UCSF

UC San Francisco Previously Published Works

## Title

Digital rhythm training improves reading fluency in children

Permalink

https://escholarship.org/uc/item/1bs810c5

Authors

Zanto, Theodore P

Giannakopoulou, Anastasia

Gallen, Courtney L

et al.

Publication Date

2024-01-09

DOI

10.1111/desc.13473

Copyright Information

This work is made available under the terms of a Creative Commons Attribution-NonCommercial-NoDerivatives License, available at
https://creativecommons.org/licenses/by-nc-nd/4.0/

Peer reviewed

eScholarship.org Powered by the California Digital Library
University of California

Received: 30 January 2023 | Revised: 6 December 2023 | Accepted: 11 December 2023

DOI: 10.1111/desc.13473

RESEARCH ARTICLE

Developmental Science WILEY

# Digital rhythm training improves reading fluency in children

Theodore P. Zanto[1,2] | Anastasia Giannakopoulou[3] | Courtney L. Gallen[1,2] | Avery E. Ostrand[1,2] | Jessica W. Younger[1,2] | Roger Anguera-Singla[1,2] | Joaquin A. Anguera[1,2,4] | Adam Gazzaley[1,2,4,5]

[1]Department of Neurology, University of California-San Francisco, San Francisco, California, USA

[2]Neuroscape, University of California-San Francisco, San Francisco, California, USA

[3]School of Psychology, University of Bedfordshire, Luton, UK

[4]Department of Psychiatry, University of California-San Francisco, San Francisco, California, USA

[5]Department of Physiology, University of California-San Francisco, San Francisco, California, USA

**Correspondence**
Theodore P. Zanto, Department of Neurology (0444), 675 Nelson Rising Lane, San Francisco, CA 94158, USA.
Email: theodore.zanto@ucsf.edu

**Funding information**
Neuroscape Network; Hart Foundation for Deep Rhythm

## Abstract

Musical instrument training has been linked to improved academic and cognitive abilities in children, but it remains unclear why this occurs. Moreover, access to instrument training is not always feasible, thereby leaving less fortunate children without opportunity to benefit from such training. Although music-based video games may be more accessible to a broader population, research is lacking regarding their benefits on academic and cognitive performance. To address this gap, we assessed a custom-designed, digital rhythm training game as a proxy for instrument training to evaluate its ability to engender benefits in math and reading abilities. Furthermore, we tested for changes in core cognitive functions related to math and reading to inform how rhythm training may facilitate improved academic abilities. Classrooms of 8–9 year old children were randomized to receive either 6 weeks of rhythm training ($N = 32$) or classroom instruction as usual (control; $N = 21$). Compared to the control group, results showed that rhythm training improved reading, but not math, fluency. Assessments of cognition showed that rhythm training also led to improved rhythmic timing and language-based executive function (Stroop task), but not sustained attention, inhibitory control, or working memory. Interestingly, only the improvements in rhythmic timing correlated with improvements in reading ability. Together, these results provide novel evidence that a digital platform may serve as a proxy for musical instrument training to facilitate reading fluency in children, and that such reading improvements are related to enhanced rhythmic timing ability and not other cognitive functions associated with reading performance.

KEYWORDS
executive function, math, music, reading, rhythm training, timing

## Research Highlights

- Digital rhythm training in the classroom can improve reading fluency in 8–9 year old children

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.
© 2024 The Authors. *Developmental Science* published by John Wiley & Sons Ltd.

- Improvements in reading fluency were positively correlated with enhanced rhythmic timing ability
- Alterations in reading fluency were not predicted by changes in other executive functions that support reading
- A digital platform may be a convenient and cost-effective means to provide musical rhythm training, which in turn, can facilitate academic skills

## 1 | INTRODUCTION

Music is deeply intertwined with both math and language. Musical scales can be expressed as mathematical ratios (Crocker, 1964), and the origins of music may have common roots with that of language (Brown, 2017). As such, much research has been dedicated to understanding whether music engagement and instruction may facilitate math and language ability—particularly their acquisition in children who are in the process of learning these essential skills. Meta-analyses on the relationship between music engagement and math/language have been somewhat mixed. Several meta-analyses have converged to show music engagement can have a positive effect on math and language abilities in children (Cogo-Moreira et al., 2012; Cooper, 2020; Gordon et al., 2015; Vaughn, 2000), but a recent meta-analysis describes a null effect when accounting for study quality (Sala & Gobet, 2020). However, it should be noted that music engagement can take many forms—including instrument, song, or dance training, music theory, or music listening to name a few. Therefore, when controlling for study quality *and* music engagement type, musical instrument training (but not other forms of music engagement) was shown to be related to better language and cognitive abilities (Román-Caballero et al., 2022).

While it is encouraging to know that musical instrument training can improve academic performance in children, there are numerous challenges associated with implementation of such training at home or in school en masse. Two of the largest barriers to entry are that of cost and convenience (Burland, 2020; Henley & Barton, 2022). Musical instruments can be expensive, and even if a cheap used instrument can be procured, the recurring costs of professional instruction results in high long-term costs that will inevitably price-out low-income families and the school districts that serve them. Beyond prohibitive costs, instrument training is often inconvenient. Many working families, particularly those living in rural areas, simply do not have time to escort their children to and from music lessons. Similarly, schools typically do not have time in their curriculum to make available proper music lessons (Russell-Bowie, 2009). Therefore, there is a critical need for a new approach to bridge the gap that limits access to musical instrument training and the benefits it may engender.

One possibility to address the issue of cost and convenience is to provide digital musical instruction via a mobile app as a proxy to instrument training. Indeed, 97% of the US population (83% worldwide) own a smart mobile device (e.g., smartphone, tablet) (Pew Research Center, 2021; Statista Research Department, 2022). Interestingly, in the US, smartphone ownership is only slightly less in low-income families (97% when income < $30k) compared to high income families (100% when income > $75k) (Pew Research Center, 2021). As such, a mobile app that could offer musical training akin to instrument training would provide a widely accessible solution with unparalleled convenience due to the mobile platform. Despite the rise in popularity of music-based video games (e.g., Dance-Dance Revolution, Guitar Hero, Rock Band, Beat Saber, etc.), research into the potential efficacy of digital music training is lacking.

Our primary goal was to assess whether playing a digital musical rhythm training game, *Coherence*, could improve math and reading abilities in children—similar to prior research indicating traditional musical instrument training provides academic and cognitive benefits (Román-Caballero et al., 2022). Rhythm training was selected because rhythm is a core feature of most forms of musical instrument training. It is important to learn how to maintain a steady beat before one can create more complex rhythms or melodies. Moreover, rhythm ability is thought to be related to reading (Bonacina et al., 2021; Goswami, 2011; Ozernov-Palchik & Patel, 2018) as language utilizes rhythmic structures. On the other hand, math may benefit from rhythm training due to common demands on memory (Brower, 1993; Raghubar et al., 2010) or pattern identification ability (Edelson & Johnson, 2012). Thus, Coherence was designed to be an easy way for non-musicians to learn a fundamental aspect of musical performance—rhythm.

Here we utilize tablets to deliver the rhythm training because a touch screen interface is ideal for tapping rhythms, analogous to certain forms of drumming. Furthermore, the software enables closed-loop adaptive algorithms that adapt to the ability level of individuals to challenge the student similar to in-person instruction. This adaptivity provides a distinct advantage over commercial music-based games. Thus, Coherence may serve as a proxy to musical instrument training with a lower barrier to entry as it focuses on a core aspect of musical performance (rhythm) without the need to learn to read sheet music, access to a musical instrument, a music teacher, or a dedicated space to play.

To achieve the primary goal of assessing efficacy of this intervention, elementary school classrooms were randomized to receive either digital rhythm training (Coherence) for 6 weeks or receive classroom instruction as usual (Control). Math and reading fluency were assessed pre- and post-training. It was hypothesized that only the Coherence (rhythm training) group, and not the Control group, would exhibit improvements in math and reading fluency.

14677687, 0, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/desc.13473, Wiley Online Library on [10/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Our secondary goal was to provide mechanistic insight into why digital rhythm training improves math and reading fluency—if such improvements were observed. It has been hypothesized that musical training results in improvements in cognitive control (Hannon & Trainor, 2007), which in a domain-general manner then facilitates math and language abilities (Kljajević, 2010; Patel, 2003; van de Cavey & Hartsuiker, 2016). Indeed, we have recently demonstrated that digital rhythm training can improve cognitive control in healthy older adults, specifically, temporal attention (the ability to orient attention in time) (Nandi et al., 2023) and short-term memory (Zanto et al., 2022). It is therefore plausible that children will also exhibit improvements in cognitive control functions following rhythm training, which may predict alterations in math and language ability.

To address this secondary goal, we assessed various forms of cognitive control function pre- and post-training, including working memory, sustained attention, inhibitory control and temporal attention (via, sensorimotor synchronization). The allocation of attention, and hence the prioritization of the input of information, at a particular point in time is called temporal attention. Exogenously oriented temporal attention often occurs in response to rhythmic stimuli or stimuli with a predictable temporal structure, which is also referred to as beat-based or rhythmic timing (Coull & Nobre, 1998; Krampe et al., 2001; Repp, 2005; Teki et al., 2011). Thus, exogenous temporal attention refers to the process by which attention is oriented to the environment to drive internal timing representations. Temporal attention was assessed as it is a critical component of rhythm production, such as sensorimotor synchronization (Large & Jones, 1999; Vibell et al., 2021; Zalta et al., 2020). Moreover, prior research has linked this ability to orient attention in time with math (Landerl & Willburger, 2010) and language development (de Diego-Balaguer et al., 2016; Ruffino et al., 2014).

Similar to temporal attention, working memory is critically involved in musical performance (Berz, 1995), as well as math (Bull et al., 2008; Menon, 2016; Raghubar et al., 2010) and language skills (Archibald, 2016; Baddeley, 2003). Moreover, prior research has demonstrated that musical training can improve working memory in children (Nutley et al., 2014; Roden et al., 2013). Therefore, we aimed to test whether digital rhythm training may also improve working memory, particularly as it may underlie alterations in math or reading performance. Sustained attention was assessed because it can be enhanced in musicians (Strait & Kraus, 2011) and deficient sustained attention has been linked to learning disorders (Dainer et al., 1981; Finneran et al., 2009; Smolak et al., 2020; Stern & Shalev, 2013). As such, we tested whether rhythm training may alter sustained attention, which may have downstream effects on math or reading. Finally, inhibitory control was assessed because it has been shown to be higher in percussionists compared to vocalists or non-musicians (Slater et al., 2017), and inhibitory control is also utilized during math and language performance (Gandolfi & Viterbori, 2020; Kieffer et al., 2013). And so, we assessed changes in these cognitive functions to provide important insight regarding the underlying mechanism for how rhythm training may benefit math and reading abilities.

## 2 | METHODS

### 2.1 | Procedure

Three classrooms of students, aged 8–9 years, were recruited from the same school in England. One classroom was randomly selected to participate in a digital rhythm training intervention (i.e., Coherence) three times per week, 20 min each day, for 6 weeks. The other two classrooms participated in classroom instruction as usual, which served as the Control. Pre- and post-intervention, all three groups were given assessments of math and reading fluency (primary outcome measures), as well as cognitive abilities: working memory, sustained attention, inhibitory control, and sensorimotor synchronization (secondary outcome measures). However, one of the two Control groups completed the post-assessments 8 weeks late. Therefore, data analysis focused on the two groups that adhered to the planned research schedule. All outcome assessments were conducted on computers in the school's media center. The order of the outcome assessments were fixed so that all participants at each time point (pre/post) conducted the tasks in the same order: reading fluency, math fluency, sensorimotor synchronization, working memory, sustained attention, inhibitory control, executive function.

### 2.2 | Participants

Parents of the students (Coherence $N = 34$; Control $N = 22$) provided informed consent as approved by the University of Bedfordshire Institutional Review Board. Each child participant also provided assent prior to participation. Two students from the Coherence group and one from the Control group did not complete both the pre- and post-intervention assessments (i.e., missed all pre or all post assessments). These students were therefore excluded from analysis, resulting in 32 students in the Coherence group (mean = 8.91 years; 16 female) and 21 students in the Control group (mean = 8.91 years; nine female). Of note, some students did not complete some of the outcome assessments at both time-points. This was due to the research being conducted in the school, where missing data points occurred for various reasons. This includes sick days (absent on testing day), not understanding or following task directions (resulting in unusable data), technical problems, and running out of time to complete all outcomes (some children took more time between tasks). Students missing data at one time point were included in the linear mixed model. However, students missing data at both time points were excluded from analysis of that specific outcome. Thus, we chose to analyze the usable data available, rather than discarding each participant's dataset due to a missing outcome measure. Similarly, participants who exhibited performance two standard deviations or more outside mean performance were excluded from analysis of that specific outcome.

14677687, 0, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/desc.13473, Wiley Online Library on [10/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License


**FIGURE 1** Screenshot of coherence.

## 2.3 | Digital rhythm training

Musical rhythm training was conducted using a custom-designed video game, *Coherence* (Figure 1). Coherence was created at UCSF Neuroscape and incorporates closed-loop adaptive algorithms to consistently challenge the participant at a high level, an approach which is thought to optimize training effects (Mishra et al., 2016; Ziegler et al., 2022) and lead to transfer of benefits to an array of cognitive abilities (Anguera et al., 2013, 2022; Mishra et al., 2014; Nandi et al., 2023; Wais et al., 2021; Zanto et al., 2022; Ziegler et al., 2019). It was played in the classroom on an iPad tablet that permits tapping on the screen akin to certain types of drumming. Although Coherence was played in the classroom three times per week, the specific days of training periodically shifted from week-to-week, because finding time to train during the school day was at the discretion of the teacher.

Participants tapped the screen of the tablet in synchrony with the musical "beat", which was also visually cued by moving colored orbs. Specifically, colored orbs fly from a tree in the distance towards a semi-transparent target region in the foreground (see Figure 1). Participants were instructed to tap the target region when the orb fully overlaps it, which temporally coincided with the musical beat. The game was designed to challenge rhythm and timing abilities, such that a non-musician could learn to tap a steady rhythm. Personalized adaptivity was built into Coherence so that with practice and skill acquisition, the rhythms become increasingly difficult, but if performance falters, the rhythmic demands become easier. As difficulty increases in response to sufficient progress, participants earn stars that can be used to unlock new songs.

Difficulty of rhythms adapted along three dimensions: temporal complexity, spatial complexity, and memory load. Each song within Coherence started at the lowest (of four) temporal complexity levels, and the lowest (of four) spatial complexity levels, resulting in 16 total difficulty levels per song to be sequentially passed. Temporal complexity refers to the metrical position of the requested tap. For example, easy rhythmic patterns consist of taps that coincide with "down" beats (i.e., first & third beat of a measure in a 4/4 time signature), while a more difficult rhythm includes taps that are syncopated. Every song started with a basic temporal pattern (e.g., tap on the first beat of a measure) and successful performance resulted in an increase in complexity (e.g., tap on the first two beats of a measure). As performance faltered, temporal complexity became easier. Spatial complexity refers to the number of spatial positions invoked by the rhythmic pattern. Each song within Coherence started with two spatial target positions—one for each hand—and works up to as many as four spatial positions per hand (eight positions total). In order to advance to a higher level of spatial complexity, participants must first pass four increasingly difficult levels of temporal complexity. Once the highest level of temporal complexity (for that song) is passed, spatial complexity increased and temporal complexity started back at the easiest level. Memory load was manipulated in two ways. First, memory was taxed by altering the number of taps required before the rhythm repeats. When beginning Coherence, only four "beginner" songs were available, which required a limited number of taps before the pattern repeated. Upon sufficient performance, new songs unlocked that required a greater number of taps per rhythmic pattern. Second, memory was further challenged by having the visual cues disappear after participants demonstrated

14677687, 0, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/desc.13473, Wiley Online Library on [10/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

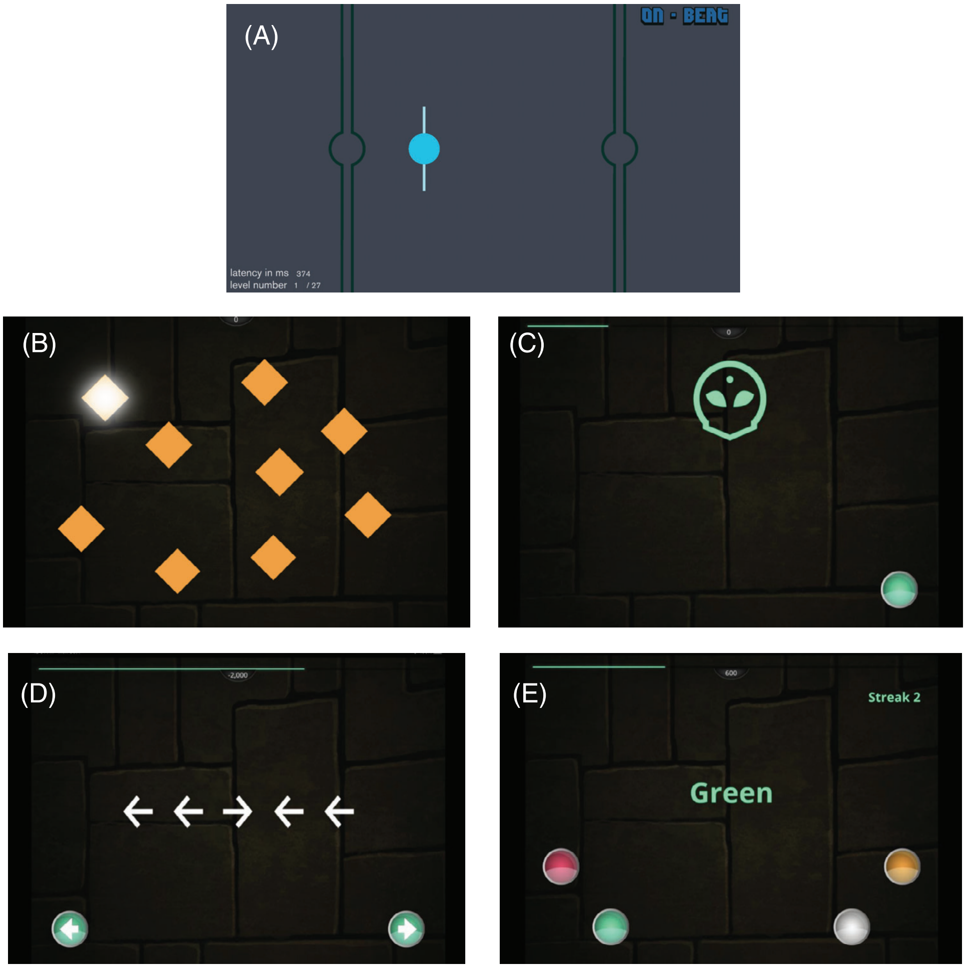


**FIGURE 2** Screenshots of outcome measures tasks: (a) Rhythmicity, (b) Working memory task, (c) Sustained attention task, (d) Flanker task, (e) Stroop task.

sufficient performance in tapping the rhythmic pattern with the visual cues present. During these training periods the cues were "invisible", and participants were forced to rely on their memory to produce the rhythmic pattern. Participants were required to pass this "invisible mode" prior to advancing to the next level of temporal or spatial complexity.

## 2.4 | Primary outcome measures

Computerized math and reading fluency tests served as the primary outcome measures and were similar to subtests from the Woodcock-Johnson IV Tests of Achievement (WJ4) (Schrank et al., 2014). Specifically, math was assessed using addition and subtraction problems similar to the Math Facts Fluency subtest of the WJ4. In this assessment, simple arithmetic problems were presented (e.g., 1 + 6, 4 – 2, etc.) and participants were instructed to answer as many as possible within 3 min. Reading fluency was assessed in a manner similar to the Sentence Reading Fluency subtest of the WJ4. In this assessment, a short sentence was presented (e.g., "The sky is blue.", "A cow can dance.") and participants were instructed to indicate whether the sentence was true or false. Again, participants were given 3 min to answer as many correctly as possible. To account for potential speed-accuracy trade-offs, in both assessments, we calculated an efficiency metric as the trial-wise accuracy (1 = correct, 0 = incorrect) divided by the trial-wise response time and then all trials are averaged together. Thus, higher values indicate better performance. This efficiency metric is related to the Rate Correct Score (Woltz & Was, 2006) and inversely related to the Inverse Efficiency Score (Townsend & Ashby, 1983), except this approach has the advantage of accounting for the trial-wise relationship between speed and accuracy. These math and reading efficiency metrics were then used in statistical analyses.

## 2.5 | Secondary outcome measures

Computerized tests of sensorimotor synchronization, working memory, sustained attention, and inhibitory control served as the secondary outcome measures. Each of these cognitive abilities, except sensorimotor synchronization, were assessed via Neuroscape software: Adaptive

14677687, 0, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/desc.13473, Wiley Online Library on [10/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Cognitive Evaluation-Explorer (ACE-X) (Hsu et al., 2021; Younger et al., 2021; Younger et al., 2021) and sensorimotor synchronization was assessed using Neuroscape software: Rhythmicity (Johnson et al., 2020; Zanto et al., 2019).

### 2.5.1 | Sensorimotor synchronization

To assess sensorimotor synchronization, participants engaged in Rhythmicity, a rhythmic synchronization test (see Figure 2). Briefly, this paradigm required participants to tap different metronome-like sequences using the spacebar on a keyboard across 12 levels. These levels parametrically manipulated three variables: tempo of the metronome, the audio-visual information provided, and the rhythmic task performed. The tempo varied between medium (525 ms) and fast (350 ms) inter-onset intervals (IOIs). The stimuli presented varied between a visual-only stimulus where the movement of a ball between two lines on each side of the screen denoted the metronome "beat", an audio-only stimulus where a distinct tone denoted the metronome "beat", and an audio-visual stimulus where these cues were integrated. Lastly, participants were asked to perform two tasks: (1) On-beat: tap along with each stimulus event (i.e., sound onset and/or when the ball touched the lines at either side of the screen) or (2) Continuation: after four stimulus events (i.e., four beats), the stimuli were discontinued, and participants had to continue the metronomic rhythm by tapping for four beats without disrupting the tempo. After the four-beat "silent period" where participants were to tap, stimuli were resumed for another four beats and followed by another four-beat "silent period" where participants were instructed to tap. The stimuli and silent periods continued to alternate for the duration of the level. Together, the rhythmic synchronization paradigm consisted of 12 levels (2 tempos × 3 stimulus types × 2 tasks) each lasting approximately 30 s. To characterize performance, tap asynchrony and variability were assessed. Asynchrony was calculated as the absolute offset in milliseconds from the instructed tap onset. Variability was calculated as the standard deviation of tap offsets. Data were averaged over stimulus types and tasks in order to obtain an estimate of sensorimotor synchronization ability.

### 2.5.2 | Working memory

The working memory task was based on the Corsi block-tapping task (Kessels et al., 2010). Participants observed a distribution of squares on a computer screen that became illuminated one at a time (see Figure 2b). Participants were then instructed to use a mouse to click on the reverse order of illumination. To start, three squares were illuminated. After two correct trials, an additional square became illuminated (i.e., increased set size). This continued until three consecutive incorrect trials occurred. The average set size correctly recalled was used as an index of working memory capacity.

### 2.5.3 | Sustained attention

Sustained attention was assessed via two Continuous Performance Tasks from ACE-X (Figure 2c) based on the Test of Variables of Attention (Greenberg et al., 1996). During both tasks, a symbol appeared either at the top or bottom of the screen and participants were instructed to respond only when the symbol appeared at the top of the screen (target). For the vigilant attention task (80 consecutive trials), target probability was 20% (infrequent condition). For the impulsive attention task (40 consecutive trials), target probability was 80% (frequent condition). Sustained attention was then indexed by response time variability (standard deviation of response times).

### 2.5.4 | Inhibitory control

Inhibitory control was assessed in two tasks, the Flanker task (Eriksen & Eriksen, 1974) and the Stroop task (Mead et al., 2002). In the Flanker task (Figure 2d), participants were presented five arrows in a row and were instructed to indicate the direction of the center arrow. For congruent trials (50% probability) all five arrows pointed in the same direction. For incongruent trials (50% probability), the center arrow pointed in the opposite direction on the flanking arrows. In total, 28 trials were presented (not including practice trials). During the Stroop task (Figure 2e), participants were presented with a word that was the name of a color and they were instructed to indicate the color of the text, not the word itself. For congruent trials (50% probability), the word and its color matched (e.g., the word "green" in green font). For incongruent trials (50% probability), the word and the color of the word did not match (e.g., the word "green" in white font). In total, 40 trials were presented (not including practice trials). To account for potential speed-accuracy trade-offs, in both the Flanker and Stroop tasks, we calculated an efficiency metric as accuracy (1 = correct, 0 = incorrect) divided by response time. Thus, higher values indicate better performance. These inhibitory control efficiency metrics were then used in statistical analyses.

## 2.6 | Statistical analyses

Data from the outcome measures were submitted to linear mixed models with Group (Coherence, Control), Session (Pre, Post), and Group × Session interaction as fixed effects and intercepts as random effects. For analysis of sustained attention and inhibitory control data, Condition (Frequent, Infrequent; Congruent, Incongruent) and the corresponding interactions were also included as fixed effects. These analyses were conducted using the JASP software (JASP Team, 2020). Permutation tests using 5000 iterations were used to assess interactions in MATLAB. To assess the relationship between outcomes, Spearman's rho was used. A *p*-value of $<0.05$ was used for significance testing.

14677687, 0, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/desc.13473, Wiley Online Library on [10/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

**TABLE 1** Assessment scores for both the coherence and control groups pre- and post-intervention.

| | Rhythm training | | Control | |
|---|---|---|---|---|
| Assessment | Pre | Post | Pre | Post |
| Math fluency ($N = 31/19$) | 0.17 (0.01) | 0.18 (0.01) | 0.18 (0.02) | 0.18 (0.02) |
| Reading fluency ($N = 31/19$) | **0.22 (0.02)** | **0.28 (0.02)** | 0.24 (0.02) | 0.26 (0.02) |
| SMS: asynchrony ($N = 29/21$) | 94 (3) ms | 87 (3) ms | 89 (4) ms | 94 (4) ms |
| SMS: variability ($N = 29/21$) | **98 (3) ms** | **86 (3) ms** | 93 (4) ms | 92 (4) ms |
| Working memory ($N = 29/17$) | **4.05 (0.13)** | **4.49 (0.12)** | 4.47 (0.16) | 4.66 (0.17) |
| Sustained attention ($N = 23/16$) | 181 (17) ms | 187 (17) ms | 225 (20) | 175 (20) |
| Inhibitory control: Flanker ($N = 27/19$) | 0.85 (0.04) | 1.09 (0.04) | 0.90 (0.05) | 1.14 (0.05) |
| Inhibitory control: Stroop ($N = 29/19$) | **0.70 (0.04)** | **0.94 (0.04)** | 0.81 (0.05) | 0.94 (0.05) |

*Note*: Numbers in parentheses indicate standard error of the mean. Bold values indicate significant ($p < 0.05$) within group changes. $N$ = Number of participants analyzed in the Rhythm/Control groups.
Abbreviation: SMS, sensorimotor synchronization.

# 3 | RESULTS

## 3.1 | Primary outcomes

### 3.1.1 | Math fluency

Results from the linear mixed model on math efficiency scores indicated no main effect for Group [$F(1,48.09) = 0.267$, $p = 0.608$] or Session [$F(1,46.57) = 0.465$, $p = 0.499$]. Importantly, no Group × Session interaction was observed [$F(1,46.57) = 0.125$, $p = 0.725$]. Indeed, the Coherence group and the Control group each exhibited similar performance pre- and post-intervention (Table 1). This indicates digital rhythm training did not significantly improve math performance.

### 3.1.2 | Reading fluency

Results from the linear mixed model on reading efficiency scores indicated no main effect for Group [$F(1,47.80) = 0.000$, $p = 0.999$]. However, a main effect of Session [$F(1,47.04) = 22.898$, $p < 0.001$] was observed such that performance generally improved. More importantly, there was a Group × Session interaction [$F(1,47.04) = 4.210$, $p = 0.046$] indicating the Coherence group improved more than the Control group (Figure 3a). Permutation tests were then used to assess within group changes pre- to post-intervention. Results demonstrated that the Coherence group [$p = 0.006$, Cohen's $d = 0.707$], but not Control group [$p = 0.385$, Cohen's $d = 0.275$], exhibited a significant improvement in reading fluency (Figure 3b). No baseline differences were observed between groups [$p = 0.580$]. To assess whether the observed training effects may be attributed to regression to the mean, we implemented the extended Mee-Chua Test (Ostermann et al., 2008). Results showed that when the true mean reading efficiency score is less than 0.31, the training effects are not likely driven by regression to the mean ($t_{max} = 6.928$, $p_{min} < 0.001$). Given that all observed sample means were less than 0.31 (see Table 1), it is unlikely that regression to the mean played a role in the observed training effects. Thus, these results reveal that digital rhythm training improved reading fluency.

## 3.2 | Secondary outcomes

### 3.2.1 | Sensorimotor synchronization

Performance was first assessed via asynchrony data from the sensorimotor synchronization task. Results from a linear mixed model showed no main effects for Group [$F(1,48) = 0.161$, $p = 0.690$] or Session [$F(1,48) = 0.055$, $p = 0.815$]. However, a Group × Session interaction was observed [$F(1,48) = 5.279$, $p = 0.026$] such that the Coherence group exhibited a slight decrease in asynchrony (better performance) post-intervention, while the Control group displayed a slight increase in asynchrony (Figure 4a). Permutation tests were then used to assess within group changes pre- to post-intervention. Results showed that neither the Coherence group [$p = 0.109$, Cohen's $d = 0.433$], nor the Control group [$p = 0.294$, Cohen's $d = 0.333$], exhibited a significant change in asynchrony (Figure 4b). Thus, the observed interaction is due to differential change between groups pre- to post-intervention.

Performance variability was then assessed in a linear mixed model. Results showed no main effect for Group [$F(1,48) = 0.008$, $p = 0.931$]. However, there was a main effect of Session [$F(1,48) = 4.097$, $p = 0.049$] and a trend toward a significant Group × Session interaction [$F(1,48) = 3.924$, $p = 0.053$] such that the Coherence group exhibited a greater decrease in variability post-intervention compared to the Control group (Figure 4c). Permutation tests were then used to assess within group changes pre- to post-intervention. Results showed that only the Coherence group [$p = 0.008$, Cohen's $d = 0.648$], and not the Control group [$p = 0.837$, Cohen's $d = 0.057$], exhibited a significant improvement in performance variability (Figure 4d). No baseline differences were observed between groups [$p = 0.304$]. Results from an extended Mee-Chua Test showed that when the true mean variability is greater than 93, the training effects are not likely driven by regression to the mean [$t_{max} = 4.567$, $p_{min} < 0.001$]. Given that several

14677687, 0, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/desc.13473, Wiley Online Library on [10/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

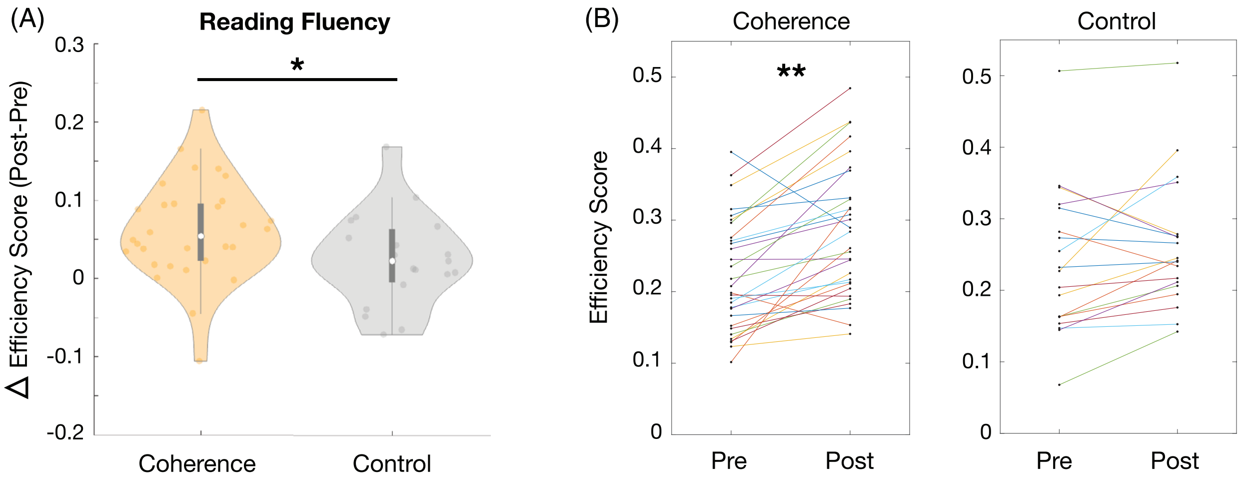


**FIGURE 3** Reading fluency data. (a) Violin plot of the change in efficiency score for each group. (b) Ladder plot of efficiency scores for all participants pre- and post-intervention. Colored circles and lines represent individual students for each group in (a) and (b), respectively, *$p < 0.05$, **$p < 0.01$.

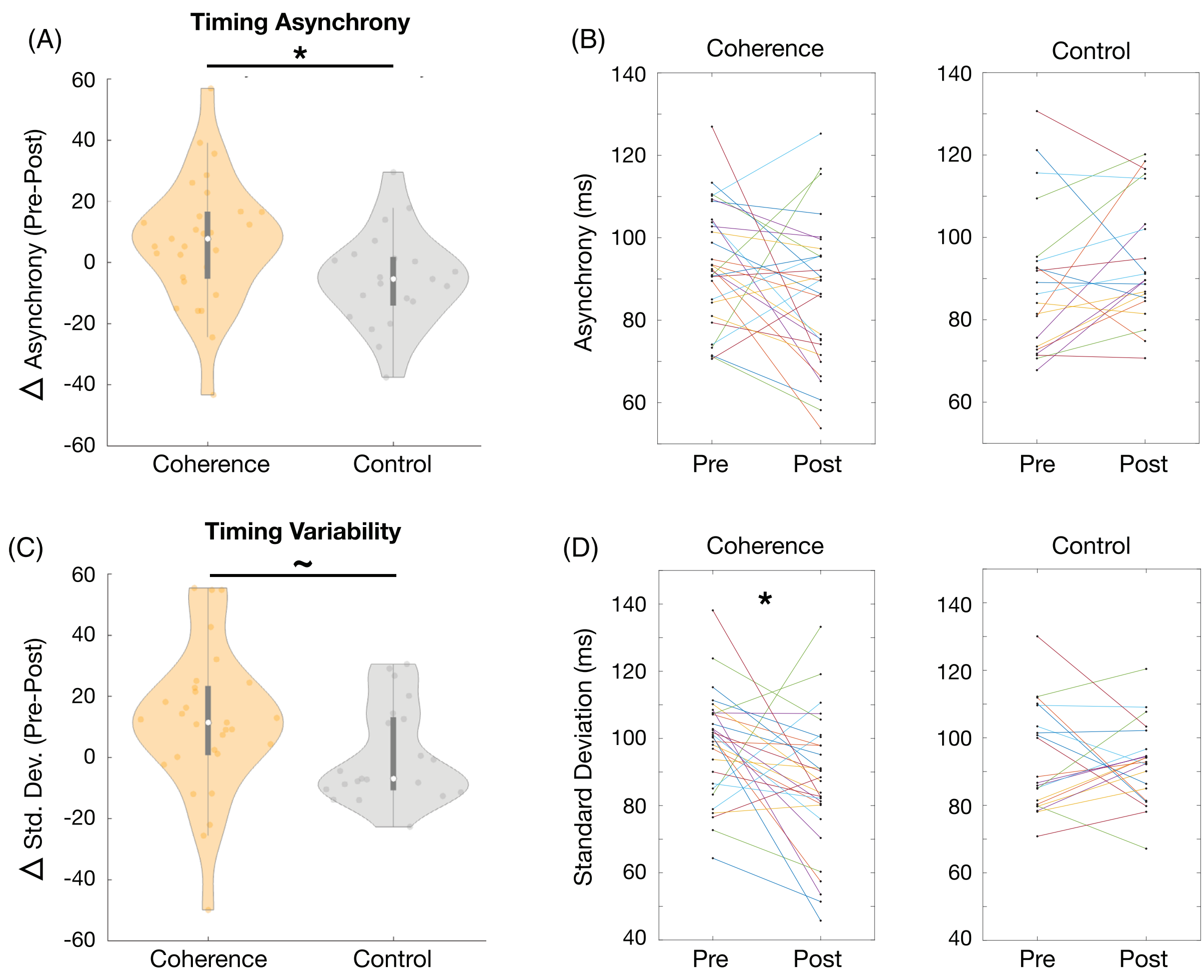


**FIGURE 4** Sensorimotor synchronization data. (a) Violin plot of the change in asynchrony for each group. Higher values = better performance. (b) Ladder plot of asynchrony data for all participants pre- and post-intervention. Lower values = better performance. (c) Violin plot of the change in performance variability (standard deviation) for each group. Higher values = better performance. (d) Ladder plot of variability data for all participants pre- and post-intervention. Lower values = better performance. ~$p < 0.06$, *$p < 0.05$.

14677687, 0, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/desc.13473, Wiley Online Library on [10/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

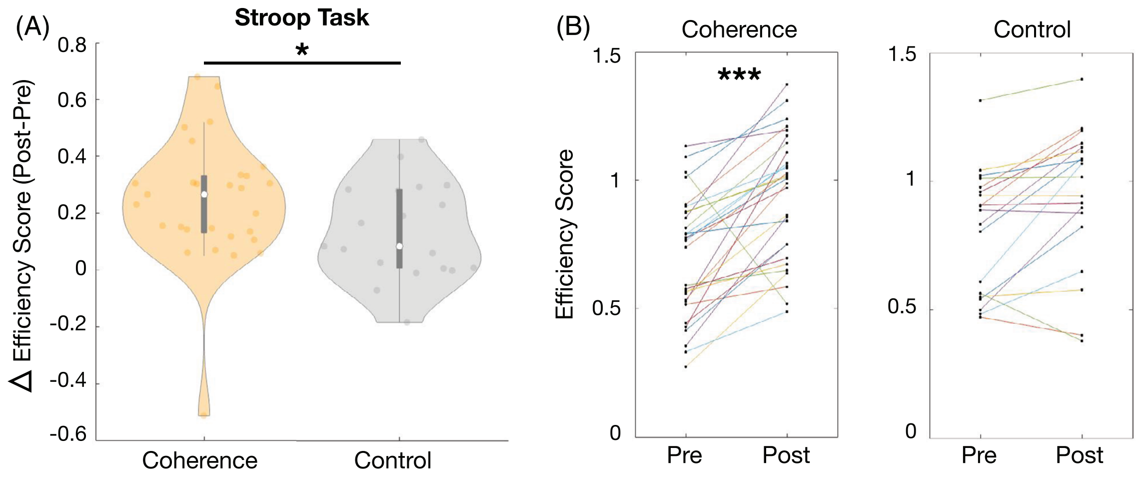


**FIGURE 5** Performance data via Stroop task. (a) Violin plot of the change in efficiency score for each group. (b) Ladder plot of efficiency scores for all participants pre- and post-intervention. *$p < 0.05$, ***$p < 0.001$.

sample means were around this threshold (see Table 1), it is possible that regression to the mean played a small role in the observed training effects on timing variability.

### 3.2.2 | Working memory

Working memory capacity scores were assessed with a linear mixed model and exhibited no main effect of Group [$F$(1,43.62) = 2.775, $p$ = 0.103]. However, a main effect of Session was observed [$F$(1,42.62) = 8.510, $p$ = 0.006], such that working memory capacity improved from pre [mean (*SEM*) = 4.21 (0.11)] to post [mean (*SEM*) = 4.56 (0.09)]. Although the Coherence group showed a significant improvement pre- to post-training ($p$ = 0.020; Table 1), no Group × Session interaction was observed [$F$(1,42.62) = 1.369, $p$ = 0.249]. Thus, working memory capacity was not likely affected by digital rhythm training.

### 3.2.3 | Sustained attention

Sustained attention variability was assessed via response time standard deviation in a linear mixed model. Results yielded no main effect of Group [$F$(1,37) = 0.686, $p$ = 0.413] or Session [$F$(1,111) = 1.787, $p$ = 0.184]. However, a main effect of Condition was observed [$F$(1,111) = 15.817, $p$ < 0.001] such that performance was less variable during the Frequent [mean (*SEM*) = 159 (13) ms] compared to the Infrequent condition [mean (*SEM*) = 225 (13) ms]. Importantly, no interactions were observed (all $p$ > 0.100). Most notably, there was no Group × Session [$F$(1,111) = 2.727, $p$ = 0.102] or Group × Session × Condition interaction [$F$(1,111) = 0.001, $p$ = 0.982]. Of note, d-prime, a metric of signal detection based on hits and false alarms, showed no main effects or interactions (all $p$ > 0.380). Together, there was no evidence that digital rhythm training affected sustained attention ability.

### 3.2.4 | Inhibitory control

Inhibitory Control was assessed via the Flanker and Stroop tasks. Efficiency scores from the Flanker task were submitted to a linear mixed model and exhibited no main effect of Group [$F$(1,44) = 0.799, $p$ = 0.376]. However, main effects were observed for Session [$F$(1,132) = 52.662, $p$ < 0.001] and Condition [$F$(1,132) = 21.274, $p$ < 0.001], such that performance improved post-intervention [mean (*SEM*): pre = 0.87 (0.03), post = 1.12 (0.03)] and was better during congruent trials [mean (*SEM*): Congruent = 1.07 (0.03), Incongruent = 0.92 (0.03)]. No interactions were observed (all $p$ > 0.18). Most notably, there was no Group × Session [$F$(1,132) = 0.006, $p$ = 0.937] or Group × Session × Condition interaction [$F$(1,132) = 0.827, $p$ = 0.365].

Next, efficiency scores from the Stroop task were submitted to a linear mixed model and exhibited no main effect of Group [$F$(1,46) = 0.703, $p$ = 0.406]. However, main effects were observed for Session [$F$(1,138) = 78.867, $p$ < 0.001] and Condition [$F$(1,138) = 46.008, $p$ < 0.001], such that performance improved post-intervention [mean (*SEM*): pre = 0.75 (0.04), post = 0.94 (0.04)] and was better during congruent trials [mean (*SEM*): Congruent = 0.92 (0.04), Incongruent = 0.77 (0.04)]. Importantly, there was a Group × Session interaction [$F$(1,138) = 6.182, $p$ = 0.014] indicating the Coherence group had greater improvement in performance post-intervention compared to the Control group (Figure 5a). Permutation tests were then used to assess within group changes pre- to post-intervention. Results demonstrated that the Coherence group [$p$ < 0.001, Cohen's $d$ = 1.008], but not Control group [$p$ = 0.118, Cohen's $d$ = 0.526], exhibited a significant improvement in inhibitory control (Figure 5b). No baseline differences were observed between groups [$p$ = 0.131]. Results from an extended Mee-Chua Test showed that when the true mean efficiency score is less than 1.10, the training effects are not likely driven by regression to the mean [$t_{max}$ = 10.092, $p_{min}$ < 0.001]. Given that all sample means were less than this threshold (see Table 1), it is unlikely that regression to the mean played a role in the observed training effects. No other interactions were observed [all $p$ > 0.22],

14677687, 0, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/desc.13473, Wiley Online Library on [10/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

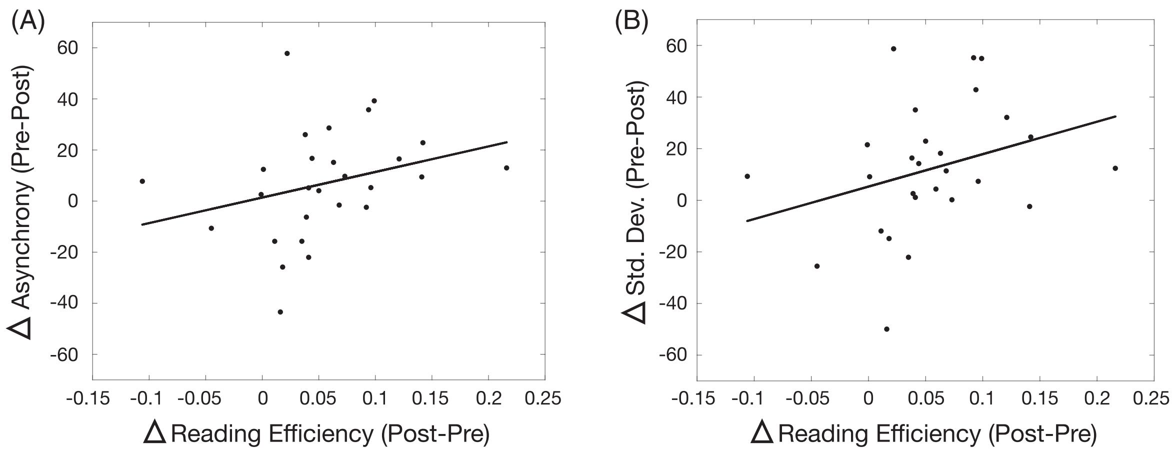


**FIGURE 6** Correlations within the Coherence group between changes in reading efficiency and metrics of timing performance: (a) asynchrony and (b) standard deviation. Change scores are calculated so positive values indicate better performance.

notably, no Group × Session × Condition interaction [$F(1,138) = 0.001$, $p = 0.972$]. Together, these results show that digital rhythm training did not improve inhibitory control. However, rhythm training resulted in a general improvement in performance only during the task with a reading component (Stroop task), but was not specific to incongruent trials.

### 3.3 | Predictors of reading improvement

Change score data from the Coherence training group was analyzed with Spearman's rho to assess whether the improvements in either of the two metrics that exhibited Coherence-related improvements (i.e., Stroop and sensorimotor synchronization) were predictive of improvements in reading efficiency. Results from the correlation between the change (post-pre) in Stroop efficiency scores and change (post-pre) in reading efficiency scores demonstrated no significant correlation [$r = 0.137$, $p = 0.495$].

Significant correlations were observed between the change (post-pre) in reading efficiency and the change (pre-post) in sensorimotor synchronization, as indexed by both performance asynchrony [$r = 0.453$, $p = 0.018$; Figure 6a] and variability [$r = 0.387$, $p = 0.046$; Figure 6b]. These results indicate those individuals who exhibited the largest improvements in sensorimotor synchronization were those with the greatest increases in reading efficiency.

## 4 | DISCUSSION

The primary objective of this study was to ascertain whether digital rhythm training may serve as a proxy for musical instrument training to improve math and reading ability in elementary school children. Results showed that rhythm training improved reading, but not math fluency. The secondary objective was to characterize changes in other cognitive abilities that may be associated with observed improvements. Whereas both rhythmic timing (via sensorimotor synchronization) and language-based executive control (via Stroop task) were enhanced by rhythm training, only rhythmic timing was predictive of reading improvements. Together, these results provide intriguing evidence that digital rhythm training enables benefits in reading performance similar to musical instrument instruction, and that these improvements may stem from an enriched ability to orient attention in time.

Numerous studies have demonstrated positive effects of musical training on reading abilities in typically developing children (Butzlaff, 2000; Kraus, Hornickel, et al., 2014; Kraus, Slater, et al., 2014; White & Wesolowski, 2021), as well as those with dyslexia (Flaugnacco et al., 2015). Yet, much less work has been done exploring the utility of digitally-based musical training, which would be much more cost-effective and accessible to a larger population. In addition, using more targeted, custom-designed interventions may allow us to identify which components of music training lead to the most benefits in academic skills. Some previous efforts to provide musical training in a digital format have focused on music education, rather than performance, which includes learning to identify musical elements such as chords, intervals, and melodic contour (Portowitz et al., 2014; Wiener & Bradley, 2020). A different music-based intervention with a digital component, in which some rhythmic production was included, demonstrated efficacy in numerous cognitive domains including auditory processing, verbal intelligence, and executive function (Carpentier et al., 2016; Janus et al., 2016; Moreno, Bialystok, et al., 2011; Moreno et al., 2015; Moreno, Friesen, et al., 2011). However, rhythm production was only a small component of that intervention and a music teacher lead all instruction. Here, we extend this prior research to a fully digital musical rhythm production intervention, and show that reading benefits are not limited to approaches that involve learning analog musical instruments under traditional or hybrid instruction.

Despite the practical promise this technology may hold, additional research is needed. For example, it is unclear why math performance did not improve, as has been previously reported for other musical training (Bergee & Weingarten, 2020; Vaughn, 2000). One possibility is that our math assessment was not sensitive enough to detect potentially small improvements. Prior research has indicated that enhanced math ability due to musical training are less pronounced than those

14677687, 0, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/desc.13473, Wiley Online Library on [10/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

observed for language-based improvements (dos Santos-Luiz et al., 2015). Thus, it is possible that the simple addition and subtraction questions posed here (e.g., 1 + 2, 5 − 3) were not challenging enough to observe a subtle improvement. Perhaps tasks that challenged different types of math sub-skills, such as those that require estimation or more difficult calculations would exhibit enhanced performance after rhythm training. Another possibility is that other aspects of musical training, and not necessarily rhythm production, may underlie the rapid recall/calculation of basic arithmetic.

Beyond demonstrating the efficacy of a digitally-delivered, musical, rhythm-based intervention, these results provided insight as to the mechanism by which rhythm training facilitates reading ability. Here, we observed a correlation between reading efficiency and two metrics of sensorimotor synchronization: asynchrony and variability (standard deviation). Models of sensorimotor synchronization often attribute this ability to a combination of sensorimotor processing speed and rhythmic timing ability (Aschersleben, 2002; Wing & Kristofferson, 1973), where the latter reflects the orienting of attention in time (Large & Jones, 1999). These results therefore support prior research associating timing abilities with reading performance (Bekius et al., 2016; Flaugnacco et al., 2014; Tierney & Kraus, 2013) and language skills (Swaminathan & Schellenberg, 2020) as well as theories that attribute reading deficiencies to dysfunctional timing (Nicolson et al., 2001).

The importance of regular rhythmic timing in reading performance may lie in the quasi-periodic structure of language (Langus et al., 2017), in which rhythmic patterns may be embedded within an irregular sequence of words and/or phrases. As such, rhythm training may strengthen a “temporal scaffolding” that can be used to promote sensorimotor processing in the service of reading (Bekius et al., 2016). Regarding the brain regions that may support such a temporal scaffolding, we recently showed that in an older adult population, improvements in timing following digital rhythm training were localized to a sensorimotor network that includes pre-motor cortex, anterior cingulate cortex, and the left inferior parietal lobule (Nandi et al., 2023). Importantly, these brain regions have also been associated with various aspects of reading (Boissonneau et al., 2022; Kotz & Schwartze, 2010; Meister et al., 2007; Pardo et al., 1990; Sliwinska et al., 2015). Additional research will be required to determine if these brain regions indeed underlie the observed changes in temporal attention in children, and whether such neuroplastic changes predict improvements in reading.

It is interesting to note that of the two assessments of inhibitory control, only the language-based measure (Stroop task) demonstrated improvement following rhythm training. However, it is important to note that the change in Stroop task performance was observed across both Congruent and Incongruent conditions. A change in inhibitory control should demonstrate a change in performance selectively during the Incongruent condition, but this was not observed. Similarly, we did *not* observe changes in inhibitory control as assessed by the Flanker task. We therefore conclude that inhibitory control was not improved. Given that reading is considered a prepotent response that forms the basis for the Stroop effect (Washburn, 2016), an improvement in reading fluency could result in speeded response times during both the Congruent and Incongruent conditions of the Stroop task. Yet, there was no correlation between the change in Stroop performance and the change in reading fluency. Although additional research will be required to understand these effects, the observed changes in performance during the Stroop task are likely related to language-based executive control.

Similar to inhibitory control, we also observed no alterations in sustained attention or working memory performance. This helps to provide additional specificity regarding how rhythm training affects reading fluency. Indeed, reading has been linked to both sustained attention (Stern & Shalev, 2013) and working memory performance (Peng et al., 2018), and that musical training can facilitate both of these cognitive abilities (Carey et al., 2015; Hansen et al., 2013; Talamini et al., 2016; Wang et al., 2015). It is therefore reasonable to hypothesize that rhythm training may improve reading through alterations in these cognitive functions, but this was not observed.

In contrast to our null effect of rhythm training on working memory, we recently observed that digital rhythm training can improve short-term memory for faces in older adults (Zanto et al., 2022). Although more research will be needed to understand the specificity of rhythm training on memory ability, there are several reasons why rhythm training may differentially affect memory. One possibility is that older adults, compared to children, are in greater need of memory improvement and therefore stand to benefit from rhythm training. Another possibility is that perhaps rhythm training can improve only the short-term encoding and storage of content (i.e., short-term memory), but not when the content needs to be manipulated or protected from distraction (i.e., working memory). A third possibility has to do with our assessment of working memory capacity, compared to our previous assessment that was more closely related to short-term memory fidelity. In this case, we speculate that the rhythm training task, where temporal structures were held in memory, did not tax memory capacity as much as it strained memory fidelity. In other words, we suggest that precise timing is more likely a matter of memory fidelity rather than capacity. Nonetheless, future research will need to address these possibilities.

It is worth noting several limitations of this study. For example, the control group was not engaged in a tablet-based control paradigm. This was a conscious decision made due to ethical concerns regarding control training during school hours—where children should be engaging in activities designed to help them learn, rather than a placebo game that is not designed to benefit the children. As such, children in the control group maintained classroom instruction as usual, thereby matching the Coherence group in terms of cognitive engagement. Other limitations include a modest sample size and that demographic information was not collected from the participants beyond age and gender due to constraints on data collection and student privacy. Future research would benefit from a larger sample, which will not only enable stronger conclusions, but it would promote the use of mediation analyses to draw a stronger link between rhythm training, changes in timing abilities, and changes in reading fluency. Moreover, collecting demographic data may yield important information regarding the extent to which rhythm training may be affected by factors such as prior musi-

14677687, 0, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/desc.13473, Wiley Online Library on [10/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

cal experience, socioeconomic status, or the presence of a learning difference.

Finally, it is worth noting that the effects of rhythm training may be limited by the duration of the outcome measures and the training itself. It could be argued that short tasks with few trials may affect their reliability. Although we implemented well-established outcome measures in line with prior work, future research may benefit from multiple tasks that form a composite metric of the cognitive constructs of interest. Regarding training duration, participants in this study engaged with Coherence for only 6 weeks, which is nowhere close to the years of training that goes into becoming a musician. Although we speculate that more than 6 weeks of training would yield greater (and longer lasting) effects on cognitive function, some research has shown that amateur musicians exhibit metrics of more youthful brains compared to professional musicians (Rogenmoser et al., 2018). This begs the question as to whether there is an optimal amount of time to spend on musical training for cognitive benefits, where professional-level training may take away time from other cognitively enriching activities.

Overall, these results open the doors for further research and consideration of the adoption of digitally-based musical rhythm training as a means to facilitate core literacy skills, which may be critically important for those with learning disorders. Indeed, our media-saturated world is already full of smartphones and tablets, even in low-income populations (Pew Research Center, 2021). Taken together, the ubiquity of smartphones and tablets and the fact that digital musical rhythm training addresses two of the greatest barriers to entry, cost and convenience, this approach represents a powerful way to enable widespread access to musical training.

## 5 | CONCLUSION

This research demonstrated that digital rhythm training improved reading fluency in 3rd grade school children. This work shows that musical instruction, in this case rhythm training, can be implemented in a digital format without specialized musical equipment or professional instruction and still yield cognitive benefits beyond the trained ability. We also show that rhythm training improved rhythmic timing abilities, as well as language-based executive control. Despite this language-based improvement in executive control, only changes in rhythmic timing were predictive of changes in reading fluency. Thus, rhythm training alters core timing functions that can be deployed in a generalized manner to facilitate reading ability.

### ACKNOWLEDGMENTS

We would like to thank Tracy Rosenthal-Newsom, Jo Gazzaley, Rob Garza, Whitmire Vo, Brianna Jeska, and Mickey Hart for their assistance in creating Coherence. Finally, a special thanks to the school, teachers, parents, and students who made this research possible. This research was made possible through generous donations from the Neuroscape Network and the Hart Foundation for Deep Rhythm.

### CONFLICT OF INTEREST STATEMENT

A. Gazzaley is co-founder, shareholder, BOD member, and advisor for Akili Interactive Labs, a company that produces therapeutic video games, but has no connection with Coherence.

### DATA AVAILABILITY STATEMENT

Data are freely available to download at DOI: 10.17632/4cnvn89pvn.1

### ETHICS STATEMENT

This study was approved by the University of Bedfordshire Institutional Review Board.

### ORCID

*Theodore P. Zanto* https://orcid.org/0000-0003-4449-691X
*Courtney L. Gallen* https://orcid.org/0000-0002-4828-268X

### REFERENCES

Anguera, J. A., Boccanfuso, J., Rintoul, J. L., Al-Hashimi, O., Faraji, F., Janowich, J., Kong, E., Larraburo, Y., Rolle, C., Johnson, E., & Gazzaley, A. (2013). Video game training enhances cognitive control in older adults. *Nature*, *501*, 97–101. https://doi.org/10.1038/nature12486

Anguera, J. A., Volponi, J. J., Simon, A. J., Gallen, C. L., Rolle, C. E., Anguera-Singla, R., Pitsch, E. A., Thompson, C. J., & Gazzaley, A. (2022). Integrated cognitive and physical fitness training enhances attention abilities in older adults. *NPJ Aging*, *8*(1), 1–13. https://doi.org/10.1038/s41514-022-00093-y

Archibald, L. M. D. (2016). Working memory and language learning: A review. *Child Language Teaching and Therapy*, *33*(1), 5–17. https://doi.org/10.1177/0265659016654206

Aschersleben, G. (2002). Temporal control of movements in sensorimotor synchronization. *Brain and Cognition*, *48*, 66–79. https://doi.org/10.1006/brcg.2001.1304

Baddeley, A. (2003). Working memory and language: An overview. *Journal of Communication Disorders*, *36*(3), 189–208. https://doi.org/10.1016/S0021-9924(03)00019-4

Bekius, A., Cope, T. E., & Grube, M. (2016). The beat to read: A cross-lingual link between rhythmic regularity perception and reading skill. *Frontiers in Human Neuroscience*, *10*(425). https://doi.org/10.3389/FNHUM.2016.00425/BIBTEX

Bergee, M. J., & Weingarten, K. M. (2020). Multilevel models of the relationship between music achievement and reading and math achievement. *Journal of Research in Music Education*, *68*(4), 398–418. https://doi.org/10.1177/0022429420941432

Bergman Nutley, S., Darki, F., & Klingberg, T. (2014). Music practice is associated with development of working memory during childhood and adolescence. *Frontiers in Human Neuroscience*, *7*(926), 1–9. https://doi.org/10.3389/fnhum.2013.00926

Berz, W. L. (1995). Working memory in music: A theoretical model. *Music Perception*, *12*(3), 353–364. https://doi.org/10.2307/40286188

Boissonneau, S., Lemaître, A.-L., Herbet, G., Ng, S., Duffau, H., & Moritz-Gasser, S. (2022). Evidence for a critical role of the left inferior parietal lobule and underlying white matter connectivity in proficient text reading. *Journal of Neurosurgery*, *1*(aop), 1–10. https://doi.org/10.3171/2022.7.JNS22236

Bonacina, S., Huang, S., White-Schwoch, T., Krizman, J., Nicol, T., & Kraus, N. (2021). Rhythm, reading, and sound processing in the brain in preschool children. *NPJ Science of Learning*, *6*(1), 1–11. https://doi.org/10.1038/s41539-021-00097-5

Brower, C. (1993). Memory and the perception of rhythm. *Music Theory Spectrum*, *15*(1), 19–35. https://doi.org/10.2307/745907

14677687, 0, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/desc.13473, Wiley Online Library on [10/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Brown, S. (2017). A joint prosodic origin of language and music. *Frontiers in Psychology*, *8*, 1894. https://doi.org/10.3389/fpsyg.2017.01894

Bull, R., Espy, K. A., & Wiebe, S. A. (2008). Short-term memory, working memory, and executive functioning in preschoolers: Longitudinal predictors of mathematical achievement at age 7 years. *Developmental Neuropsychology*, *33*(3), 205. https://doi.org/10.1080/87565640801982312

Burland, K. (2020). Music for all: Identifying, challenging and overcoming barriers. *Music & Science*, *3*, 1–6. https://doi.org/10.1177/2059204320946950

Butzlaff, R. (2000). Can music be used to teach reading? *Journal of Aesthetic Education*, *34*(3/4), 167. https://doi.org/10.2307/3333642

Carey, D., Rosen, S., Krishnan, S., Pearce, M. T., Shepherd, A., Aydelott, J., & Dick, F. (2015). Generality and specificity in the effects of musical expertise on perception and cognition. *Cognition*, *137*, 81–105. https://doi.org/10.1016/J.COGNITION.2014.12.005

Carpentier, S. M., Moreno, S., & McIntosh, A. R. (2016). Short-term music training enhances complex, distributed neural communication during music and linguistic tasks. *Journal of Cognitive Neuroscience*, *28*(10), 1603–1612. https://doi.org/10.1162/JOCN_A_00988

Cogo-Moreira, H., Andriolo, R. B., Yazigi, L., Ploubidis, G. B., Brandão de Ávila, C. R., & Mari, J. J. (2012). Music education for improving reading skills in children and adolescents with dyslexia. *The Cochrane Database of Systematic Reviews*, *8*, 1–25. https://doi.org/10.1002/14651858.CD009133.PUB2

Cooper, P. K. (2020). It's all in your head: A meta-analysis on the effects of music training on cognitive measures in schoolchildren. *International Journal of Music Education*, *38*(3), 321–336. https://doi.org/10.1177/0255761419881495

Coull, J. T., & Nobre, A. C. (1998). Where and when to pay attention: The neural systems for directing attention to spatial locations and to time intervals as revealed by both PET and fMRI. *Journal of Neuroscience*, *18*(18), 7426–7435. <Go to ISI>://000075893000035 https://doi.org/10.1523/JNEUROSCI.18-18-07426.1998

Crocker, R. L. (1964). Pythagorean mathematics and music. *The Journal of Aesthetics and Art Criticism*, *22*(3), 325. https://doi.org/10.2307/427236

Dainer, K. B., Klorman, R., Salzman, L. F., Hess, D. W., Davidson, P. W., & Michael, R. L. (1981). Learning-disordered children's evoked potentials during sustained attention. *Journal of Abnormal Child Psychology*, *9*(1), 79–94. https://doi.org/10.1007/BF00917859

de Diego-Balaguer, R., Martinez-Alvarez, A., & Pons, F. (2016). Temporal attention as a scaffold for language development. *Frontiers in Psychology*, *7*(44), 1–15. https://doi.org/10.3389/fpsyg.2016.00044

dos Santos-Luiz, C., Mónico, L. S. M., Almeida, L. S., & Coimbra, D. (2015). Exploring the long-term associations between adolescents' music training and academic achievement. *Musicae Scientiae*, *20*(4), 512–527. https://doi.org/10.1177/1029864915623613

Edelson, R. J., & Johnson, G. (2012). Music makes math meaningful. *Childhood Education*, *80*(2), 65–70. https://doi.org/10.1080/00094056.2004.10521259

Eriksen, B. a., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics*, *16*(1), 143–149. https://doi.org/10.3758/BF03203267

Finneran, D. A., Francis, A. L., & Leonard, L. B. (2009). Sustained attention in children with specific language impairment (SLI). *Journal of Speech, Language, and Hearing Research*, *52*(4), 915–929. https://doi.org/10.1044/1092-4388(2009/07-0053)

Flaugnacco, E., Lopez, L., Terribili, C., Montico, M., Zoia, S., & Schön, D. (2015). Music training increases phonological awareness and reading skills in developmental dyslexia: A randomized control trial. *PLOS ONE*, *10*(9), e0138715. https://doi.org/10.1371/JOURNAL.PONE.0138715

Flaugnacco, E., Lopez, L., Terribili, C., Zoia, S., Buda, S., Tilli, S., Monasta, L., Montico, M., Sila, A., Ronfani, L., & Schön, D. (2014). Rhythm perception and production predict reading abilities in developmental dyslexia. *Frontiers in Human Neuroscience*, *8*(JUNE), 392. https://doi.org/10.3389/FNHUM.2014.00392/BIBTEX

Gandolfi, E., & Viterbori, P. (2020). Inhibitory control skills and language acquisition in toddlers and preschool children. *Language Learning*, *70*(3), 604–642. https://doi.org/10.1111/LANG.12388

Gordon, R. L., Fehd, H. M., & McCandliss, B. D. (2015). Does music training enhance literacy skills? A meta-analysis. *Frontiers in Psychology*, 1–16. https://doi.org/10.3389/fpsyg.2015.01777

Goswami, U. (2011). A temporal sampling framework for developmental dyslexia. *Trends in Cognitive Sciences*, *15*(1), 3–10. https://doi.org/10.1016/J.TICS.2010.10.001

Hannon, E. E., & Trainor, L. J. (2007). Music acquisition: Effects of enculturation and formal training on development. *Trends in Cognitive Sciences*, *11*(11), 466–472. https://doi.org/10.1016/J.TICS.2007.08.008

Hansen, M., Wallentin, M., & Vuust, P. (2013). Working memory and musical competence of musicians and non-musicians. *Psychology of Music*, *41*(6), 779–793. https://doi.org/10.1177/0305735612452186

Henley, J., & Barton, D. (2022). Time for change? Recurrent barriers to music education. *British Journal of Music Education*, *39*(2), 203–217. https://doi.org/10.1017/S026505172200016X

Hsu, W. Y., Rowles, W., Anguera, J. A., Anderson, A., Younger, J. W., Friedman, S., Gazzaley, A., & Bove, R. (2021). Assessing cognitive function in multiple sclerosis with digital tools: Observational study. *Journal of Medical Internet Research*, *23*(12), 1–15. https://doi.org/10.2196/25748

Janus, M., Lee, Y., Moreno, S., & Bialystok, E. (2016). Effects of short-term music and second-language training on executive control. *Journal of Experimental Child Psychology*, *144*, 84–97. https://doi.org/10.1016/J.JECP.2015.11.009

JASP Team. (2020). JASP (Version 0.14.1). In *[Computer software]*.

Johnson, V., Hsu, W. Y., Ostrand, A., Gazzaley, A., & Zanto, T. P. (2020). Multimodal sensory integration: Diminishing returns in rhythmic synchronization. *Journal of Experimental Psychology: Human Perception and Performance*, *46*(10), 1077–1087. https://doi.org/10.1037/XHP0000833

Kessels, R. P. C., Van Zandvoort, M. J. E., Postma, A., Kappelle, L. J., & De Haan, E. H. F. (2010). The Corsi block-tapping task: Standardization and normative data. *Applied Neuropsychology*, *7*(4), 252–258. https://doi.org/10.1207/S15324826AN0704_8

Kieffer, M. J., Vukovic, R. K., & Berry, D. (2013). Roles of attention shifting and inhibitory control in fourth-grade reading comprehension. *Reading Research Quarterly*, *48*(4), 333–348. https://doi.org/10.1002/RRQ.54

Kljajević, V. (2010). Is syntactic working memory language specific? *Psihologija*, *43*(1), 85–101. https://doi.org/10.2298/PSI1001085K

Kotz, S. A., & Schwartze, M. (2010). Cortical speech processing unplugged: A timely subcortico-cortical framework. *Trends in Cognitive Sciences*, *14*(9), 392–399. https://doi.org/10.1016/j.tics.2010.06.005

Krampe, R. T., Engbert, R., & Kliegl, R. (2001). Age-specific problems in rhythmic timing. *Psychology and Aging*, *16*(1), 12–30. https://doi.org/10.1037/0882-7974.16.1.12

Kraus, N., Hornickel, J., Strait, D. L., Slater, J., & Thompson, E. (2014). Engagement in community music classes sparks neuroplasticity and language development in children from disadvantaged backgrounds. *Frontiers in Psychology*, *5*(DEC), 1403. https://doi.org/10.3389/FPSYG.2014.01403/BIBTEX

Kraus, N., Slater, J., Thompson, E. C., Hornickel, J., Strait, D. L., Nicol, T., & White-Schwoch, T. (2014). Music enrichment programs improve the neural encoding of speech in at-risk children. *Journal of Neuroscience*, *34*, 11913–11918. https://doi.org/10.1523/jneurosci.1881-14.2014

Greenberg, L., Kindschi, C., Dupuy, T., & Corman, C. (1996). Test of Variables of Attention: Clinical guide. *Los Alamitos*, CA: Universal Attention Disorders.

Landerl, K., & Willburger, E. (2010). Temporal processing, attention, and learning disorders. *Learning and Individual Differences*, *20*(5), 393–401. https://doi.org/10.1016/J.LINDIF.2010.03.008

14677687, 0, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/desc.13473, Wiley Online Library on [10/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Langus, A., Mehler, J., & Nespor, M. (2017). Rhythm in language acquisition. *Neuroscience & Biobehavioral Reviews*, *81*, 158–166. https://doi.org/10.1016/J.NEUBIOREV.2016.12.012

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

Mead, L. A., Mayer, A. R., Bobholz, J. A., Woodley, S. J., Cunningham, J. M., Hammeke, T. A., & Rao, S. M. (2002). Neural basis of the Stroop interference task: response competition or selective attention? *Journal of the International Neuropsychological Society: JINS*, *8*(6), 735–742. https://doi.org/10.1017/s1355617702860015

Meister, I. G., Wilson, S. M., Deblieck, C., Wu, A. D., & Iacoboni, M. (2007). The essential role of premotor cortex in speech perception. *Current Biology: CB*, *17*(19), 1692–1696. https://doi.org/10.1016/J.CUB.2007.08.064

Menon, V. (2016). Working memory in children's math learning and its disruption in dyscalculia. *Current Opinion in Behavioral Sciences*, *10*, 125–132. https://doi.org/10.1016/J.COBEHA.2016.05.014

Mishra, J., Anguera, J. A., & Gazzaley, A. (2016). Video games for neuro-cognitive optimization. *Neuron*, *90*(2), 214–218. https://doi.org/10.1016/j.neuron.2016.04.010

Mishra, J., de Villers-Sidani, E., Merzenich, M., & Gazzaley, A. (2014). Adaptive training diminishes distractibility in aging across species. *Neuron*, *84*(5), 1091–1103. https://doi.org/10.1016/j.neuron.2014.10.034

Moreno, S., Bialystok, E., Barac, R., Schellenberg, E. G., Cepeda, N. J., & Chau, T. (2011). Short-term music training enhances verbal intelligence and executive function. *Psychological Science*, *22*(11), 1425–1433. https://doi.org/10.1177/0956797611416999

Moreno, S., Friesen, D., & Bialystok, E. (2011). Effect of music training on promoting preliteracy skills: Preliminary causal evidence. *Music Perception*, *29*(2), 165–172. https://doi.org/10.1525/MP.2011.29.2.165

Moreno, S., Lee, Y., Janus, M., & Bialystok, E. (2015). Short-term second language and music training induces lasting functional brain changes in early childhood. *Child Development*, *86*(2), 394–406. https://doi.org/10.1111/CDEV.12297

Nandi, B., Ostrand, A., Johnson, V., Ford, T. J., Gazzaley, A., & Zanto, T. P. (2023). Musical training facilitates exogenous temporal attention via delta phase entrainment within a sensorimotor network. *Journal of Neuroscience*, *43*(18), 3365–3378. https://doi.org/10.1523/JNEUROSCI.0220-22.2023

Nicolson, R. I., Fawcett, A. J., & Dean, P. (2001). Developmental dyslexia: the cerebellar deficit hypothesis. *Trends in Neurosciences*, *24*(9), 508–511. https://doi.org/10.1016/S0166-2236(00)01896-8

Ostermann, T., Willich, S. N., & Lüdtke, R. (2008). Regression toward the mean—A detection method for unknown population mean based on Mee and Chua's algorithm. *BMC Medical Research Methodology*, *8*, 52. https://doi.org/10.1186/1471-2288-8-52

Ozernov-Palchik, O., & Patel, A. D. (2018). Musical rhythm and reading development: does beat processing matter? *Annals of the New York Academy of Sciences*, *1423*(1), 166–175. https://doi.org/10.1111/NYAS.13853

Pardo, J. v., Pardo, P. J., Janer, K. W., & Raichle, M. E. (1990). The anterior cingulate cortex mediates processing selection in the Stroop attentional conflict paradigm. *Proceedings of the National Academy of Sciences*, *87*(1), 256–259. https://doi.org/10.1073/PNAS.87.1.256

Patel, A. D. (2003). Language, music, syntax and the brain. *Nature Neuroscience*, *6*(7), 674–681. https://doi.org/10.1038/nn1082

Peng, P., Barnes, M., Wang, C. C., Wang, W., Li, S., Swanson, H. L., Dardick, W., & Tao, S. (2018). Meta-analysis on the relation between reading and working memory. *Psychological Bulletin*, *144*(1), 48–76. https://doi.org/10.1037/BUL0000124

Pew Research Center. (2021). *Mobile fact sheet*.

Portowitz, A., Peppler, K. A., & Downton, M. (2014). In Harmony: A technology-based music education model to enhance musical understanding and general learning skills. *International Journal of Music Education*, *32*(2), 242–260. https://doi.org/10.1177/0255761413517056

Raghubar, K. P., Barnes, M. A., & Hecht, S. A. (2010). Working memory and mathematics: A review of developmental, individual difference, and cognitive approaches. *Learning and Individual Differences*, *20*(2), 110–122. https://doi.org/10.1016/J.LINDIF.2009.10.005

Repp, B. H. (2005). Sensorimotor synchronization: A review of the tapping literature. *Psychonomic Bulletin & Review*, *12*(6), 969–992. https://doi.org/10.3758/BF03206433

Roden, I., Grube, D., Bongard, S., & Kreutz, G. (2013). Does music training enhance working memory performance? Findings from a quasi-experimental longitudinal study. *Psychology of Music*, *42*(2), 284–298. https://doi.org/10.1177/0305735612471239

Rogenmoser, L., Kernbach, J., Schlaug, G., & Gaser, C. (2018). Keeping brains young with making music. *Brain Structure and Function*, *223*(1), 297–305. https://doi.org/10.1007/s00429-017-1491-2

Román-Caballero, R., Vadillo, M. A., Trainor, L. J., & Lupiáñez, J. (2022). Please don't stop the music: A meta-analysis of the cognitive and academic benefits of instrumental musical training in childhood and adolescence. *Educational Research Review*, *35*, 100436. https://doi.org/10.1016/J.EDUREV.2022.100436

Ruffino, M., Molteni, M., Boccardi, D., Facoetti, A., & Gori, S. (2014). Spatial and temporal attention in developmental dyslexia. *Frontiers in Human Neuroscience*, *8*(331), 1–13. https://doi.org/10.3389/fnhum.2014.00331

Russell-Bowie, D. (2009). What me? Teach music to my primary class? Challenges to teaching music in primary schools in five countries. *Music Education Research*, *11*(1), 23–36. https://doi.org/10.1080/14613800802699549

Sala, G., & Gobet, F. (2020). Cognitive and academic benefits of music training with children: A multilevel meta-analysis. *Memory and Cognition*, *48*, 1429–1441. https://doi.org/10.3758/s13421-020-01060-2

Schrank, F. A., Mather, N., & McGrew, K. S. (2014). *Woodcock-Johnson IV Tests of Achievement*.

Slater, J., Azem, A., Nicol, T., Swedenborg, B., & Kraus, N. (2017). Variations on the theme of musical expertise: Cognitive and sensory processing in percussionists, vocalists and non-musicians. *The European Journal of Neuroscience*, *45*(7), 952–963. https://doi.org/10.1111/EJN.13535

Sliwinska, M. W., James, A., & Devlin, J. T. (2015). Inferior parietal lobule contributions to visual word recognition. *Journal of Cognitive Neuroscience*, *27*(3), 593–604. https://doi.org/10.1162/JOCN_A_00721

Smolak, E., McGregor, K. K., Arbisi-Kelm, T., & Eden, N. (2020). Sustained attention in developmental language disorder and its relation to working memory and language. *Journal of Speech, Language, and Hearing Research*, *63*(12), 4096–4108. https://doi.org/10.1044/2020_JSLHR-20-00265

Statista Research Department. (2022). *Number of smartphone subscriptions worldwide from 2016–2027*.

Stern, P., & Shalev, L. (2013). The role of sustained attention and display medium in reading comprehension among adolescents with ADHD and without it. *Research in Developmental Disabilities*, *34*(1), 431–439. https://doi.org/10.1016/J.RIDD.2012.08.021

Strait, D. L., & Kraus, N. (2011). Can you hear me now? Musical training shapes functional brain networks for selective auditory attention and hearing speech in noise. *Frontiers in Psychology*, *2*(113), 1–10. https://doi.org/10.3389/fpsyg.2011.00113

Swaminathan, S., & Schellenberg, E. G. (2020). Musical ability, music training, and language ability in childhood. *Journal of Experimental Psychology: Learning Memory and Cognition*, *46*(12), 2340–2348. https://doi.org/10.1037/XLM0000798

Talamini, F., Carretti, B., & Grassi, M. (2016). The working memory of musicians and nonmusicians. *Music Perception*, *34*(2), 183–191. https://doi.org/10.1525/MP.2016.34.2.183

Teki, S., Grube, M., Kumar, S., & Griffiths, T. D. (2011). Distinct Neural Substrates of Duration-Based and Beat-Based Auditory Timing. *Journal of*

14677687, 0, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/desc.13473, Wiley Online Library on [10/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

*Neuroscience*, *31*(10), 3805–3812. https://doi.org/10.1523/JNEUROSCI.5561-10.2011

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

Townsend, J. T., & Ashby, F. G. (1983). *The stochastic modeling of elementary psychological processes*, p. 501.

van de Cavey, J., & Hartsuiker, R. J. (2016). Is there a domain-general cognitive structuring system? Evidence from structural priming across music, math, action descriptions, and language. *Cognition*, *146*, 172–184. https://doi.org/10.1016/J.COGNITION.2015.09.013

Vaughn, K. (2000). Music and mathematics: Modest support for the oft-claimed relationship. *Journal of Aesthetic Education*, *34*(3/4), 149. https://doi.org/10.2307/3333641

Vibell, J., Lim, A., & Sinnett, S. (2021). Temporal perception and attention in trained musicians. *Music Perception*, *38*(3), 293–312. https://doi.org/10.1525/MP.2021.38.3.293

Wais, P. E., Arioli, M., Anguera-Singla, R., & Gazzaley, A. (2021). Virtual reality video game improves high-fidelity memory in older adults. *Scientific Reports*, *11*(1), 1–14. https://doi.org/10.1038/s41598-021-82109-3

Wang, X., Ossher, L., & Reuter-Lorenz, P. A. (2015). Examining the relationship between skilled music training and attention. *Consciousness and Cognition*, *36*, 169–179. https://doi.org/10.1016/J.CONCOG.2015.06.014

Washburn, D. A. (2016). The Stroop effect at 80: The competition between stimulus control and cognitive control. *Journal of the Experimental Analysis of Behavior*, *105*(1), 3–13. https://doi.org/10.1002/JEAB.194

White, C., & Wesolowski, B. (2021). Exploring the effect of rhythmic interventions on first- and second-grade music students' oral reading fluency. *Visions of Research in Music Education*, *33*(1), 1–34. https://opencommons.uconn.edu/vrme/vol33/iss1/5

Wiener, S., & Bradley, E. D. (2020). Harnessing the musician advantage: Short-term musical training affects non-native cue weighting of linguistic pitch. *Language Teaching Research*, *27*(4), 1016–1031. https://doi.org/10.1177/1362168820971791

Wing, A. M., & Kristofferson, A. B. (1973). Response delays and the timing of discrete motor responses. *Perception & Psychophysics*, *14*(1), 5–12. https://doi.org/10.3758/BF03198607

Woltz, D. J., & Was, C. A. (2006). Availability of related long-term memory during and after attention focus in working memory. *Memory and Cognition*, *34*(3), 668–684. https://doi.org/10.3758/BF03193587/METRICS

Younger, J., O'Laughlin, K. D., Anguera, J. A., Bunge, S., Ferrer, E. E., Hoeft, F., McCandliss, B., Mishra, J., Rosenberg-Lee, M., Gazzaley, A., & Uncapher, M. (2021). Development of executive function in middle childhood: A large-scale, in-school, longitudinal investigation. *PsyArXiv*. https://doi.org/10.31234/OSF.IO/XF489

Younger, J. W., O'laughlin, K. D., Anguera, J. A., Bunge, S. A., Ferrer, E. E., Hoeft, F., Mccandliss, B. D., Mishra, J., Rosenberg-Lee, M., Gazzaley, A., & Uncapher, M. R. (2021). Better together: novel methods for measuring and modeling development of executive function diversity while accounting for unity. *Frontiers in Human*, *17*(1195013), 1–19. https://doi.org/10.21203/RS.3.RS-1032581/V2

Zalta, A., Petkoski, S., & Morillon, B. (2020). Natural rhythms of periodic temporal attention. *Nature Communications*, *11*(1), 1–12. https://doi.org/10.1038/s41467-020-14888-8

Zanto, T. P., Johnson, V., Ostrand, A. E., & Gazzaley, A. (2022). How musical rhythm training improves short-term memory for faces. *Proceedings of the National Academy of Sciences*, *119*(41), e2201655119. https://doi.org/10.1073/pnas.2201655119

Zanto, T. P., Padgaonkar, N. T., Nourishad, A., & Gazzaley, A. (2019). A tablet-based assessment of rhythmic ability. *Frontiers in Psychology*, *10*, 2471. https://doi.org/10.3389/fpsyg.2019.02471

Ziegler, D. A., Anguera, J. A., Gallen, C. L., Hsu, W.-Y., Wais, P. E., & Gazzaley, A. (2022). Leveraging technology to personalize cognitive enhancement methods in aging. *Nature Aging*, *2*(6), 475–483. https://doi.org/10.1038/s43587-022-00237-5

Ziegler, D. A., Simon, A., Gallen, C. L., Skinner, S., Janowich, J. R., Volponi, J. J., Rolle, C. E., Mishra, J., Kornfield, J., Anguera, J. A., & Gazzaley, A. (2019). Closed-loop digital meditation improves sustained attention in young adults. *Nature Human Behavior*, *3*, 746–757. https://doi.org/10.1038/s41562-019-0611-9

**How to cite this article:** Zanto, T. P., Giannakopoulou, A., Gallen, C. L., Ostrand, A. E., Younger, J. W., Anguera-Singla, R., Anguera, J. A., & Gazzaley, A. (2024). Digital rhythm training improves reading fluency in children. *Developmental Science*, e13473. https://doi.org/10.1111/desc.13473

14677687, 0, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/desc.13473, Wiley Online Library on [10/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License