.10	0.43	− 0.93	0.69	.025⁶
Paced tapping to music ¹	Pre	12	0.76	0.23	0.36	0.99	11	0.64	0.29	0.16	0.97	.32
	Post	13	0.79	0.22	0.36	0.98	12	0.60	0.35	0.10	0.97	.11
	Δ^3	12	0.19	0.47	− 0.28	1.05	11	− 0.05	0.52	− 0.56	0.83	.015⁶
Paced tapping to metronome ¹	Pre	13	0.82	0.11	0.62	0.97	12	0.81	0.12	0.57	0.94	.99
	Post	13	0.83	0.17	0.30	0.96	12	0.82	0.13	0.53	0.96	.73
	Δ^3	13	>0.01	0.91	− 2.62	0.96	12	0.01	0.62	− 1.25	0.83	.14
Rhythm perception d'	Pre	13	1.41	1.31	− 0.29	3.54	12	1.70	0.80	0.74	3.07	.53
	Post	13	1.55	1.05	− 0.16	3.07	12	1.74	0.76	0.76	2.79	.55
	Δ^3	13	0.13	0.86	− 1.80	1.37	12	0.03	0.61	− 1.13	10.7	.69

¹Synchronization consistency score²Due to missing data for some participants who could not complete all the tasks because of task difficulty (e.g., tapping in antiphase or double-time) or task-specific inattention³Change scores⁴Averages based on z-scores⁵Wilcoxon rank sum test p value⁶ p value of the main effect of the *game Played* in linear model:

Difference score = 1 + Game Played * Cumulative Play Time * Symptom Severity

Note: In bold $p < .05$

game compared to those who played the FB game (see Table 4). The model intercept was significant, $t(17) = 2.58$, $p = .02$, and because RW was coded as 0 and FB as 1, this finding indicates that the increase in the BTI after the training was greater than 0 in this model. The other interaction terms in the model involving the experiment conditions (*game played * symptom severity* and *game played * continuous playing time * symptom severity*) were not significant ($p \geq .33$) and the omnibus model (*difference score = 1 + game played * continuous playing time * symptom severity*) provided an overall good fit, $F(7, 17) = 2.00$, $p = .12$, $R^2 = .45$, with a medium effect size ($\eta^2 = 0.11$).

Similarly, for tapping to music there was a positive effect of the training condition, $t(15) = -2.75$, $p = .015$, for those who played the RW game compared to those who played the FB game (see Table 4). We also observed within-group improvement for RW, as indicated by a significant model intercept, $t(15) = 3.04$, $p = .008$. No interaction terms in the model were significant ($p \geq .19$), and the omnibus model provided an overall good fit ($F(7, 15) = 2.69$, $p = .051$, $R^2 = .56$), with a medium effect size ($\eta^2 = 0.12$).

The omnibus models were not statistically significant for paced tapping to a metronome ($p = .46$) and the BAT rhythm perception task ($p = .30$). The correlation between

improvement in rhythm perception and the music tapping tasks was positive but not statistically significant ($p = .25$).

To assess whether the positive effect of the rhythmic training was linked to the individual amount of training, we tested the relation between continuous playing time and rhythmic improvements (see Fig. 5). For RW, continuous playing time was strongly and positively correlated with improvement in paced tapping to music, $r(10) = .68$, $p = .008$, and the BTI, $r(11) = .53$, $p = 0.03$, but not for FB ($p \geq .16$). We found a similar trend for total training duration, which was positively correlated with improvements in paced tapping to music, $r(10) = .63$, $p = .01$, and for the BTI, $r(11) = .50$, $p = .04$, for RW group, but not FB ($p \geq .14$). We also found that pre-training scores on the BTI for those who played RW were negatively correlated with BTI improvement, $r(11) = -0.56$, $p = .045$.

Executive functioning

Table 5 reports the pre-, post-training, and difference scores for the various measures of the three executive functioning tasks, namely the Go/No-Go, flanker, and set-shifting task according to each game.

Training with RW had a positive effect on proportional response time scores of the combined executive functioning

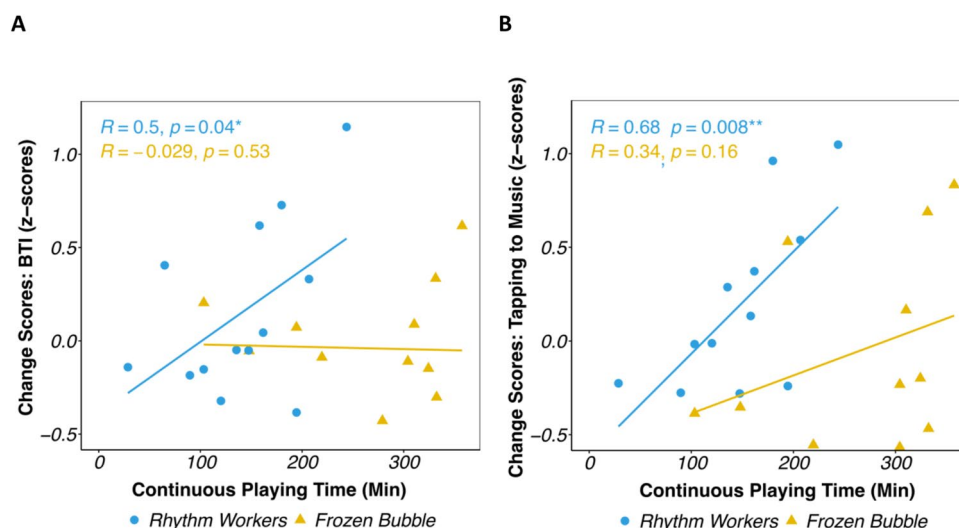


Fig. 5 Relationship between training dose and improvement. In **A** the Beat Tracking Index and **B** the paced tapping to music task by game

index compared to playing FB, $t(24) = 1.72, p = .049$, with a medium effect size, $\omega^2 = 0.07$. Children who played RW showed an improvement (i.e., mean change greater than 0), $t(11) = 1.86, p = .045$; this was not the case for FB ($p = .73$).

Discussion

We conducted a proof-of-concept study to test gamified rhythmic training for children with ADHD employing a parallel-arm randomized control trial design. The protocol was carried out remotely using digital training, online tools, and equipment mailing. The rhythmic “serious game” on a tablet, RW, was compared to an active control condition (non-rhythmic game, FB). The primary goal was to assess the feasibility of the training program in children with ADHD, whose impairments in attention are linked to rhythmic deficits (Puyjarinet et al., 2017) – a proposed risk factor in neurodevelopmental disorders more broadly (Ladányi et al., 2020; Lense et al., 2021), which may in turn be associated with deficits in executive functioning. A secondary goal was to test the effectiveness of the training on rhythmic abilities using BAASTA and, as an exploratory aim, on executive functioning.

Participants achieved an 87% completion rate of the entire research protocol, surpassing the expected rate (70%) for pediatric mental disorders (Bogdan et al., 2023). The target training duration of 300 min was met at 88% for RW and 100% for FB. Both games exhibited similar enjoyment levels and comparable amounts of motor activity (finger taps). Enjoyment values were high and around 3.5/5. Therefore, we expect that children would be willing to play the game in a more extended training program while maintaining their

enjoyment. Despite RW being perceived as more difficult, this was not related to the enjoyment children experienced during the 2-week training sessions; moreover, this did not impact the improvement of sensorimotor or executive functioning. It is noteworthy that participants spent more continuous time playing FB due to RW's level navigation time. Each level in RW ranged between 1 and 3 min; then, participants spent time on the score, medal, and map screens between levels. This imbalance worked in favor of the study's research objectives and showed that even less training than anticipated is sufficient for producing specific training effects. Another encouraging statistic was that only 18% of responding participants who played RW and 13% of those who played FB did not recommend the game they played. This proof-of-concept assessment provides a suitable empirical basis for analyzing and interpreting the training's effectiveness in improving rhythmic and executive functioning abilities.

The present findings establish FB as a suitable active control game, sharing fundamental characteristics with RW – such as comparable graphics, music, objectives, and motor demands – while excluding the critical experimental manipulation of movement synchronization to a musical beat. The inclusion of a rigorously designed active control is essential for ensuring the validity of intervention effects, as it mitigates the influence of confounding factors such as placebo effects or general engagement. By replicating non-specific elements of the intervention (e.g., duration, interaction) while systematically excluding the core therapeutic component, an active control facilitates the isolation of underlying mechanisms responsible for observed outcomes, thereby enabling robust causal inferences (Grau-Sánchez et al., 2022).

Table 5 Executive functioning (EF) performance of children with ADHD

EF Domain		Rhythm Workers					Frozen Bubble					<i>p</i> ⁶
		N ³	Mean	SD	Min	Max	N ³	Mean	SD	Min	Max	
EF index (Accuracy) ⁵	Pre	13	− 0.03	0.12	− 0.23	0.32	13	− 0.08	0.11	− 0.36	0.07	.26
	Post	13	− 0.02	0.09	− 0.22	0.11	13	− 0.05	0.07	− 0.19	0.06	.51
	Δ^4	13	> 0.00	0.09	− 0.20	0.15	13	0.04	0.13	− 0.14	0.38	.75 ^a
EF index (Speed) ⁵	Pre	13	− 0.11	0.81	− 1.27	1.42	13	0.11	0.76	− 0.61	2.09	.47
	Post	13	0.50	1.31	− 1.00	4.05	13	0.09	0.85	− 1.78	1.32	.35
	Δ^4	13	0.61	0.94	− 0.71	2.68	13	− 0.03	0.96	− 1.87	1.20	.05^a
Go/No-Go (A')	Pre	13	0.90	0.06	0.75	0.96	13	0.94	0.04	0.86	0.99	.05
	Post	13	0.87	0.10	0.58	0.95	13	0.93	0.03	0.87	0.98	.07
	Δ^4	13	− 0.03	0.07	− 0.17	0.04	13	− 0.01	0.04	− 0.10	0.06	.78 ^a
Incongruence effect (Accuracy) ¹	Pre	11	− 0.03	0.09	− 0.25	0.09	13	− 0.11	0.16	− 0.46	0.00	.15
	Post	11	− 0.05	0.11	− 0.34	0.06	13	− 0.05	0.10	− 0.32	0.06	.99
	Δ^4	11	− 0.02	0.08	− 0.13	0.13	13	0.06	0.15	− 0.13	0.49	.12 ^a
Incongruence effect (Speed) ²	Pre	11	− 0.05	0.05	− 0.13	0.02	13	− 0.03	0.06	− 0.14	0.04	.23
	Post	11	− 0.02	0.08	− 0.15	0.11	13	− 0.06	0.07	− 0.24	0.04	.24
	Δ^4	11	0.03	0.09	0.15	0.18	13	− 0.03	0.07	− 0.12	0.10	.04^a
Cognitive flexibility effect (Accuracy) ¹	Pre	13	− 0.05	0.14	− 0.21	0.32	13	− 0.05	0.10	− 0.26	0.18	.99
	Post	13	− 0.02	0.10	− 0.13	0.15	13	− 0.04	0.07	− 0.20	0.06	.59
	Δ^4	13	0.03	0.13	− 0.20	0.27	13	0.03	0.13	− 0.23	0.26	.37
Cognitive flexibility effect (Speed) ²	Pre	13	− 0.47	0.19	− 0.72	− 0.13	13	− 0.47	0.20	− 0.71	0.08	.99
	Post	13	− 0.39	0.30	− 0.98	0.31	13	− 0.36	0.20	− 0.61	− 0.10	.75
	Δ^4	13	0.08	0.27	− 0.60	0.52	13	0.11	0.30	− 0.40	0.53	.61

¹Proportion of correct responses (0.00 = no incongruence)²Proportional reaction time score (0.00 = no incongruence)³Missing data for some tasks because of internet connectivity disruptions⁴Change scores⁵Means based on *z*-scores⁶Welch two-sample *t* test^aOne-tailed hypothesis, otherwise two-tailedNote: In bold *p* < .05

Effects of a “serious” rhythmic game on rhythmic abilities in ADHD

This study presents the first empirical evidence that gamified rhythmic training can selectively enhance rhythmic abilities in children with ADHD, a population characterized by rhythmic impairments (Noreika et al., 2013; Puyjarinet et al., 2017). The effect of the rhythmic training was observed in improved general rhythmic skills in BAASTA tasks (Dalla Bella, Foster et al., 2024a). No comparable improvement was observed with the non-rhythmic video game (FB). Notably, time spent on RW correlated strongly with general rhythmic improvements on the BTI (Beat Tracking Index – BTI; Puyjarinet et al., 2017).

This study marks the first use of the BTI in neurodevelopmental disorders with a randomized controlled trial design and supports the sensitivity of the tablet version of BAASTA

to detect general sensorimotor training effects in ADHD. The use of the BTI enhanced reliability and power in this at-home proof-of-concept study by compensating for missing or invalid trials caused by distractions, environmental noise, or symptom severity during remote testing. The effect in the BTI was more heavily weighed by the specific contributions of the music tapping subtask and the rhythmic perception increases in RW. However, this appears to be due to a high level of pre-training tapping consistency in metronome tapping, leaving little space for improvement for that task.

An individualized approach to training is crucial, as demonstrated by research on rhythmic cueing in Parkinson’s disease, where individuals with relatively preserved abilities to track the beat showed more positive responses (Dalla Bella, Benoit et al., 2017a, Dalla Bella et al., 2018). In contrast, rhythmic abilities in individuals with ADHD are impaired, though perhaps not as severely as in Parkinson’s

disease. In this study, participants with weaker initial rhythmic skills gained more from the RW training, suggesting that those with lower baseline abilities had greater potential for improvement. This suggests that some participants may have reached a performance ceiling, while others were more sensitive to skill transfer effects during the training.

Effects of a “serious” rhythmic game on executive functions in ADHD

Beyond observing sensorimotor improvement, we investigated the transfer of skills from sensorimotor synchronization to executive functioning. Despite the limited training time compared to full-fledged music training programs (300–19,500 min; Jamey et al., 2024), our findings show initial causal evidence of improved executive functioning in children with ADHD trained with RW, but not in those who played FB. This increase in executive functioning on combined inhibition control and cognitive flexibility tasks affected response speed but not accuracy, which was above 90% correct in both groups and likely at ceiling. These results are promising and might lead to even more prominent effects of rhythmic training on executive functioning with a longer training duration and a larger sample size.

Our findings align with Diamond’s integrated theory of executive functioning (Diamond, 2013), which emphasizes inhibitory control and cognitive flexibility as interconnected processes essential for adaptive behavior and gradually developing over time. Synchronizing movements to complex rhythmic patterns requires inhibiting premature responses, filtering out distracting off-beat sounds, and keeping a stable alignment of movement to the beat over time. Since RW training difficulty increases via musical stimulus complexity, it primarily engages interference control (resisting irrelevant auditory information), explaining stronger effects on the **flanker** task. Improvements in response inhibition (Go/No-Go task) and cognitive flexibility (set-shifting task) were also observed after RW training, likely due to set-shifting depending on inhibition to stop the previous rule set and inhibit previously learned sequences in order to make way for learning new sequences; however, at this proof-of-concept study’s sample size and training duration, these increases did not reach statistical significance. These results support recent reviews identifying inhibitory control and cognitive flexibility as the most critical components of executive functioning during music training in childhood development (Jamey et al., 2024; Rodriguez-Gomez and Talero-Gutié, 2022). The observed benefits of rhythmic training on executive functioning suggest that extending the duration of training may lead to even more pronounced effects. The influence of rhythmic training on motor and executive functions may be explained by the cognitive and neural mechanisms underlying predictive timing – the ability

to anticipate future events based on regular temporal cues. Predictive timing is supported by associations between subcortical and cortical brain regions (Jones, 2019; Large & Jones, 1999; Piras & Coull, 2011; Schwartze & Kotz, 2013). Interventions like gait rehabilitation using auditory cues are thought to engage these neural circuits. Explicit timing tasks, often categorized as “cognitively controlled timing,” rely on basal ganglia-cortical networks, which are also critical for executive functioning. Because executive functioning depends on timing information to coordinate perception-action sequences, improvements in predictive timing efficiency are likely to translate into enhanced executive functioning. Response time metrics, which are central to assessing changes in executive functioning, further underscore this connection. Consequently, we propose that predictive timing is closely linked to executive functioning abilities.

Predictive timing and executive functioning are closely connected, as both depend on timing information to coordinate perception-action sequences, with response time serving as a key metric for assessing executive function. Recent work highlights how rhythmic entrainment, or cognitive-motor entrainment, enhances executive functioning by optimizing cognitive and motor processes through synchronized neural oscillations (Schmid, 2024). Frameworks like dynamic attending theory and active sensing explain how rhythmic temporal structures improve attentional control and reduce cognitive load, particularly in dual-task scenarios. EEG studies show that active sensorimotor synchronization boosts executive functioning, evidenced by increased P300 ERPs and beta-power peaks, underscoring the specificity of these benefits to active entrainment processes (Conradi et al., 2016; Schmidt-Kassow et al., 2009, 2013; Schmidt-Kassow & Kaiser, 2023). Our findings provide behavioral support for these theories, highlighting the potential of rhythmic entrainment to enhance executive functioning, though future studies should further investigate the neural mechanisms using diverse methodologies.

Auditory rhythm-based training may target the atypical timing abilities observed in children with ADHD, including deficits in beat-based and interval timing (Noreika et al., 2013; Zelaznik et al., 2012). These timing impairments, often characterized by greater variability and reduced accuracy in synchronization tasks, have been linked to broader executive functioning deficits, including attention regulation and motor planning (Kliger Amrani & Zion Golumbic, 2020; Marx et al., 2017; Puyjarinet et al., 2017). This reasoning aligns with the hypothesis that rhythm-based interventions can enhance sensorimotor synchronization and, consequently, improve motor coordination, attention, and executive functioning (Dalla Bella, Benoit et al., 2017a; Teki et al., 2011). Rhythm training may offer a structured approach to addressing these difficulties by utilizing predictive timing

mechanisms to enhance temporal consistency and attention regulation. Synchronizing movements to an external rhythmic cue, such as tapping to a beat, may tap into internal neural mechanisms that strengthen both motor and cognitive processes in children with ADHD. These findings are consistent with the proposal that rhythm-based training could mitigate attentional deficits and timing irregularities by engaging basal ganglia-cortical networks responsible for cognitive control and timing regulation (Rubia et al., 2009; Teki et al., 2011).

Importantly, this type of gamified, individualized training may also appeal to children with ADHD who face difficulties engaging in conventional therapy or highly structured behavioral interventions. At-home rhythm-based interventions could offer an accessible and effective entry point for addressing core deficits in timing and executive functioning. At the very least, such approaches have the potential to supplement existing therapeutic practices, providing an innovative avenue for managing ADHD symptoms and improving cognitive and behavioral outcomes.

Limitations and future directions

This proof-of-concept study had some methodological and statistical limitations. In line with Whitehead et al. (2016) guidelines for pilot studies, formal power calculations were not necessary. Drawing from a meta-analysis on music training and inhibition control, we anticipated a medium-to-large effect size (Jamey et al., 2024). With 80–90% power at a 5% significance level, a sample size of 13–15 participants per group was deemed sufficient. However, for broader generalization, replication, and more advanced statistical analyses, a larger sample size and extended training duration are suggested.

The sample size was tailored for proof-of-concept, limiting the scope of analyses. Our results did not detect a relationship between training dose and executive functioning or general rhythmic improvements and changes in executive functioning; this may be due to the small sample size of the study and the brief training duration. Further research is required to draw definitive conclusions about the interconnections between rhythm-induced executive functioning improvement via improved general rhythmic skills. A larger cohort is recommended for extrapolating and replicating findings, enabling more sophisticated statistical analyses, such as mediation effects and longitudinal analyses (for example, of session-by-session feedback). Modification of the Go/No-Go task's difficulty is suggested, as it reached ceiling performance. The study lacked double-blinding verification, but the methodology is innovative for music training because it can technically afford a certain degree of double-blinding. When more general music training is administered, it can be difficult for a

laboratory specializing in music and psychology to hide the research objective from participants. By including music in both conditions, the more subtle manipulation of synchronization demands conceals the research objective more effectively.

A 6:1 male-to-non-male ratio resulted from simple random sampling in the recruitment process. While parents of both boys and girls had an opportunity to participate, the sample is skewed towards boys, limiting generalizability to girls. However, the inclusion of three girls and one non-binary child suggests RW and FB are suitable for all genders. Some subtypes of ADHD may be more prevalent in this sample than in the ADHD population. As the sample was not based on formal diagnoses, future RCTs should include formal diagnoses and ADHD symptom screening tools. To better understand how individual differences in symptom severity may affect the effectiveness of the training, we recommend that future studies incorporate a measure of clinical severity. However, the current study sets the stage for a randomized clinical trial with a larger sample. Future research will explore structural and functional brain changes, shedding light on perceptual and motor processes in rhythmic performance. Longitudinal studies with larger cohorts will examine the potential long-term effects of rhythmic training using “serious games” on social activities such as conversational skills and family quality of life.

This rhythmic training format could benefit other clinical populations, such as children on the autism spectrum (AS) for whom poor predictive timing and cerebellar dysfunction may contribute to social and communication challenges, with potential effects on cognition (Geretsegger et al., 2022; Kelly et al., 2021; Ladányi et al., 2020; Lense et al., 2021; Marquez-Garcia et al., 2022). Children on the AS often face difficulties adhering to therapy schedules (Sandoval-Norton & Shkedy, 2019), and the minimally social rhythmic “serious game” format may be particularly engaging for them. Extending similar rhythmic training to children on the AS would help explore how potential enhancements in sensorimotor skills could affect other core autistic symptoms like repetitive behaviors, speech, and communication deficits, and whether these improvements co-occur with increases in certain specific executive functioning (such as inhibition and cognitive flexibility) after training. Another relevant group is children who stutter, as evidence suggests non-verbal sensorimotor timing deficits in adolescents with higher levels of stuttering severity (Falk et al., 2015). Applying the protocol to children who stutter may yield beneficial outcomes for restoring specific speech functions.

Conclusion

RW and the control game FB were successfully validated in children with ADHD. The current results provide initial causal evidence that playing RW improves these children's

sensorimotor synchronization and specific executive functions. The training duration of approximately 300 min was sufficient for observing these improvements, with a positive correlation between training duration and the strength of improvement in sensorimotor synchronization. These findings suggest that mechanism-driven approaches in music training are efficient for enhancing non-musical skills, requiring a lower dose to generate effects, and enabling tailored training for specific clinical populations. Future investigations could assess this protocol in other neurodevelopmental disorders and in the context of a larger double-blinded longitudinal RCT. To further understand the neural underpinnings related to the training games, it is strongly encouraged to explore brain activity while playing the games.

Funding This work was supported by funding from grant 05453 from the Natural Sciences and Engineering Research Council of Canada (NSERC), grant 115050 from the Canadian Institute of Health Research (CIHR), and grant 0160 from NSERC Tier 1 Canada Research Chairs to Simone Dalla Bella, Canada Research Chair in Music Auditory-Motor Skill Learning and New Technologies.

Availability of data and materials The datasets generated during and/or analyzed during the current study are not publicly available due to participant confidentiality but are available from the corresponding author on reasonable request. Because of this limitation, the analysis code is illustrated with a synthetic dataset, which allows readers to check the correctness of their implementation. See the Open Practices Statement for links to stimuli.

Code availability Upon request to the authors.

Declarations

Conflicts of interest/Competing interests SDB is on the board of the BeatHealth company dedicated to the design and commercialization of technological tools for assessing rhythm abilities such as the BAASTA tablet and implementing rhythm-based interventions. Other authors have no competing interests to disclose.

Ethics approval This study was conducted according to the ethical standards of the Comité d'éthique de la recherche en éducation et psychologie (CEREP) of the Université de Montréal - CEREP-20-008-P.

Consent to participate All participants consented to participate.

Consent for publication All co-authors consent to publication.

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- Open Practices Statement** Stimuli, gameplay examples, data and code are available at: https://osf.io/gykjd/?view_only=26be79399f1e48fe838107df437e0ceb. This proof-of-concept study was not preregistered.
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