RHYTHMIC PRIMING AND VERBAL MEMORY

FROM BEAT TO MEMORY: RHYTHMIC PRIMING EFFECTS ON VERBAL MEMORY PERFORMANCE

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Lay Abstract

The notion that music and speech are highly relevant to our auditory environment has been demonstrated across developmental, cognitive, and neurological work. As such, it might be expected that features of these stimuli interact with one another for fundamental human cognitive processes. Studies have been published in support of this interaction and in favour of listening to predictable rhythms versus unpredictable rhythms before language tasks to enhance performance. The studies contained within this thesis investigated the specific role that predictable musical rhythm plays in *verbal memory* performance. Across three chapters, the data provide mixed evidence that listening to a predictable musical rhythm prior to a verbal memory task positively affects its performance. As such, this work demonstrates the fragility of rhythmic priming before verbal memory tasks within standard laboratory settings and makes a significant theoretical contribution in understanding the role of rhythmic priming in specific linguistic domains.

Abstract

Listening to musical rhythms has been reported to enhance performance on language tasks for people with typical and atypical language abilities. In children and adults, priming with predictable rhythms (i.e., short-term rhythmic stimulation with music) has been shown to facilitate grammaticality judgements, even among children and adults with poor rhythm processing skills. Children and adults with atypical language skills have been better able to identify incorrect grammar within sentences when they have been primed with a predictable musical beat compared to an unpredictable beat or sound scene. Until the present thesis, to our knowledge there is no research demonstrating whether these beneficial rhythmic priming effects extend to verbal memory in children and adults. In Chapter 2, I report the finding that 9–11-year-old children with and without dyslexia may be unable to better recognize novel words when first primed with a predictable musical rhythm compared to an unpredictable environmental sound scene. Furthermore, children were better at judging grammatical and ungrammatical sentences after listening to an unpredictable environmental sound scene. However, in Chapter 3, I found that listening to a predictable musical rhythm compared to an environmental sound scene before repeating a nonsense sentence may enhance immediate recall from verbal memory in both adult musicians and non-musicians. Chapter 4 examines how the tempo of the predictable musical rhythm affects the priming of nonsensical sentences during passive listening. No ideal tempo amongst slow, moderate, and fast tempi could be detected. Together, these data show that rhythmic priming does not consistently provide benefits for verbal memory or specific language tasks. As such, this work makes contributions to the understanding of the interactions between rhythm, speech, and memory, and provides future considerations for investigating rhythmic priming and its potential connections to rehabilitation research.

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List of all Abbreviations and Symbols

η^2: Eta squared

η_p^2: Partial eta squared

ANOVA: Analysis of variance

BPM: Beats per minute

CTOPP: Comprehensive Test of Phonological Processing

***d'*:** d prime

DAT: Dynamic Attending Theory

DLD: developmental language disorder

F: F-test statistic

Hz: Hertz

LPC: Late Positive Component

M: mean

MSE: mean squared error

n: sample size

p: p-value

PSTM: phonological short-term memory

RPE: rhythmic priming effect

s: seconds

SD: standard deviation

SLI: specific language impairment

SPM: syllables per minute

STM: short term memory

TOWRE-2: Test of Word Reading Efficiency- Second Edition

VSTM: verbal short-term memory

VWM: verbal working memory

WM: working memory

z: z-score

Declaration of Academic Achievement

The author of the present thesis is the primary author of all three manuscripts and was responsible for conceptualization, experimental design, linguistic stimulus creation for pseudowords in Chapter 2, data collection, analysis, and manuscript preparation. Dr. Daniel Pape (McMaster University) is the second author on Chapter 4 and assisted with musical stimuli creation and manuscript preparation. Dr. Jonathan Cannon (McMaster University) is the third author on Chapter 4 and assisted with manuscript preparation. Dr. M. Elisabet Service (McMaster University), the thesis supervisor, is the final author on all three manuscripts.

Chapters 3, and 4, further explore the findings from Chapter 2, and so the methodology and stimuli overlap to certain extents.

Chapter 1: General Introduction

The question, 'Does music benefit the brain?' often prompts a straightforward answer. The plethora of evidence reported over decades of research in music cognition, music education, cognitive neuroscience and neuroscience support the notion that performing, listening to, and moving to music often has various cognitive and motor benefits (e.g., Altenmüller, Wiesendanger, & Kesselring, 2006; Kraus & Chandrasekaran, 2010; Román-Caballero et al., 2022). Music, much like speech, can convey and create emotional messages and responses to the listener (Juslin, 2013). Experience with these messages and responses can be important for the development of cognitive processes, such as attentional processing (Vuilleumier, 2005), and learning and memory processing (Phelps, 2004; for a review see Tyng et al., 2017). Music, like speech, contributes to language acquisition and development. For instance, musical training has been shown to enhance phonological awareness—the ability to segment out and mentally manipulate the sounds of spoken language (Moreno et al., 2009). This appears to be similar to how exposure to rich language environments supports vocabulary growth and language development (Hoff, 2006).

The question of whether the temporal predictability of musical rhythm can enhance cognitive processes is a more complicated one and remains a topic of recent interest among music cognition researchers, cognitive neuroscientists, and neuroscientists. The main purpose of the experiments in this thesis was to address this question by investigating how regularly structured auditory stimuli (i.e., musical rhythm) affect verbal short-term memory

(VSTM). My investigation included conditions when participants could easily predict temporal patterns in an auditory stimulus and when temporal patterns were difficult to extract from the stimulus. I investigated the role that temporally regular musical rhythm primes and arrhythmic environmental sound scene primes presented before verbal stimuli play in listeners' verbal short-term and long-term memory performance. The listeners I studied in the experiments came from different populations. Some had known difficulties with verbal short-term memory processing, some had superior abilities with verbal short-term memory, and some had typical VSTM. Interestingly, and in contrast to a large body of existing work with rhythmic priming, this thesis found mixed evidence for a benefit of listening to temporally regular musical rhythms compared to arrhythmic environmental sound primes before verbal short-term memory tasks.

To present the theoretical question and to introduce the research methodologies, the following literature overview is organized into five sections. Section I reviews the literature on speech, verbal short-term memory and temporal processing in the dyslexic brain and the beneficial effects of musical training on language tasks. Section II provides an overview of VSTM in musicians, who are known to excel in memory tasks, relative to non-musicians. Section III reviews work on the overall benefits of rhythm on memory. Section IV introduces the main theoretical questions, and Section V presents an overview of the experimental manipulations and the three experimental reports that comprise this thesis.

Literature Overview

Section I: Speech, verbal memory, and auditory temporal processing in the dyslexic brain

My first experiment was designed to study the possibility of using music to improve sentence processing and memory for embedded novel words, especially in children with reading difficulties. Below, I will describe the research findings motivating a study on music and verbal memory in groups with different reading abilities.

Developmental dyslexia (henceforth termed dyslexia) is a neurodevelopmental learning disorder characterized by poor reading and spelling (Snowling, 2000). Often, these difficulties are attributed to challenges in the phonological processing of language. These challenges make it difficult for individuals with dyslexia to connect spoken sounds to written letters or symbols (Bradley & Bryant, 1983; Catts et al., 2005; Joanisse et al., 2000). Despite having normal intelligence, individuals with dyslexia may experience various levels of difficulty in reading, spelling and sometimes speech (e.g., recalling nonwords; Joanisse et al., 2000; see Snowling, 2019 for a review). Although dyslexia is a lifelong condition, it is important to note that with appropriate support and interventions, individuals with dyslexia can develop effective strategies to manage their difficulties, resulting in improved literacy and language skills and an overall improved quality of life (Snowling, 2013).

Speech processing. Neuroimaging studies have suggested that individuals with dyslexia process speech differently from typical readers. For instance, a recent study showed that children with dyslexia had difficulties tracking the syllable rate and prosodic information of a children's story read aloud (Mandke et al., 2022). If a child has difficulties processing prosodic information in speech, this can negatively affect other aspects of how language is represented in their brain (e.g., phonology). If one's phonological representation of words is deficient, this will subsequently affect one's ability to decode text back to speech— as often seen in individuals with dyslexia.

It has been suggested that musical training can enhance the neural processing of speech (see Kraus & Chandrasekaran, 2010 for an overview). For example, musicians demonstrate greater neural processing for speech sounds in the auditory brainstem and have greater prosodic sensitivities (Musacchia et al., 2007; Parbery-Clark et al., 2009; Swaminathan & Schellenberg, 2020; Zioga et al., 2016). Furthermore, Nitin et al. (2023) suggest that musically trained children have an advantage when processing grammar and syntax (i.e., word order in a sentence). Prosody is the rhythm of speech, consisting of patterns of relative syllable loudness, duration, and pitch, among other factors such as, stressed vs. unstressed syllable compression effect and vowel reduction phenomena. Given musicians' practice in rhythm production and perception, it is not surprising that musicians have been reported to be more sensitive to prosody than similar individuals without musical training (Heffner & Slevc, 2015).

Musical training has also been found to positively impact the frequently deficient rhythm processing skills of dyslexic children (Huss et al., 2011), facilitating both language and reading abilities (Habib et al., 2016). The positive effect of music on linguistic abilities is often attributed to the overlap of neural networks between music and language processing (e.g., Patel, 2011). Moreover, it has been hypothesized that not only do neural music and language networks overlap, but they also include common cognitive resources, such as memory and attentional resources, that are employed by both music and language processing (Rogalsky et al., 2011). Musical training, particularly rhythm training, is specifically helpful in alleviating the challenges associated with perceptual temporal processing skills which have been found to be deficient in many people with dyslexia (Leong & Goswami, 2014; Overy et al., 2003). The benefits that could stem from musical/rhythm training may lead to enhanced timing skills in language processing, which may help to refine rhythmic and prosodic understanding. Thus, syllable and word segmentation could be better supported, leading to improved auditory attention—all contributing towards efficient speech processing (Guerra et al., 2024; Milankov et al., 2021).

Verbal short-term memory. Verbal memory can be defined as the maintenance of verbal information in a temporary store in the brain. Baddeley's (1986) multicomponent model originally consisted of a "central executive" component that controls attention, subserved by two modality-specific subsystems for storage of visuo-spatial and verbal content, respectively. The framework for the working memory system posits that one subcomponent coined the *phonological loop* plays a key role in retaining and repeating speech-based information in the span of short time frames. This specialized loop is subdivided into the phonological store (where verbal information is stored) and the articulatory process, which allows the stored verbal information to be rehearsed and repeated aloud (Baddeley, Gathercole & Papagno, 1998). The working memory framework was later updated to include an additional component coined the episodic buffer (Baddeley, 2000). This component is responsible for integrating the temporal dynamics of verbal and visual information to create a unified memory. It has also been hypothesized to create unique memories by blending primed or activated memories from our long-term storage with information actively being maintained in the phonological loop. Importantly, such information blending appears to occur automatically, even in individuals with severe long-term memory deficits, as demonstrated by densely amnesic patients in Baddeley & Wilson's (2002) study.

Studies of school-age children (e.g., Booth, Boyle & Kelly, 2014; Pham & Hasson, 2014) have reported a positive correlation between verbal/phonological working memory and reading fluency, suggesting that verbal memory measures are salient predictors of reading fluency. However, the results are somewhat mixed. For instance, one study found that there was no relationship between phonological working memory and reading fluency in a dyslexic group of school-age children compared to a positive relationship found in typically developed children (De Carvalho et al., 2014). In general, the evidence for phonological working memory deficits in dyslexic children is strong. Children with dyslexia often score significantly lower than their typically developed peers on word recall (e.g., Schuchardt et al., 2013), verbal span tasks (e.g., Menghini et al., 2011) and nonword repetition tasks (e.g., Ehrhorn et al., 2021; Jeffries & Everatt, 2004; Snowling, 1981).

Verbal STM has been linked to other cognitive skills with a temporal component, such as musical abilities. The literature strongly suggests that musical training is associated with increased verbal memory (Fennell et al., 2021). For instance, in a sentence processing task in Fennell et al. (2021), the results showed that musicians outperformed non-musicians in verbal and visuospatial memory. One possibility for this superior performance in visuospatial memory is that extensive experience reading musical scores and interpreting spatial relationships from scores may enhance visuospatial processing (Brochard, Dufour & Després, 2004). Additionally, musical training may provide direct benefits specifically toward verbal memory processing by organizing information using syntactic patterns (known as chunking). Addressing and enhancing verbal memory through targeted interventions like musical training can offer promising avenues for improving literacy skills among those with dyslexia (Gordon, Fehd & McCandliss, 2015; Habib et al., 2016).

Auditory temporal processing. Auditory temporal processing refers to the brain's ability to perceive and analyze the timing and sequencing of acoustic events in sound. This complex and crucial cognitive function is fundamental for daily acoustic experiences such as speech recognition, music appreciation, and sound localization (Zatorre & Gandour, 2008). Accurate discrimination of auditory temporal features can be attributed to the intricate neural mechanisms that underlie temporal coding in the brain, including neural synchrony to speech.

Auditory temporal processing impairments in the dyslexic brain have attracted the attention of cognitive researchers and neuroscientists over the last several decades. These temporal processing impairments are operationalized in different ways across the literature but can be described generally as deficits in perceiving changing auditory events over different timescales (Amitay, Ahissar & Nelken, 2002). Several examples of 'auditory events' that are poorly processed in dyslexic individuals are phonemes, syllables, and the prosodic features of speech (i.e., intonation, stress, and rhythm; Farmer & Klein, 1995; Goswami, 2011; Goswami, Gerson, & Astruc, 2010). A previous study (Molinaro et al.,

2016) used magnetoencephalography to record brain synchronization to spoken sentences in a group of dyslexic individuals and age-matched controls. Compared to the control group, individuals with dyslexia showed a reduction of neural synchrony in the right auditory cortex and the left inferior frontal gyrus. They also showed weaker brain responses to speech rhythms in the slow delta range (0.5-1 Hz). Furthermore, it was found that this poor synchronization persisted from childhood through adulthood. These findings suggest that individuals with dyslexia have poor speech-brain entrainment, possibly contributing to their phonological and reading deficits.

It has been suggested that temporal processing deficits seen in dyslexia can be alleviated through music interventions such as regular music lessons (Overy, 2000). Research motivated by resemblances in music and language (Patel, 2007, 2011) has indicated that extensive musical training can enhance individuals' sensitivity to sounds and their ability to process phonological information (Flaugnacco et al., 2015). For instance, musicians are more sensitive to differences in pitch and duration of non-verbal stimuli (Bishop-Liebler et al., 2014). Data from Bishop-Liebler et al. (2014) revealed that musicians with dyslexia had the same level of auditory sensitivity and rhythm perception as musicians without dyslexia. Additionally, dyslexic musicians had better abilities in phonological processing compared to non-musicians with dyslexia. Performing music is a multisensory activity and may be an effective mode of supporting learning for individuals with dyslexia as it engages auditory and rhythm processing skills that benefit language learning (Oglethorpe et al., 1996).

In sum, while there is strong evidence supporting music's benefits for enhancing verbal memory as well as speech and auditory temporal processing in the dyslexic brain, the precise mechanisms underlying these effects remain unclear. It is possible that rigorous studying and producing of musical elements such as pitch, rhythm, beat, and structure, heightens one's ability to attend to and perceive patterns of these temporal elements a little more effortlessly.

Section II: Verbal working memory in musicians and non-musicians

My second experiment was designed to explore the potential of using music to enhance verbal short-term memory, specifically by examining the influence of musical rhythm in musicians and non-musicians. This study focuses on sentence repetition using nonsense sentences as a way to isolate and test rhythm's influence on memory performance. Below I will describe the research findings that motivated this investigation into how musical expertise and rhythmic sensitivity may shape verbal memory outcomes in distinct populations.

Given that there is a high degree of temporal similarity between music and language (Patel, 2007, 2011), it would not be surprising to find that musicians often perform better than non-musicians in verbal memory tasks. A brief overview of several hypotheses related to this claim is presented here, including how musical training promotes neuroplasticity in memory-related brain regions, fosters functional specialization in auditory and memory networks and enhances behavioural performance on verbal memory tasks.

There is substantial structural brain evidence suggesting that musicians' and non-musicians' brains differ in memory related brain regions. First, experienced musicians often show increased hippocampal volume compared to non-musicians and even amateur musicians (Gaser & Schlaug, 2003). Gaser and Schlaug (2003) also found that musicians have increased gray matter volume in regions associated with auditory processing, motor control and spatial awareness all of which are important for memory performance. Furthermore, functional differences were found in a functional magnetic resonance imaging (fMRI) study by Pallesen et al. (2010), where musicians had greater activation in memory-related brain areas during working memory tasks requiring continuous memory updating. Additionally, Herdener et al. (2010) suggested that musical training over long time periods is associated with functional changes in the hippocampus and earlier work found that extensive musical training is associated with functional changes in the brainstem (Musacchia et al., 2007).

Moreover, there is behavioural evidence suggesting that musicians often outperform non-musicians on various working memory tasks. For example, musicians demonstrated enhanced working memory capacity and duration on tonal discrimination tasks compared to non-musicians (Ding et al., 2018). These findings indicate that musicians can retain more tonal items in memory and hold on to these items in memory longer than non-musicians. Although several studies (Franklin et al., 2008; Ho, Cheung & Chan, 2003; Taylor & Dewhurst, 2017) reported that musicians perform better on memory tasks than non-musicians, the type of stimuli has been shown to influence the size of the effect. For instance, in a meta-analysis, Talamini et al. (2017) found that tonal stimuli proved advantageous for observing a large effect in short-term and working memory. Additionally, effect sizes were medium and in favour of musicians' short-term and working memory performance for verbal stimuli.

Memory advantages in musicians compared to non-musicians may stem from multiple underlying factors. These include self-selection, the cognitive benefits of musical training, and musicians' enhanced auditory discrimination skills. Together, these factors may contribute to musicians' superior verbal short-term memory performance.

One possible explanation for the observed memory advantage in musicians is the self-selection hypothesis. This theory suggests that individuals with innately better memory capabilities are more likely to become musicians (Talamini et al., 2017). These individuals may excel in verbal memory tasks not as a consequence of musical training but due to pre-existing cognitive strengths. Talamini et al. (2017) contrasted this hypothesis with the possibility that better memory capabilities could develop as a result of musical training emphasizing the importance of considering self-selection as a contributing factor.

Another explanation is that musicians' superior verbal memory arises from the cognitive benefits of musical training. According to the domain specificity hypothesis (Ericsson & Kintsch, 1995), learning to play an instrument might enhance the recall of tonal stimuli, explaining why musicians outperform non-musicians in tonal memory tasks. However, favorable effect sizes also extend to verbal memory tasks (Chan, Ho & Cheung, 1998; Ho, Cheung & Chan, 2003; Jakobson, Cuddy & Kilgour, 2003). This can be accounted for by suggesting that musicians process auditory stimuli better than non-musicians (e.g., Rammsayer & Altenmüller, 2006; Spiegel & Watson, 1984; Tervaniemi et al., 2005). Enhanced auditory processing skills can benefit verbal memory by supporting better auditory encoding of stimuli, thus strengthening memory traces, and increasing recall (Talamini et al., 2017). This is also compatible with small or null effect sizes for differences in visual memory tasks between musicians and non-musicians (Okhrei, Kutsenko, & Makarchuk, 2017; Talamini, Carretti & Grassi, 2016). For instance, in Talamini et al. (2016), musicians performed better than non-musicians in a digit span task when the stimuli were presented orally; however, the effect was attenuated when these stimuli were presented visually.

The overlap between music and language processing (Patel & Iverson, 2007) may further amplify these benefits. Music perception skills, such as rhythm reproduction and pitch perception are closely tied to phonological awareness and the early stages of reading proficiency (Anvari et al., 2002; Douglas & Willats, 1994; Lamb & Gregory, 1993). For instance, rhythm perception strongly correlates with phonological awareness and literacy skills (Steinbring et al., 2019) since both tasks rely on storing and manipulating auditory stimuli in working memory. This interplay between music and language suggests that musical training may bolster memory for verbal stimuli by enhancing these shared cognitive mechanisms.

Furthermore, musicians' enhanced auditory discrimination skills may also contribute to their superior verbal memory. These skills are crucial for accurate discrimination amongst rhythmic and linguistic pitch patterns (Kishon-Rabin et al., 2001; Kumar, Sanju, & Nikhil, 2016; Wong et al., 2007). This may consequently translate to musicians' enhanced phonological processing abilities, a key component of verbal memory. Notably, the relationship between phonological awareness and phonological short-term memory may be bidirectional: greater phonological awareness can improve phonological encoding and maintenance, while greater phonological short-term memory may support the development of phonological awareness. Studies have shown that heightened auditory processing skills can lead to improvements in tasks requiring the manipulation of verbal and pitch information in working memory (e.g., Schön, Magne, & Besson, 2004).

Overall, several factors may collectively contribute to the superior verbal short-term memory (VSTM) skills observed in musicians compared to non-musicians. These include structural adaptations in memory related brain regions and functional specialization in auditory and memory networks driven by neuroplasticity from musical training. Additionally, self-selection of individuals with inherently better memory abilities and the cognitive benefits of musical training—including enhanced auditory discrimination skills highlight the interplay between musical expertise and verbal memory performance.

Section III: Rhythm and memory

Similar to the second experiment, my third experiment sought to isolate a specific feature of musical rhythm (e.g., tempo) and explore its influence on verbal short-term memory and sentence repetition, building on methodologies used in my first and second experiments. This study aimed to investigate how tempo affects memory. Below, I will outline the broader relationship between rhythm and memory, emphasizing how rhythm might facilitate performance in verbal tasks.

In line with the previous section's observations, research on the influence of rhythm on memory highlights that rhythmic patterns can enhance memory performance (irrespective of one's musical expertise) through enhancement of overall attention, entrainment of dynamic attending (via entrainment of neural oscillations) with external stimuli and chunking of information.

Rhythm has been suggested to play a beneficial role in directing, sustaining, and enhancing attention, which is important for memory encoding and retrieval. Dynamic Attending Theory (DAT; Jones, 1976, 2019) posits that neural activity oscillates in synchronization with rhythmic patterns, enhancing cognitive processes during moments of maximal attention. By facilitating temporal expectancies, rhythmic patterns enable individuals to heighten their attention and can subsequently improve memory processing. Evidently, attention is a critical component of memory processing, as it will determine what and how well information is processed, encoded, and stored for later retrieval (Posner & Petersen, 1990).

Building on this, the role of specific neural oscillations, such as theta rhythms, have gained attention for its involvement in memory processing. Theta oscillations (4-8 Hz) are important for memory processing (for a review see Herweg, Solomon, & Kahana, 2020). External rhythmic stimuli in the theta frequency range have been shown to enhance theta synchronization of brain rhythms and subsequently memory performance (Schonhaut et al., 2024; Solomon et al, 2017). Moreover, auditory (rhythmic) stimulation has been found to enhance episodic memory by synchronizing theta frequency activity in the hippocampus (Lisman & Jensen, 2013). Such rhythmic entrainment has been shown to improve the coupling between the hippocampus and the prefrontal cortex (Fell & Axmacher, 2011)—

brain regions critical for working memory processing, memory formation, and memory consolidation.

Another cognitive mechanism through which rhythm helps memory processing is ‘chunking’. Chunking is founded in the notion that the human brain has the capacity to hold a limited number of items in memory (Miller, 1956). Chunking is a process whereby smaller units of information are grouped into larger, more manageable units. For example, grouping a lengthy string of digits into several groups will be easier to remember compared to attempting to remember each individual digit in the string—much like recalling a phone number. By organizing information into memorable chunks and reducing the amount of information being processed, the human brain experiences less cognitive load (e.g., Thalmann, Souza & Oberauer, 2019). This reduction in cognitive load allows for easier memory encoding (Sweller, 1988).

In verbal memory tasks, rhythm plays an important role in segmenting speech into more memorable units. For instance, rhythmic patterns and structures found in poetry and lyrics often makes them more memorable compared to arrhythmic prose (Rubin, 1995). Studies have suggested that the presence of rhythm in music, and rhyme and meter in poetry, aid in chunking information to facilitate memory encoding, storage, and retrieval (e.g., Dowling, 1973; Tillmann & Dowling, 2007). Tillmann & Dowling (2007) found that participants were better at recalling poetry because of the rhythmic cues embedded in the structure compared to prose with less rhythmic structure. In addition to reducing our cognitive load by simplifying information, chunking can reduce distractions and enhance attention by grouping related items, making them easier to focus on (Cowan, 2001).

Event-related potential (ERP) data in Gilbert, Boucher, and Jemel (2014) revealed neural markers that are associated with processing chunked vs. non-chunked speech. The chunked speech elicited ERP components (N400, P300 and a Late Positive Component) indicative of efficient neural processing. In this study, the N400 component, which is typically interpreted as related to processing semantic information, was smaller in magnitude for chunked speech compared to non-chunked speech, suggesting less effortful semantic processing and more efficient neural processing. A robust P300 response, which is associated with attentional capture and working memory (WM), was observed for chunked speech indicating that attentional resources had been successfully allocated and available to subsequently enhance encoding into WM. Finally, the Late Positive Component (LPC) has been associated with retrieval and recognition of information. The data revealed a more prominent LPC for chunked speech, indicating that chunked information was more accessible from memory storage. Furthermore, behavioural data from this study showed that participants had better recall and recognition for temporally chunked speech vs. non-chunked speech.

In summary, a review of the literature suggests that rhythm plays an important role in enhancing memory by supporting neural entrainment allocation of attentional resources and chunking of information. The patterns heard in auditory rhythmic stimuli create regular structures for internal entrainment, particularly in brain regions such as the hippocampus. Furthermore, rhythm naturally promotes chunking information into smaller, more manageable groups—facilitating efficient memory storage and retrieval.

Section IV: The main questions

The main questions addressed in this thesis were derived from the key findings highlighted in the literature reviewed above. Specifically, prior research has shown that rhythmic regularity in auditory stimuli and musical training are both associated with enhanced cognitive processing, including improvements in verbal memory performance. We now turn to an outline of three explorative questions that investigate how rhythmic regularity impacts performance in verbal memory tasks, with a particular focus on its potential facilitation for verbal short-term memory.

Large amounts of converging evidence strongly suggests that musical training can facilitate stronger memory performances, and in particular verbal short-term memory (VSTM; Miendlarzewska & Trost, 2014). So far, rhythmic priming has been found to influence grammar processing, attention, and sentence processing (e.g., Bedoin et al., 2016, 2018; Canette et al., 2020; Chern et al., 2018; Fiveash et al., 2023; Ladányi, Lukács & Gervain, 2021; Przybylski et al., 2013). However, past cognitive studies have not explored whether listening to a temporally regular/predictable musical rhythm can enhance subsequent VSTM in children or adults with typical or atypical language abilities. Broadly, the exploration in this thesis can be categorized into three research questions. The first one concerns finding a *rhythmic priming effect for VSTM*. The second one *compares the rhythmic priming effect in musicians and non-musicians*. Finally, the third *question concerns the possibility of an ideal prime tempo for observing a rhythmic priming effect on verbal memory*. Each of these three explorations should help to extend the evidence for the benefits of musical training and listening to temporally regular patterns (e.g., musical rhythms) beyond its current scope. The three studies aiming to produce answers to these questions are outlined below.

Rhythmic priming effect and memory for new words. A number of studies (e.g., Bedoin et al., 2016, 2018; Canette et al., 2020; Chern et al., 2018; Ladányi, Lukács & Gervain, 2021; Przybylski et al., 2013) have demonstrated that the rhythmic priming effect (RPE) can be found for grammar judgement and phonological processing tasks, irrespective of the tested individual's stage of cognitive development. For instance, the RPE was found in children with specific language impairment (SLI; Bedoin et al., 2016; Przybylski et al., 2013), recently renamed developmental language disorder (DLD). Groups of children with DLD show impairments in language processing but also in rhythm and meter perception (Huss et al., 2011). The RPE was also observed in adults with dyslexia (Canette et al., 2020), adults with typical language abilities (Cason, Astésano & Schön, 2015) and children with typical language abilities (Chern et al., 2018). Importantly for this thesis, a previous study observed the RPE beyond the scope of grammar processing in sentence repetition (Fiveash et al., 2023). This finding was interpreted within the domain of complex syntax. However, the observed RPE might have implications for the domain of memory and particularly, verbal short-term memory (VSTM). Sentence repetition relies on VSTM. Sequences of words have to be maintained and stored in order in short-term memory before recall. In addition to chunking words together following syntactic rules, the reproduction of a sentence requires accurate word processing, word manipulation (to attain the correct order), and word rehearsal (to maintain the sentence in memory), all crucially dependent on VSTM.

Most previous studies on rhythmic priming have investigated the effect in the language and motor domain (for an overview see Kotz, Ravignani & Fitch, 2018) but not often in the memory domain. As such, it also remains unknown whether the rhythmic priming effects that have been reported can be extended to provide intervention strategies for populations with verbal memory limitations such as people with dyslexia, traumatic brain injuries, strokes, Alzheimer's disease, and other dementias. In this thesis, I investigate the effects of listening to rhythmically structured compared to unstructured stimuli on pseudoword recognition and repetition accuracy. In addition to verbal memory tests, participants' grammar judgments were tested.

Rhythmic priming effect in musicians vs. non-musicians. Investigating rhythmic priming effects in musicians provides a novel opportunity to explore how musical expertise influences cognitive processes such as speech, rhythm processing, and memory. While the rhythmic priming effect has been largely studied in younger populations with atypical language abilities, such as children with DLD and dyslexia (e.g., Przybylski et al., 2013), no research to date has explored the rhythmic priming effect in musicians. This represents a significant gap in the literature as musicians' enhanced rhythm processing skills make them an ideal population for investigating how rhythmic priming mechanisms may depend on prior musical experience.

Rhythm deficits in both language and music are well-documented in children with DLD and dyslexia, (e.g., Corriveau & Goswami, 2009; Corriveau, Pasquni, & Goswami, 2007; Cumming et al., 2015; Goswami et al., 2002), populations in which the rhythmic priming effect (RPE) has been observed (Bedoin et al., 2016; Ladányi et al., 2021;

Przybylski et al. 2013). RPEs have also been demonstrated in adults with dyslexia (Canette et al., 2020). In these rhythm-deficient populations, the RPE may be less robust or perhaps rely on compensatory strategies, raising the question of how the rhythmic priming effect manifests in populations with enhanced rhythm processing skills, such as musicians. Musicians may demonstrate more pronounced rhythmic priming effects due to their training and ability to engage rhythm processing mechanisms more effectively and automatically.

Musical training, particularly rhythm training can also improve speech rhythm processing (for reviews see Fiveash et al., 2021; Fujii & Wan, 2014). While speech rhythms are less predictable and metrically structured than musical rhythms, listeners can still perceive and entrain to regularities in speech (Lidji et al., 2011; Schmidt-Kassow & Kotz 2009). Moreover, it has been often reported that musicians outperform non-musicians in speech-in-noise tasks (Du & Zatorre, 2017; Parbery-Clark et al., 2009; Slater & Kraus, 2016; Yates et al., 2019) an ability suggested to be attributed to their enhanced speech rhythm tracking. Despite this well-established connection between musical training and speech rhythm processing, no studies have investigated rhythmic priming in musicians.

Investigating the RPE in musicians can offer critical insights into whether rhythmic priming depends on rhythm processing expertise. Investigating the RPE specifically in the domain of verbal memory which has not yet been studied, not only bridges gaps between music and rhythmic priming research, but also may provide insights into whether musical training enhances RPEs for populations with rhythm, memory, and speech deficits (e.g., Habib et al., 2016; for an overview see Miendlarzewska & Trost, 2014).

This initial effort to investigate RPE in musicians will address a critical gap in the literature and offer a clearer understanding of the mechanisms underlying rhythmic priming and how it operates across populations with varying levels of rhythm and verbal memory processing abilities. This novel perspective not only enhances our theoretical understanding but also points to broader applications for rehabilitative interventions.

Ideal tempo for rhythmic primes. If rhythmically predictable stimuli can prime language processing in a positive way, the question arises whether all rhythms are equally effective. In particular, do different temporal rates have different effects? Considering that the optimal speech rate for processing is approximately 150 words per minute (Marslen-Wilson, 1973) and that the rhythm prime used to elicit an RPE in language tasks in previous studies was approximately 120 beats per minute (bpm, e.g., Bedoin et al., 2016; Chern et al., 2018; Przybylski et al., 2013), one question is, can the prime's tempo fluctuate to still elicit an RPE in the verbal short-term memory domain? It is therefore unknown whether slower or faster rhythmic primes can elicit a rhythmic priming effect. This exploration will provide insights into the strengths and limitations of the prime itself and enhance our understanding regarding the mechanism of the rhythmic priming effect. Furthermore, the information about the ideal tempo of the rhythmic prime could be used in planning future intervention/rehabilitation strategies for clinical language populations. For instance, research on the effects of tempo on emotion highlight that music with fast tempi typically evokes positive emotions while slower tempi can evoke negative emotions (Juslin & Sloboda, 2001; Peretz, Gagnon & Bouchard, 1998). If individuals with DLD and/or dyslexia are undergoing rhythm training for speech/language therapy but also have comorbidities with mood disorders (e.g., Xiao et al., 2023; for a review see Hendren et al., 2018), the tempi chosen for any type of rhythm training or even for music therapy, may influence intervention outcomes.

Given the influential role of rhythm in verbal STM, it is possible that the previously reported rhythmic priming effects on grammaticality judgements may extend to verbal memory. Data in support of rhythmic priming effects in the domain of memory processing would further substantiate previous reports on the beneficial effects of rhythm on language processing, but, potentially, also extend the evidence to a domain-general cognitive benefit.

Section V: Thesis overview

To date, a number of studies (Bedoin et al., 2016, 2018; Canette et al., 2020; Chern et al., 2018; Ladányi, Lukács & Gervain, 2021; Przybylski et al., 2013) have shown that listening to a regular, predictable musical prime before a linguistic task can produce a rhythmic priming effect (RPE). The performance on a linguistic task is improved due to listening to a regular, predictable musical prime, compared to an unpredictable (temporally unstructured) prime. Much of this work includes a linguistic task such as a grammaticality judgement. As such, it remains unclear whether this rhythmic priming effect can extend beyond the morpho-syntactic domain. The studies contained within the following three experimental chapters were designed to replicate and test the rhythmic priming effect in the interdisciplinary domain of linguistics and verbal short-term memory. If the rhythmic priming effect can extend beyond the linguistic domain and into the verbal short-term memory domain, it would imply that listening to regular, predictable musical rhythms might have a broader effect on cognitive processes than previously reported. These implications can then be used as intervention tools in education to facilitate, improve or remediate particular presentations of verbal short-term memory deficits. If not, the implication is that this rhythmic priming effect may only strongly influence grammaticality judgements in linguistic processing which could constrain our investigation for the cognitive and neural underpinnings of the rhythmic priming effect.

Research approach. All experiments in this thesis measure the rhythmic priming effect using a rhythm prime paradigm adopted from Przybylski et al. (2013). In published rhythmic priming paradigms, an auditorily presented unpredictable stimulus (e.g., an environmental sound scene) or a simple musical rhythm have been presented for ~30 s before a block of approximately six sentences containing a morpho-syntactic language task (i.e., grammar judgement task). It is thought that regular or predictable rhythmic primes are entraining brain oscillations at the beat and meter levels. Rhythmic priming facilitates a transition from a non-dynamic to a dynamic mode of attention, enhancing the ability to process temporal patterns in auditory inputs. This enhancement does not depend on the prime aligning with linguistic elements such as morpho-syntactic properties (i.e., grammar). Instead, the prime predisposes the cognitive system to detect and respond to temporal cues present in natural speech, thus supporting sentence processing.

There are two key reasons why this paradigm was chosen. First, the rhythmic priming paradigm is ideal for measuring cognitive performance after passively listening to music compared to listening to random sounds (e.g., an environmental sound scene). That is, cognitive performance on verbal memory tasks (here non-word recognition and sentence recall) can be measured using the rhythmic priming paradigm. Secondly, a number of existing studies (Bedoin et al., 2016; Canette et al., 2020; Chern et al., 2018; Fiveash et al., 2020) have been carried out using this paradigm in the domain of linguistics. For example, one of the first studies on rhythmic priming in the language domain from Przybylski et al. (2013) used this paradigm with children aged 6–12 years old who were typical readers or children diagnosed with dyslexia or DLD. This study demonstrated that passively listening to a temporally regular rhythm improved grammaticality judgments in all groups compared to listening to an irregular rhythm prime. Together, these findings make the rhythmic priming paradigm ideal to examine the effects of passive listening to a regular rhythmic structure on verbal memory performance.

Sample size determination. Sample sizes for all experiments presented in this thesis were determined via a priori power analyses using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007). Prior research has found medium-to-large effect sizes regarding the extent of rhythmic priming for linguistic stimuli with ~15 to 20 participants in each group, including control groups (see for example Bedoin et al., 2016; Fiveash et al., 2023; Przybylski et al., 2013). Hence, we recruited approximately 15 to 30 participants for each group for experiments within this present thesis.

The current task. For the rhythmic priming paradigm used in this thesis, participants were presented with a rhythmic prime or an environmental sound scene for ~30 s before one sentence or a block of six sentences (depending on the experiment). The paradigm was repeated for an approximate total of 20 to 50 sentences (dependent upon the experiment). Participants were then asked to make grammaticality judgements and to perform a pseudoword recognition task (Chapter 2) or to repeat out loud a sentence consisting of pseudowords that they heard (Chapters 3 and 4). Grammaticality judgements, pseudoword recognition and sentence repetition accuracies were compared between and within different populations.

Chapter 2. The experiment in this chapter investigated if a rhythmic priming effect (RPE) could be found in the domain of verbal short-term memory (VSTM) amongst children with and without reading difficulties. Within the rhythmic priming paradigm, a pseudoword was placed at the end of auditorily presented sentences. Pseudowords were then subsequently auditorily presented amongst distractors for a pseudoword recognition task. This experiment also sought to replicate the results of an observed RPE from previous studies where grammaticality judgements were improved after listening to a temporally regular rhythm prime (e.g., Bedoin et al., 2016; Canette et al., 2020; Chern et al., 2018; Fiveash et al., 2020). Surprisingly, the results revealed that participants' grammaticality judgements were better after listening to the control prime—an environmental sound scene compared to a regular, predictable rhythmic prime. Moreover, there were no effects of rhythmic priming on pseudoword recognition. As such, the experiment within this second chapter uncovered a dual task effect similar to one previously reported where the RPE was removed, possibly demonstrating interference caused by competition between linguistic processing or judgment and verbal short-term memory.

Chapter 3. The study in this chapter investigated if a rhythmic priming effect (RPE) would be found in the verbal short-term memory (VSTM) domain amongst adult musicians and non-musicians. The grammaticality judgement task was replaced by simple recall of nonsensical sentences after passively listening to a rhythmic prime or an environmental sound scene prime. Results were compared between musicians and non-musicians and between a rhythmic prime and an environmental sound scene (unpredictable) prime. The results showed an RPE in both groups with no significant difference between groups. Thus, the rhythmic priming effect may extend into verbal STM.

Chapter 4. The final experimental chapter investigated the role of tempo in the rhythmic prime used in the previous chapters. The rhythmic prime was presented in varied tempi before nonsensical sentences were to be repeated aloud. Here, the tempi were slow (60 bpm), moderate (120 bpm; the one used in the experiments in Chapters 2 and 3) and fast (360 bpm). Results were further compared between musicians and non-musicians. Surprisingly, the results failed to replicate those of Chapter 3, indicating no evidence of a rhythmic priming effect (RPE) for either group of participants or for any tempo. Thus, it appears that the data did not replicate its finding from Chapter 3 even with the moderate tempo—previously used in previous chapters. This chapter suggests that tempo in the range that was studied has no effect on eliciting an RPE and provides mixed evidence that listening to a temporally regular musical rhythm prior to a verbal memory task positively affects its performance.

Finally, **Chapter 5** is a **General Discussion**, in which the results of the experiments are discussed regarding existing literature and the relevance of rhythmic priming in verbal short-term memory.

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Chapter 2: Effects of rhythmic priming on pseudoword recognition and sentence judgement in children with and without dyslexia

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Abstract

Previous research has demonstrated that regular, predictable musical rhythmic primes can benefit subsequent grammar processing in children compared with irregular rhythmic primes. In the framework of the Dynamic Attending Theory, rhythms with regular, predictable beats orient listeners' attention over time through neural entrainment—facilitating predictive cognitive processing. Up to now, this rhythmic priming effect has largely been demonstrated to facilitate grammaticality judgements, sentence repetition and motor (re)-learning. To investigate the presence of a rhythmic priming effect on verbal recognition memory, children with and without dyslexia listened to regular, predictable beats (32 s) or an irregular environmental sound scene (30 s) before hearing a spoken sentence containing a pseudoword at the end. Surprisingly, grammaticality judgements were poorer for children with and without dyslexia after listening to a regular, predictable rhythm compared to the environmental sound scene prime. The addition of a pseudoword recognition component to sentence processing may have counter-acted benefits from rhythmic priming. Comparison of the observed performance to previous data suggests that the verbal memory component interfered with the regular prime benefit and potentially created a dual-task condition.

Keywords: Dyslexia; Music; Rhythm processing; Verbal memory

Introduction

Recently, a number of studies have suggested that temporally regular rhythms play a role in language processing (Boucher, Gilbert & Jemel, 2019; Tierney & Kraus, 2015; for reviews, see Fujii & Wan, 2014; Goswami, 2022). One theoretical framework, the Dynamic Attention Theory (Jones, 1976), proposes that rhythmic patterns in stimuli induce and align internally created rhythmic brain oscillations to allow processing and memory encoding of temporally structured material, such as language. Furthermore, experimental research (e.g., Bedoin et al., 2016; Canette et al., 2019, 2020; Chern et al., 2018; Fiveash et al., 2023; Przybylski et al., 2013) has shown that processing of language structure can be enhanced by auditory rhythmical primes presented before spoken sentences.

In rhythmic priming experiments, in the linguistic domain, structured/predictable rhythmic primes and unstructured/unpredictable primes are auditorily presented before each of a set of spoken sentences. Participants then perform a linguistic task on the sentences. For instance, results show that for children and adults with both typical and atypical language abilities (e.g., dyslexia, developmental language disorder), grammaticality judgements are improved after passively listening to the structured/predictable prime compared to the unstructured/unpredictable prime, highlighting a rhythmic priming effect (Bedoin et al., 2016; Canette et al., 2019, 2020; Chern et al., 2018; Fiveash et al., 2023; Przybylski et al., 2013). The present study builds on this empirical research to test if memory for new word forms as well as grammatical processing can be enhanced by such rhythmical priming. The target population was children between the ages of 9 and 11. Both children with typically developing reading skills and those with dyslexia were tested.

It is estimated that 6% to 17% of children have developmental dyslexia (Fletcher, 2009) the most prevalent of developmental learning disabilities. Developmental dyslexia has been characterized as an inability to develop age-appropriate reading, spelling, and writing skills despite normal intelligence, and in the absence of obvious sensory impairments or neurological damage (Snowling, 2000). Apart from poor literacy skills, children with dyslexia often show deficiencies in their spoken language and novel word acquisition abilities (e.g., Kimppa et al., 2018), measurable through their poor performance on tasks involving phonemic awareness, non-word repetition and word retrieval (for a review, see Vellutino et al., 2004). Previous evidence highlights a deficit specific to acquiring novel phonological word forms accompanied by semantic and visual associations (e.g., Aguiar & Brady, 1991; Di Betta & Romani, 2006; Litt & Nation, 2014; Mayringer & Wimmer, 2000; Vellutino, Scanlon & Spearing, 1995). However, these studies were not able to establish at what phase of verbal memory processing (initial memory encoding, memory storing, memory retrieval or production)—the problems occurred. Some evidence suggests that the deficiency lies in the memory encoding phase (Ahissar, 2007), for example, dyslexics do not benefit from stimulus repetition (e.g., Mather & Plunkett, 2009; Pugh et al., 2008) in the same way as typical readers do (Oganian & Ahissar, 2012).

The most commonly accepted core theory behind reading and spoken language failures in dyslexic children suggests that deficient phonological processing decreases the reader’s ability to mentally conceptualize speech sounds in words. This leads to inconsistent memory traces and mappings between letters and speech sounds (Baddeley, 1986; Baddeley, Gathercole & Papagno, 1998; Baddeley & Hitch 1974; Bradley & Bryant 1983; Gathercole & Baddeley, 1990). Poorly established grapheme-phoneme mappings then negatively affect dyslexics' ability to read (decode) novel, and even familiar, words. Poor mapping may be due to deficient storage of phonological information in phonological short-term memory (PSTM). PSTM, the ability to retain, rehearse and immediately recall phonological information stored over short time frames, is thought to involve a speech-based phonological store and a rehearsal-based refreshment mechanism (a "phonological loop"; Baddeley & Logie, 1999; Gathercole & Baddeley, 1993; for a review see Baddeley, 2012).

A previous investigation explored the possibility that PSTM impairments in dyslexia are not specific to phonological awareness deficits, but also connected to temporal deficits (Laasonen et al., 2012). Dyslexic adults' STM was tested using non-linguistic stimuli (i.e., light flashes, tactile stimulation, and tone bursts). Participants were asked to match pairs of sequences of these non-linguistic stimuli as they increased in length. Dyslexic adults performed more poorly than control readers, suggesting they had a general difficulty in their ability to store temporal sequential representations in their STM. Furthermore, reading and spoken language acquisition may involve more than just phonological STM. If the dyslexic readers' STM deficit were restricted to phonological material, the temporal sequences of non-linguistic stimuli should have been stored in the dyslexic adults' brains at the same accuracy level as in the brains of control readers.

Recently, attention has been directed to a temporal–dependent framework to supplement the phonological explanations behind reading and spoken language failures in dyslexia (e.g., Giraud & Poeppel, 2012; Goswami, 2011, 2018). In particular, it is proposed that internal neural oscillations (brain rhythms) must synchronize with external auditory speech rhythms for successful speech processing (Power et al., 2013). The synchronization of these two rhythms is termed 'speech entrainment' or 'neural entrainment'. Previous studies have shown reduced neural entrainment to speech rhythms at lower frequencies, such as syllable or word rate in individuals with dyslexia (Hämäläinen et al., 2012; Molinaro et al., 2016; Power et al., 2013). This has been proposed to decrease the quality of phonological and reading skills.

Converging research has focussed on investigating shared neural resources between music and language processing, particularly rhythm ability (for a review, see Gordon et al., 2015) and syntax processing (for a review, see Patel, 2003). Evidence for resources being shared between music and language was reported in a study simultaneously manipulating musical and linguistic syntax (Slevc, Rosenberg & Patel, 2009). Results from this self-paced reading paradigm with the accompaniment of musical chords highlighted interactive effects when violations were perceived in both linguistic and musical syntactic structure, suggesting a sharing of neural resources in the two domains.

Several studies have reported impaired rhythm and meter processing in dyslexia (e.g., Boll-Avetisyan, Bhatara & Höhle, 2020; Flaugnacco et al., 2014; Huss et al., 2011; Leong & Goswami, 2014; Overy et al., 2003; Thomson et al., 2006). For instance, when dyslexic children were asked to tap the rhythm of familiar songs such as "Happy Birthday" while singing, their performance was poor (Overy et al., 2003). It correlated with their spelling skills, possibly reflecting poor syllable segmentation abilities. It is also possible that dyslexic children were unable to combine the tasks of singing and tapping the rhythm effectively.

Although there is growing evidence that rhythm provides a processing advantage in the cognitive domain (see Van Rullen, 2016; for a review see Haegens & Zion Golumbic, 2017), its effect on verbal memory is largely unexplored. In this study, rhythmic priming of recognition memory for new word forms was studied in the context of sentence comprehension in dyslexic and typically reading children.

One theoretical framework assumes that listening to regular, predictable musical rhythms before a linguistic task can improve rhythmic attending abilities in individuals with a developmental language disorder (DLD) and/or dyslexia, and thus will enhance linguistic task performance. Typically, individuals with DLD exhibit general language problems in the absence of other developmental deficits (see Reilly et al., 2014 for a review). A previous study (Haebig et al., 2017) investigated neural responses to sentence processing in adolescents with persistent DLD, adolescents that were recovered from DLD and adolescents with typical language development. This study found that adolescents that were recovered from DLD exhibited similar neural responses to typically developed adolescents with slight variations, whereas adolescents with persistent DLD had significantly less robust neural responses for sentence processing compared to the other two groups.

Przybylski et al. (2013) studied children with DLD and dyslexia within the theoretical framework that passively listening to a predictable musical rhythm might enhance language task performances. Grammar judgements were assessed after they had listened to regular/predictable and irregular/unpredictable musical rhythms. Performance was better after listening to a regular musical rhythm. Another study investigated the impact of regular, predictable musical primes on syntactic processing of children with DLD and dyslexia (Bedoin et al., 2016). Results showed that attending to the regular, predictable musical prime enhanced performance in subsequent syntax processing tasks compared to when children attended to an environmental sound scene (without salient temporal regularities).

These beneficial rhythmic priming effects have been interpreted within the Dynamic Attending Theory (DAT) framework (Jones, 1976, 2019; Large & Jones, 1999). According to this account, neural oscillators entrain to external regularities (i.e., with the beat of a song), allowing one to maximally attend to the external stimulus and develop timing expectations to successfully process and predict future events at expected time points (e.g., grammatically correct words placed within sentences). It is plausible that rhythmic primes may also bolster attention and memory encoding to later support memory retrieval for verbal word recognition purposes. The way in which information is processed during memory encoding and storing determines how efficiently memories are subsequently retrieved (Davachi & Dobbins, 2008). For example, attending to particular items during encoding leads to better memory for the attended items versus unattended items (Berry et al., 2010).

Given that aspects of rhythm and verbal memory processing are poorer in children with dyslexia than in typical readers, and that rhythmic timing and verbal memory are crucial for speech processing, we designed a rhythmic priming experiment adapted from the methodology of Przybylski et al.’s (2013) paradigm to investigate the temporal underpinnings of verbal memory processing in children with variable reading abilities. In our online experiment, we modified three aspects of the original paradigm. First, we implemented the sound primes from Bedoin et al. (2016). Second, the sentences were adapted from Haebig et al. (2017) and were modified to include a pseudoword at the end of each sentence—replacing a real-word noun (e.g., “Every day, the horses *gallop/gallops* to the top of the *dalt*”). Third, we not only tested performance on grammaticality judgements, but also pseudoword recognition, to assess the facilitative effects of predictable musical rhythms on verbal memory. We predicted that attending to a predictable musical rhythm compared to an environmental sound scene without salient temporal regularities before grammar judgements and pseudoword recognition tasks would enhance linguistic performance. Dyslexic children were expected to demonstrate more accurate grammar and memory processing in predictable rhythmic priming conditions compared to unpredictable priming conditions.

Method

Participants. The present experiment included a group of 13 dyslexic children and a group of 26 typically reading children as controls, all between 9 and 11 years. None of the typical readers reported a history of speech, hearing, or learning impairments. For all children included in this experiment, English was the native language; fifteen participants reported bilingualism and nineteen reported a background of musical training longer than

6 months at the time of participation. None of the participants had sensory deficits (based on parental report). We assessed the reading fluency of all children to determine if they met inclusion criteria for the dyslexic or control group. Reading fluency was measured using form B of the *Test of Word Reading Efficiency Second Edition* (TOWRE-2; Torgesen, Wagner & Rashotte, 2012), which provides a sub-test scaled score of sight word reading along with phonological decoding skills for individuals aged 6 to 24 years.

Children were classified as having dyslexia if this had been previously diagnosed and/or they scored below the 16th percentile (scaled score ≤ 85) on the TOWRE-2. Consistent with a previous study that used the same selection criteria (Adlof et al., 2021). Our cut off represents a midpoint up to the 30th percentile in which children with dyslexia vary widely across studies (7th to 30th percentile; Badian *et al*., 1990; Manis *et al*., 1996). We also obtained scores from the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen & Rashotte, 1999). The CTOPP assesses phonological awareness, phonological memory, and rapid naming in individuals aged 5 to 24 years.

Fifty-three children were recruited via online advertisements directed to the general population in Canada (*n* = 36; twenty-five were included in the analyses), the United States (*n* = 11; ten were included in the analyses), and the United Kingdom (*n* = 6; four were included in the analyses). Overall, ten were excluded due to experiment malfunction, and four controls were excluded due to low phonological STM scores <85, for a total of 39 participants (age range = 9–11; mean age = 10 years, 1 month; *SD* = 0.75; 18 females) included in the analyses. Our dyslexic and control groups did not significantly differ in age (see Table 1). However, compared to the control group, the dyslexic group exhibited a clear profile of impaired reading ability associated with the symptomatology of developmental dyslexia, as evidenced by significant group differences in word reading efficiency measures (see Table 1).

All children provided verbal informed assent, and, upon study completion, children received a $15 gift card and a congratulatory certificate for compensation. Informed consent was obtained from all caregivers, and they were debriefed about the aims of the study, which was cleared by the McMaster Research Ethics Board.

Stimulus Selection. The stimuli were auditory sentences ending with a pseudoword. Forty-eight English sentences that were either grammatically correct (24) or incorrect (24) were adopted from the study by Haebig et al. (2017) and used in the acquisition phase during this study. Twelve trials contained a third-person singular subject marked with the correct verb agreement (e.g., "Every day, the dog *growls* when someone passes his crov"). Twelve trials contained a third-person singular subject and a verb with an agreement omission error (e.g., "Every day, the dog *growl* when someone passes his crov”). Twelve trials contained a plural subject and a verb correctly marked for agreement (e.g., "Every day, the trucks *rumble* down the flaf"). Twelve trials contained a plural subject and a verb with an agreement commission error marked for agreement (e.g., "Every day, the trucks *rumbles* down the flaf"). A complete list of the stimuli appears in **Appendix A**.

The mean sentence length was 8.75 words (*SD* = 1.21). The average duration of the sentences was approximately 3.2 s (ranging from 2.7 to 4.9 s). The sentences were recorded by a Canadian female native English speaker, one of the authors of this present paper who was aware of the study’s objectives.

Altogether, twenty-four pronounceable pseudowords were used in this study: twelve target pseudowords were selected from a previous study investigating novel word recall in healthy adults (Owusu & Burianová, 2020) and the remaining twelve pseudowords were slightly modified and served as distractors during the recognition task. All pseudowords were monosyllabic. Distractor pseudowords began with the same letters as their matched target word (i.e., flaf-target and fline-distractor). Each sentence was auditorily presented once and was randomized in 8 blocks across individuals.

Sentence presentation was preceded by an excerpt of temporally structured or unstructured acoustic material. The predictable musical sequence and the environmental sound scene previously studied by Bedoin et al. (2016) were used. The musical prime with a regular temporal structure was played by percussion instruments (a tam-tam and maracas). It had a duration of 32 s and contained a regular, predictable beat with a tempo of approximately 120 beats per minute (see Figure 1). The control prime was an environmental sound scene with a duration of 30 s. The environmental sounds included general playground ambiance, such as laughter, distant voices, and sirens—without any distinct melodic or rhythmic patterns. Snippets of children's speech could be heard within environmental noise, but full sentences were not discernible. Musical and linguistic stimuli were presented on the participant's computer during a recorded call on the Skype platform. The experiment was run on PsychoPy software (Peirce et al., 2019).

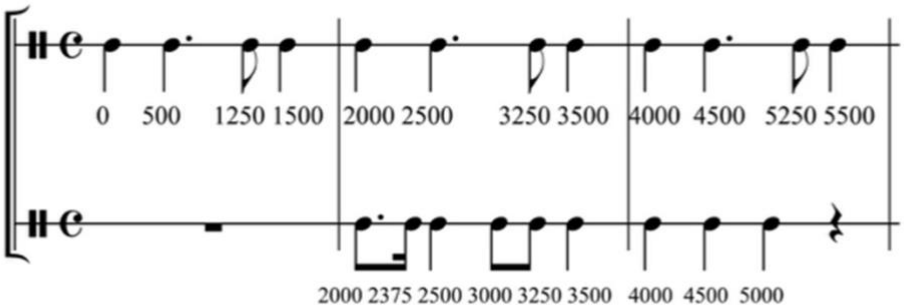

FIGURE 1 | *Musical score of the beginning of the predictable musical prime.* The timeline under the score part indicates the onsets of each note (in milliseconds). Source: Przybylski et al. (2013). Rhythmic auditory stimulation influences syntactic processing in children with developmental language disorders. *Neuropsychology, 27*, 121–131. Reproduced with permission from American Psychological Association. No further reproduction or distribution is permitted.

Standardized Assessments. Four out of 13 subtests from the CTOPP were selected to assess participant's phonological awareness and short-term memory. We selected the following subtests: Elision, Blending Words, Memory for Digits and Nonword Repetition as these are the core subtests in CTOPP listed to assess phonological awareness and memory, both of which are fundamental skills that are often deficient in dyslexic individuals (Snowling, 2000). Phonological awareness composite scores comprise the age-adjusted standard scores of two subtests—Elision and Blending Words. A deficit in phonological awareness is the crucial indicator of reading disability or dyslexia. Phonological memory composite scores comprise the standard scores of two subtests—Memory for Digits and Nonword Repetition. These scores provide an assessment of the phonological loop component of the working memory framework by Baddeley and Hitch (1974). A phonological loop deficit does not necessarily lead to poor reading of familiar stimuli but is likely to impair listening and reading comprehension for complex sentences and novel word decoding (Hulme & Snowling, 2009). For TOWRE-2, form B was used to assess sight word fluency ability for all participants.

Performance Measures. Children participated in a *Sentence Judgement task* that required them to judge whether or not each of the 48 sentences was grammatically correct. During the acquisition phase, sound files for each sentence were presented using PsychoPy and followed by an image of a computer keyboard highlighting the letters “P” and “Q” for button responses. Participants were instructed to press ‘P’ if they thought the sentence was correct or ‘Q’ if they thought the sentence was incorrect. In previous cognitive experiments (e.g., Kochari, 2019; Owusu & Burianová, 2020; Simi et al., 2023), the “P” and “Q” keys are often selected for binary response collection. Their spatial separation on the keyboard can minimize errors for random key presses and ensures clear distinctions between ‘correct’ and ‘incorrect’.

In the *Recognition* task, participants were auditorily presented with the 12 previously presented pseudowords and the 12 matched distractors in a randomized order. Each pseudoword had to receive input from the keyboard as ‘P’ if they recognized it from one of the sentences in the previous task or as ‘Q’ if they did not. Participants were instructed to produce fast responses via keystrokes responding to indicate whether or not they thought they recognized the presented pseudoword.

Procedure. Trained research assistants administered the experiment. The standardized reading assessments (CTOPP and TOWRE-2) were administered at the beginning of the study and took approximately 30 minutes to complete. Results were not announced for any of the assessments. Once having completed the tests, participants were offered a short break before the start of the grammar judgement task.

In the *Grammar Judgement* task, 48 sentences were presented in 8 blocks of six sentences. Before each block of sentences, a prime (either temporally predictable or unpredictable) was auditorily presented while a fixation cross appeared on screen for the duration of the prime. Four blocks were preceded by the temporally predictable prime and four by the environmental sound scene prime. Participants were instructed to listen to the music or the environmental sound scene until a blue exclamation mark appeared on the screen (1.5 s) and was followed by an auditorily presented sentence. Participants were also instructed to remember the “silly” pseudoword at the end of each sentence for a later task. Within each block, the order of the sentences was randomized so that each grammatically correct and matched incorrect sentence were represented equally in each block. Participants were prompted to take a break after the fourth block was complete. They were instructed to continue at any time by pressing the ‘Spacebar’. Participants first practiced this task with 8 unique trials (four followed the regular prime and four followed the control prime) to become comfortable with the controls and to ensure that the instructions were understood. The duration of this task was approximately 20 minutes. Subsequent to the grammar judgement task, an unrelated filler task was administered. In this, participants spoke aloud as many animals and insects they could think of in three minutes. The purpose of the filler task was to prevent covert rehearsal of pseudowords before the final recognition task.

The *Recognition* task began immediately after the filler task. Participants were instructed to make key presses to pseudowords recognized as having been or not been presented in the grammar judgement task. Participants heard pseudowords (targets and distractors) one at a time and pressed ‘P’(recognized) or ‘Q’(unrecognized) as fast as possible to indicate whether or not they had recognized the “silly” pseudoword as previously presented. There were 24 trials (12 targets and 12 distractors) in one block without interruptions. This task took approximately 1 minute to complete.

Results

Standardized Reading Assessments. Four of the 13 CTOPP subtests were administered to both groups (Elision; Blending Words; Memory for Digits and Nonword Repetition). Average performance score of phonological awareness for the dyslexic group was 87.1 (*SD* = 12.6; range: 64–103; with 100 being the average score of the reference population). Average performance score of phonological awareness for the control group was 98.7 (*SD* = 13.3; range: 67–115). Average performance score of phonological memory for the dyslexic group was 84.8 (*SD* = 9.60; range: 67–100; with 100 being the average score of the reference population). Average performance score of phonological memory for the control group was 94.6 (*SD* = 8.61; range: 76–112). Form B of TOWRE-2 was administered to both groups. Averaged normalized score for the dyslexic group was 76.2 (*SD* = 9.08; range: 55–85; with 100 being the average score of the reference population). The averaged normalized score for the control group was 104 (*SD* = 10.9; range: 88–126). See Table 1 for a summary of standard scores on the CTOPP and scaled scores for the TOWRE-2 for both groups.

Table 1. Mean participant age, standard, composite and scaled scores.

	Dyslexic[a]		**Control**[b]		***t*(1, 37)**
Variable	**Mean**	***SD***	**Mean**	***SD***	
Age (years)	10.1	0.74	10.1	0.77	.074
CTOPP elision standard score*	11.7	4.73	16.2	4.16	3.07*
CTOPP blending words standard score	10.1	3.43	11.4	3.44	1.12
CTOPP memory for digits standard score*	12.3	2.72	14.5	2.25	2.68*
CTOPP nonword repetition standard score	6.31	2.36	8.08	2.87	1.92
Composite phonological awareness score*	87.1	12.6	98.7	13.3	2.63*
Composite phonological memory score*	84.8	9.60	94.6	8.61	3.23*
TOWRE-2***	76.2	9.08	104	10.9	7.81***

[a] $n = 13$ [b] $n = 26$ * $p<0.05$ *** $p<0.001$

Grammaticality Judgements. Grammatical judgment accuracy for each participant was analyzed using signal detection theory (hits and false alarm proportions) calculating discrimination sensitivity with *d'* for each condition (Macmillan & Creelman, 1991). Measures for *d'* were corrected using .99 for participants with a maximum number of hits and .01 for participants without false alarms. Discrimination sensitivity (*d'*) is defined as z[Hits] – z[False Alarms]. These measures were analyzed by ANOVAs with prime (predictable, unpredictable) as a within-participants factor and group (dyslexia, control) as a between-participants factor. Effect sizes were calculated as partial η^2 and Cohen's *d* (Cohen, 1988).

For *d'* (see Figure 2, and Table 2), the main effect of group was significant, $F_{(1,37)} = 14.2$, $p < 0.001$, MSE = 2.13, $\eta_p^2 = 0.28$, revealing, as expected, that typically reading children performed better than children with dyslexia (see Figure 2**)**. Most interestingly, the main effect of musical prime was significant, $F_{(1,37)} = 11.01$, $p = 0.002$, MSE = .657, $\eta_p^2 = 0.23$ and did not interact with group, $p = 0.17$. However, surprisingly, for both participant groups, performance was better after the temporally unpredictable prime compared to the temporally predictable musical prime. As the focus of the study was on children with dyslexia, we performed further analyses to ensure that the effect for children with dyslexia was indeed significant for this group, $t_{(1,12)} = 4.05$, $p = 0.002$. The effect size as measured by Cohen's d was $d = 1.12$.

Table 2. *d'* data pattern of grammaticality judgements averaged over participants, by prime (predictable, unpredictable).

	Average *d'*		*SE*	
Group	Predictable prime	Unpredictable prime	Predictable prime	Unpredictable prime
Dyslexic	0.92	1.29	0.26	0.32
Control	1.97	2.88	0.25	0.23

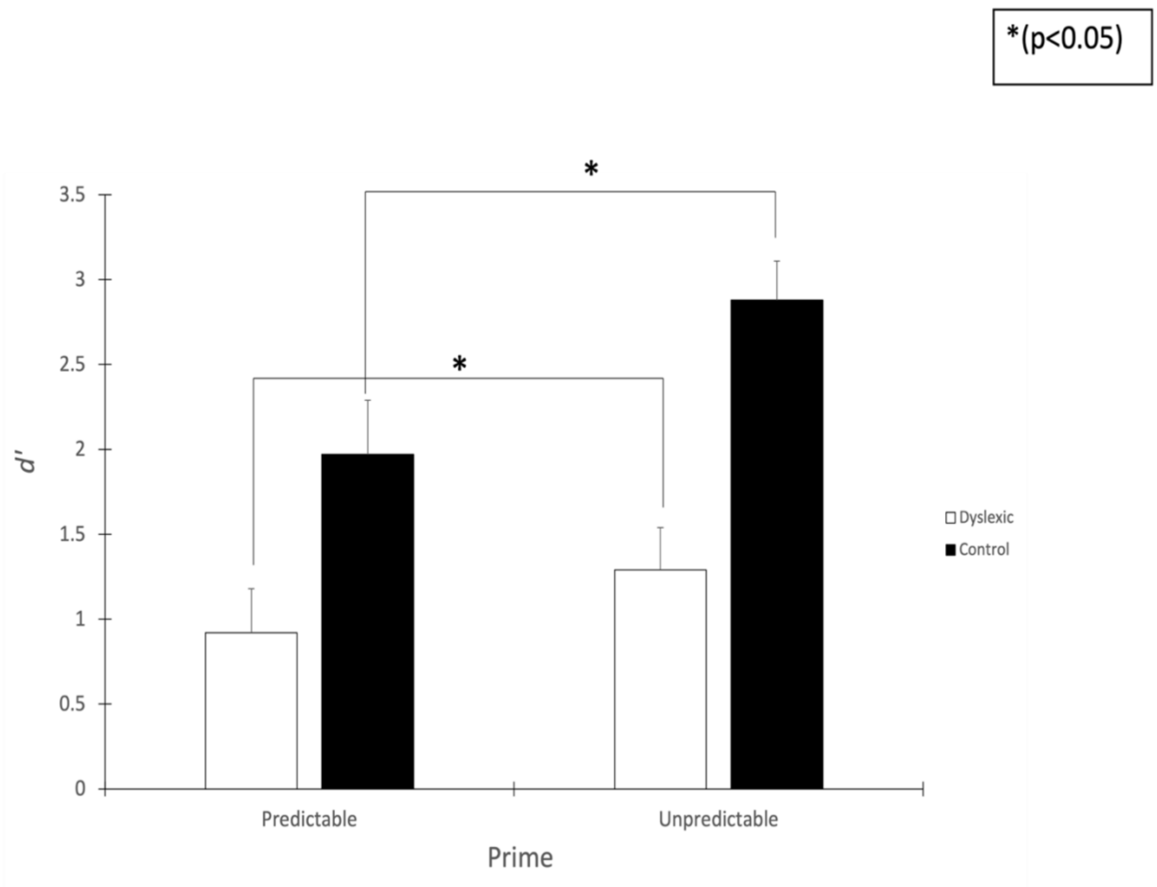

FIGURE 2 | *Discrimination Sensitivity*. *d'* measures for grammaticality judgements averaged over participants, presented as a function of prime (predictable vs. unpredictable) and group (dyslexic and control). Error bars indicate between-participant standard errors.

Recognition Task. Discrimination sensitivity measures were also used to assess performance on pseudoword recognition comparing trials with predictable and unpredictable primes as a within-participants factor and group (dyslexia, controls) as between-participants factor. For *d'* (see Figure 3, and Table 3). Recognition of target pseudowords from distractors was not associated with a significant main effect of group, $F_{(1,37)} = 0.23$, $p = 0.634$, MSE = 1.98, $\eta_p^2 = 0.006$, or main effect of musical prime, $F_{(1,37)} = 1.66$, $p = 0.205$, MSE = 0.49, $\eta_p^2 = 0.043$. The interaction between the musical prime and group were also not significant, $F_{(1,37)} = 0.21$, $p = 0.651$. These results suggest that, regardless of group (dyslexia vs. control), predictable, musical priming did not benefit subsequent verbal memory recognition in children.

Table 3. *d*' data pattern of pseudoword recognition averaged over participants, by prime (predictable, unpredictable).

	Average *d'*		*SE*	
Group	Predictable prime	Unpredictable prime	Predictable prime	Unpredictable prime
Dyslexic	0.86	1.16	0.29	0.28
Control	1.10	1.24	0.22	0.23

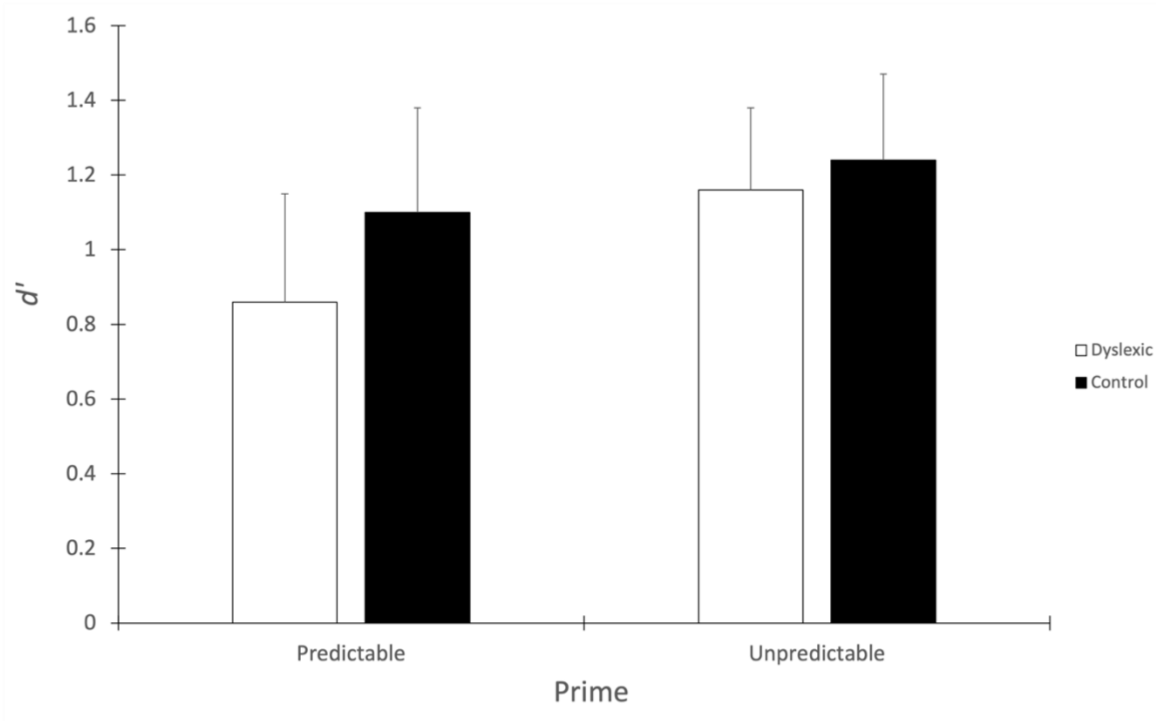

FIGURE 3 | *Discrimination Sensitivity. d'* measures for pseudoword recognition averaged over participants, presented as a function of prime (predictable vs. unpredictable) and group (dyslexic and control). Error bars indicate between-participant standard errors.

Discussion

The present study builds on previous research that demonstrated a benefit on grammar processing following attending to predictable musical rhythm primes (e.g., Bedoin et al., 2016; Przybylski et al., 2013). Here we introduced a verbal memory recognition task to investigate whether the observed predictable rhythm effect extends into additional cognitive domains (i.e., working memory). Children with and without dyslexia performed grammar judgements and attempted to memorize pseudowords after passively listening to a predictable musical prime or an unpredictable environmental sound scene. Results showed no significant differences in performance for pseudoword recognition for either group of children after listening to the predictable musical prime compared to an unpredictable environmental sound scene prime. However, unlike in previous studies (e.g., Bedoin et al., 2016; Canette et al., 2019, 2020; Chern et al., 2018; Przybylski et al., 2013), our results revealed instead significantly better performance of grammaticality judgements in both groups after listening to the environmental sound scene prime—without salient regularities. As this effect was opposite to the one anticipated, firm conclusions cannot be made. However, some procedural differences with previous studies suggest possible explanations.

Our findings are compatible with the possibility that the previously reported positive rhythmic priming effect may be affected by task requirements. The previous findings were reported for grammar processing alone, without any additional cognitive tasks. The addition of the verbal memory task may have removed the typically observed benefit of rhythmic priming, and, perhaps, imposed a deficit to beat-based perception.

Dual-task Interference. Performing two tasks simultaneously may have led to the absence of a rhythmic priming effect in pseudoword recognition. The children were instructed to process both grammar and recognize a pseudoword at the same time. They likely treated this as two separate tasks as opposed to one integrated task. This dual-task scenario may have caused interference with the primary (grammar judgement) task demanding more cognitive resources, leaving fewer resources for the secondary (pseudoword recognition) task. As a result, the expected rhythmic priming effect was not observed, and no significant differences were found. Dual task paradigms often reveal the cognitive toll of performing concurrent tasks (e.g., Pashler, 1994).

Moreover, the rhythmic priming effect heavily relies on the brain's ability to extract and use rhythmic cues to enhance performance. However, when more resources are allocated to the primary task, the brain may be less able to benefit from rhythmic stimulation.

Reversed Effect of Rhythmic priming on Grammaticality Judgements. The current study found that children performed significantly better on grammaticality judgements after listening to an environmental sound scene containing sounds of playground noise and children's voices, compared to a musical rhythmic prime. These results contrast previous studies that reported better performance following rhythmic primes than environmental sounds (Bedoin et al., 2016, 2018). One possible explanation for this reversal is that the environmental sounds acted as novel and arousing stimuli, which heightened the children's attention, and better prepared them for the grammar judgement task. This effect may have been more pronounced due to the current study being conducted online, in a home environment during lockdowns. In this home environment, children were possibly more isolated from external auditory stimuli and such environmental sounds involving playground noise, may have triggered associations with social interaction and outdoor play. This environment may have influenced arousal levels differently than an in-lab setting. In contrast, Bedoin et al.'s studies (2016, 2018) were conducted in a lab environment, without the external stressors of a pandemic. The lab setting may have been less prone to induce an arousing effect from environmental playground noise, reducing the novelty or attention-boosting effects of environmental noise observed in the current study.

This heightened state of attentional arousal might also have facilitated better pseudoword recognition, although the difference was not statistically significant. However, it is notable that children remembered more pseudowords in sentences primed with the environmental sounds, suggesting that the arousing effect may have had some benefit for memory performance.

Limitations and Future Directions. First, it is noteworthy that the control group's phonological short-term memory average from the CTOPP was nearly six points below the normative reference population. This deviation raises several important considerations. Further examination of the control group's phonological awareness might reveal individual differences that could explain the discrepancy. Additionally, as experimental conditions were online compared to in-person, the environmental difference of an uncontrolled setting opposed to a controlled (in-person) setting may have yielded this experimental anomaly. It is also important to acknowledge the limitation posed by the small sample size of the dyslexic group. The small sample size reduces statistical power and potentially hinders the detection of significant group differences. Thus, our results should be interpreted with caution within the confines of a small sample size.

Second, while all participants were native English speakers, it is important to acknowledge that exposure to other languages may have influenced rhythmic processing. Fifteen participants reported bilingualism and different language families may exhibit distinct prosodic structures, with variations in timing and rhythm (e.g., syllable-timed vs. stress-timed languages). Varied prosodic sensitivities within different language backgrounds poses as a potential limitation of the current study.

Based on a previous auditory-motor study showing beneficial verbal processing when participants tapped to speech rhythms (Falk & Dalla Bella, 2016), the inclusion of a motor component could benefit beat perception and synchronization to a rhythmic prime. Therefore, asking participants to tap along to a regular, rhythmic prime compared to passively listening to an auditory prime might enhance the rhythmic priming effect. Conversely, implementing an additional task while attending to the regular rhythm, judging the grammar of sentences, and recognizing pseudowords may become too complex if the lexico-phonological and lexico-syntactic information cannot be integrated as one task. Future research could test these tapping effects by separating the two tasks in two exclusive conditions.

Together with previous results, it appears that rhythmic stimulation from regular, predictable beats may be beneficial only under certain circumstances, particularly relating to the duration of attention and grammar processing domains. Attending to a regular, musical prime for 32 s is an optimal duration for children aged 9 years old for subsequent beneficial grammar processing (Fiveash et al., 2020). However, in this present study, 32 s primes may have been too short to stimulate memory encoding *and* maintenance before the recognition task began. In future experiments investigating the facilitation of rhythmic, predictable stimuli on verbal memory processing, it would be valuable to add the recognition task closer in proximity to the prime, as the duration of entrainment effects are largely unknown.

Conclusion

Our study showed that attempting to recognize pseudowords and judge the grammar of sentences after passively attending and listening to a regular, predictable musical beat, resulted in a reversal of the expected benefit. Specifically, a regular rhythmic prime did not improve grammar processing compared to the environmental sound scene prime. Additionally, listening to the musical prime did not benefit verbal memory processing. These results suggest that in the presence of the primary grammar judgement task, the secondary task of pseudoword recognition may have detracted from beneficial rhythmic entrainment and instead an unpredictable environmental sound scene prime without temporal regularities was beneficial only for grammaticality processing.

These findings contrast with previous research (Bedoin et al., 2016, 2018), where the musical rhythmic prime enhanced grammar processing in children with language impairments (Bedoin et al., 2016) and even cochlear implants (Bedoin et al., 2018). The observed differences could be attributed to experimental settings (i.e., home vs. in-lab). Children in our study may have found that the environmental sounds were more arousing or novel, given their social isolation during lockdowns. This could explain why the environmental prime, rather than the musical prime, facilitated grammar processing.

Our results also raise important questions about the interaction between rhythmic entrainment and cognitive load. Children's cognitive resources may have been overwhelmed by the dual-task nature of the current experiment. Consequently, the effectiveness of rhythmic entrainment for grammar processing and potentially verbal memory processing may have been reduced. Future research could explore whether reducing the dual-task condition to one verbal memory task would allow for a beneficial rhythmic priming effect.

Overall, while our findings challenge the notion that passively listening to a regular, predictable musical sequence can benefit verbal memory processing, they open up new considerations for understanding contextual factors that may modulate this effect. Future studies should consider the role of cognitive load, the testing environment, and individual differences, such as participants' music exposure and language background. Additionally, further exploration of how environmental sounds and their arousing properties influence cognitive performance could provide valuable theoretical insights underpinning prediction-based theories of verbal memory processing.

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Chapter 3: Rhythmic priming may enhance verbal working memory in musicians and non-musicians

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Abstract

Presenting rhythmic (regular, predictable) musical primes before linguistic stimuli has been shown to enhance language processing and facilitate grammaticality judgements. However, little is known about how rhythmic and arrhythmic primes influence subsequent verbal memory recall. In this study, 27 musicians and 30 non-musicians were presented with nonsensical jabberwocky sentences to recall immediately after listening to rhythmic or arrhythmic (random, unpredictable) sound primes. We hypothesized that attending to a regular, predictable structure would strengthen a temporal component in phonological short-term memory and support subsequent memory for language. We also predicted that temporal processing and immediate recall performance would be stronger for the musicians and after the prime with the regular rhythmic structure. As expected, recall was better for sentences presented after a rhythmic prime relative to an arrhythmic prime. Musicians showed a trend for better verbal memory, but the two groups did not significantly differ. Results suggest that listening to a regular, predictable musical sequence may help both trained musicians and non-musicians to enhance immediate memory for unfamiliar rhythmical structures, such as novel language material.

Keywords: Music; Rhythmic Stimulation; Sentence Repetition; Verbal Memory

Introduction

The temporal structure of a sequence has been observed to influence its memorability. Whether the sequence consists of digits (Cowan, 2001) or text (Purnell-Webb & Speelman, 2008), sequences that are rhythmic take less effort to recall compared to sequences that are temporally random, unpredictable, or irregularly grouped (Ryan, 1969a, 1969b). This notion that retrieving information from memory is better when it is embedded in a rhythmic structure, makes it no surprise, that texts, such as poems (Tillmann & Dowling, 2007), and song lyrics—which largely comprise rhyme and alliteration (Hyman & Rubin, 1990), are often structured in a rhythmical manner, set to a predictable metre to facilitate memory. There is substantial inter-individual variation in the ability to utilize rhythmic structure and there may be substantial within-individual variation. This present study investigates two possible sources of this variation: external priming and individual musical experience. We ask, specifically, whether listening to a regular, predictable musical sequence with a rhythmic structure may be used to support verbal short-term memory (VSTM) for meaningless sentences consisting of pseudowords. This type of phonological short-term memory is thought to be involved in language acquisition (Baddeley, Gathercole, & Papagno, 1998).

Understanding how rhythmic structures support verbal memory may require consideration of the phonological loop, a key component of Baddeley's (1986) working memory model that facilitates the temporary storage and rehearsal of verbal information. This loop is a specialized system involved in retaining verbal information over short time frames. It is thought to store information regarding the sound structure of words in the form of memories (Baddeley, Gathercole & Papagno, 1998). Deficits of the phonological loop in working memory have been used to explain poor verbal memory performance in children with developmental language disorder (Gathercole & Baddeley, 1990). Particularly, the contents of a storage component of the phonological loop, the phonological buffer, have been proposed to be vulnerable in these children. The other part of the phonological loop has been proposed to be an articulatory process (e.g., Baddeley, 2000). Other researchers have described it as the phonological output buffer (e.g., Biran & Friedmann, 2005). This is a short-term memory component that could be responsible for assembling words by sorting phonemes in a metrical structure.

The importance of the phonological loop in memory processing has also been pointed out by Saito (2001), who found a close relationship between digit span and short-term memory for rhythms in non-musicians. For instance, participants with high auditory and visual memory spans also showed high scores for a rhythm tapping task. Saito (2001) proposed that memory for rhythms came from a component of the phonological loop that is specialized on temporal structure. This component would maintain the temporal dynamics of verbal information (e.g., phonemic, and lexical information).

In recent years, attention has been devoted to investigating how temporal expectation shapes perception and behavior (see Nobre & van Ede, 2018, for a review). Temporal expectation refers to the ability to predict or anticipate the timing of an event, based on a preceding temporal experience or temporal regularity. An example is being able to continuously clap to the beat of a song. Temporal predictions may play a role in speech comprehension and learning. For example, infants can detect temporal patterns in speech syllables that help predict where speech units begin and end (Nazzi & Ramus, 2003; Saffran, Werker & Werner, 2006; Trehub & Thorpe, 1989). This is thought to facilitate language acquisition.

Expectations about when an event will occur can shift based on the information attended to immediately preceding the event. For example, there is mounting evidence suggesting that using a predictable, regular musical sequence as a prime before spoken sentences are presented can facilitate syntax and grammar judgement abilities. This rhythmic priming effect (RPE) has been found for children with developmental language disorders (Bedoin et al., 2016; Przybylski et al., 2013), typically developing children (Chern et al., 2018), adults (Canette et al., 2019) and adults with dyslexia (Canette et al., 2020).

Analysis of event related brain potentials (ERPs) to stimuli during encoding for later recognition suggest a difference in processing when items are presented at rhythmically predictable compared to unpredictable time points. When comparing old and new test items in recognition memory tests, ERP studies have established two components; the FN400 old/new *familiarity* effect (e.g., Curran 2000; Duarte et al., 2004; Rugg & Curran, 2007) and the parietal *recollection* old/new effect (e.g., Curran 1999, 2000; Duarte et al., 2004; Rugg & Curran, 2007), which involves conscious memory. Deeper semantic processing has often been associated with an increased parietal old/new effect, while the FN400 is unaffected by processing depth (Rugg et al., 1998). A previous study (Jones & Ward, 2019) investigated these components within memory encoding for everyday objects. The results showed that behavioural recognition was greater following encoding of objects at temporally predictable time points compared to arrhythmic encoding. The parietal old/new effect appeared only for the items encoded at temporally predictable times.

A common question is whether musical training affects temporal regularity effects. A recent meta-analysis (Talamini et al., 2017) showed that musicians often outperform non-musicians in memory tasks. However, the types of stimuli presented in many studies are related to the effect size. For instance, musicians' memory advantage was observed with a high effect size when the stimuli were tones, and a moderate effect size when the stimuli were verbal.

According to Patel (2014), musical training can strengthen the shared neural resources for music and speech processing. Musical experience has been suggested to enhance auditory attention and working memory (Besson et al., 2011). Musical training might facilitate efficient learning strategies such as 'chunking', which provides a strong hypothesis for the reason behind musicians having a cognitive advantage with memory. Chunking is a strategy used to facilitate short-term memory by grouping smaller pieces of information into larger and more easily remembered groups, or by dividing large units of information into smaller groups (Miller, 1956). For instance, when attempting to memorize a song on the piano, chunking the piece into smaller musical phrases is beneficial in order to commit an entire song to memory. Another more granular example would be learning a scale on the piano for the first time. Instead of learning a scale note-by-note, musicians often chunk the notes into groups of threes and fours, as these relate to the traditional fingering for an 8-note (octave) scale.

The current study examined the relationship between regular rhythmic stimulation and verbal memory recall from immediate memory in musicians and non-musicians. Two kinds of sound primes borrowed from previous studies (Bedoin et al., 2016; Przybylski et al., 2013) were presented before a verbal learning task. A regular musical sequence served as the experimental prime and an environmental sound scene (i.e., people outside near a playground), served as the control prime. We predicted that both groups would perform better on verbal recall of sentences consisting of pseudowords after listening to the regular musical prime. Additionally, we predicted that musicians would recall pseudoword sentences better than non-musicians. Non-musicians may exhibit an inferior ability to process temporally predictable input due to several factors. First, musicians typically undergo extensive musical training, which might increase their ability to anticipate and align with rhythmic patterns (Chen, Penhune & Zatorre, 2008a; Smith, 1983). Non-musicians lacking rigorous training may not develop the same level of sensitivity to rhythmic or temporal cues. Second, musical training can enhance working memory, attention, and temporal processing, which are all involved in rhythm perception (for a review see Miendlarzewska & Trost, 2014). Non-musicians may be presented with fewer opportunities to enhance these processes, leading to a less-developed ability to process temporally predictable input.

Method

Participants. Two groups of adult participants were recruited. Based on the methods of previous studies (e.g., Başkent & Gaudrain, 2016; Parbery-Clark et al., 2009;

Zhao & Kuhl, 2015), participants were considered musicians if they had received more than 9 years of formal music lessons. For the musician group, 30 participants were recruited; three were excluded for not speaking English as their dominant language, leaving 27 musician participants (age range = 18–29; mean age = 19.33; *SD* = 2.30; 25 females). Twenty-five out of the twenty-seven musicians included in the analyses had 10 or over 10 years of formal music training on at least one instrument, whereas two musicians received 9 years of formal music lessons.

For the non-musician group, 30 dominant English-speaking participants were recruited (age range = 18–46; mean age = 19.8; *SD* = 5.12; 25 females). Participants in the non-musician group, were selected similarly to a previous study (Zhao & Kuhl, 2015), that is, they had never learned an instrument, or they had received less than 2 years of formal music lessons. No participant reported any history of trauma to the brain, hearing, vision, speech, or language difficulties. Informed consent was obtained from all participants, and they were debriefed about the aims of the study, which had been cleared by the McMaster Research Ethics Board. All participants were compensated with 15 Canadian dollars.

Stimuli. Twenty-four nonsensical jabberwocky sentences were adopted from a previous study (Service et al., 2022) examining the relationship between short-term memory for auditory temporal patterns and foreign language learning. Four trial sentences were used during the practice phase. The remaining 20 were included in the analyses. Jabberwocky sentences were spoken by a female native English speaker, and the mean sentence length was 5.5 non-words (*SD* = 0.51) with a speech rate of 196.63 to 247.68

syllables per minute (spm) (*M* = 224.37; *SD* = 13.66)[1]. The jabberwocky sentences had been constructed by first replacing content words in English sentences with pseudowords that adhered to normal English phonology and phonotactics and then replacing all function words (e.g., prepositions, conjunctions) with pseudowords of the same phonological length. This process was adopted to create sentences that sounded like English sentences, but without semantic meaning (e.g., ROO MUTHTIN FANED IM GRASHNIT).

Two sound prime recordings were prepared for presentation before the jabberwocky sentences. The regular, predictable musical sequence and the environmental sound scene from the study by Bedoin et al. (2016) were used. The metrical musical prime was played at approximately 120 beats per minute (bpm) by synthesized percussion instruments (i.e., a tam-tam and maracas) and had a duration of 32 s. The control prime was an environmental sound scene recorded outside with a playground nearby and had a duration of 30 s. PsychoPy software (Peirce et al., 2019) was used to present all stimuli on an iMac computer through Sony MDRZX110NC headphones.

Sentence Repetition Task. The participants first heard either a musical prime or a control prime and then a jabberwocky sentence followed. They were asked to immediately repeat out loud the nonsense sentence they had heard. Responses were recorded using a Samson Go Mic Portable USB Condenser Microphone. Half of the participants of each

[1] The musical prime is 120 bpm, while the speech rate is 224.37 spm. This indicates that the speech rate is nearly twice as fast as the musical prime, suggesting that the speaker produced approximately two syllables per beat. This suggests a moderate alignment between the rhythmic prime and the speech rate of the jabberwocky sentences.

group heard the alternating primes with the control played first. The other half heard the musical prime first. Sentence order was maintained across all participants.

Repetition accuracy was scored by a native English speaker (B.O. the first author). Following much of the literature for scoring pseudoword repetition tasks, the repeated sentences were scored for the number of correct syllables without phoneme errors, and for the number of word forms correctly repeated. A subsample of responses from 10 participants were scored by a second native English speaker. Inter-rater reliability was high at the word form level (86%).

Procedure. Trained research assistants administered the experiment. Participants first practiced the sentence repetition task with 4 unique trials, where 2 followed the musical prime and two followed the control prime in counterbalanced order. Following the practice trials, the primes continued in a counterbalanced order and were auditorily presented while a fixation cross appeared on the screen for the duration of the prime. Participants were instructed to listen to the prime, after which a blue exclamation mark was presented on the screen during the auditorily presented jabberwocky sentence (~ 3 s). A 'break' prompt appeared on the screen after the tenth trial was complete. The duration of this entire task was approximately 20 minutes.

Results

The repetition accuracy proportions can be seen in Table 1 and Figure 2. The pseudoword and syllable level scores were analyzed by two 2 (participant group) x 2 (sound prime regularity) repeated measures ANOVAs with group as a between-subjects factor and sound prime regularity as a repeated factor. Both musicians and non-musicians showed significantly higher repetition accuracy after listening to the musical rhythm prime, scored both in terms of correctly repeated pseudowords [$F(1,55) = 4.59$, $p = .037$, $\eta_p^2 = .077$] and syllables [$F(1,55) = 4.04$, $p = .049$, $\eta_p^2 = .068$] (see **Figure 1)**. The effect of group was not significant: although musicians performed a little better overall, this did not approach significance for either the pseudoword repetition score [$F(1,55) = 0.29$, $p = 0.596$, $\eta_p^2 = .005$], or the syllables-within-sentences repetition score [$F(1,55) = 0.31$, $p = 0.58$, $\eta_p^2 = .006$]. There were no significant interactions between group and priming condition for either pseudoword repetition score [$F(1,55) = 1.08$, $p = 0.30$, $\eta_p^2 = .02$], or the syllables-within-sentences repetition score [$F(1,55) = 0.52$, $p = 0.48$, $\eta_p^2 = .009$]. These findings suggest that regular, predictable musical sequences with a rhythmic structure can enhance memory for unfamiliar words, regardless of whether the listener is a musician or non-musician. Table 1 shows mean sentence repetition scores.

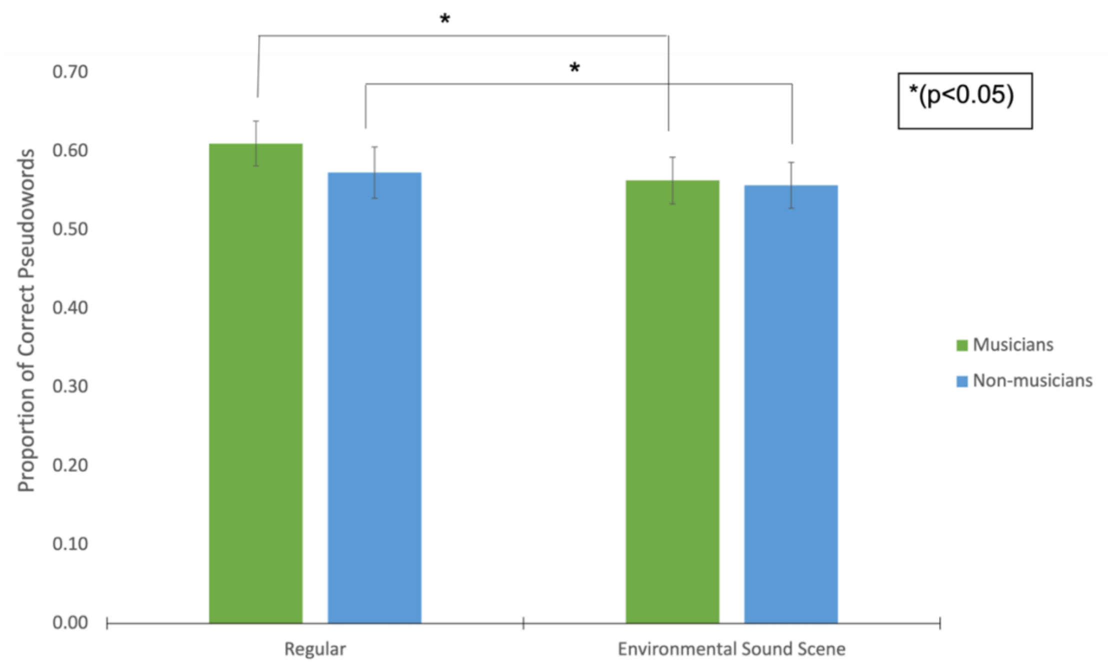

FIGURE 1 | Sentence repetition accuracy proportions averaged, presented as a function of prime (regular vs. environmental sound scene) and group (musician and non-musician). Error bars indicate between-participant standard errors.

Table 1. Mean sentence repetition scores.

	Proportion of Correct Pseudowords		**Proportion of Correct Syllables**	
Group	**Regular prime (SD)**	**Environmental prime (SD)**	**Regular prime (SD)**	**Environmental prime (SD)**
Musician [a]	0.61 (.15)	0.563 (.15)	0.6 (.16)	0.552 (.17)
Non-musician [b]	0.573 (.18)	0.557 (.16)	0.56 (.19)	0.542 (.16)

[a] *n* = 27.
[b] *n* = 30.

As a demographic factor, we also asked the participants about their language background[2]. Based on the responses, they were divided into monolinguals (n = 22), bilinguals (n = 24), and multilinguals (n = 11). The results of an ANOVA where musician group was replaced by language background group again indicated a significant main effect of sound regularity [$F(1,54) = 4.813$, $p = 0.033$, $\eta_p^2 = .082$], suggesting that sound regularity influenced repetition scores (see **Figure 2**). Although there was a tendency for the bilinguals and multilinguals to perform better in the jabberwocky sentence repetition task, this effect was not significant [$F(2,54) = 0.247$, $p = 0.78$, $\eta_p^2 = .009$], nor did language background significantly interact with the priming condition [$F(2,54) = 0.326$, $p = .72$, $\eta_p^2 = .012$]. Table 2 shows mean sentence repetition scores between monolingual, bilingual and multilingual participants.

[2] Participants were not explicitly asked about their proficiency in school-learned French (e.g., in-class French from mandatory curricula in Canadian schools). As such, those with minimal or classroom only French exposure may have self-identified as bilingual.

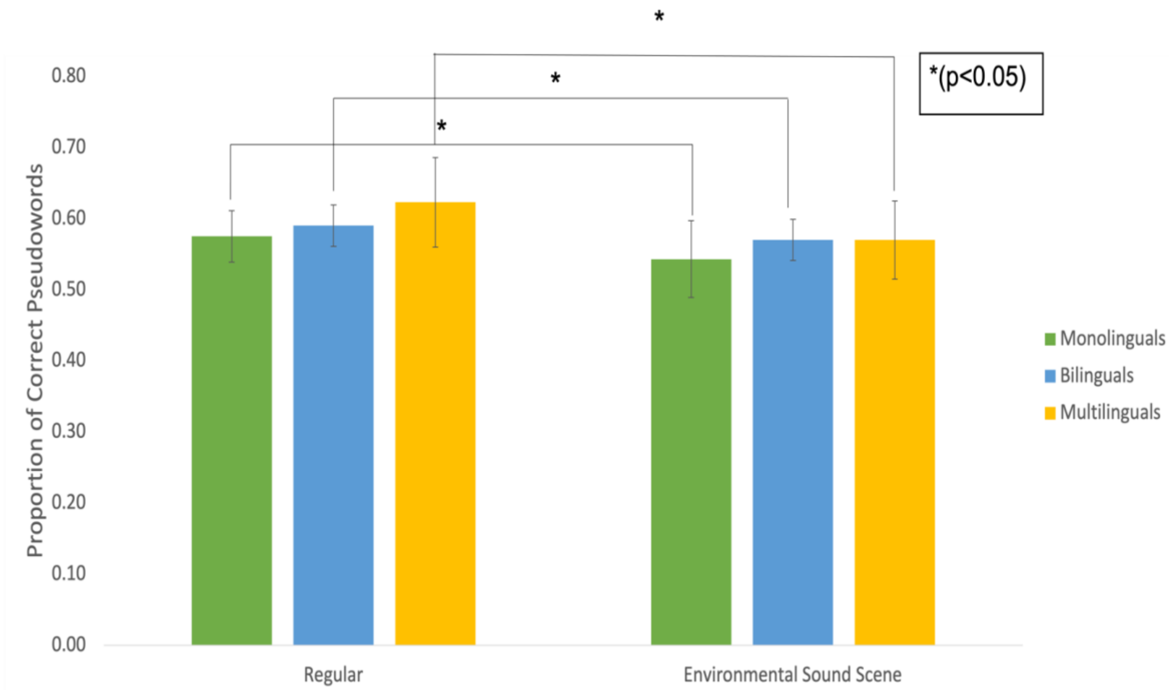

FIGURE 2 | Sentence repetition accuracy proportions averaged, presented as a function of prime (regular vs. environmental sound scene) and group (monolingual vs. bilingual vs. multilingual). Error bars indicate between-participant standard errors.

Table 2. Mean sentence repetition scores.

Group	Proportion of Correct Pseudowords: Regular prime (SD)	Proportion of Correct Pseudowords: Environmental prime (SD)
Monolingual [a]	0.575 (0.04)	0.543 (0.03)
Bilingual [b]	0.59 (0.03)	0.57 (0.03)
Multilingual [c]	0.623 (0.06)	0.57 (0.05)

[a] *n* = 22.
[b] *n* = 24.
[c] *n* = 11.

Discussion

Two questions were explored in this study: 1) the effects of metrically predictable rhythmic primes on creation of phonological representations at the sentence level and 2) musical experience as a possible moderator of such effects. Previous studies have explored the effects of regular, predictable rhythmic priming on grammar judgement abilities in children and adults with atypical and typical language development. These studies demonstrated that attending to a regular, predictable musical sequence with a predictable rhythmical structure can enhance grammaticality judgements in both neurocognitively typical and atypical populations. Based on these findings, we explored the possibility that the positive effects of regular, predictable musical primes could extend from grammar processing and cross into the memory domain. As hypothesized, recall from immediate verbal memory improved after listening to a regular, predictable musical prime compared to an environmental sound scene. However, music training did not significantly affect phonological memory or the priming effect.

Rhythmic Priming on Verbal Memory. Previous studies (Cason & Schön, 2012; Gordon et al., 2011) have demonstrated that matching musical metrical structure to prosodic features of subsequent speech and linguistic stress in songs can enhance phonological speech processing. Our study adds to these findings by highlighting the effect of a predictable, regular musical prime on the processing of subsequent nonsense sentences to be repeated aloud. Interestingly, our findings suggest that musical priming may have an effect on memory processing at a broader level, rather than relying on an exact match to the rhythm of the sentences. Our data also further extends the recent work reporting rhythmic priming effects in grammar processing in populations with atypical and typical language and across ages (e.g., Bedoin et al., 2016; Canette et al., 2019; Chern et al., 2018; Przybylski et al., 2013). Here we observed a rhythmic priming effect in typically developed adult musicians and non-musicians in the domain of verbal memory processing. The involvement of verbal short-term memory raises the possibility of relevance for support of linguistic development. For instance, presenting musical stimuli with predictable rhythmic patterns before word-learning tasks could facilitate better verbal memory encoding enhancing linguistic development. Furthermore, the rhythmic priming effect occurred both in musically trained and untrained populations. As these groups can be expected to differ in their sensitivities to rhythm, this suggests that listening to predictable, regular musical sequences could provide instant support for language tasks even without extensive musical training (Kraus & Chandrasekaran, 2010; Pino, Giancola & D'Amico, 2023; Politimou et al. 2019).

Dynamic Attending Theory and the Phonological Loop Concept as explanatory frameworks. The growing evidence that rhythm provides a cognitive processing advantage can be understood in terms of the Dynamic Attending Theory (DAT; Jones, 1976, Large & Jones, 1999). This theoretical framework suggests that internal attentional rhythms entrain to external rhythmic stimuli. Thus, the rhythmic prime in the present study may have strengthened the encoding of words by orienting the listener's attention toward the temporal structure of the sentence. However, while DAT explains allocation of attention toward the temporal structure of the sentence, the phonological loop

(Baddeley, 1986) could be the key mechanism driving the maintenance and repetition of jabberwocky sentences.

This phonological loop component of working memory has been modelled by Burgess and Hitch (1999). In their model, the signals used to track the order and timing of verbal information during encoding are rerun at recall and phonemic information feeds back from output to input—allowing for successful repetition. In the case of the rhythmic prime preceding the nonsense sentences in the present study, the regularity of the rhythm may establish a metrical temporal structure in the phonological loop, which then allows for less effort in establishing the timing signal to be rerun and leads to better recall performance compared to after the environmental sound scene prime.

As suggested in previous work and by the Dynamic Attending Theory, a rhythmic prime preceding the jabberwocky task might have directed temporal attention towards the onsets of the pseudowords in the following sentences. This may have allowed the encoding of a stronger temporal representation of verbal information in the phonological store of the phonological loop or a phonological output buffer, subsequently facilitating pseudoword repetition. The environmental sound scene does not contain salient temporal regularities to extract and therefore cannot successfully modulate temporal attention towards target verbal information. This is important to note as previous studies demonstrated that orienting the temporal attention of an individual to a relevant, expected stimulus can benefit working memory performance (Thavabalasingam et al., 2016; van Ede, Niklaus & Nobre, 2017; Wilsch et al., 2015). As an alternative to inner-speech based rehearsal, a purely attention-based model to maintain information comes from the idea that items to be remembered can be reactivated by a scanning process or by the recycling of items through focussed attention (Cowan, 1992; Cowan 1995).

Limitations and Future Directions. Several limitations of this study need to be noted. First, if a more fine-grained difference between the primes had been presented, for example, a more complex musical rhythm, it may have revealed differences between non-musicians and musicians. With advanced musical training and likely increased exposure to complex rhythms, musicians might be better equipped to process and predict more complex rhythmic structures (Chen, Penhune & Zatorre, 2008b). Conversely, non-musicians may encounter difficulties with processing complex rhythms due to their lack of training and experience in recognizing rhythmic variations. Additionally, the effect size for the rhythmic priming effect on verbal memory was not robust, necessitating cautious interpretation of the conclusions. Future research could consider testing a larger sample size of participants and including rhythm sensitivity tests as an objective measure.

Nevertheless, rhythmic priming related interventions remain a possible remediation tool for developmental language disorder and co-morbid language and temporal processing deficits in children with dyslexia (Habib, 2021). Previous studies have shown that rhythmic training can, indeed, lead to enhanced phonological awareness among children with dyslexia (Flaugnacco et al., 2015). Moreover, using regular musical primes during speech therapy sessions has been found to result in improvement of phonological abilities (Bedoin et al., 2018). Thus, this rhythmic priming effect on verbal memory processing should be investigated within populations where temporal processing and verbal memory deficits often occur (e.g., dyslexic populations; Huss et al., 2011; Kramer, Knee & Delis, 2000).

However, many questions remain. For instance, it would be necessary to determine how many sessions of rhythmic stimulation are needed to induce a long-term beneficial effect for working memory processing to potentially help language processing and memory in clinical populations. Future research should also aim to investigate whether there is an ideal tempo for observing the rhythmic priming effect. Exploring the influence of different tempi could provide further insight into potentially refining interventions for clinical populations.

Conclusion

In conclusion, the present study showed a facilitative effect of regular, predictable rhythmic priming on verbal memory processing within adult non-musicians and musicians. It adds to previous findings that have shown rhythmic priming to facilitate subsequent grammar processing in children and adult populations with typical and atypical language development. For instance, rhythmic priming could be integrated into educational settings to facilitate language skills in children with learning disabilities, including dyslexia, where rhythm processing has been shown to be deficient (e.g., Huss et al., 2011). Rhythmic interventions might help improve prosodic sensitivities in dyslexic individuals (Goswami, Gerson & Astruc, 2010), as well as improve rhythm deficits seen in their speech production (e.g., Smith et al., 2008). Our results offer a preliminary starting point to both develop nuanced music-based interventions to support language learning and to reveal the cognitive mechanisms underpinning prediction-based theories of verbal memory.

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Chapter 4: Effects of tempo and rhythmic priming on verbal memory

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Abstract

Research has shown that temporally regular musical rhythmic primes can benefit subsequent verbal memory tasks in both musicians and non-musicians compared to an environmental sound scene prime, with musicians generally showing greater benefits than non-musicians. Up to now, this rhythmic priming effect has largely been demonstrated to facilitate grammaticality judgements when the tempo of the prime is ~120 beats per minute (bpm). To investigate the ideal tempo for the presence of a rhythmic priming effect on verbal memory recall in adult participants, musicians and non-musicians passively listened to a regular beat presented at 60 bpm, 120 bpm and 360 bpm or an irregular environmental sound scene before hearing a nonsensical sentence consisting of pseudowords that they were instructed to repeat aloud. Verbal memory recall performance after listening to the regular predictable prime compared to the irregular environmental sound scene was not significantly different. While participants performed marginally better after having attended to the slow tempo (60 bpm) rhythmic prime, this difference was not statistically different, and no significant differences were observed across the varied tempi of the rhythmic prime. These findings suggest that the rhythmic primes used in this current study do not yield a robust rhythm priming effect on verbal short-term memory. Implications for future rhythmic priming paradigms investigating the ideal tempo for a rhythmic priming effect will be discussed.

Keywords: Attention; Music; Rhythmic Priming; Tempo; Verbal Memory

Introduction

Daily activities, like remembering a phone number or recalling words on a grocery list, require efficient verbal memory processing to avoid forgetting. When we rehearse phone numbers or a grocery list, we tend to do it in a rhythmic manner. Accumulating evidence over the last decades suggests that rhythmicity, can positively influence memory processing for sentences (Fiveash et al., 2023; Owusu & Service, 2023) and spoken word recognition (Sidiras et al., 2017), as well as non-verbal memory processes like motor (re)-learning (Thaut & Abiru, 2010; Thaut & McIntosh, 2014). Additionally, musical training has been shown to improve memory for word lists (Chan, Ho & Cheung, 1998; Jakobson et al., 2008; Ho, Cheung & Chan, 2003), and non-verbal tasks like face recall (Zanto et al., 2022). Musical rhythms are typically regular and predictable, providing a distinct temporal structure that helps focus attentional resources on items to be remembered (Jones & Ward, 2019).

One prosodic feature of speech is its rhythm. As such, it is not surprising that musicians have been reported to be more sensitive to prosodic phenomena than non-musicians (Jansen et al., 2023; Obergfell et al., 202; Zioga, Di Bernardi Luft, & Bhattacharya, 2016). For instance, Moreno et al. (2008) found that 8-year-old children without any prior musical training showed improved prosodic discrimination abilities after receiving 6 months of musical training compared to a group of children that received painting training. Speech rhythms contain fewer salient temporal regularities but can still facilitate temporal predictions of speech elements (Goswami, 2022) such as syllable onset and grammar errors. Together, musical rhythms and speech rhythms demonstrate how rhythmic patterns play a crucial role in guiding attention and facilitating memory.

An early study comparing varied temporal regularities of musical primes in children with language difficulties was reported by Przybylski et al. (2013). In this study, three groups of French speaking children aged 6-12 years old participated. Two out of the three groups had language difficulties (i.e., developmental language disorder and dyslexia). The third group consisted of age-matched children with typical language abilities. The task required children to make grammaticality judgements on French sentences, auditorily presented after a temporally regular musical prime or an irregular musical prime. It was found that all groups of children made more accurate grammaticality judgements on sentences that were heard after the regular musical prime, compared to the irregular prime. A follow-up study was conducted by Bedoin et al. (2016) to investigate whether this enhancement was due to the rhythmicity of the prime and not due to a detrimental effect of the irregular prime. To resolve this confounding variable, Bedoin et al. (2016) used the same regular musical prime and an environmental sound scene prime that did not contain salient temporal regularities. Grammaticality judgements were again improved for children with developmental language disorder after listening to the regular musical prime compared to the environmental sound scene prime.

Further evidence for enhanced grammar processing after attending to a temporally regular musical prime compared to an irregular prime has been replicated among English speaking children (Chern et al. 2018), French speaking adults (Canette et al., 2020), children with cochlear implants (Bedoin et al., 2018) and Hungarian-speaking children

(Ladányi, Lukács & Gervain, 2021). The positive rhythmic priming effect (RPE) observed for grammaticality judgements can be understood through the lens of the dynamic attending theory (DAT; Jones 1976, 2019). This theory posits that our brain tracks music and speech rhythms through neural synchronization to facilitate accurate temporal predictions of upcoming events. In the context of grammaticality judgements, DAT suggests that rhythmic priming entrains neural oscillations that continue into and then align with the subsequent speech, allowing listeners to focus their attention at key moments in the speech signal and thus more accurately detect grammatical errors.

Much of the recent research that adopted the rhythmic priming paradigm used in Przybylski et al. (2013), has focused on the effects of rhythmic priming within the domain of grammaticality judgements (Bedoin et al., 2016, 2018; Canette et al., 2020; Chern et al., 2018; Ladányi, Lukács & Gervain, 2021). In these studies, replication of positive rhythmic priming effects was always observed; however, control tasks often failed to yield a rhythmic priming effect. For instance, non-linguistic control tasks were included in Chern et al. (2018). This study tested for a general influence of rhythmic priming on cognition by including a math and a visuo-spatial task. Participants (aged 5 to 8) showed improvements on grammaticality judgements from rhythmic priming but did not benefit from rhythmic priming on the control tasks. This suggests that rhythmic priming may be largely confined to language tasks involving grammatical structures. Owusu and Service (2023) examined whether rhythmic priming effects could extend beyond grammaticality judgements to the domain of verbal short-term memory (VSTM) in musicians and non-musicians. The results showed that both musicians and non-musicians benefitted from rhythmic priming compared to listening to an environmental sound scene prime in a repetition task with sentences consisting of meaningless pseudowords. They proposed that the observed small RPE on verbal memory may be linked to the involvement of the phonological loop, a key component of working memory responsible for the rehearsal of verbal information (see Baddeley, 2012 for a review). They suggested, in line with the DAT, that the rhythmic musical prime may have enhanced the efficiency of this rehearsal process, facilitating the encoding and retrieval of the jabberwocky sentences.

The present study was designed, first, to replicate the rhythmic priming effect for VSTM. Our second objective was an initial effort to explore whether the rhythmic priming effect on verbal memory was sensitive to variations in speed (hereafter referred to as 'tempo'). In other words, could a faster or slower tempo also elicit a rhythmic priming effect? Finally, we compared how rhythmic priming effects with different tempi might differ between musicians and non-musicians. Canette et al. (2019) found moderating effects of music-related experience on rhythm priming of grammatical judgments by young adults.

Based on previous research demonstrating that individuals prefer tempos from 85 to 120 bpm (London, 2002; McAuley et al., 2006; Parncutt, 1994; Van Noorden & Moelants, 1999), we tested the effect of rhythmic priming using three different tempi: 60 bpm (1 Hz), 120 bpm (2 Hz) and 360 bpm (6 Hz). We predicted that the musical prime presented at 2 Hz would elicit a stronger RPE compared to the other tempi. Also, given that intelligible syllable rate processing occurs between approximately 2 to 5 Hz (Hall, 2012; Scott et al., 2006), we predicted that the 1 Hz and 6 Hz tempos might even fail to elicit an RPE, with the fastest tempo (6 Hz) being particularly ineffective due to the greater difficulty of neural entrainment at extreme tempi. Previous research indicates that neural entrainment to musical beats presented at slower or faster tempi, outside the preferred range of approximately 1-2.5 Hz (Parncutt, 1994; Van Noorden & Moelants, 1999), are difficult to synchronize to (e.g., Nozaradan, Peretz & Keller, 2016). According to the changing-state hypothesis (Jones, Madden & Miles, 1992), faster tempo music can exhaust working memory, due to the increased number of acoustic changes in state per unit of time. This hypothesis suggests the frequent triggering of the involuntary process of tracking of acoustic elements in a rapid stream (Jones, 1999) can overload working memory, as observed in previous research (e.g., Day et al., 2009) subsequently leading to decreased performance. We predicted that the rhythmic prime presented at 2 Hz would readily entrain to participant's verbal processing of the jabberwocky sentence, enhancing effectiveness and eliciting a rhythmic priming effect. In contrast, we predicted that the faster and slower tempi, might not facilitate this entrainment, with the fastest tempo expected to produce even less facilitation due to the increased cognitive load associated with rapid acoustic changes. Specifically, we hypothesized a gradient effect, where the moderate tempo would elicit the strongest RPE, followed by the slower tempo, and finally, the fastest tempo which would yield the least facilitation, compared to the environmental sound scene prime.

Method

Participants. A total of 48 native English-speaking adults participated in the experiment. Four participants were excluded from analyses and were excluded as outliers due to their repetition performance being more than 2 standard deviations below the mean.

Participants that were included in the analyses were aged between 18 and 25 years old (*M* = 19.2, *SD* = 1.56) and reported no history of hearing or language impairments, or neurological disorders. Participants who had received 2 years or less of formal musical training were classified as non-musicians, and participants who had received over 9 years of formal music training on at least one instrument were classified as musicians. The sample contained 17 musicians and 27 non-musicians. Informed consent was given by the participants. Participants were not made aware of the aims of the study. Each participant was compensated with 15 Canadian dollars for their time. The experiment was cleared by the McMaster Research Ethics Board.

Materials. Musical Stimuli: Three 32-second isochronous rhythmic primes were adapted from Przybylski et al. (2013)[3]. All primes featured the same synthesized percussion instruments (a tam-tam and a maracas), but differed in their tempo: slow (60 bpm, or 1 Hz), moderate (120 bpm, or 2 Hz), and fast (360 bpm, or 6 Hz). The moderate prime was identical to the one used in Przybylski et al. (2013); the fast and slow primes differed from the moderate prime only in tempo and number of sound events. The fast and slow primes were generated as follows: Instead of time-stretching and/or time-compressing the original prime (which led to audible artefacts) the procedure was to sample the individual musical instruments from the moderate prime and construct the 60 bpm and 360 bpm version with identical rhythm (as the moderate prime) but different tempi. All instrument characteristics and musical properties were preserved, i.e., the approach was indeed an electronic tempo-varying version of a drummer playing the same rhythm at either 60, 120 or 360 bpm.

[3] We thank Jan Maihorn for creating the musical stimuli.

A 30-second-long environmental sound scene used in Bedoin et al. (2016) served as the control prime. The sound scene consists of children's voices and street ambiance near a playground. While some speech patterns can be detected, sentences are not fully discernable and remain difficult to distinguish.

Linguistic stimuli: A total of 44 jabberwocky sentences consisting of pseudowords but following regular English sentence prosody were presented in this experiment. Four unique trial sentences were used during a practice phase, and the remaining 40 were included in the analyses. The sentences were spoken with natural prosody and very similar (natural) speech rate by a female native English speaker[4]. Loudness normalization across all sentences was carried out by Praat, a software tool for speech analyses (Boersma & Weenink, 2009). The mean sentence length was 5.4 pseudowords (*SD* = 0.5). The jabberwocky sentences were first created by substituting content words in English sentences with pseudowords that followed typical phonotactic and phonological rules. Next, all function words such as conjunctions and prepositions were replaced with pseudowords of equivalent phonological length. The sentences were constructed to resemble English sentences (e.g., WOE UPLING JIDED MO NAFF). A complete list of the stimuli appears in **Appendix B**.

Design. The jabberwocky repetition priming task consisted of four primes (environmental sound scene / slow rhythmic primes / moderate rhythmic primes / fast rhythmic primes) and 40 jabberwocky sentences. The sentence order remained consistent across each participant, and primes for these sentences cycled through the four conditions,

[4] We thank Fiza Ahmad for helping with creating and recording the linguistic stimuli.

with the initial prime counterbalanced across participants. This design ensured that each sentence appeared with each prime an equal number of times across participants. Primes and subsequent sentences were presented to participants over headphones. Each prime was immediately followed by playback of the paired jabberwocky sentence, after which the participant immediately repeated the sentence to the best of their ability.

Procedure. The experimenter told the participants that they would hear either some musical rhythms or a sound clip with "background" noise such as children outside a nearby playground, that they would hear a nonsensical sentence after each sound clip, and that they would have to repeat it out loud to the best of their ability. Participants heard four practice sentences, one after each of the four primes. After the practice trials were complete, the experimenter left the room, and recorded instructions reminded the participant to repeat the sentence back as best as they could, although it would be difficult. Participants were offered a break after 20 sentences. Each new trial began with a keypress from the participant. Participant responses were recorded with a Samson Go Mic Portable USB Condenser Microphone. The entire task took ~32 minutes.

Scoring. B.O. the first author and a trained assistant scored the accuracy of participants' repetition responses based on audio recordings, comparing them to the written (target) sentences. Researchers were blind to the prime condition of the sentences during scoring. The research assistants used an all-or-nothing approach for word accuracy, awarding one point for each correctly pronounced word with no phoneme substitutions, additions, or deletions. Given the challenge of always precisely perceiving participant responses, especially in cases of subtle pronunciation variations (e.g., "IMM" sounding like

"INN"), scorers were instructed to be lenient and accept phonetic approximations if participants were consistent across trials with the same target word. Percentage agreement was calculated for a subset of 11 participants. The inter-rater reliability across these participants was averaged, resulting in an agreement rate of 88%.

Results

The proportion of correctly repeated pseudowords is shown in Figure 1. The repetition accuracy proportions were analyzed by a 2 (participant group) x 4 (sound prime type) repeated measures ANOVA with group as a between-subjects factor and sound prime type as a repeated factor. There was no significant main effect of prime type: participants appeared to perform similarly on all primes [$F_{(3,126)} = 0.63$, $p = .60$] (see **Figure 1**). The main effect of group was also not significant [$F_{(1,42)} = 0.30$, $p = 0.59$], although musicians performed a little better overall (for musicians, $M = 0.65$, $SD = 0.10$; for non-musicians, $M = 0.63$, $SD = 0.09$), except in the fast (360 bpm) condition. Also, there were no significant interactions between group and prime type [$F_{(3,126)} = 0.36$, $p = 0.79$]. These findings suggest that regular, predictable musical sequences with a rhythmic structure might not enhance memory for unfamiliar words.

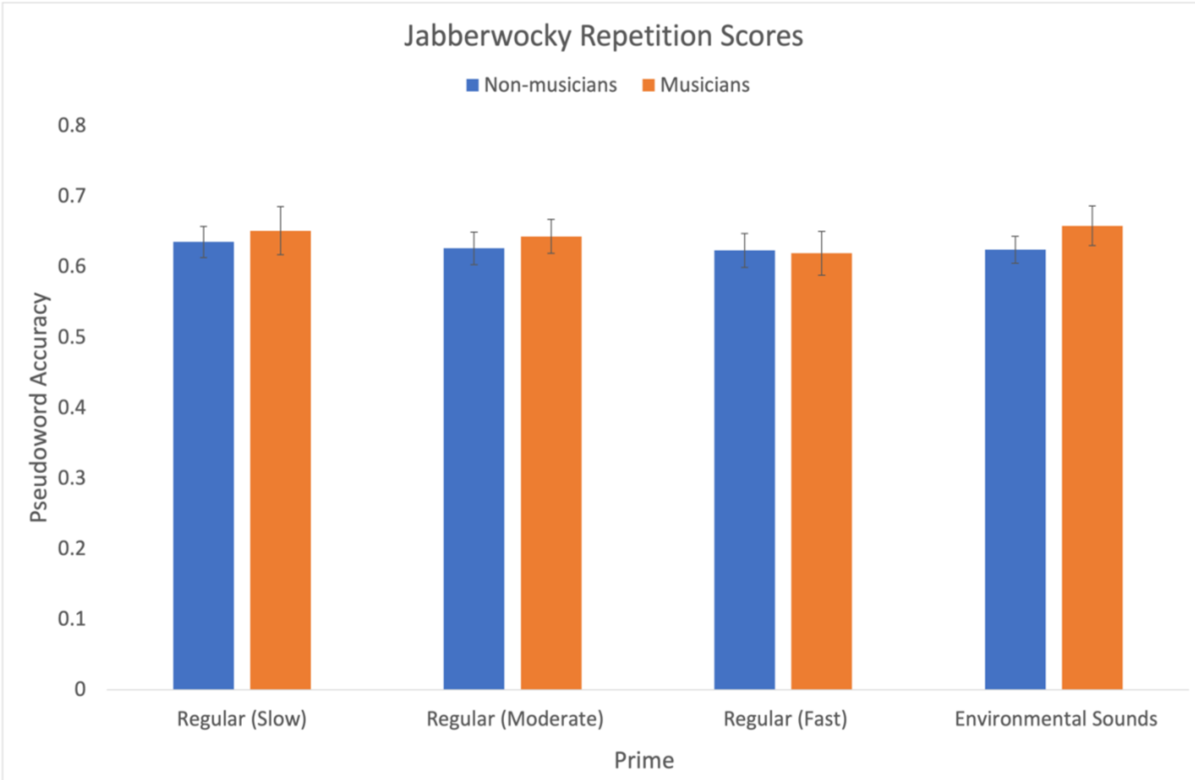

Figure 1. | *Jabberwocky repetition accuracy (prime x group).* Mean pseudoword repetition accuracy scores for non-musicians and musicians across four prime conditions: regular (slow), regular (moderate), regular (fast) and the environmental sound scene. Error bars indicate between-participant standard errors.

As the statistical analysis failed to show significant effects, a Bayesian Repeated Measures ANOVA with default prior model odds (P(M) = .200 for separate models for each main effect, their combination and the combination including their interaction) was conducted to quantify both H_1s (effects) and H_0s (lack of effects) of the sound prime type, musicianship, and their interaction on jabberwocky repetition accuracy (JASP Team, 2018; Morey & Rouder, 2018; Rouder et al., 2012). Model comparison for the H_1 revealed that the null model with only participants as a predictor received the strongest support from the data with a posterior probability of P (M | $data$) = 0.686 and served as the baseline for comparison (BF_{10} = 1.00). The model including only sound prime type added to the null model received no support (*P* (*M* | *data*) = 0.036, BF_{10} = 0.053; BF_{01} = 7.9). Instead, there was moderate support for no difference from the null model. The model including only a main effect of musicianship also yielded no support for being different from the null model (*P* (*M* | *data*) = 0.263, BF_{10} = 0.383; BF_{01} = 2.69) but the support for no difference from the null model remained inconclusive in this analysis, with BF_{01} below 3. A model with both main effects and the interaction factor compared to the null model received very close to zero support, (*P* (*M* | *data*) = 0.001; BF_{10} = 0.002).

To summarize, all Bayes factors for models including effects of the independent variables compared to a null model including the effect of participants only were below 1, not providing any evidence in favour of either prime type or musicianship affecting jabberwocky sentence repetition accuracy. Instead, evidence for a true null effect was moderate for prime type although inconclusive for musicianship.

Discussion

The present study builds on our previous research that demonstrated a benefit on verbal STM following a temporally regular musical prime (Owusu & Service, 2023). Here, we investigated if varied tempi of the musical prime (slow, moderate, fast) could elicit and replicate the rhythmic priming effect (RPE) compared to an environmental sound scene prime. Musicians and non-musicians performed a verbal memory repetition task on nonsensical (jabberwocky) sentences, after passively listening to a musical prime presented at varied tempi or an environmental sound scene prime. Results showed no significant differences for sentence repetition in either participant group after attending to the different primes. Although musicians performed a little better on all primes except those in the fast condition, the data did not reveal significant differences between groups. These results will be discussed below in terms of how tempo variation in musical primes may influence cognitive load and temporal expectations, as well as the potential limitations in capturing subtle differences in rhythmic priming effects between groups.

Differences Between Slow, Moderate and Fast Tempi. The effects of tempo on verbal memory performance were assessed to determine whether slow, moderate, and fast musical primes influenced sentence repetition performance differently for musicians and non-musicians. Prior research with positive priming results (Owusu & Service, 2023) highlighted the possible role of temporal regularity enhancing attention and subsequent memory. The temporally regular musical prime used in that study had a moderate tempo of approximately 120 bpm. The present study aimed to replicate the rhythmic priming effect using the same prime. We also investigated whether two other primes with different tempi (slow and fast) could elicit the RPE or if they would yield a detrimental effect. Surprisingly, results showed that neither non-musicians nor musicians demonstrated significant differences in sentence repetition scores across the three tempo conditions.

The overall pseudoword repetition scores are notably different in Owusu and Service’s (2023) earlier study. The participants in the current study performed better (means between 0.619 and 0.658 in two groups and four conditions), which might suggest differences in sample characteristics. Specifically, the lower scores observed in the previous study (means between 0.557 and 0.610 in two groups and two conditions) could indicate a sample with less optimal baseline performance, creating greater variability and potentially additional space for greater improvement. In contrast, better performance seen in the present study might indicate that participants are already performing near their maximum verbal STM capacity, thereby reducing the likelihood of observing an RPE. It is possible that rhythmic stimulation is more effective in samples with lower baseline performance, where rhythm and memory processing may be more susceptible to external facilitation. This interaction between baseline ability and rhythmic priming warrants further exploration to determine whether participants with lower initial performance consistently show greater enhancement from rhythmic priming, as these investigations could inform targeted approaches for clinical and educational populations.

Interestingly, several studies suggest that music with faster tempi is associated with emotional benefits (for a review see Bruner, 1990), economic benefits (Milliman, 1982) and cognitive benefits such as better decision-making (Day et al., 2009) and enhanced memory (Chie & Karthigeyan, 2009). However, in a recent study investigating the influence of tempo on motor, visuospatial and linguistic processing speed (Lin, Kuo & Mai, 2023), results showed that listeners of slow-tempo music achieved greater accuracy in the linguistic processing task compared to those in the fast–and no-music conditions. These findings suggest that the influence of tempo on performance may be context-dependent and highlight the importance of considering the context when selecting musical primes for specific tasks. Notably, these previous studies defined slow tempi approximately in the range of 60-70 bpm, while fast tempi ranged from approximately 140-165 bpm.

Future research could further explore cognitive limits of tempo processing on verbal memory tasks, perhaps by testing a narrower range of tempi to reach the thresholds of the rhythmic priming effect. Also, examining a narrower set of tempi can refine the boundaries of the rhythmic priming effect on verbal memory tasks. In addition, examining neural responses to tempo variation in both musicians and non-musicians might provide important insights regarding the underlying mechanism of rhythmic entrainment and its influence on memory.

The Role of Tempo in Verbal STM: Implications for Interventions. Despite our explicit efforts to identify an ideal tempo for rhythmic primes to enhance verbal memory, results from this study did not highlight a specific tempo with advantages across participants. Existing research (e.g., Fanuel et al., 2018; Plancher et al., 2018; Povel & Essens, 1985, Purnell-Webb & Speelman, 2008) indicates that auditory stimuli presented with salient temporal regularities may generally benefit memory processing. For instance, Hickey et al. (2020) showed that low-frequency rhythms in background music can help the brain track a beat and improve visual memory performance for objects that appear in-sync with the beat. This finding adds to the growing body of evidence that rhythmic regularity in music can support memory. Notably, the tempo of the background music used in that study was relatively slow—75 bpm (1.25 Hz). It appears that tempo differences influence cognitive processing in more nuanced ways, suggesting there may not be a single tempo or range of tempi (slow, moderate, fast) that can universally enhance memory. Slow tempi may enhance linguistic processing (e.g., Lin, Kuo & Mai, 2023) and visual memory performance (Hickey et al., 2020), while listening to fast tempi may provide emotional

(Bruner, 1990) and attentional benefits (Woods et al., 2024). Moderate tempi have been shown to enhance grammaticality judgements in both children with known language difficulties and those with typical language development (e.g., Bedoin et al., 2016, 2018; Chern et al., 2018; Ladányi, Lukás & Gervain, 2021; Przybylski et al., 2013) as well as in adults (Canette et al., 2020).

For interventions designed to support individuals with verbal memory impairments, such as those with dyslexia or co-morbid depressive symptoms (e.g., Xiao et al., 2023; for a review see Hendren et al., 2018), finding an ideal tempo could be critical. For instance, faster tempi are associated with emotional benefits such as happiness, excitement, and delight, while slow tempi can evoke negative emotions such as sadness and depression (Balkwill & Thompson 1999; Juslin & Sloboda, 2001; Peretz, Gagnon & Bouchard, 1998). Thus, faster music, though it evokes a better mood may, paradoxically, hinder performance by overloading working memory and attention for verbal memory tasks. In contrast, slow music, though potentially suitable for memory tasks, may not be suitable for clinical interventions as it may unintentionally induce a down-regulated emotional state (for an overview, see van den Tol, 2016). Therefore, a careful selection of either slow or moderate tempi may create conducive conditions for memory enhancement but should be applied selectively based on an individual's emotional disposition.

The failure to identify an ideal tempo for verbal memory enhancement in this study highlights the complexity of using rhythmic primes in clinical settings. When designing interventions, it may be beneficial to use an individualized approach, testing various tempi to find which one best aligns with each individual's cognitive needs and emotional responses. As studies on rhythmic priming advance, they may investigate more precisely the neural connections between cognitive processing and musical tempi, as well as the emotional functions associated with passive listening to music. Such investigations could inform effective applications aimed at enhancing the rhythmic priming effect in clinical and educational populations.

Conclusion

The present study did not find a rhythmic priming effect (RPE) for verbal STM enhancement across participants. These findings contrast with our previous study that found an RPE across musicians and non-musicians (Owusu & Service, 2023). This discrepancy highlights the complexities associated with replicating rhythmic priming effects across different tasks such as grammaticality judgements (e.g., Bedoin et al., 2016; Przybylski et al., 2013) syntax comprehension, (e.g., Bedoin et al., 2018) and sentence repetition (Fiveash et al., 2023; Owusu & Service, 2023). Such complexities suggest that factors such as individual rhythm sensitivity and the choice of task might play a crucial role in determining the effectiveness of rhythmic priming interventions. Despite our efforts, identifying an ideal tempo for an RPE in the verbal memory domain proved elusive, which may suggest that RPEs in verbal memory require more nuanced parameters than previously considered.

Future research could investigate whether an ideal tempo exists for rhythmic priming in the grammar domain as rhythmic priming has been consistently shown to enhance grammaticality judgements, primarily in children (e.g., Bedoin et al., 2016, 2018;

Chern et al., 2018; Ladányi, Lukács & Gervain, 2021; Przybylski et al., 2013), though some evidence exists for similar effects in adults (Canette et al., 2019, 2020). Additionally, exploring the neural underpinnings connecting rhythm processing, memory and musical tempi could reveal more insights about the parameters necessary to produce an RPE other than simple rhythmic regularity. Such investigations could help develop and inform intervention strategies to support cognitive and linguistic rehabilitation in clinical populations. By addressing these gaps, future research can clarify the conditions under which rhythmic priming is most effective and refine its application within both typical and clinical populations.

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Chapter 5: General Discussion

The overarching goal of the work presented in this thesis was to examine if the previously reported rhythmic priming effect for grammaticality judgements (e.g., Bedoin et al., 2016; Canette et al., 2019, 2020; Chern et al., 2018; Ladányi, Lukács & Gervain, 2021; Przybylski et al., 2013) could extend beyond grammar abilities and cross into the memory domain. Specifically, we examined if rhythmic priming could benefit verbal working memory. To do so, we studied the influence of listening to a regular, rhythmic, musical beat compared to an environmental sound scene before performing a pseudoword recognition task (Chapter 2), and a sentence repetition task (Chapters 3 and 4). We also aimed to replicate a previously observed rhythmic priming benefit for grammaticality judgements in children ages 9-11 (Chapter 2) and we explored the effects of varied tempi of the rhythmic prime on sentence repetition abilities (Chapters 4). Across three chapters and three experimental studies, we employed a rhythmic priming paradigm adapted from Przybylski et al. (2013). The main result that emerged from these investigations is that previously reported beneficial rhythmic priming effects on grammaticality judgements primarily found in children (e.g., Bedoin et al., 2016; Chern et al., 2018; Ladányi, Lukács & Gervain, 2021; Przybylski et al., 2013) were reversed and became fragile once examined for its reproducibility in verbal short-term memory.

In Chapter 2, we aimed to study recognition memory for novel word forms and replicate the rhythmic priming effect for grammaticality judgements by priming grammatical and ungrammatical sentences containing a pseudoword (e.g., “Every day, the horses *gallop/gallops* to the top of the *dalt*") with a regular, predictable musical beat or an environmental sound scene. The pseudoword replaced a real word noun. We examined if the pseudowords primed with the musical beat would be more recognizable compared to those primed with environmental sounds. Given the strong evidence for the rhythmic priming effect on grammar judgements in prior studies (e.g., Bedoin et al., 2016; Canette et al., 2019, 2020; Chern et al., 2018; Ladányi, Lukács & Gervain, 2021; Przybylski et al., 2013), we expected enhanced grammaticality judgements following rhythmic priming compared to those following environmental sound priming. However, to our surprise, the data indicated a reversal effect of rhythmic priming for grammaticality judgements. Grammar judgements were better after children aged 9-11 had passively listened to an environmental sound scene compared to a rhythmic musical beat. There was also no statistical significance for a priming effect on pseudoword recognition accuracy; although, there was a tendency for children to recognize more pseudowords that were primed with environmental sounds compared to the rhythmic musical beat. These results suggest that once a secondary task is added to the primary grammar judgement task, the previously reported positive rhythmic priming effect on grammar decisions is absent and no priming could be detected in the verbal memory domain.

Chapter 3 investigated whether the dual task condition employed in Chapter 2 was responsible for the absence of rhythmic priming effects. To investigate, we removed the grammar judgement task and solely primed a repetition task with nonsensical sentences testing adult musicians and non-musicians. When grammaticality judgements were removed and only verbal short-term memory was tested, a rhythmic priming effect emerged in both musicians and non-musicians. However, it should be noted that the effect was marginally moderate and not robust. Nevertheless, data demonstrated that passively listening to a regular, predictable musical beat may enhance verbal short-term memory in both adult musicians and non-musicians.

The final experimental chapter (4) investigated whether there is an ideal tempo for presenting the rhythmic prime to replicate the rhythmic priming effect on sentence repetition in both musicians and non-musicians. When the tempo was varied, the data indicated that no particular speed in the presented range (i.e., 1 Hz, 2 Hz and 6 Hz) provided greater benefits for verbal short-term memory. Although not statistically reliable, both musicians and non-musicians showed a preference for a slower rhythmic prime compared to a fast rhythmic prime. As such, these data show that the tempo of the rhythmic prime within the presented range may not play an important role for verbal short-term memory performance in musicians or non-musicians. Importantly, this experiment did not replicate the rhythmic priming effect observed over the environmental sound scene in our previous experiment, highlighting a failure to reproduce Chapter 3's finding.

Thus, when the effects of rhythmic priming were explored in the memory domain, there was mixed or weak evidence of beneficial rhythmic priming effects on subsequent verbal short-term memory tasks. As such, these results highlight the specificity of previously reported rhythmic priming benefits, which appear to be more robust for sole grammar judgement tasks than for verbal short-term memory or for dual tasks. They additionally suggest that there may be weak to moderate benefits for sentence repetition under certain task conditions. The implications of these results are discussed in the three sections that follow. Section I discusses how these findings fit within the existing knowledge of rhythmic priming effects. Specifically, it expands on this discussion by examining the underlying reasons as to why the benefits of rhythmic priming may be domain specific, i.e., why robust effects are largely found in grammar judgement abilities and in the motor domain. Section II examines how the present set of data informs the literature on general mechanisms of verbal short-term memory, and specifically how rhythm relates to verbal memory. Finally, Section III discusses the main methodology, i.e., the rhythmic priming paradigm, and outlines other possible methodological avenues within this paradigm for future work.

Section I: Conceptualizing the current findings within rhythmic priming literature

The present thesis demonstrated that the rhythmic priming effect as reported in prior literature (Bedoin et al., 2016; Canette et al., 2019, 2020; Chern et al., 2018; Ladányi, Lukács & Gervain, 2021; Przybylski et al., 2013) likely arises from a combination of salient syntactic cues in the language task (e.g., Canette et al. 2020), lexical predictability and the prime's regularity, rather than temporal regularities within the prime's structure alone. If temporal regularities are linked to attention and contribute towards setting up a listener's brain to focus on relevant information (Jones, 1976), we might have expected to find typical rhythmic priming effects across our manipulations in the measures of verbal short-term memory. However, temporal regularities might also facilitate predictive processing, allowing the brain to anticipate future events at specific time points, as suggested by Bedoin et al. (2016) and Przybylski et al. (2013). While improved attention can help recall memory, prediction is less relevant in these tasks. Memory recall, such as retrieving words or sentences requires one to access previously stored information, rather than anticipating upcoming elements. This distinction may explain why rhythmic priming effects were more pronounced in grammar judgement tasks, where prediction helps facilitate the identification of a correct word. As such, the following paragraphs discuss a possible way to account for the discrepancy between past data and the present work: rhythmic priming benefits may be domain specific.

Rhythmic priming benefits may be domain specific. The reason that the current data showed mixed or weak evidence of a rhythmic priming boost may be that our tasks were in the domain of memory. Prior rhythmic priming benefits have been shown for syntax processing in patients with basal ganglia lesions and Parkinson's disease (Kotz & Gunter, 2012; Kotz, Gunter & Wonneberger, 2005), grammaticality judgements (Bedoin et al., 2016; Canette et al., 2019, 2020; Chern et al., 2018; Ladányi, Lukács & Gervain, 2021; Przybylski et al., 2013), phonological processing (Cason, Astésano & Schön, 2015) and motor re-learning (see Thaut et al., 1999 for a review). Additionally, rhythmic priming has been explored in other cognitive domains; however, the tasks used in these previous studies to examine the generality of rhythmic priming benefits served mainly as control tasks. For instance, several control tasks implemented in rhythmic priming research outside the domain of linguistic processing include math and visuo-spatial tasks (Chern et al., 2018), a visual cancellation task (Fiveash et al., 2023), a non-verbal stroop task and a picture naming task (Ladányi, Lukács & Gervain, 2021). In comparison to grammaticality judgements, performance on all control tasks showed that rhythmic priming effects were always specific to grammar processing.

A potential reason why rhythmic priming benefits are so pronounced in grammaticality judgements could be due to the interaction between regularity-induced attention and syntactic cueing. According to the Dynamic Attending Theory (DAT; Jones, 1976), the brain has the capacity to entrain to external temporal regularities (e.g., a musical prime) which results in heightened attention to subsequent events. This theoretical framework dovetails with the concept of syntactic cueing. When a listener's attention has been heightened and they are tasked with making grammaticality judgements in a familiar language, the primed attentional state facilitates the recognition of word order, particularly in relation to potential grammar violations. It is important to note that a recent study (György et al., 2024) investigated rhythmic priming benefits for grammaticality judgements in (unfamiliar) jabberwocky sentences. Pseudowords replaced real word nouns, but verbs and grammatical morphemes of French were preserved. The results highlighted a rhythmic priming effect when compared to irregular and silent prime conditions. However, the main finding was that the effect was short lived. The (block) design, similar to prior designs used within the literature, revealed an effect only in the first three out of six sentences after the regular prime. This diminished effect may stem from the absence of semantic content. The absence of semantics likely limits the listener's ability to engage in familiar linguistic frameworks, making syntactic cueing less robust and reducing the overall impact of rhythmic priming on grammatical processing.

In light of these observations, we note that syntactic cueing was not present in the tasks described in the present thesis. This is because the memory-related tasks all involved unfamiliar–jabberwocky sentences or pseudowords. Together with the current data, this research suggests that the benefits of rhythmic priming may not be solely attributable to the regularity of the musical prime. Instead, these effects may also require additional facilitation from task-related factors, such as the presence of syntactic cueing mechanisms with a temporal structure.

The preceding discussion focussed on cueing mechanisms in the linguistic domain. It is equally important to consider why rhythmic priming benefits extend to the motor domain. Rhythmic priming effects (RPEs) have been well-documented in motor rehabilitation research, particularly through mechanisms such as auditory-motor entrainment and applications such as neurologic music therapy (NMT, e.g., Paltsev & Elner, 1967; Rossignol & Melvill Jones, 1976; Thaut et al., 1993, Thaut, McIntosh & Rice, 1997). The favorable effects of rhythmic stimulation on motor rehabilitation can likely be attributed to the strong alignment between auditory cueing and motor coordination, as external rhythmic cues can provide a temporal scaffold for movement (Cochen De Cock et al., 2018; Sejdić et al., 2012).

Unlike verbal short-term memory tasks, where temporal structure is less relevant, motor learning directly benefits from temporal cueing and entrainment mechanisms described by the DAT. For instance, in a neurological music therapy intervention called Patterned Sensory Enhancement (Thaut, 2014), a music therapist will play a musical instrument to provide spatial, temporal and force cues to facilitate movement. Furthermore, in previous systematic reviews and meta-analyses, research has shown that rhythmically cued exercises are effective in enhancing upper-extremity functions in stroke patients (Ghai & Ghai, 2018; Yoo & Kim, 2016). Rhythmic cues can help establish a predictive model of movement (Schaefer, 2014). Auditory rhythmic cues prime the motor system, and movement disordered patients can subsequently use these cues to anticipate and plan the next action, and consequently to execute movement (Crasta et al., 2018; McIntosh et al., 1997; Thaut et al., 1993, 1996; Thaut, McIntosh & Hoemberg, 2015; Thaut, McIntosh & Rice, 1997). While rhythmic cueing and entrainment in the motor domain are highly relevant due to their crucial role in anticipating and predicting movement, their role in verbal memory is less clear. Verbal short-term memory may not inherently rely on temporal cues, which may explain the weaker RPEs in this domain.

Section II: Insights into the role of timing in verbal short-term memory

One of the broader implications of the current work concerns how these data influence the understanding of the role of timing in verbal short-term memory (VSTM). As outlined in the General Introduction, temporal factors such as rhythmic patterns in stimulus presentation have been shown to enhance memory processing by supporting neural entrainment, attention, and chunking mechanisms. However, the mixed evidence in the data of the current thesis suggests that while rhythm can influence VSTM under certain conditions, the effects may be more task-specific or context-dependent than previously thought. For example, Fiveash et al. (2023) found that rhythmic priming facilitated sentence repetition in children with DLD and with typical development. The paragraphs that follow discuss the observed limited role of time in VSTM by first providing controversial evidence within the existing literature on the relationship between positional and temporal signals in VSTM. Building on this foundation, the discussion will turn to (re)-considering how temporal factors in the phonological loop might interact with preceding rhythmic stimulation to facilitate verbal memory recall. While this discussion may not establish a definitive role of rhythm or time for the phonological loop concept, it aims to provoke thought about their relevance or perhaps lack thereof—in understanding rhythmic priming.

The limited role of timing in verbal short-term memory. Despite the benefits of temporal regularity in linguistic and motor domains, its role in verbal short-term memory appears less critical. Past research has shown that serial order in verbal short-term memory primarily encodes information via positional (order) associations rather than temporal signals (Farrell & Lewandowsky, 2002; Gorin, 2020; Ng & Maybery 2002, 2005). For instance, past work (Gorin, 2020) supports event-based models, which suggest that items are associated with a contextual signal that changes with each new item in a sequence. The contextual signal is not temporally dependent, as demonstrated by Gorin (2020) in which temporal manipulations of item presentation (e.g., regular vs. irregular) did not impact recall performance or error patterns for verbal sequences. These findings provide evidence for the limited role of absolute-time-dependent processes in verbal short-term memory.

Time-based models suggest that serial order is primarily encoded via a contextual signal that varies with real time, such as the output of neuronal oscillators (e.g., Brown, Preece & Hulme, 2000). Such models have predicted that unpredictable timing inside presented sequences or rhythmically grouped sequences can influence immediate memory recall for spoken sentences (e.g., Hartley, Hurlstone & Hitch, 2016), digits (e.g., Schwartze et al., 2020) and more broadly, working memory (Hitch et al., 1996; Ryan, 1969a, 1969b). However, other experimental findings do not support this notion (Lewandowsky & Brown, 2005; Lewandowsky et al., 2006; Nimmo & Lewandowsky, 2005; Parmentier, King, &

Dennis, 2006). For example, Jones et al. (2023) aimed to investigate the neural mechanisms underpinning temporal prediction on memory recognition. Stimulus onset was manipulated prior to recognition testing (rhythmic vs. arrhythmic), and although ERP component analysis showed an interaction effect of temporal position and rhythm at encoding, these differences did not extend to performance at recognition. Moreover, the behavioural results of this study did not replicate prior findings reporting benefits for recognition memory of predictability at encoding. These results suggest that the effects of temporal predictability on memory may be less robust than previously thought.

Nevertheless, some studies suggest that temporal factors can influence verbal working memory under specific conditions. For example, Hitch et al. (1996) demonstrates that timing producing grouping effects can enhance immediate memory for a sequence of verbal items. In Hitch et al. (1996), temporal pauses were introduced inside item lists thereby creating structured temporal groups that could facilitate memory retrieval. These findings suggest that while timing may play a limited role in serial order coding, it can facilitate grouping mechanisms in verbal memory. Similarly, chunking (often interchangeable with temporal grouping) appears to have a major impact on learning novel verbal information (Gilbert, Boucher & Jemel, 2012), suggesting that speech can be processed by chunks (temporal groups) in listeners' working memory. These findings highlight that temporal regularity may still play a secondary, context-dependent role in verbal short-term memory.

Taken together, the evidence suggests that verbal memory may predominantly rely on positional rather than temporal information. However, temporal cues may still facilitate memory performance on tasks that encourage grouping or implement rhythmic presentations. This distinction contrasts with domains like motor learning, where temporal regularity is integral to motor planning and execution, and domains like grammar learning, where syntactic cueing combined with temporal regularities is critical in predicting future elements. Thus, in the present thesis, while verbal short-term memory appears resilient to temporal irregularities, its flexibility to leverage temporal cues when available remains complex and requires further clarification.

The role of timing in the phonological loop. The phonological loop is a key component of Baddeley and Hitch's (1974) working memory model (see also Baddeley, 1986; Baddeley, Gathercole & Papagno, 1998, for reviews). This specialized loop is theorized to process verbal information by storing and rehearsing information by means of subvocal rehearsal. Burgess and Hitch's (1999) connectionist model extended this theory by introducing a context–timing signal which is critical for maintaining the temporal order of items during recall. We initially hypothesized that by providing listeners with an external temporal structure (i.e., a rhythmic musical prime) the timing mechanism in the phonological loop would be bolstered and subsequently improve the recall of novel words compared to an arrhythmic prime. However, contrary to the hypothesis, the current data suggest that a temporal structure preceding the storage and recall of verbal information does not appear critical in affecting the recall of nonsense sentences or recognition of pseudowords. As such, rhythmic stimulation was expected to provide a temporal scaffold for verbal memory recall by synchronizing neural oscillators with an external timing signal. The findings in the present thesis challenge the assumption that the phonological loop directly benefits from external rhythmic cues. It should be noted that Burgess and Hitch's (1999) model emphasizes an intrinsic timing signal, which can operate in the absence of external rhythmic inputs. This finding suggests that the role of external rhythmic priming appears less critical in relation to the phonological loop's internal timing mechanisms. However, temporally structured linguistic input such as speech rhythm and syllable timing remains essential for the development and function of these timing mechanisms. It remains possible, however, that the phonological loop's intrinsic mechanisms develop only when exposed to temporally structured linguistic input, rather than relying on external rhythmic cues. If these mechanisms depend solely on temporally structured linguistic input, such development may not be optimal in individuals with various developmental disorders, particularly those characterized by atypical processing of speech rhythm (e.g., Huss et al., 2011). This warrants further investigation.

While rhythmic priming might not consistently enhance verbal memory recall in a direct manner, it is possible that we would have seen more consistent and robust effects with different task demands or stimulus content. For instance, factors such as phonemic similarity, word frequency and semantic knowledge are known to influence the phonological loop's performance in verbal memory recall (Deese, 1959; Gregg, 1976; Hulme et al. 1997; Meschyan & Hernandez, 2002; Pollock, Rubenstein & Decker, 1959). It is well established that semantic knowledge influences verbal memory. For instance, Hulme et al. (1991) found that individuals have better recall for words than non-words. Additionally, there is evidence that individuals recall concrete words better than abstract words—also known as the concreteness effect (e.g., Romani et al., 2008; Walker & Hulme, 1999). All the pseudowords used in the present thesis were constructed with consideration of phonemic similarities within the context of the English language. However, as mentioned earlier, pseudowords lack semantic content, and this absence of meaning may have limited the effectiveness of rhythmic priming in enhancing the storage and rehearsal mechanisms of the phonological loop. Semantic representations often provide essential cues that support verbal memory processes (e.g., Pham & Archibald, 2022). Perhaps, the addition of semantic inputs could have bolstered the effectiveness of rhythmic priming across the manipulations in the present thesis. Future research could investigate this possibility by comparing nonsense sentences with real-word sentences containing semantic content.

Section III: Advancing methodologies in rhythmic priming research

Finally, it is important to consider that the inconsistent or undetected beneficial rhythmic priming effects that were observed across the studies comprising the current thesis may be attributed to the choice of experimental tasks and their design.

The current paradigm. Across all studies within this thesis, we used the rhythmic priming paradigm (Przybylski et al., 2013) in order to examine the influence of passively listening to a temporally regular musical rhythm on verbal memory processing. The typical finding with this paradigm used for grammaticality judgement tasks is that individuals are better at judging correct and incorrect grammar in sentences constructed in their native language. This is thought to occur because the musical rhythm provides an external pattern that the listener's brain can entrain to, thereby heightening attention and allowing more accurate predictions about upcoming linguistic events. These predictions, in turn, may facilitate the identification of correct grammar or the detection of violations. In this way, the rhythmic priming paradigm allows researchers to investigate the interaction between temporal processing and grammar abilities, offering insights into how rhythm influences grammar.

The rhythmic priming paradigm has been well-established in behavioural examinations of syntax and grammar abilities in children and adults in several languages (Bedoin et al., 2016; Canette et al., 2019, 2020; Chern et al., 2018; Ladányi, Lukács & Gervain, 2021; Przybylski et al., 2013), as well as in examinations of motor rehabilitation in patients with neurological and movement disorders, such as Parkinson's Disease, stroke, cerebral palsy and traumatic brain injury (see Ashoori, Eagleman & Jankovic, 2015 for a review). Furthermore, a previous study has also verified findings from the rhythmic priming paradigm using supporting neural (EEG) data (Canette et al., 2020). For example, EEG data in Canette et al. (2020) showed that both individuals with and without dyslexia exhibited larger P600 peak amplitudes—a neural marker of grammatical error detection—after listening to a regular, musical rhythm compared to an irregular prime. Taken together, these results point to the strength of the rhythmic priming paradigm in measuring syntax and grammar processing.

However, recently, the rhythmic priming paradigm has also been scrutinized for its reliability when measuring cognitive performance across different stimuli and task parameters. For example, as previously noted, tasks involving other cognitive processes like mathematics and visuo-spatial abilities (Chern et al., 2018), picture naming (Ladányi, Lukács & Gervain, 2021) and visual cancellation (Fiveash et al., 2023) have consistently failed to yield a rhythmic priming effect (RPE). Interestingly, recent work by Kim, McLaren, and Lee (2024) also failed to replicate the rhythmic priming effect for grammaticality judgements of real-word English sentences. Their findings indicated that children aged 7-12 years old performed comparably on both grammaticality judgement and sentence comprehension tasks, regardless of whether they were primed with regular or irregular musical rhythms used in Przybylski et al. (2013). Fiveash, Bedoin, and Tillmann (2025) critiqued Kim et al.'s (2024) research, suggesting two potential methodological factors that may account for the absence of an observable RPE in their study. First, there was an increased delay between the primes and the to-be-processed sentences. As seen in György et al. (2024), it is suggested that the RPE diminishes over time following the presentation of the prime, and that an increased delay between the prime and task may have resulted in the lack of an RPE (Fiveash, Bedoin & Tillmann, 2025). Secondly, in Kim et al.'s (2024) study, children were instructed to 'relax and have some rest' as they passively attended to the musical primes. Fiveash, Bedoin, and Tillmann (2025), propose that this instruction may have reduced participants' attentive processing, thereby contributing to the failure to replicate the RPE.

Future approaches. Given that the present results showed mixed and inconsistent RPEs, we wonder whether verbal short-term memory might show more benefit in paradigms that more robustly capture the effects of rhythmic priming. As such, we now turn to a discussion of the methodologies employed in all three experiments and consider potential directions for future research in rhythmic priming.

Immediate measurement of verbal working memory. One key distinction in Chapter 2's stimuli was the replacement of the final noun with a pseudoword. This modification was intended to investigate the potential influence of rhythmic priming on novel language learning. Previous studies that observed the rhythmic priming effect (Bedoin et al., 2016; Canette et al., 2019, 2020; Chern et al., 2018; Ladányi, Lukács & Gervain, 2021; Przybylski et al., 2013) used real-word sentences. The block design in Chapter 2, that is, an auditorily presented prime precedes a block of six grammatically correct or incorrect sentences, remained consistent with previous research, such as in Przybylski et al. (2013). However, a notable difference in Chapter 2's design was the inclusion of a verbal recognition task at the *end* of the experiment, following a distraction task. The decision to test verbal recognition after the distraction task was based on the notion that a delay between priming and testing phases might better reflect real-world conditions, in which priming effects are not always immediate. Furthermore, the distraction task was to prevent overt and/or covert rehearsal of pseudowords. Recent research (György et al., 2024) has shown that priming effects can be influenced by delays, as longer intervals between the prime and task may reduce the strength of the effect. It is important to note here that despite the dual-task conditions and the delay in verbal memory testing, the results showed significantly better grammar judgement abilities and marginally higher verbal recognition accuracy in the control prime condition. The implications of context settings (e.g., at home vs. in-lab testing) have already been acknowledged as a limitation in the discussion section of Chapter 2. Despite this limitation, future research could involve testing verbal memory recognition either immediately after completing a block of grammar judgements or directly after the prime, without requiring grammar judgements. This would provide more focussed measurement of verbal short-term memory. Adjusting the tasks in this way may help identify conditions under which rhythmic priming effects are most robust and can offer clearer insights into the interactions between timing and language learning under task-specific conditions.

Measuring verbal memory with familiar language. In Chapter 3, the methodology was revised to allow for immediate measurement of verbal memory following rhythmic and arrhythmic primes. The block design was eliminated, and participants no longer judged the grammar of sentences. Instead, they repeated nonsensical sentences out loud immediately following the presentation of the primes that alternated between a regular musical prime and an environmental sound scene used in Bedoin et al. (2016). This design sought to simplify the experimental procedure by isolating the rhythmic priming effect on verbal memory and by reducing potential confounds related to delayed testing or dual-task conditions. The results highlighted the presence of a rhythmic priming effect, but the overall effect size was small to moderate at best. Unlike Fiveash et al. (2023), the methodology employed in Chapter 3 of the present thesis included jabberwocky sentences. In Fiveash et al. (2023), individuals were tasked with repeating sentences in their native French. Their scoring system was adapted from Diessel and Tomasello (2005) and was based on the specific types of grammatical errors produced in each sentence. Even with the implementation of a block design (six sentences presented following a regular or irregular rhythmic prime) and a task not directly related to grammar judgements, an RPE was observed with a medium effect size.

Future research might benefit from adopting a similar method where sentence repetition occurs immediately following each prime but using real-word sentences. This approach could enhance the effect size as semanticity, lexical familiarity, and immediate measures of verbal memory are all incorporated.

Maintaining a consistent prime tempo over trials. Fiveash et al. (2020) investigated the role of prime duration on grammaticality judgements and demonstrated that shorter primes (8 s and 16 s) failed to elicit an RPE in contrast to the successful, typical, 32 s prime. In this context, the duration of the prime matters. Similarly, in Chapter 4, our objective was to isolate a specific feature of the rhythmic prime—namely, tempo and evaluate its influence on verbal memory. The results from Chapter 4 in the present thesis showed no effects of tempo on verbal memory. One possible explanation for the absence of a rhythmic priming effect is that the variation in tempo across trials may have led to inconsistent temporal encoding. In the previous experimental chapter (3), although the primes alternated between rhythmic and arrhythmic, the tempo remained constant. Participants were likely able to develop and maintain rhythmic expectations that facilitated memory performance. In contrast, the fluctuating tempi in Chapter 4 may have disrupted this process, increasing the likelihood of comparable performances across conditions, and reducing the likelihood of observing an RPE. These findings may highlight the significance of tempo consistency in eliciting an RPE and suggest that tempo-specific factors warrant further investigation in rhythmic priming paradigms.

A blocked–counterbalanced design, in which participants complete tasks after listening to separate blocks for each tempo condition (e.g., slow, moderate, or fast), with adequate breaks between blocks and compared to a control prime condition, offers several methodological advantages for future research. First, when participants are exposed to only one tempo per block, it may reduce the amount of 'adaptation' that participants must undergo when experiencing multiple tempi within the same session or block. Perhaps this approach would allow participants to better synchronize with a single tempo at one time, thereby, strengthening the effect of rhythmic priming. Second, incorporating breaks between blocks can reduce the risk of task-fatigue or attentional drift, potentially arising from prolonged exposure to varied tempos in one sitting. Undoubtedly, blocked designs are not without limitations. Individual differences in memory capabilities, or rhythmic sensitivities can still introduce variability, potentially making it difficult to detect significant trends. Despite the challenges, a blocked–counterbalanced approach may be a practical method for isolating the effects of tempo on rhythmic priming and verbal memory.

In sum, the current rhythmic priming paradigm typically used for grammaticality judgement tasks has provided highly critical information on how grammar processing, rhythm processing and attentional processes may be engaged. As such, the methodological changes proposed to elicit an RPE in verbal short-term memory advocated here – to (i) measure VSTM immediately after rhythmic priming, (ii) use stimuli composed of familiar language and, (iii) maintain a consistent prime tempo over contiguous trials – aim to capture a broader spectrum of rhythmic priming effects across a wide range of conditions and tasks.

Conclusion and Summary

Across three experimental chapters, the findings indicate weak priming effects in verbal memory, and raise questions about the robustness of rhythmic priming effects within the grammar domain. By finding mixed evidence for a rhythmic priming effect, the current thesis highlights the fragility and conditionality of rhythmic priming in verbal memory tasks. The results suggest that the strength and effectiveness of rhythmic priming may depend on specific task designs, stimuli, sampled individuals and more broadly, methodologies. This work moves beyond broad claims of the efficacy of rhythmic priming, offering a more refined understanding of its contextual dependencies and limitations.

This thesis advances our understanding of the interactions between musical rhythm and verbal memory by revealing critical gaps in our understanding of the predictability, fragility, contextual variability, and temporal factors of rhythmic priming in verbal memory. For instance, through rigorous empirical investigation, it challenges assumptions about the blanket generalizability of rhythmic priming effects through inconsistent results across cognitive domains and tasks. This challenge encourages a more cautious and context-specific interpretation of the findings in the current thesis and previously reported ones. Additionally, this thesis refines theoretical underpinnings for the functionality of rhythmic priming in memory by critically evaluating the role of rhythm in verbal memory performance, suggesting that its impact may be more specific than previously thought. Finally, this work provides a foundation for future research to advance typical methodologies used in rhythmic priming research in order to examine the boundary conditions of rhythmic priming across cognitive domains. As such, these advances can deepen our understanding of how musical rhythms interplay with linguistic cognition, particularly verbal memory. This work also invites further exploration of rhythmic priming's practical applications in educational and clinical settings.

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APPENDICES

APPENDIX A

Linguistic stimuli used in grammaticality judgements.

Syntactic structure codes:

SS_CV - third-person singular subject marked with the correct verb agreement

SS_VO - third-person singular subject and a verb with an agreement omission error

PS_CV - plural subject and a verb correctly marked for agreement

PS_VC - plural subject and a verb with an agreement commission error marked for agreement

Block	Grammati-cality	Sentence	Non-word	Structure
1	grammatical	Every day, the horses *gallop* to the top of the	bloz	PS_CV
	ungrammatical	Every day, the horses gallops to the top of the	bloz	PS_VC
	grammatical	Every day, the birds *sing* at the top of their	cret	PS_CV
	ungrammatical	Every day, the birds *sings* at the top of their	cret	PS_VC
	grammatical	Every day, the cow *grazes* to the top of the	hooze	SS_CV
	ungrammatical	Every day, the cow *graze* to the top of the	hooze	SS_VO
2	grammatical	Every day, the pennies *shimmer* in the	flaf	PS_CV
	ungrammatical	Every day, the pennies *shimmers* in the	flaf	PS_VC

	grammatical	Every day, the ballerina *dances* on her pointed	fage	SS_CV
	ungrammatical	Every day, the ballerina *dance* on her pointed	fage	SS_VO
	grammatical	Every day, the rose *wilts* in the	dalt	SS_CV
	ungrammatical	Every day, the rose *wilt* in the	dalt	SS_VO
3	grammatical	Every day, the tooth *aches* when I eat	jile	SS_CV
	ungrammatical	Every day, the tooth *ache* when I eat	jile	SS_VO
	grammatical	Every day, the rivers *overflow* the	fleem	PS_CV
	ungrammatical	Every day, the rivers *overflows* the	fleem	PS_VC
	grammatical	Every day, the lights flicker in the	tade	PS_CV
	ungrammatical	Every day, the lights flickers in the	tade	PS_VC
4	grammatical	Every day, the eagles *swoop* down to hunt their	hooze	PS_CV
	ungrammatical	Every day, the eagles *swoops* down to hunt their	hooze	PS_VC
	grammatical	Every day, the babies *cry* when they are	bloz	PS_CV
	ungrammatical	Every day, the babies *cries* when they are	bloz	PS_VC
	grammatical	Every day, the squirrels *scurry* under the	cret	PS_CV
	ungrammatical	Every day, the squirrels *scurries* under the	cret	PS_VC
5	grammatical	Every day, the dog growls when someone passes his	crov	SS_CV
	ungrammatical	Every day, the dog *growl* when someone passes his	crov	SS_VO
	grammatical	Every day, the tree *grows* taller and	furse	SS_CV
	ungrammatical	Every day, the tree *grow* taller and	furse	SS_VO
	grammatical	Every day, the boys *plan* the next	blut	PS_CV
	ungrammatical	Every day, the boys *plans* the next	blut	PS_VC
6	grammatical	Every day, the seagull *flies* over the	jile	SS_CV

	ungrammatical	Every day, the seagull *fly* over the	jile	SS_VO
	grammatical	Every day, the wax *melts* onto the	fleem	SS_CV
	ungrammatical	Every day, the wax *melt* onto the	fleem	SS_VO
	grammatical	Every day the hikers *climb* closer to the mountain’s	tade	PS_CV
	ungrammatical	Every day, the hikers *climbs* closer to the mountain’s	tade	PS_VC
7	grammatical	Every day, the gardener *digs* in the	blut	SS_CV
	ungrammatical	Every day, the gardener *dig* in the	blut	SS_VO
	grammatical	Every day, the pen *leaks* in my	furse	SS_CV
	ungrammatical	Every day, the pen *leak* in my	furse	SS_VO
	grammatical	Every day, the water *drips* into the	crov	SS_CV
	ungrammatical	Every day, the water *drip* into the	crov	SS_VO
8	grammatical	Every day, the lions roar around the	dalt	PS_CV
	ungrammatical	Every day, the lions roars around the	dalt	PS_VC
	grammatical	Every day, the shirt wrinkles in the	fage	SS_CV
	ungrammatical	Every day, the shirt wrinkle in the	fage	SS_VO
	grammatical	Every day, the trucks rumble down the	flaf	PS_CV
	ungrammatical	Every day, the trucks rumbles down the	flaf	PS_VC

APPENDIX B

Jabberwocky sentences used for verbal memory repetition task

(PRACTICE TRIAL) MO SAMPRENGS COLPS IM ROPOUTS

(PRACTICE TRIAL) PEEB STORDINS RIMPLE JISH MIPTERS

(PRACTICE TRIAL) MO HEDDIES HAYVUL CHAG UFAL

(PRACTICE TRIAL) CHAG ZUK SLURPED OT MALITONE

1. ROO MUTHTIN FANED IM GRASHNIT
2. WOE UPLING JIDED MO NAFF
3. KAY HUSS EMENTED IM KILPH
4. KADE GILPERNS KARNAYED ROO WUPS
5. ROO BEACHLORN SWEENS KAY NEDRIL
6. WOE VOTION PRUSED JISH OH ENSIAN
7. OH MUZE TOMASHED MO FLOOKMUN
8. OH DREG PRILED OT ROO BLANTIS
9. PEEB TAFFER SURFEWED ROO ZYPT
10. KADE ADLOOT CONDLES KAY DOOT
11. ROO GLOB SUBSITTED IM OH GAST
12. KADE SMORKET NOOLED OH GUZDIN
13. KAY SIPPERT SEFT JISH ROO GAUM
14. WOE HORRIDGE JEPLES IM VIGHT
15. PEEB FLOTTERS PEFT CHAG LAWMSES
16. MO JULK MEMBLED ROO BLEARNATES

17. KADE TRANTOE DRIMES JISH OH PILK
18. ROO FLOGIN JANED IM OH KINTO
19. KAY DUCTORM PRICALLS IM THORK
20. OH KALP SMIRRED MO GAPATTER
21. OH JOWLER FRINED JISH OH VULKIT
22. WOE GEPLER SEVITS OT ROO QUAWN
23. PEEB ODWAY FEETANED JISH HING
24. OH PONDLE BOYED IM ROO TROMPERS
25. KAY BAXTOY SPLOPED IM OH WOME
26. ROO NOLK WINTED ROO PRILES
27. KADE CALP GRAMUSHED MO FLOYANS
28. JISH FRANCHINESS VEGS PEEB SAMPING
29. IMM VANCASES RAPOACH ROO TARIST
30. ROO GOOKIE MUDGED IMM OH ROUNCE
31. ROO DOOZES FASHLED OT PEEB CLIMMS
32. MO GOMER SHILLERS JISH OH PURB
33. KAY ROVLE GILKED WOE RETODES
34. PEEB NATHER NEZ KADE LABBAGES
35. OH CHIPKER SPAME WOE DWORDGES
36. WOE TOOGITS FLUX IMM ROO NORP
37. KADE CHAFFS KIDDED IMM PEE BRIJE
38. OT FIME EXIRED PEEB WOE NAXIT

39. ROO DINDING SHAWTHS MO STRIZZ

40. MO THEDDER TRITS JISH KAY SHELP