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A Proof-of-Concept Study of Gamified Rhythmic Training in Preadolescents Who Stutter

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ABSTRACT

Stuttering is a developmental speech fluency disorder linked to timing deficits in speech motor control. Given the shared neural mechanisms between rhythmic timing and speech production, rhythm-based interventions may hold promise for stuttering. This proof-of-concept study evaluated the feasibility and potential benefits of a gamified rhythmic training program, *Rhythm Workers* (RW), in preadolescents who stutter. Twenty-one children (aged 9–12) were randomly assigned to RW or an active control game, which they played at home for 3 weeks. We assessed feasibility and potential training effects on rhythmic, cognitive, and speech-related abilities. Both games were well accepted, and compliance was moderate to high. Only participants trained on the rhythm game showed moderate enhancements in rhythmic synchronization, interference control, oromotor performance, and reduction of stuttering after training. The improvements (except for interference control) correlated with the training dose. Moreover, speech fluency gains were associated with improved rhythmic performance. While some effects did not reach statistical significance due to the limited sample size, the observed dose–response patterns and domain-specific improvements support the feasibility and promise of rhythmic gaming for young people who stutter. This study provides preliminary evidence that rhythm-based training can enhance speech and cognitive outcomes in preadolescents who stutter.

1 | Introduction

Stuttering, also known as developmental stuttering or childhood-onset fluency disorder (DSM-V), is a neurodevelopmental speech motor disorder characterized primarily by involuntary disruptions in the flow of speech [1]. These disruptions manifest as repetitions of sounds or syllables, prolongations of sounds, and blocks (temporary inability to initiate speech despite the intention to speak). Stuttering is sometimes accompanied by secondary behaviors (e.g., facial tension, physical movements) and can vary in frequency and intensity depending on the communicative context [2]. The condition typically emerges between ages 2 and 5, with a prevalence of approximately 5–8% in early childhood [3]. Many children recover naturally without specialized intervention, and estimates suggest that around 70–80% of affected children eventually attain fluent speech, often by late childhood or early adolescence. However, stuttering persists into adulthood in the remaining 20–30% of children with initial stuttering symptoms, corresponding to about 1% of the general population [4]. While stuttering is not caused by psychological factors, it often leads to significant psychosocial consequences, including anxiety, reduced social participation, and social stigma [5].

Previous research has found that rhythm and timing play a prominent role in stuttering (see Ref. [8] for an overview). Neuroscientific studies have converged on the basal ganglia–thalamo–cortical (BGTC) loop as a key pathway disrupted in stuttering [6–8]. The BGTC circuit, which includes the putamen, thalamus, supplementary motor area, and inferior frontal gyrus, is involved in initiating and sequencing motor actions, including speech, and in rhythmic processes beyond speech [9–15]. Altered BGTC connectivity is thought to contribute to the untimely initiation or inhibition of speech motor programs in stuttering [7, 16]. Moreover, the cerebellar–thalamo–cortical pathway, which also contributes to externally paced timing tasks such as synchronizing to a metronome, has been shown to be over-recruited in people who stutter, which can be interpreted as a compensatory response to weakened BGTC function [17–20]. Importantly, speech and rhythmic timing share overlapping neural circuits for auditory–motor coupling, particularly within the BGTC system [21]. In line with this idea, individuals who stutter display weaknesses in musical rhythm tasks [22–24]. Falk et al. [22] found that children and adolescents who stutter exhibited reduced synchronization accuracy and greater timing variability compared to controls when tapping to a metronome or music (i.e., beat synchronization). These timing alterations were more visible in those with persistent or severe stuttering and were not explained by general motor variability, suggesting specific impairments in auditory–motor integration and predictive timing mechanisms.

These findings provide a compelling rationale to explore whether rhythm training can enhance speech-related motor timing in stuttering. This idea was first proposed by Fujii and Wan [25], introducing their Sound Envelope Processing and Synchronization/Entrainment to a Pulse (SEP) hypothesis. The authors suggest that strengthening auditory–motor coupling in the BGTC via beat synchronization training may positively affect speech motor control. Rhythmic interventions built on beat synchronization may stimulate the shared neural timing network, promote temporal speech motor control, and potentially improve fluency outcomes in individuals who stutter [8]. However, beat synchronization tasks also engage neural systems involved in executive functioning, in particular attentional processes [13, 26]. Hence, it is a possibility that rhythm training in individuals who stutter could also lead to benefits in speech production via enhanced executive functioning. In recent years, rhythm training has shown promise for enhancing motor, attentional, and other cognitive skills in various populations. Rhythm-based serious games [27] were originally tested in Parkinson's disease [28, 29]. These studies showed improvements in rhythm perception and motor variability as well as a reduction of errors in manual and oromotor tasks after the training, in this group. Rhythmic skills were trained through finger-tapping to a musical beat, focusing on explicit timing precision and structured motor engagement. More recently, similar training through beat synchronization has been used to support executive functions in developmental populations, providing the first evidence of increased interference and inhibitory control in typically developing children [30], as well as in children with neurodevelopmental conditions such as attention-deficit/hyperactivity disorder (ADHD) [31] and autism [32].

1.1 | Aims and Hypotheses

Building on these advances, our study applies a serious gaming approach for rhythm training to preadolescents with developmental stuttering. While this age group has a relatively long history of stuttering, neuroplasticity during adolescence can still lead to remissions [33], potentially facilitated by rhythm training. Generally, music-based rhythmic training in stuttering remains largely unexplored. Given the potential overlap between timing deficits and speech fluency difficulties, such tools may hold promise for supporting speech functions in stuttering.

Our goal is to conduct a proof-of-concept study to evaluate the use of a rhythm-based serious game (Rhythm Workers, RW) in comparison to a motor control game (Frozen Bubble, FB) in developmental stuttering. Our primary goal was to assess feasibility, focusing on the compliance and acceptance of the training protocol by participants. We monitored if participants could engage with the training regularly, adhere to the sessions over the course of the protocol and whether they accept the game overall. We also verify known training effects in this age group, but unspecific to stuttering; first, whether the core training target is reached, that is, playing the rhythmic game enhances rhythmic abilities measured via a standardized mobile battery assessing rhythmic abilities [34, 35]. Second, whether we can observe potential effects on executive functioning, in particular interference control (flanker task), which increases in preadolescents with ADHD and autism after a similar rhythm training [31, 32].

Finally, to decide whether rhythm training holds promise for stuttering, specifically, we investigated potential transfer effects of rhythm training on speech motor skills and stuttering symptoms. Here, we assess potential improvements in basic oromotor skills as well as the reduction of stuttered dysfluencies. Improvement in oromotor skills (measured through a diadochokinetic task) could be beneficial in sustaining more stable articulatory processes in stuttering [28]. Reduction of stuttered dysfluencies after rhythm training would be the most direct evidence for potential benefits. In relation to this effect, we also examined the potential basis of speech effects by testing whether potential improvements in either speech-related skill are related to enhanced rhythmic abilities and executive functioning.

2 | Methods

2.1 | Participants

Twenty-four French-speaking participants who stutter between 9 and 12 years were recruited in the province of Québec, Canada, between July 2022 and August 2024. According to parental reports, participants self-identified as having a stutter and did not show any speech or language difficulties aside from stuttering, nor any hearing, physical, or cognitive developmental disorders. Three participants were excluded from the training study following recruitment: two based on a parental report of comorbidities after enrollment, and one withdrew after the initial testing due to lack of availability. The final sample was composed

TABLE 1 | Comparison between the two game groups at baseline (T1; Mann–Whitney tests).

Characteristics	RW group (n=11)					FB group (n=10)					
	M	SD	min	max	n	M	SD	min	max	n	p
Age (month)	128.1	16.1	105	150	11	130.1	16.3	108	50	10	0.56
OASES-S	2.1	0.5	1.5	3.3	11	2.1	0.4	1.5	2.4	9	0.82
IQ (Raven's Matrices)	99.2	15.3	75	124	11	101.3	11.8	86	120	10	0.61
Paced Tapping Index	−0.08	0.74	−1.24	0.61	11	0.00	0.92	−1.31	2.12	10	0.81
Response inhibition (A′; Go/No-Go task)	0.92	0.03	0.87	0.96	10	0.91	0.07	0.74	0.97	8	0.76
Interference control (flanker accuracy)	−0.02	0.05	−0.10	0.07	10	−0.02	0.04	−0.11	0.05	8	0.89
Interference control (flanker speed)	−0.04	0.04	−0.13	0.00	10	−0.07	0.07	−0.19	0.03	8	0.32
Cognitive flexibility (Set-shifting accuracy)	−0.06	0.10	−0.21	0.09	10	−0.09	0.23	−0.46	0.34	8	0.63
Cognitive flexibility (Set-shifting speed)	−0.38	0.12	−0.60	−0.19	10	−0.51	0.41	−1.29	0.21	8	0.15
Short-term memory (N-back 1)	0.93	0.08	0.75	1.00	10	0.92	0.11	0.66	0.99	8	1.00
Short-term memory (N-back 2)	0.87	0.08	0.79	0.99	10	0.75	0.23	0.41	0.96	8	0.72
Oromotor raw error %	12.7	10.0	0.0	32.9	10	6.0	5.1	0.0	15.1	10	0.17
Oromotor speed	0.6	0.1	0.6	0.9	10	0.6	0.1	0.7	0.6	10	0.48
Stuttered dysfluencies	5.2	6.8	0.3	22.6	11	1.9	1.8	0.0	5.2	10	0.22

Abbreviations: M, mean; n, number of participants per group; SD, standard deviation of the mean.

of 21 preadolescents who stutter (mean age 10.8 ± 1.3; 8.8–12.5 years), including nine girls. Ten of them had musical training, and five were left-handed. According to the Stuttering Severity Instrument–4 [36], stuttering severity in the sample was mostly very mild and mild (n = 13), with a few participants in the moderate (n = 5) and severe range (n = 3). Participants were assigned to either the rhythmic game (RW) or the nonrhythmic game (FB). Initially, the first six participants were randomly assigned to either group. Thereafter, stratified randomization based on gender was implemented to ensure an even distribution of boys and girls across both groups. The groups did not differ in handedness (p = 0.64), musical training history (p = 1.0), video game use (p = 0.21), and socioeconomic status (p = 0.62)—tested via χ^2 tests or Fisher tests. Moreover, they were comparable in baseline cognitive abilities (IQ, short-term memory, response inhibition), as well as in stuttering severity, both subjectively (OASES-S [37]) and objectively (% stuttered syllables on the SSI-4 [36]), as summarized in Table 1.

2.2 | Procedure and Training Protocol

The study included three assessment points: baseline (T0), pre-intervention (T1), and post-intervention (T2), each separated by approximately 3 weeks. Each testing session lasted 3 h. Testing sessions were separated into two parts whose order was counterbalanced across participants: nonverbal testing, which included executive functioning and rhythmic abilities, and verbal testing, which included stuttering assessment and articulatory performance, among some other tasks not reported here. Testing occurred online via the online platforms Zoom (nonverbal testing), JATOS using the BRAMS online testing platform (executive functioning [31] and IRIS; verbal testing).

At the end of the second testing session, a nonblinded research coordinator explained the game to the participants. Once participants understood the instructions, they started playing the game. A Samsung Galaxy Tab A 8.0″ (2019 model, SM-T290) tablet was provided for the study, featuring a 2 GHz processor, 1280 × 800 pixels display resolution, and 32 GB of RAM. All materials required for the study, including the tablet, which contained the game assigned to the participant and a standardized rhythmic assessment application, a gooseneck phone holder, Samson SR850 headphones, a Marantz professional M4U microphone, paper questionnaires, game-specific instructions and sanitizing kits, were mailed to participants via postal and courier services. Participants used the touchscreen to navigate and play the applications, while the headphones were used to play the sounds and music from the applications.

Participants were instructed to play their assigned game for 30 min a day, 5 days a week, for 3 weeks (target of 450 min of game engagement—how long the session is reported by participants and how much time was logged operating the game application). They were also informed that they could play more if they wished, but were advised not to exceed 1 h of gameplay per day. Participants were asked to log their daily gameplay in a handwritten journal. During gameplay, time is also spent navigating menus, receiving medals, and launching levels. To accurately assess active engagement, we logged cumulative playing time, defined as the total minutes spent in live gameplay within levels. Prior studies with these game versions indicate that cumulative playing time can be up to 30% lower than the total time spent within the app. To estimate training duration (dose), we adopted this more conservative metric. We considered approximately 300 min of cumulative gameplay as a benchmark for good compliance in this study.

2.3 | Rhythmic "Serious Game"

This proof-of-concept study incorporated an adapted version of *Rhythm Workers* (RW), a rhythm-based training game originally developed for adults [27]. Specific design adjustments tailored for a pediatric population are detailed in Jamey et al. Players tap in time with the musical beat to build a virtual building with progression tied to tapping performance. For example, when players tap with perfect consistency for eight beats, they get 100% accuracy, which contributes to their general score. When the general score reaches a certain threshold, a new floor rises on the virtual building. The goal is to finish the building within a given time limit. There is a total of 32 distinct levels, each built around a unique music stimulus ranging from 2 to 4 min long and presented at a consistent tempo. All 32 levels must be completed to finish the game. Difficulty is increased via the rhythmic complexity of the musical stimuli. Scoring was calculated using the same accuracy metrics as described in Bégel et al. [27].

The control game was a modified version of *Frozen Bubble* (FB), adapted from an open-source Android build hosted on GitHub (https://github.com/videogameboy76/frozenbubbleandroid). This arcade puzzle shooting game challenges players to eliminate clusters of colored bubbles by launching matching ones from a cannon using touch input. The same music as RW is played in the background, but players do not need to synchronize to it to progress in the game. The upper rows of bubbles steadily move downward, and play ends if the bubbles reach the bottom edge of the screen. The objective is to match and clear groups of three or more identically colored bubbles, which also causes any attached lower bubbles to drop. For a visual overview of the RW and FB game environment and further details, see Jamey et al. [31].

2.4 | Feasibility: Evaluation of Game Compliance and Acceptance

We quantitatively evaluated participant compliance by collecting data recorded on the tablet device, including: the time spent per session (target ∼450 min), in active gameplay (cumulative playing time, target ∼300 min), and the total number of taps on the screen. A short debriefing was requested from participants, but not mandatory. Children were asked to provide information about their level of enjoyment of the game on 5-point Likert scales (1 = boring, 5 = very fun). They were asked how they felt about playing the game for 3 weeks, if they would play for another 2 and 4 weeks. Other items included whether they found the game difficult to play, how often they felt frustrated, how they felt time went by, and whether they would recommend others play the game.

2.5 | Outcome Measures

We evaluated rhythmic, executive functioning and speech performance at baseline (T0) and (T1) and change scores by subtracting post- minus pre-training means (T2−T1). Participants whose change scores on any task construct (e.g., flanker accuracy) exceeded ±3 standard deviations from the group mean were considered outliers and excluded from the analyses, along with their corresponding T1 and T2 scores. For example, one participant scored 100% incorrect responses on the flanker task at T1 and 76% at T2—a pattern that is implausible as an effect of training and suggests task disengagement or error. Sample sizes vary slightly across tasks due to remote testing constraints (such as internet interruptions), occasional participant fatigue affecting whether a task was finished, and the exclusion of outliers exceeding ±3 SD from the group mean.

2.5.1 | Core Training Effect: Rhythmic Abilities

We evaluated rhythmic abilities using sensorimotor tasks from Battery for the Assessment of Auditory Sensorimotor Timing Abilities (BAASTA [34, 35]), which has been previously used in children, including those with developmental disorders [38, 39]. In paced tapping tasks, participants tapped the index finger of their dominant hand in time with either a metronome (inter-onset intervals: 450, 600, 750 ms) or a musical sequence (inter-onset interval: 600 ms). We computed logit-transformed vector lengths to quantify tapping consistency—that is, the regularity and temporal alignment of taps occurring at the same rate as the cued stimuli. A value of 1 indicated perfectly isochronous tapping. For unpaced tapping tasks (regular and fast spontaneous tapping), we quantified motor variability using the coefficient of variation of the inter-tap intervals (CV-ITI). CV-ITI was calculated as the standard deviation of the inter-tap intervals divided by their mean [40].

Tapping consistency and CV-ITI subtask values at each time point were z-scored using the group mean and standard deviation from the pre-training session (T1), allowing for standardized comparisons of change over time. To align the directionality of change with other tapping consistency measures (e.g., vector length), z-scored CV-ITI values were inverted so that higher scores reflected lower variability (i.e., better performance). If T1 or T2 scores were missing for a specific task, the corresponding single T1 or T2 score was excluded from analyses. We averaged the z-scores of each task (Music, Metronome 450 ms, Metronome 600 ms, Metronome 750 ms) by time point (T1 and T2) to form a paced tapping index. Unpaced tasks were averaged similarly to calculate an unpaced tapping index.

2.5.2 | Exploratory Hypothesis: Executive Functioning

We administered the Eriksen flanker fish task to assess interference control. On each trial, participants saw either one or five fish aligned horizontally and indicated the direction of the central fish (left/right) by pressing a key, ignoring the surrounding (flanking) fish. Trials were either neutral (single fish), congruent (flankers swam the same direction), or incongruent (flankers swam opposite). Each trial allowed 2000 ms to respond (500 ms stimulus + 1500 ms fixation), with a 750 ms fixation cross preceding each. The task included 96 trials and lasted 3–5 min. After removing incorrect or premature responses, raw response times (RTs) below 200 ms and above 1000 ms were excluded to capture performance ranges related to interference control. Following prior studies, we calculated proportional RT from RT values as a sensitive measure of change in executive functioning after intervention [41, 42]. The proportional RT (interference control speed) was computed as (Congruent RT—Incongruent RT) / (Congruent RT), where higher (less negative) scores indicate better attentional functioning. Finally, we computed the difference between the proportional RT of congruent and incongruent trials. The same procedure was used for calculating the proportion of correct responses (interference control accuracy).

2.5.3 | Transfer to Speech-Related Skills: Oromotor Skills

The oral diadochokinesis (DDK) task was used to assess articulatory performance by measuring participants' ability to produce rapid, repetitive syllable or word sequences. DDK is a standard maximum performance task to measure articulation speed and accuracy [43]. It is widely used in speech-language pathology to assess oromotor speech function, particularly in the context of acquired motor speech disorders such as dysarthria and apraxia of speech [44]. Importantly, although the task measures aspects of speech motor control, it does not assess "fluency" in the sense of stuttering-related disfluencies. Findings regarding DDK performance in developmental stuttering are mixed, with some studies suggesting differences in sequencing or variability of rates [43]. Nevertheless, DDK remains a useful measure to explore potential transfer to oromotor skills, as it does not directly overlap with stuttering severity.

Participants were first introduced to the task through a structured familiarization phase, in which they were shown the pseudo-word (/pataka/) on a screen. This classical stimulus is used in sequential DDK tasks because it combines bilabial, alveolar, and velar places of articulation in a rapid sequence [44]. Using a pseudo-word rather than isolated syllables ensures that all participants produce the sequence with a consistent prosodic pattern, including word-final accent, final lengthening, and predictable pauses, minimizing variability that could arise if syllables were produced individually. Participants were asked to read it aloud, and then prompted to repeat it progressively first once, then three times, then five times to familiarize themselves with the required task. In the test phase, they were instructed to take a deep breath and repeat /pataka/ as quickly and accurately as possible until they ran out of air, completing two recorded trials. The task was repeated if participants did not follow the instructions, experienced severe speech initiation problems due to stuttering or ran out of breath after only two or three words, and in cases where a participant could not complete it, an additional attempt was made at the end of the session or in a subsequent visit. To evaluate oromotor skills, we calculated the number of oromotor errors and oromotor speed (i.e., interword-intervals, IWI). Higher oromotor speed (i.e., shorter IWIs) and fewer errors indicate higher oromotor skills [45]. Six types of errors were coded, following guidelines provided by Scott Yaruss and Logan [37]: (1) insertions or (2) deletions of sounds (e.g., production of incomplete sequences), (3) changes in voicing or (4) placement, (5) exchanges between sounds, and (6) perseveration of sounds. The percentage of words containing errors over all words produced was calculated to obtain a measure of oromotor errors (error %). For oromotor speed assessment, we segmented the duration of IWIs using Praat [46], a standard approach to measuring speech rate [47], beginning with the burst of /p/. Oromotor speed was derived from these intervals, with shorter mean IWI duration reflecting faster production speed. It is important to note that this measure was intended to capture oromotor timing, not speech fluency in the clinical sense (i.e., absence of stuttering).

2.5.4 | Transfer to Speech: Stuttered Dysfluencies

To assess speech dysfluencies, we measured stuttered dysfluencies using the percentage of stuttered syllables in a naturalistic speech sample, following the procedures outlined in the Stuttering Severity Instrument (SSI-4 [36]). Participants produced both a spontaneous and a read speech sample at each time point. After the testing, a research assistant counted a total number of ~300 syllables per sample and the number of stuttered syllables therein. The percentages of stuttered syllables for both spontaneous and read speech were averaged to obtain a composite dysfluency score per time point.

2.6 | Statistical Tests

To evaluate changes related to game play (post-training [T2] minus pre-training [T1]) and effect size estimate between groups, we used independent samples *t*-tests and, if assumptions for parametric testing were not met, the Mann–Whitney test from the *rstatix* package in R Studio [48]. Effect size interpretations were based on Ref. [49]. Normality was tested using the Shapiro–Wilk test and homogeneity of variance using Levene's test. Spearman correlations were calculated between the outcome measures and training dose (cumulative playing time). We conducted one-tailed tests when assessing change scores based on the theoretical proposal that training rhythmic abilities would improve rhythmic, executive functioning and speech abilities [8, 21, 25], and empirical evidence that rhythmic training improved some of these functions in previous studies [28, 31].

2.7 | Ethical Approval

The study received prior approval from the ethics board of the University of Montreal (CEREP-21-063-P) and the Centre intégré universitaire de santé et de services sociaux du Centre-Sud-de-l'Île-de-Montréal (CIUSSMTL 2024-1926). Written informed consent was obtained from all participants' parents, and all participants assented orally.

3 | Results

3.1 | Pre-Training Comparisons for Rhythmic, Executive, and Speech Functioning

Participants did not differ on any of the rhythmic tasks between games at T0 ($p \geq 0.16$) and T1 ($p \geq 0.34$). There were no baseline differences on any of the executive functioning scores between games at T0 ($p \geq 0.14$) or T1 ($p \geq 0.24$). We also found no statistically significant differences in baseline measures between games on any of the speech tasks (oromotor measures or dysfluencies) at T0 ($p \geq 0.24$) or T1 $p \geq 0.17$). For details on T1 scores, see Table 1.

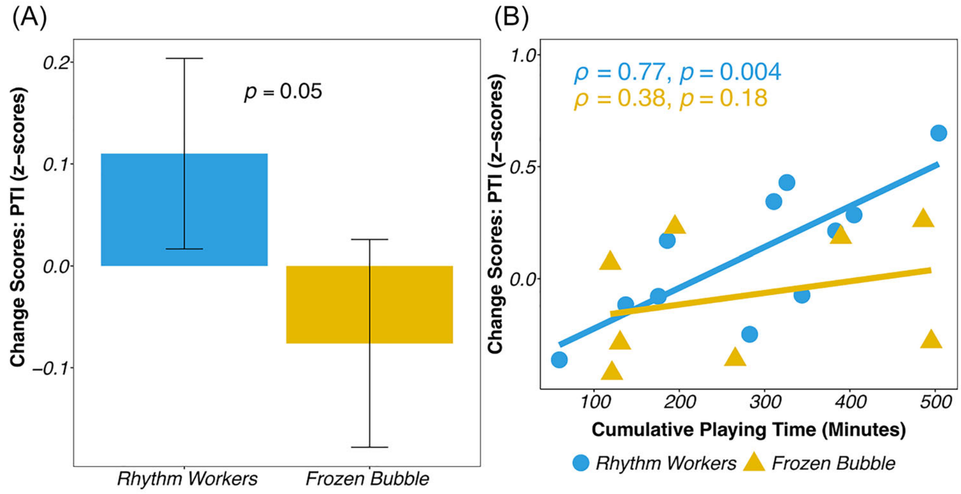

FIGURE 1 | Change scores (T2–T1) of paced rhythmic tasks by game—(A) a bar graph of the mean change scores of the Paced Tapping Index (PTI), lines represent standard errors, (B) correlations (Spearman) per group between mean PTI change score and cumulative playing time in minutes.

3.2 | Feasibility: Compliance and Acceptance

Participants playing RW (M = 283 min; SD = 131; range = 59–504) and FB (M = 279 min; SD = 151; range = 119–495) accumulated similar playing time, $W = 56$, $p = 0.97$, showing a satisfactory compliance. Twelve participants showed high compliance (88–168% of the target time of 300 min of actual game play), eight participants showed moderate compliance (39–65% of the target time), and one participant showed poor compliance (17% of the target). Participants in RW (M = 23,819 taps; SD = 10,898 taps; range = 5531–45,458 taps) and FB (M = 17,884 taps; SD = 11,864 taps; range = 6490–38,630 taps) showed a similar total number of taps recorded on the tablet, $W = 72$, $p = 0.25$. Hence, there was a comparable amount of motor engagement with both games over the training period. Approximately 55% of participants (12/22) voluntarily provided feedback about their experience playing the game (acceptance). Overall, children in both groups reported high levels of enjoyment and engagement with the game. Ratings of global motivation after 3 weeks were generally positive and very high, with no statistically significant differences between RW (M = 4.0/5) and FB (M = 4.6/5, $p = 0.10$). Willingness to continue playing for 2 or 4 more weeks, perceived difficulty, frustration, and subjective flow did not differ significantly between groups ($p \geq 0.80$). On average, both groups rated the game as moderately difficult and reported low levels of frustration. Children also indicated that time went by relatively quickly while playing, and most participants were willing to recommend the game to others. Together, these findings suggest a generally positive user experience, with no significant differences in acceptability between groups.

3.3 | Effects of RW Training on Rhythmic Abilities

Here, we test the hypothesis that rhythmic abilities (paced and unpaced tapping; Table S1) are higher in the RW compared to FB after training. An independent samples *t*-test revealed that the RW group, on average, improved their rhythmic abilities more than the FB group, but this effect was on the margin of statistical significance, $t(17) = 1.33$, $p = 0.05$, one-tailed, but not FB ($p = 0.18$, one-tailed) (Figure 1A). As expected, for those who played RW, cumulative playing time was positively correlated with improvement in paced tapping, $\rho = 0.77$, $p = 0.004$, but not FB ($p = 0.18$) (Figure 1B, one-tailed). Baseline scores were not related to change scores for paced tapping ($p \geq 0.46$). There were no differences between games for unpaced tapping, $W = 58$, $p = 0.14$, nor was there a relation with training dose ($p \geq 0.14$, one-tailed).

3.4 | Exploring Executive Functioning: Enhanced Interference Control After Rhythmic Training

Figure 2 shows the results for interference control as measured by the incongruence effect of the flanker task on speed and accuracy [31]. A one-tailed independent samples *t*-test revealed that the RW group (M = 0.89) performed significantly better than the FB group (M = −0.45), $t(16) = 3.03$, $p = 0.004$, with a large effect size, $d = 1.43$, 95% CI [0.37, 2.46] (see Figure 2A). Cumulative playing time was not correlated with interference control speed improvement for either game ($p \geq 0.16$, one-tailed; Figure 2B). No difference or correlation was found for interference control accuracy, suggesting only speed-specific improvements in this sample. Note that for those who played RW, baseline scores on this measure were negatively correlated with improvement on *rho* = −0.65, and on the cusp of statistical significance, $p = 0.067$. This was not the case for FB ($p = 0.27$), highlighting that those with lower pre-training scores (T1) on the flanker task tended to improve more on that task after RW training (Table S2).

3.5 | Speech Effects: Improvements in Oromotor Skills and Dysfluencies

To assess whether rhythmic training is likely to transfer to speech-related skills (enhancing oromotor control and reducing stuttered dysfluencies), we compared change scores after training between RW and FB and as a function of training dose (cumulative playing time).

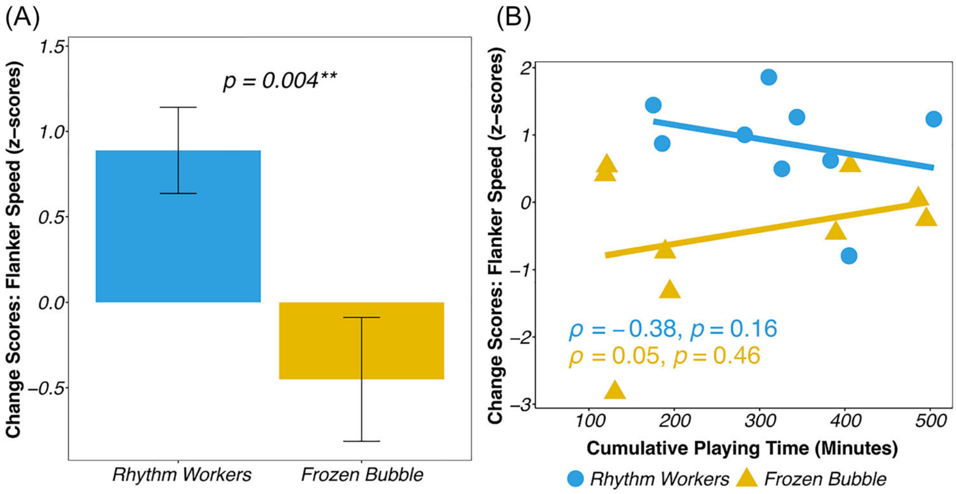

FIGURE 2 | Interference control for the flanker task—(A) change score means (T2–T1) after training between games interference control speed (flanker speed), lines represent standard errors, (B) correlations (Spearman) between mean flanker speed change scores and cumulative playing time in minutes.

3.5.1 | Oromotor Skills—Errors and Speed

One participant who did not correctly perform the DDK task (breathing between every word) was excluded from further analyses. To test oromotor errors (%), we performed a one-tailed Wilcoxon rank-sum test to compare error percentages between RW (M = −5.42; SD = 12.01) and FB (M = 0.61; SD = 5.79) and found a significant difference ($W = 26.5$, $p = 0.041$), with a moderate effect size ($r = 0.46$). To assess oromotor speed (Inter-Word-Interval in seconds) between RW and FB, we used a one-tailed Welch's t-test and found no significant difference between games ($p = 0.36$).

To examine whether training dose (i.e., cumulative playing time) was associated with less oromotor errors, one-tailed Spearman's rank-order correlations were computed between cumulative playing time and errors within each group. A negative relationship between training dose and error rate change was detected (Figure 3A) in the RW group, $\rho = -0.64$, $p = 0.025$, one-tailed. That is, with more RW training, participants showed a reduction of up to 24% in oromotor errors. No such relationship was observed in the FB group ($\rho = -0.16$, $p = 0.33$, one-tailed). For oromotor speed (Figure 3B), no significant association was found in the RW group ($\rho = 0.37$, $p = 0.15$, one-tailed) or FB ($\rho = -0.46$, $p = 0.10$, one-tailed). Overall, this pattern of results suggests that participants playing RW were producing less oromotor errors (as expected). An ad-hoc Spearman correlation between change scores in oromotor errors and speed suggests no speed-accuracy trade-off in either group ($p \geq 0.18$, two-tailed).

3.5.2 | Stuttered Dysfluencies

Two participants who received speech therapy during the study were excluded from fluency analyses. A one-tailed t-test revealed that the RW group (M = −0.27) did not have a significantly lower percentage of stuttered dysfluencies in naturalistic speech than the FB group (M = 0.47), $t(17) = -1.28$, $p = 0.11$, 95% CI [$-\infty$, 0.27]. However, in the RW group, there was an association between the reduction of stuttered dysfluencies and cumulative playing time, $\rho = -0.72$, $p = 0.018$ (one-tailed). As can be seen in Figure 3C, the reduction reached 1–2% (∼ 3–6 stuttered syllables in 300 syllables) of dysfluencies post-training. In contrast, no significant association was found in the FB group, $\rho = 0.27$, $p = 0.22$ (one-tailed).

3.5.3 | Relationships Between Rhythmic, Attentional, and Speech Improvements

Finally, we tested whether improvements in rhythmic abilities or cognitive abilities were associated with gains in oromotor skills or with a reduction of stuttered dysfluencies. We found a negative association between rhythmic and dysfluency scores ($\rho = -0.63$, $p = 0.038$, one-tailed) in the RW group. The FB group showed an opposite, but nonsignificant trend ($p = 0.06$, one-tailed) (Figure 3D). That is, participants who showed greater improvement in paced tapping following RW training exhibited fewer stuttered dysfluencies during both read and spontaneous speech. This finding suggests that the relationship between motor timing and speech improvement may be specific to the rhythm-based intervention. There were no statistically significant correlations between rhythmic and oromotor improvements ($p \geq 0.17$ for errors, and $p \geq 0.41$ for speed, two-tailed). In the RW group, there was an unexpected positive correlation between improvements in executive function and slowing of oromotor speed ($\rho = 0.74$, $p = 0.046$, two-tailed), but nothing in the FB group ($\rho = -0.22$, $p = 0.581$). However, interpretation of this correlation remains difficult, as no clear mechanistic explanation is evident and visual inspection suggests the effect may be driven by a few influential datapoints. Additionally, there were no significant associations between improvements in attention and speech measures, nor between changes in oromotor errors and flanker performance in either group (RW: $\rho = -0.24$, $p = 0.582$; FB: $\rho = 0.30$, $p = 0.437$, two-tailed).

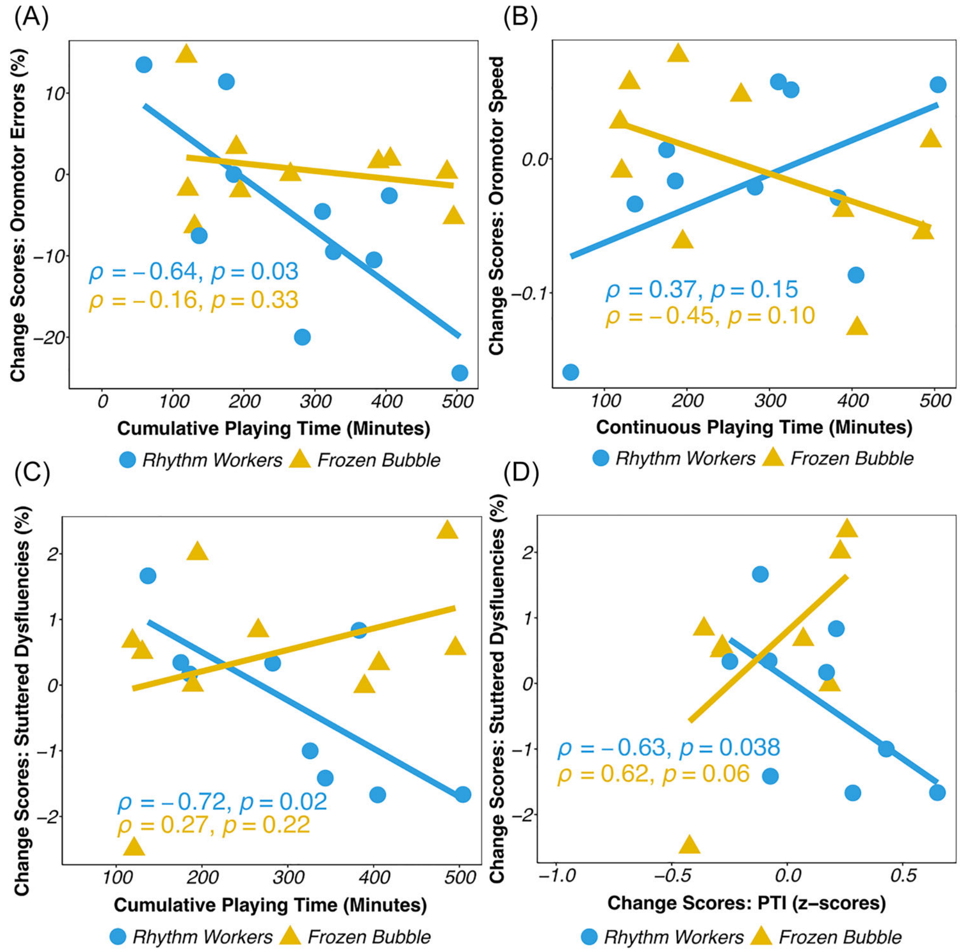

FIGURE 3 | Change scores (T2–T1) after training on speech tasks by game—(A) correlations between the errors as a percentage of all words produced in the diadochokinesis task (oromotor errors) and cumulative playing time, (B) correlations between inter-word-interval (in seconds) of the diadochokinesis task (oromotor speed) and cumulative playing time. (C) Correlation between the change scores in percentage of stuttered syllables (from overall ∼300 syllables; stuttered dysfluencies) and cumulative playing time, (D) the relationship between reduction of stuttering as a function of improvement in rhythmic abilities on the Paced Tapping Index (PTI).

4 | Discussion

In this proof-of-concept study, we used a gamified approach to examine the effect of rhythmic training to enhance speech production in preadolescents who stutter [8, 25, 50]. Here, we focused on the potential benefits of rhythm training by comparing the effect of a rhythm-based training game on a tablet [27, 31] to a nonrhythmic active control game. Training with a gamified approach for 3 weeks was generally successful in our sample, showing moderate to high compliance and reporting that participants generally enjoyed playing the games for 3 weeks. Hence, we conclude that feasibility goals were met and that we can recommend this approach for future studies.

The present findings provide partial support for the hypothesis that rhythmic training enhances rhythmic tapping performance in children. While the RW group exhibited, on average, greater improvement in paced tapping compared to the FB group, this effect did not reach statistical significance. However, the direction of the effect and the moderate effect size suggest a potential benefit of rhythm-based gameplay on sensorimotor synchronization. Crucially, within the RW group, cumulative gameplay duration was strongly associated with improvement in paced tapping performance. This dose–response relationship suggests that extended engagement with the rhythmic game may promote entrainment and timing precision, consistent with previous literature on rhythm-based interventions (e.g., Refs. [25], [31], and [51]). Baseline performance did not predict change, suggesting that the observed improvements were not merely due to regression to the mean or initial skill level. Together, these findings support the feasibility and potential of rhythm-based serious games to enhance synchronization abilities in preadolescents who stutter, although further studies with larger samples are needed to confirm these preliminary trends.

The second finding of this study is that preadolescents who trained with *RW* showed gains in interference control, a sub-component of a core executive function called inhibition control [52]. This aligns with previous findings on the same training and outcome measure provided to ADHD and autism populations who show impairment in inhibition control [31, 32]. In stuttering, there exists some evidence that inhibition control may be lower compared to individuals without stuttering [53]. Considering the high number of comorbidities between stuttering and ADHD

[54], it is possible that some preadolescents with stuttering are at risk of weaker inhibition control. In line with this idea and our previous results with other neurodevelopmental groups, some participants in the RW group with lower initial scores showed greater improvements after playing the game. Although regression to the mean could partly account for this finding, we did not observe the same pattern in the group playing the control game, suggesting that rhythmic training, as in our previous studies, can have a specific effect on interference control in at-risk or impaired populations. For impaired groups who have shown a similar beneficial effect in our studies [31, 32], we propose that the underlying mechanism lies in the nature of the training itself: RW gradually increases rhythmic complexity by making the beat less predictable and more syncopated, requiring players to ignore conflicting or misleading timing cues and to stay focused on the underlying pulse. This mirrors the cognitive demands of interference control, which involves filtering out irrelevant information to prioritize goal-relevant cues [52].

Crucially, our findings suggest that training with the rhythmic game may improve speech-motor control (i.e., oromotor skills measured by a DDK task and reduction of stuttered dysfluencies measured in naturalistic speech). Specifically, preadolescents who played the rhythmic musical game, but not the control game, showed improvements in oromotor accuracy and, most notably, less stuttering symptoms as training time increased. Participants who engaged in the rhythmic game for approximately 300 min or more (see Figure 3A,C) exhibited up to 24% reductions in oromotor errors in the DDK task and 2% in stuttered dysfluencies in naturalistic speech. Although promising, these findings should be interpreted with caution due to the small sample size and modest effect magnitude. Similar oromotor benefits following rhythmic training have been reported in clinical populations, such as individuals with Parkinson's disease [28]. One possible explanation for the observed effects is the close functional relationship between oromotor and manual motor systems, both of which rely on finely timed sequential movements and share overlapping neural substrates, particularly in the cerebellum and basal ganglia [9–15]. Thus, rhythm-based training may strengthen the temporal framework that underlies both manual and speech-motor coordination.

Concerning stuttered dysfluencies, one may object that the observed 2.2% reduction is modest and may fall within the range of daily variability. However, the reduction associated with cumulative rhythmic training time is promising, especially as it emerged in the absence of explicit speech targets during training and after a relatively short time of training (i.e., 300–400 min across 3 weeks). Note that even traditional speech therapy often requires months or years to yield significant effects [55, 56]. Hence, we recommend to further investigate the effects of rhythmic training in stuttering with a sufficiently high training dose, across different age groups, and with a focus on individual outcomes and predispositions.

In sum, the results of this proof-of-concept study are in line with recent theoretical frameworks for rhythm-based interventions in supporting speech rehabilitation through shared sensorimotor mechanisms [21]. The speech-related improvements in our study can be interpreted through the lens of models underscoring the potential role of overlapping auditory—motor circuits for speech and musical rhythm and timing in the brain in rhythm training [25]. Participants engaging in rhythm-based training likely strengthen the neural circuits responsible for precise timing in motor actions, a process that is crucial for fluent speech production. The absence of similar improvements in the *FB* group may be due to the lack of rhythmic engagement in their training, which does not target the same auditory—motor synchronization mechanisms. These promising results mark the first demonstration of gamified rhythmic training through a tablet-based serious game in developmental stuttering, warranting further investigation.

4.1 | Limitations and Future Directions

While this study holds promise for the benefits of rhythm-based training in preadolescents who stutter, there are several limitations to consider. First, the sample size was relatively small, which may limit the generalizability of the findings. Future studies should aim to replicate these results in a larger sample, ideally with stratification by stuttering severity, to confirm and enhance the external validity of the effects. Another limitation concerns baseline differences between groups: although not statistically significant, the FB group showed a tendency to fewer stuttering dysfluencies than the RW group. Given the small sample size, this imbalance may have influenced change scores and limited the strength of between-group comparisons. A further important avenue for future research is exploring the underlying neural mechanisms that drive these improvements, particularly in relation to the SEP hypothesis [25], which posits that rhythm-based interventions tap into neural circuits responsible for timing and motor coordination. Investigating these mechanisms through neuroimaging or electrophysiological methods could shed light on how rhythmic training influences brain activity and improves speech-motor control. Finally, testing the efficacy of the *Rhythm Workers* program in a larger randomized controlled trial design, potentially across different neurodevelopmental conditions, would provide stronger evidence for its therapeutic potential and establish its place in evidence-based interventions for children and adolescents with speech as well as cognitive disorders.

In conclusion, this study shows the first evidence that rhythm-based training is feasible with a young population who stutters and can potentially enhance, as a function of practice, rhythmic abilities, executive functioning, and speech-motor control after 300–400 min of training. These results contribute to the growing body of studies discussing the therapeutic potential of rhythm training for children with various neurodevelopmental disorders. Future research combining rhythm training with established therapeutic approaches for neurodevelopmental conditions will further refine our understanding of the applications of this innovative therapeutic tool.

Author Contributions

S.F. and S.D.B. designed the overall study and hypotheses with the game design stemming from S.D.B.'s lab. All authors contributed to designing the test protocol. S.F. secured the funding and supervised the study. S. Finlay recruited participants and coordinated participants' training and

testing. K.J. and S.F. supervised data collection. K.J., S. Finlay, S.F., and N.F. analyzed the data. K.J. and S.F. performed statistical analysis. All authors contributed to the interpretation of the results. K.J. wrote the first draft of the manuscript. All authors contributed to and approved the final version of the manuscript.

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Conflicts of Interest

S.D.B. 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.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supplementary Material: nyas70188-sup-0001-TableS1 **Supplementary Material**: nyas70188-sup-0002-TableS2