PREFACE

This dissertation is the result of my own work and includes nothing that is the outcome of work done in collaboration, except where specifically indicated in the text. This dissertation is 19,888 words long (excluding figures, tables, bibliography, and appendices). Thus, it does not exceed the 20,000 words limit laid out by the University of Cambridge Graduate School of Life Sciences Degree Committee.
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ABSTRACT

Developmental dyslexia is associated with a deficit in phonological awareness. This phonological deficit has been linked to auditory processing difficulties with prosodic rhythm and musical beat perception. Accordingly, rhythm-based musical training could be effective in improving dyslexics' literacy skills. In speech, acoustic cues to prosodic rhythm include amplitude rise time, duration, and frequency (pitch). Since children with dyslexia have diminished rhythmic awareness, but may have unimpaired tonal (pitch) awareness, we were interested in whether dyslexic children could use tonal changes to compensate for their poor sensitivity to temporal rhythmic cues. Accordingly, we developed a new beat perception task based on Huss et al. (2011) and Goswami et al. (2012), with the addition of pitch as a cue. In this task, children were asked to make same-different judgments on pairs of rhythmic tone sequences, either with or without the aid of pitch as a co-varying cue. Seventeen dyslexic children and 22 age- and IQ-matched control children took part in the study. These children also received a music- or language-based (Graphogame Rime) intervention as part of a wider ongoing MRC research project. The beat perception task was administered twice, before and after the intervention, to determine whether these interventions would improve children's rhythmic sensitivity. In the baseline condition (no-pitch), we predicted that dyslexic children would perform worse than the controls, as in previous studies. However, with the addition of pitch cues (+pitch), we expected performance of both groups to improve, particularly the dyslexic group. We also expected both groups of children to improve in beat perception after the music intervention, but not after Graphogame Rime. Contrary to prediction, dyslexic children performed marginally worse than controls overall ($p=0.063$). Furthermore, both groups of children performed significantly better on the no-pitch task compared to the +pitch task, suggesting that children may have struggled to integrate information across the dimensions of pitch and rhythm. All children showed equivalent improvement in beat perception after receiving musical intervention. However, for the Graphogame Rime intervention, control children showed greater rhythmic improvement than dyslexic children. As expected, individual differences in beat perception were strongly associated with phonological and reading measures, and sensitivity to duration and rise time were associated with beat perception. These findings support the view that rhythm is related to phonological and literacy skills, and musical interventions may be particularly beneficial for dyslexic children, although care must be taken when incorporating additional perceptual dimensions like pitch into tasks designed for young-aged subjects.
1 INTRODUCTION

1.1 Developmental dyslexia

Developmental dyslexia is a specific learning disability that is characterized by difficulty with reading and spelling, without diminished intelligence, motivation, access to education, or gross neurological or sensory mechanism deficits (Demonet et al., 2004; Lyon et al., 2003; Schulte-Korne & Bruder, 2010). Dyslexia can interfere with academic achievement and even daily life with reading-required tasks. In any given population, five to ten percent of children are affected by dyslexia. It is a disability that remains with individuals throughout their lives (Katusic et al., 2001; McCandiss & Noble, 2003; Shaywitz et al., 1990).

In an effort to better treat dyslexia, there has been extensive research as to its possible causes. It is widely accepted that a deficit in phonological processing is a core cognitive characteristic of dyslexia (Bradley & Bryant, 1983; Stanovich, 1998; Wagner & Torgesen, 1987). The representation, storage, and/or retrieval of speech sounds – together labeled phonological awareness or PA, is critical for literacy; because learning to read requires learning the correspondence between letters (graphemes) and the essential sounds (phonemes) of speech (Bradley & Bryant, 1978; Vellutino, 1979; Snowling, 1981; Brady & Shankweiler, 1991). Across languages, individual differences in phonological awareness (PA) can predict children’s reading acquisition (Ziegler & Goswami, 2005; Snowling, 2000). The temporal sampling theory (Goswami, 2011; Kuppen et al., 2011) suggests accurate perception of amplitude envelope rise time influences the development of PA. Therefore, what underlies the PA impairment in dyslexia is a neural difficulty in processing the auditory speech signal, specifically the perception of amplitude envelope rise time (Goswami et al., 2002; Corriveau et al., 2007; Hamalainen et al., 2012; Pasquini et al., 2007; Richardson et al., 2004; Thomson & Goswami, 2008). The temporal sampling theory was developed to explain why many children with developmental dyslexia had impaired amplitude envelope rise time perception across languages (Goswami et al., 2010b), and why this difficulty may lead to diminished PA, linguistic prosody, rhythmic perception, and even musical skills in the respective languages (Goswami, 2011, 2012; Huss et al., 2011; Goswami et al., 2012; Goswami et al., 2010a, 2002; Corriveau et al., 2007; Hamalainen et al., 2005, 2012; Pasquini et al., 2007; Rocheron et al., 2002).
1.1.1 Amplitude envelope rise time

In speech, the amplitude envelope is a power-weighted summation of amplitude modulations in different frequency bands within the speech stream. The variations in intensity of sound are made by the various vocal organs (articulators) that take part in the production of speech sound. The amplitude envelope can be thought of as a slowly-varying dynamic ‘modulator’ that governs the energy level of the quickly-varying 'fine structure' of speech (i.e. pitch and formant information). The envelope is predominantly comprised of low frequency fluctuations (~3-5 Hz) associated with the production of syllables. The amplitude envelope carries speech rhythm, and its accurate perception is essential for speech intelligibility (Zion Golumbic et al., 2012) and for phonological development (Goswami, 2011). When the fine structural information is stripped from sentences, they remain intelligible (Shannon et al., 1995), suggesting that the envelope itself carries sufficient cues to speech intelligibility.

Auditory amplitude envelope rise time (rise time) is the rate of change of the amplitude envelope at the onset of sound. Rise times in the speech signal are associated with syllable onsets. For example, syllables with plosive initial consonants like /k/ have rapid onsets and sharp rise times, whereas syllables with sonorant initial consonants like /m/ have gentle onsets and more gradual rise times. See Figure 1 for an example of different rise times.

![Figure 1. Schematic depiction of amplitude envelopes with a sharp (left) and gradual (right) rise time. The envelope depicted on the left has a 15 ms linear rise time, 735 ms steady state, and a 50 ms linear fall time. The envelope depicted on the right has a 300 ms linear rise time, 450 ms steady state, and a 50 ms linear fall time. Both standard tones were created on Audacity computer software. The schematic provides an example visual representation of non-speech sounds with a sharp rise time (left), or a gradual rise time (right).](image-url)
The accurate perception of auditory rise time is necessary for the deliberate rhythmic timing of speech by “perceptual centers,” or “P-centers.” The P-center is the moment in time when we experience sound to occur (Goswami, 2012; Hoequist, 1983; Morton et al., 1976). Although the exact acoustic correlates of P-centers are still unclear, P-centers in syllables typically occur along their onset (rise) slopes (Scott, 1993; Gordon, 1987; Vos & Rasch, 1981) rather than at their precise physical onset. Thus, when listeners attend to P-centers to determine speech rhythm, they do not attend to the physical onset of the syllables. For example, if the syllables “ba” and “la” are said in an alternating fashion with the syllable-onset times spaced isochronously, they will be heard by the adult brain as non-rhythmic in timing. Only when the P-centers are aligned isochronously is the sequence perceived as rhythmically regular. When an individual deliberately speaks to a rhythm, the speaker times the P-centers of his/her vowels in each syllable, rather than timing the onset of the syllable itself. For auditory stimuli to be perceived as being regularly timed, the P-centers of the stimuli must be evenly spaced. If the rise time becomes more rapid the P-center is shifted towards the onset (Figure 1, left), whereas if the rise time becomes more gradual the P-center appears later (Figure 1, right; Scott, 1998). Use of P-centers is seen across languages, including those with different rhythm classes like Japanese (‘mora-timed’), Spanish (‘syllable-timed’), and English (‘stress-timed’) (Hoequist, 1983; Goswami et al., 2010b). Even infants perceive the timing of syllables by reference to the syllables’ P-centers (Fowler et al., 1986), suggesting that early sensitivity to rise times (and therefore syllable P-centers) is important for accurate prosodic rhythm perception in infancy. Prosodic rhythm perception, in turn, is crucial for early language acquisition.

1.1.2 Prosody, and language and literacy development

Prosody involves every property of grouping, rhythm, and prominence, from syllabic sub-parts to the organization of words within phrases. Prosody enables the segmentation of the speech stream into phrases, words, and syllables, informs syntactic structure, and emphasizes salient information to facilitate understanding (Bolinger, 1978; Cutler et al., 1997; Speer et al., 1993; Warren 1996). In English, prosodic stress patterns of alternating strong and weak syllables are used as a first pass to locate the potential onsets of words in speech (Metrical Segmentation Strategy), because strong syllables generally mark the beginning of content words (Cutler & Norris, 1988; Cutler & Butterfield, 1992). Approximately 85% of English content words begin with a strong syllable (Cutler & Carter, 1987). Prosodic cues are among the first features of the speech stream utilized by infants to aid in language acquisition (Jusczyk et al., 1993). For example, by 9 months, infants favor
words with the predominant stress pattern, an initial strong syllable followed by one or more weak syllables, of their native language (Jusczyk et al., 1993). As infants develop, they become perceptually attuned to analyze and utilize prosodic patterns in the speech stream, such as rhythm, syllabic and word stress, and pauses at phonological boundaries (Wanner & Gleitman, 1982). This allows infants to segment the speech stream into comprehensible units, and enables further analysis by highlighting important syntactic and semantic features necessary for learning language (Morgan & Demuth, 1996).

Prosody also plays a significant role in the development of literacy skills (Wood & Terrell, 1998; Goswami et al., 2002; Richardson et al., 2004; Whalley & Hansen, 2006; Goswami et al., 2010a). For example, Whalley & Hansen (2006) found that for children aged 8-10 years old, phrase-level prosody (measured using a 'Dee-Dee' task) predicted unique variance in decoding and reading comprehension, and word-level prosody predicted unique variance in children’s word reading. To explain their findings, Whalley & Hansen (2006) suggested that sensitivity to prosody may have enabled the children to arrange, segment, and chunk spoken language into syntactically comprehensible units, which reduced memory load and enhanced comprehension. Goswami et al. (2002) posited that sensitivity to prosody may also contribute to reading skills by supporting the development of phonological awareness via the accurate perception of rise time.

The essential properties of prosody: grouping, rhythm, and prominence, translate to pauses and changes in fundamental frequency, duration, and amplitude at the auditory signal level (Pierrehumbert, 2003). Amplitude and durational cues contribute most to prosodic prominence at this level; specifically rise time, as it is the key cue to stress accent or syllable prominence (Choi et al., 2005; Kochanski et al., 2005; Greenberg, 1999; Arvaniti, 2009; Marie et al., 2011). Thus, slow amplitude modulation of the speech waveform can be thought of as being representative of speech rhythm and prosody. Furthermore, impaired perception of rise time should reduce sensitivity to speech prosody and rhythm, and reduced sensitivity to these cues should also affect PA development and ultimately literacy skills. Indeed, robust relationships have been found between auditory rhythmic cues, and PA and literacy (Huss et al., 2011; Goswami et al., 2012; Corriveau & Goswami, 2009; Corriveau et al., 2007). For example, individual differences in rise time perception are correlated to individual differences in PA-related tasks like rhyme awareness and phoneme segmentation (Goswami et al., 2012; Huss et al., 2011; Richardson et al., 2004; Pasquini et al., 2007; Suranyi et al., 2009; Muneaux et al., 2004). These differences also correlate to literacy skills. For example, Goswami et al. (2002) varied the rise times of ‘beats’ in an auditory stream to create percepts
of either a single sound with continuous loudness modulation (slow rise times) or distinct alternating beats (fast rise times). Goswami et al. (2002) found that dyslexic children (aged 7-11 years) showed significantly poorer rise time sensitivity compared with controls, as evidenced by flatter psychometric functions. By contrast, children with superior literacy skills showed significantly superior rise time detection. These results led Goswami et al. (2002) to argue that sensitivity to the rhythmic properties of speech could contribute to word-level reading skills by aiding the development of phonological representations underlying PA.

In children with developmental dyslexia, difficulties with rhythmic timing have led some to characterize the brains of dyslexic children as “in tune, but out of time” (Goswami et al., 2012; Huss et al., 2011; Corriveau & Goswami, 2009; Thomson & Goswami, 2008). This phrase contrasts to that used for amusic brains as being “out of tune, but in time” (Hyde & Peretz, 2004). When considering dyslexia, the cognitive model for amusia (Peretz & Coltheart, 2003) provides an insightful theoretical framework (Goswami, 2012). In the amusia model, acoustic processing follows two ‘streams:’ an organization of pitch stream (impaired in amusia), and an organization of time stream (preserved in amusia). The temporal organization stream includes rhythmic analysis, metrical beat analysis, and rhythmic entrainment skills. All of these rhythmic timing skills are fundamental attributes of prosody via rise time, and are intimately linked to phonological development (Huss et al., 2011; Goswami et al., 2012; Corriveau & Goswami, 2009; Corriveau et al., 2007). Thus, there are skills that are preserved in amusia, but impaired in children with language and literacy problems (Waber et al., 2000; Wolff, 2002; Wolff et al., 1990). For example, children with developmental dyslexia have impaired rhythmic entrainment, tapping to a beat, and tempo perception (Corriveau & Goswami, 2009; Thomson & Goswami, 2008). These impairments in auditory entrainment are strongly related to perceptual deficits in the auditory processing of rise time. They are not related to deficits in the processing of pitch (Thomson & Goswami, 2008), despite there being some children with developmental dyslexia who are also impaired in simple pitch perception (Ziegler et al., 2012; Baldeweg et al., 1999).

Impaired pitch processing, or frequency discrimination, has been occasionally linked to dyslexia (Ahissar et al., 2000; Baldeweg et al., 1999; Santos et al., 2007; Ziegler et al., 2012; Goswami et al., 2012; Thomson & Goswami, 2008; Kuppen et al., 2013), but the reason for this frequency discrimination (FD) deficit is unclear. In a meta-analysis, Hamalainen et al. (2012) found that impaired FD was associated with dyslexia in only 57% of the dyslexia studies they reviewed. Also, there is compelling evidence that suggests a deficit in FD does not affect literacy skills. Halliday & Bishop (2005) found that children
with hearing loss and poor FD thresholds could still have unimpaired reading skills. Thus, although some dyslexics may experience problems with FD, impaired FD may not cause their literacy development and PA deficit (Goswami et al., 2012; Thomson & Goswami, 2008).

Some propose that the link found between dyslexia and FD is actually a link between low IQ and FD (Kuppen et al., 2013; Halliday & Bishop, 2006). In a longitudinal study of 103 children with low or typical IQ and good or poor word reading, Kuppen et al. (2013) found that sensitivity to pitch is related to IQ, whereas sensitivity to auditory rise time and duration are not related to IQ, but are related to literacy development and PA. This link between pitch and IQ has been previously reported in adults (Banai & Ahissar, 2004; Halliday & Bishop, 2006; Hulslander et al., 2004) and in children, including in a study with 1,469 child participants (Moore et al., 2010). For studies suggesting that FD deficits underlie the PA and reading impairment in dyslexia, participant sample sizes were either small (e.g. 17 dyslexic participants and under in Ziegler et al., 2012; 10 in Santos et al., 2007; 10 in Baldeweg et al., 1999), and/or IQ was not properly controlled for (e.g. Ahissar et al., 2000; Ziegler et al., 2012; Baldeweg et al., 1999). Additionally, studies that did measure IQ also found a correlation with FD (Ahissar et al., 2000; Kuppen et al., 2013). Taken together, we propose that rhythmic processing difficulties, not FD difficulties, are more likely to affect PA and literacy development in dyslexia. Thus, “in tune, but out of time” may provide an accurate characterization of the brains of dyslexic children with average and above average IQs (Goswami et al., 2012; Huss et al., 2011; Corriveau & Goswami, 2009; Thomson & Goswami, 2008).

Given the strong relationship between impaired auditory rise time perception, impaired rhythmic timing, and dyslexia (Huss et al., 2011; Goswami et al., 2012), the exaggerated rhythmic cues found in music might provide a promising source of material for the treatment and study of developmental dyslexia.

1.2 Musical rhythm and developmental dyslexia

1.2.1 The rhythmic analogy between music and language

Rhythm in music is similar to prosody in language. In music, the temporal and spectral place of notes, their rhythm and pitch, act as ‘musical syntax’ (Thaut, 2005). In language, prosody provides ‘phonological grammar’ through rhythm and pitch (Port, 2003). Musical rhythm involves the free or systematic grouping of tones. If systematic, at least one component within the durations and patterns of the musical texture will produce a stable pulse, or beat. In Western music, each time value is calculated as a fraction or multiple
of a beat, with recurrent accents forming a periodicity to create measures and meter (Arom, 2000; Lerdahl & Jackendoff, 1983; White, 1976). Musical units are organized in a hierarchical structure, such that the combination of smaller temporal units (musical notes) create larger units, with the organization of notes forming musical phrases, themes, and movements by grouping. Similarly in language, linguists organize prosodic units into a hierarchical structure. For example, syllables form feet (strong and weak syllables), feet form words, and words form phrases (Nespor & Vogel, 1986; Pierrehumbert, 2003). For rhythm in language, there is the grouping of words and clauses, a patterned pulse of syllables, and the alternation of stressed and unstressed syllables creating a linguistic beat (Patel, 2003a, 2003b; Kohler, 2009). While the energy fluctuations in the speech signal are not periodic, as they are in music, they are rhythmically-patterned (Chandrasekaran et al., 2009; Echols, 1996; Cutler, 1996). In speech, the alternation of strong and weak beats is necessary to avoid stress clashes, and is associated with grouping and the relative prominence in prosody (Arvaniti, 2009). This alternation of strong and weak beats found in speech and music is central to the sequential organization of sounds in both domains. So individual differences in phonological processing in language should be related to individual differences in non-linguistic musical tasks based on the patterns of beat distribution. Furthermore, developmental inefficiencies in basic auditory processing like rise time, which underlie phonological processing, may affect both language and musical development.

Rise time plays multiple important roles in music. Musical notes have different rise times or 'attack times,' depending on how they are produced. For example, the note G4 produced by a slow on-string bowing style on a violin will have a longer rise time than if it is produced by a rapid, off-string bowing style. An even shorter rise time will be produced if G4 is played by blowing sharply on a trumpet. Notes with shorter rise times are perceived as having a stronger beat than notes with longer rise times. When musicians play a note together at the same time they must align the rise times of their respective instrumental sounds (Patel, 2003b; Goswami, 2012). In children, accurate auditory rise time perception can be used as a longitudinal predictor for accurate musical beat perception (Goswami et al., 2012), as well as a significant concurrent predictor for perception of rhythmic structure in language (strong and weak syllable stress; Goswami et al., 2010a). Therefore, impaired rise time perception in dyslexics not only affects PA and prosody, but also affects accurate musical rhythmic beat perception (Huss et al, 2011; Goswami et al., 2012). Because of this association, interventions based on musical beat perception may prove helpful for improving phonological processing in children, and thus reading development for those with
developmental dyslexia.

1.2.2 Beat perception and dyslexia

Musical beat is the pulse, the basic rhythmic unit, which underlies a piece. Musical rhythm is characterized by a repeated sequence of stressed and unstressed beats, and beat perception is the measure of sensitivity to that rhythmic temporal structure. Despite the potential for musical beat training for developmental dyslexics, relatively little research has been done to study the relationship between musical rhythm and dyslexia. Of the few earlier studies investigating musical rhythm in dyslexia (Overy et al., 2003; Forgeard et al., 2008; Anvari et al., 2002; Dege & Schwarzer, 2011), none have shown significant correlations between musical rhythm and either phonology, or reading and spelling. However, in a study conducted with 78 typically-developing English speaking 8-year-old children, after controlling for vocabulary development, significant correlations were found between musical rhythm and reading and spelling (Douglas & Willatts, 1994). In the same study, no such significant link was found between musical pitch measures and reading and spelling. This study not only provided preliminary support for the link between musical rhythm and literacy development, but also possible support for the particular importance of rhythm over pitch in literacy development. It was not until Huss et al. (2011), that strong support for a link between musical rhythmic beat perception and reading was reported with individuals with and without developmental dyslexia.

In their beat perception study, Huss et al. (2011) reported that the accurate perception of beat structure in music was strongly associated with reading and phonology in their sample of 64 eight to ten year-old children with and without dyslexia. Note that in Huss et al. (2011), they described musical beat perception as the perception of musical meter. Here, it will be referred to as simply “beat perception.” In their experimental design, the musical beat task comprised of short, 6 – 15 note beat sequences played on the note of G4 (392Hz), in either 4/4 or 3/4 time signatures. All sequences were based on an isochronous beat structure of 2 Hz (120 bpm, 500 ms interval); and all sequences were created using Sibelius Version 4 software from a sound set produced by Native Instruments (Kontakt Gold). Huss et al. chose Sibelius to create notes with real instrumental timbre and slow natural decay times. The control beat sequence (standard) was constructed by playing all notes with identical rise time, pitch, and intensity, with one accented note occurring at either the first, second, third, or fourth beat in the sequence (for a 4/4 time signature). This note was accented using a standard Sibelius accent, which increased both the intensity and duration of the note. Huss et al. used the Sibelius accent with the intention of increasing the intensity of the accented note, while
maintaining a true representation of music production. Each sequence varied slightly from one another in rhythmic pattern. Within each sequence, the rhythmic pattern repeated itself in every measure. The children heard the sequences in pairs. In half of the trials (labeled “different” trials), the accented note in the second sequence was briefly elongated (e.g. AAAA – AA,AA). In the other half of the trials (labeled “same” trials), the temporal pattern of the sequences remained the same (e.g. AAAA – AAAA). The beat sequences were paired such that the rhythmic patterns were identical, with the exception of a slightly elongated note in the different trials. In the different trial, the second sequence differed from the standard sequence by elongating the accented note by either 100 ms or 166 ms using the Sibelius fermata. The children listened to a randomized presentation of the paired sequences and had to decide whether in each case they heard a same-paired sequence (AAAA – AAAA, standard then standard), or different-paired sequence (AAAA – AA,AA, standard then elongated). The number of paired sequences that the children chose correctly determined their beat perception accuracy. An example of the Sibelius-generated same-paired sequence and different-paired sequence is shown below in Figure 2.
11

a. Same-paired sequence (standard + standard)

b. Different-paired sequence (standard + different)

Figure 2. *Sibelius-generated musical notation of a same (a) and different (b)-paired sequence of the 36 pairs used in the Huss et al. (2011) musical beat perception task.* Both sequences (a) and (b) are in 4/4 time at 120bpm on G4 (392Hz). The second note in each measure of (a) and (b) is accented using standardized Sibelius accents with the second note in (b) lengthened by a 166ms fermata. The accent created by Sibelius increases the volume and strike of the note to *fortissimo* (ff, ‘very loud’) from the standard *mezzo piano* (mp, ‘medium soft’). The instrument used on Sibelius to play the sequences was a standard triangle bell.
For all participants, Huss et al. also conducted standardized tests of reading, spelling, receptive language, auditory sensitivity (to auditory rise time, intensity, frequency, and duration), PA, and phonological short-term memory prior to the beat task.

The children’s performance in the musical task along with their age and IQ explained over 60% of the variance in concurrent single word reading. Beat perception predicted 42% of unique variance in reading, which was greater than with traditional PA measures like rhyme awareness, which predicted 33% of unique variance. Given the strength of the association between beat perception and reading development, and the correlation between reading development and PA development, Huss et al. (2011) suggested that accurate beat perception could likely underlie both musical and phonological/prosodic processing. In addition, accuracy in beat perception predicted 24% of unique variance in auditory processing of rise time, and 38% of unique variance in overall auditory measures (including duration and intensity). Current literature considers prosodic awareness to be more important for the development of reading comprehension than for single word decoding (Whalley & Hansen, 2006; Miller & Schwanenflugel, 2008). Thus, individual differences in sensitivity to non-linguistic patterns of beat distribution in the musical task should predict development in reading comprehension as well as single word reading. Furthermore, Huss et al. (2011) reported that children with dyslexia were significantly poorer at perceiving changes in beat distribution compared to typically-developing, chronologically age matched (10-year-old) children, but performed at the same level as typically-developing, younger (8-year-old) reading-level matched children. Their data support the theoretical view that beat perception is a key parameter in linking the processing of music to the processing of language in children. The data also suggest that a shared underlying sensory/neural mechanism may be the auditory processing of rise time.

In a follow-up study, Goswami et al. (2012) used the same task from Huss et al. (2011) with a modified description, calling it a measure of “sensitivity to patterns of beat distribution.” They administered the beat task a year after the Huss et al. (2011) study to 88 children with and without dyslexia, using the same participants from Huss et al. (2011). Goswami et al. also used new auditory processing measures to provide a more comprehensive picture of the auditory correlates of the beat task. Furthermore, they measured reading comprehension and non-word reading in addition to single word reading. Goswami et al. found that children with dyslexia performed more poorly in the musical beat task than younger children reading at the same level. This result indicated a significant perceptual deficit for musical beat patterns in children with dyslexia. These dyslexics also had
significantly poorer perception of sound rise time than younger children. Longitudinal analyses showed that the musical beat task was a significant longitudinal predictor of development in reading; accounting for over half of the variance in reading comprehension along with a linguistic measure of phonological awareness. The different longitudinal versus concurrent associations between musical beat perception and auditory processing suggest that individual differences in rhythm perception have an important shared neural basis for individual differences in linguistic and musical processing in children.

In Goswami et al. (2012), exploration of concurrent auditory predictors identified sensitivity to rise time and rising and falling pitch (an additional psychoacoustic measure) as uniquely related to performance in the musical beat perception task. Sensitivity to rising pitch was not related to reading development, whereas sensitivity to rise time was (single word reading, nonword reading, and reading comprehension). Sensitivity to sound duration was not a significant concurrent predictor of individual differences in musical beat perception, even though musical beat structure was disrupted by increasing the duration of the accented notes (consistent with Huss et al., 2011). The predictive strength of the beat perception measure may have arisen in part because certain aspects of auditory processing are related to both musical perception and phonological awareness (Anvari et al., 2002).

Although these results provide promising evidence in support of a meaningful association between musical beat perception and development of PA and literacy skills, there were some significant weaknesses in Huss et al.’s experimental design. First, Huss et al. originally intended to design their experiment to test accurate metric perception, despite the fact that meter did not change in the task (i.e. from 3/4 to 4/4 time signatures). What varied in the task was the duration of the accented notes; specifically, the temporal patterns between accented and unaccented notes, which altered the patterns of beat distribution. Therefore, Huss et al.’s ‘metrical’ task is better described as a measure of sensitivity to musical beat structure. Second, by using Sibelius, a software that uses real timbre and performance of musical instruments, Huss et al. inadvertently altered auditory rise time, intensity, and duration with every musical notation. That is, auditory rise time, intensity, and duration simultaneously changed when they accented and elongated notes (via accent and fermata respectively). Third, the changes in duration created by the Sibelius fermata on the accented note also affected the rhythmic temporal structure of all notes following the fermata within each measure. Because the duration of all notes following the fermata were altered, there were additional basic auditory cues available to the children to perform the task. Fourth, it was uncertain whether the auditory measures of pitch and duration used by Huss et al. were
those most likely to be associated with the perceptual grouping of musical beats. For example, Huss et al.’s psychoacoustic duration task measured sensitivity to relatively long durations (tone stimuli that were 400-600 ms long), while the durational changes in the musical task were relatively short (note durations were increased by either 100 ms or 166 ms). Therefore Huss et al. (2011) and Goswami et al. (2012) could not attribute solely duration, rise time, or intensity to any of the beat perception effects they observed. They did observe an association between rise time and beat perception, but the nature and extent of that relationship was not measured.

To better understand the relationship between rise time, duration, intensity, beat perception, PA/prosody, and literacy, the beat perception stimuli will have to be created with software in which basic auditory measures, like rise time, can be separately controlled, allowing for the independent alteration of each acoustic feature. To determine whether perceptual sensitivity to sound rise time contributes uniquely to both musical beat perception and written language development, changes in rise time should not co-occur with changes in duration in the beat task. Also, if a change in duration is made in one note, it should not alter the duration of neighboring notes. To simplify the task, more metrically complex sequences can be eliminated, as the beat perception effect was observed most strongly in the simplest rhythmic pattern, and in a 4/4 time signature. The rhythmic pattern was four-quarter notes per measure. The greatest perceptual differences between dyslexics and controls were observed in shorter sequences, thus the length of each presented sequence can be shortened to one measure (4 beats). In addition to these modifications, we can incorporate pitch as an additional cue to accompany the durational change on the different note. Adding pitch would inform us as to whether dyslexic participants (excluding those with low IQ) are indeed “in tune, but out of time.” That is, if pitch perception is unimpaired or even heightened in dyslexics, the dyslexic children performing the beat task could use the tonal changes to compensate for their poor sensitivity to temporal rhythmic cues.

With these modifications, we will be able to more rigorously assess Huss et al.’s hypothesis that difficulties in processing rise time impair both musical processing and reading development in affected children. Furthermore, such a study would contribute to the theoretical research concerning possible shared neural bases for processing music and language (Patel, 2008; Shahin et al., 2010; Besson et al., 2011; Strait & Kraus, 2011; Huss et al., 2011). The exploration of basic auditory sensory predictors of performance in musical beat perception is promising, because preliminary results (Huss et al., 2011; Goswami et al., 2012) suggest that accurate beat perception should be important for phonological
development. For example, beat perception may aid in the accurate segmentation of syllables and words from the speech stream (Echols, 1996). The developmental links between rhythmic processing and phonology made by the rise time hypothesis (Goswami, 2011) would also predict links between the musical beat distribution task and sub-word phonological awareness, as the detection of the timing of stress beats in language also supports the accurate perception of syllable nuclei and the onset-rime division. Hence individual differences in the sensitivity to non-linguistic patterns of beat distribution should also be a significant predictor of development in non-word reading, which is a relatively pure measure of the phonological recoding of sound.

The current data on auditory rise time discrimination and musical beat perception (Huss et al., 2011; Goswami et al., 2012) suggest that children with dyslexia would benefit from musical rhythmic training, particularly if the links between prosodic patterning in language and beat structure in music were made explicit. Also, if musical beat tasks are able to predict longitudinal variance in reading development, that would further support the theoretical view that musical interventions should be important for developing reading skills in children with dyslexia (Overy, 2003; Forgeard et al., 2008; Besson et al., 2011; Huss et al., 2011) as well as typically-developing children (Douglas & Willatts, 1994; Anvari et al., 2002; Dege & Schwarzer, 2011). Since the Huss et al. (2011) beat perception task is a non-linguistic musical task, performance on the beat task should theoretically improve with musical intervention. In addition to conducting a modified version of the Huss et al. (2011) beat task, comparing the task before and after a musical intervention would provide insight into the efficacy of such interventions on rhythmic timing improvement. If rhythmic timing improves, then so too should the perception of musical P-centers. To our knowledge, no study like this has been done, however research on musical interventions as a method for developing reading skills in children has been conducted (Bhide et al., 2013; Overy, 2003; Forgeard et al., 2008; Besson et al., 2011; Huss et al., 2011). This research suggests rhythmic musical interventions with poor readers may improve rhythmic entrainment and beat perception, and consequently improve reading and phonological skills.

1.2.3 Rhythmic musical intervention for dyslexics

Parallels between language and music have long been drawn (Peretz & Zatorre, 1999; Patel, 2008; Besson & Schon, 2001; Patel & Daniele, 2003; Koelsch et al., 2004) yet relatively little has been done to study how music may serve to assist language in the study of developmental dyslexia. We propose that accurate rhythmic perception is important in language development. Since rhythmic structure is more overt in music than in language,
there may be potential for musical interventions to benefit individuals with developmental
dyslexia (Bhide et al., 2013; Goswami et al., 2012; Huss et al., 2011; Forgeard et al., 2008;
Overy, 2000, 2003). Most interventions for dyslexia involve training in spelling-sound
correspondence. For example, Graphogame Rime, and its precursor, Graphogame, is a
software intervention developed for the transparent Finnish language. The Finnish
Graphogame has been shown to enable significant gains in reading, with large effect sizes
(Saine et al., 2010). Graphogame Rime is an English version of this game based on rhyme
analogy theory (Goswami, 1986). In a small-scale intervention study, Graphogame Rime led
to larger effect sizes for English poor readers aged 6–7 years compared to Graphogame
Phoneme, another English version of the game, which taught phoneme-grapheme
correspondences via “synthetic phonics” (Kyle et al., 2013). Kyle et al. also demonstrated
that Graphogame Rime led to significant improvements (with large effect sizes) in reading,
spelling, non-word reading, rhyme, and phoneme awareness in comparison to an untreated
control group.

In an exploratory study on poor readers by Bhide et al. (2013), the effects of a musical
intervention were compared to those of Graphogame Rime, a spelling-sound intervention of
known efficacy based on rhyme training and phoneme-grapheme learning. Bhide et al.
investigated whether the musical intervention would produce comparable gains to
Graphogame Rime for children who were falling behind in reading development.
Specifically, Bhide et al. explored whether training children’s rhythmic abilities via musical
games and linking musical rhythms to rhythm in language would impact rise time sensitivity,
reading, and phonology as much as Graphogame Rime. The musical intervention
incorporated syllable stress and rise time discrimination in addition to rhythm. Of the 19 six
to seven-year-old participants in the study (all of whom were referred by their schools for
failure to progress in reading at the expected level for their peer group), 10 participated in the
musical intervention, and 9 in Graphogame Rime.

The data from Bhide et al. (2013) suggested that musical training was as effective as
Graphogame Rime training in providing benefits for literacy. This is theoretically interesting,
as sub-lexical phonological awareness and letter-sound correspondences were not being
taught in the musical intervention. These effects suggest that giving children rhythmic
training, and linking non-linguistic rhythms to rhythms in language, have a positive effect on
literacy acquisition and phonological skills. This small-scale intervention study suggests that
musical intervention based on rhythm and on linking metrical structure in music and
language can have benefits for the development of literacy and phonological awareness.
Although the children used in Bhide et al. (2013) had relatively low language skills and relatively low cognitive ability, they were not identified as having a developmental language learning disability like developmental dyslexia. It would be interesting to test whether rhythm-based musical training is at least as effective in improving PA/prosodic skills as direct grapheme-to-phoneme training with children who are developmentally dyslexic. As discussed previously, it would be insightful to test whether a musical intervention would improve accurate musical beat perception. Given the importance of rhythm in speech, one would expect improved rhythmic beat perception to play an important role in PA and literacy development.

1.3 Specific aims of this study

The current study sought to address four primary questions:

(1) Given that children with dyslexia have diminished rhythmic awareness, but may have unimpaired tonal awareness, could dyslexic children use tonal changes to compensate for their poor sensitivity to temporal rhythmic cues?

(2) After given a rhythmic musical intervention akin to that in Bhide et al. (2013), would accuracy in beat perception improve for dyslexic and age-matched control children? Furthermore, would a Graphograme Rime intervention provide equivalent improvements in beat task performance?

(3) In a musical beat perception task, modified from Huss et al. (2011), would individual differences in beat perception still relate to phonological and reading measures for dyslexic and typically-developed, chronologically-aged matched children?

(4) Would improvements in the modified musical beat task be predicted by rise time sensitivity, rather than by other auditory measures in dyslexic and typically-developed, age-matched children?

To address these questions, we developed a new beat perception task based on Huss et al. (2011), with the addition of pitch as a co-varying cue. We included all modifications suggested for Huss et al. (2011) in our new version (modifications discussed in section 1.2.2). The beat task was created using Audacity software to control for duration, rise time, intensity, and pitch in ways that Sibelius could not. The two most distinctive modifications to the Huss et al. task were the addition of pitch cues, and the isolation of duration as the sole rhythm variable. Furthermore, we sought to alter the temporal beat distribution without altering the duration of succeeding beats. Specific details of the modified beat task are...
outlined in the Methods (section 2.4). Seventeen dyslexic children and 22 age- and IQ-matched control children took part in the new study. These children also received a music- or Graphogame Rime-based intervention, as part of an on-going longitudinal study being conducted by the Center for Neuroscience in Education. The music intervention was a modified version of that used in Bhide et al (2013); it was developed on the basis of Goswami’s temporal sampling theory (Goswami, 2011), and aimed to train all the components of rhythm perception found to be impaired in developmental dyslexia. Standardized reading, spelling, and phonological awareness background measures were also administered. Details of the standardized background measures and interventions can be found in the Methods (sections 2.3 and 2.5).

The beat perception task was administered twice, before and after the intervention, to determine whether these interventions would improve the children's rhythmic sensitivity. Two versions of the beat perception task were presented, in which pitch was either present or absent as a co-varying cue to the main rhythm pattern (cued by duration changes).

We predicted that the dyslexic children would perform worse than the controls in the no-pitch condition. In the +pitch condition, we expected performance for both groups to improve, particularly the dyslexic group. For all children, we anticipated comparable improvements in beat task performance after their music intervention, but not after Graphogame Rime intervention. Finally, we expected performance on the beat task to predict phonological awareness and literacy skills for all subjects via sensitivity to rise time.
2 METHODS

2.1 Participants

A total of 39 children aged between 6 and 9 years old participated in this study. Of these, 17 children (11 males: mean age 91.10 (9.19 SD) months, range 29.00) either had a statement of developmental dyslexia from their local education authority, or showed severe literacy and phonological deficits according to our own test battery. A further 22 age-matched and IQ-matched control children (14 males: mean age 88.36 (9.27 SD) months, range 29.00) were recruited from the same schools as the dyslexic participants. These children were taking part in the first year of a wider longitudinal study on developmental dyslexia being conducted by the University of Cambridge Center for Neuroscience in Education. As part of this larger study, children were receiving either a music-based or language-based (“Graphogame Rime”) intervention. These intervention programs are described further in section 2.5.

The children who participated in the current study had no diagnosed additional learning difficulties such as attention deficit hyperactivity disorder, autistic spectrum disorder, dyspraxia, or speech and language impairments. Also, all participants had a nonverbal IQ within 85 to 135. An individual with an IQ below 85 may have a greater chance of impaired pitch perception (Kuppen et al., 2013). To ensure that children had normal hearing, a hearing screen with an audiometer was administered, which involves sounds being played at a range of frequencies (250, 500, 1000, 2000, 4000, 8000 Hz) in the left and right ear. All children were sensitive to sounds within the 20dB HL range according to this hearing test. The Cambridge Psychology Research Ethics Committee approved the study and all participants provided written, informed consent from their legal guardians.

2.2 Tasks

A range of standardized background measures were administered to assess the participant's general ability, reading, spelling, phonological awareness, and psychoacoustic sensitivity. These background tests were administered both before and after the intervention. Natalie Matthews, Natasha Mead, and Angela Wilson (University of Cambridge) conducted all standardized background measures, which included the standardized ability, literacy, phonological awareness, and psychoacoustic tests.

A new beat perception task was designed and administered to test the main hypotheses in this study. These hypotheses were that (1) dyslexics' poor rhythm sensitivity
can be compensated for by the addition of co-varying pitch cues, (2) musical training should improve rhythmic ability for dyslexic children, (3) beat perception should predict phonological awareness and literacy skills, and (4) sensitivity to rise time should predict accurate beat perception.

2.3 Standardized Background Measures

2.3.1 General Ability Measures

General ability was assessed using the Wechsler Intelligence Scale for Children (WISC-III; Wechsler, 1992), the British Picture Vocabulary Scales (BPVS; Dunn et al., 1997), and the Working Memory Test Battery for Children (WMTB-C; Pickering & Gathercole, 2001).

2.3.1.1 Full Scale IQ (FSIQ)

All participants completed four subscales of the Wechsler Intelligence Scale for Children (WISC-III; Wechsler, 1992): Block Design, Picture Arrangement, Similarities, and Vocabulary. Full scale IQ scores (mean of 100 and standard deviation of 15) were computed from these subtest scores following the procedure adopted by Sattler (1982).

2.3.1.2 Receptive Vocabulary (BPVS)

The British Picture Vocabulary Scales (BPVS; Dunn et al., 1997) was administered as a measure of receptive vocabulary. Participants were asked to identify a picture that illustrated a word that the experimenter read aloud. There was one of four pictures the child had to choose from; only one picture illustrated the read word accurately. As the task progressed, the words increased in difficulty. The raw score was converted to a standard score with a mean of 100 and a standard deviation of 15.

2.3.1.3 Working Memory (WMTB-C)

The Working Memory Test Battery for Children (WMTB-C) was used to provide an accurate assessment of the participant’s working memory (Pickering & Gathercole, 2001). The children heard a list of short, monosyllabic words which they were required to repeat back in identical order. The trials were administered in blocks of six with the sequence of words increasing in length by one word for each block. If a child scored four correct trials in the current block, he/she moved to the next block. If a child failed on any three trials in a block, the task was terminated. The number of correct trials (raw score) was converted to a standard score with a mean of 100 and a standard deviation of 15.
2.3.2 Literacy Measures

Literacy skills were assessed using the British Ability Scales (BAS3; Elliott & Smith, 2011) and the Test of Word Reading Efficiency, Form A (TOWRE; Torgesen et al., 1999).

2.3.2.1 BAS Reading

Reading ability was assessed using the British Ability Scales (BAS3; Elliott & Smith, 2011). The children read aloud lists of words provided by BAS3. The words increased in difficulty as the test progressed. The reading score was based on the number of words pronounced correctly and the level of difficulty at which the participant began the test. This was converted to a standard score with a mean of 100 and standard deviation of 15.

2.3.2.2 BAS Spelling

Spelling was assessed using the spelling test from the British Ability Scale III (BAS3, Elliot & Smith, 2011). The children spelled words provided by the test that the experimenter read aloud. The words increased in difficulty as the test progressed. The ability score was based on the number of words spelled correctly and the level of difficulty at which the participant began the test. This was converted to a standard score with a mean of 100 and standard deviation of 15.

2.3.2.3 TOWRE word and non-word

Timed reading was assessed using two subsets of the Test of Word Reading Efficiency, Form A: Sight Word Efficiency and Phonemic Decoding Efficiency (TOWRE; Torgesen et al., 1999).

a. TOWRE word

The children had 45 seconds to read as many words aloud as they could. The words increased in difficulty, although children were instructed only to read words they knew they could pronounce. The raw score was the number of items read correctly, and this was converted to a standard score with a mean of 100 and a standard deviation of 15.

b. TOWRE non-word

The children had 45 seconds to read as many non-words aloud as they could. The non-words were word-like (e.g. um, durd, luddy), and increased in difficulty over time. The children were instructed only to read words they knew they could pronounce. The raw score was the number of items read correctly, and it was converted to a standard score with a mean of 100 and a standard deviation of 15.
2.3.3 Phonological Awareness Measures

2.3.3.1 Rhyme Awareness (PhAB Rhyme Test)

Rhyme awareness was assessed using the Phonological Assessment Battery (PhAB) rhyme oddity task (Frederickson et al., 1997). The children listened to the experimenter read aloud sets of three words, two of which rhymed. Each set of the 21 trials was presented in three fixed random orders, including the 3 practice trials. The children were instructed to repeat aloud the two words that rhymed (e.g. cat and mat in the sequence cat, lag, mat). The children were scored out of 21 with 1 point given for each correct answer. The raw score was converted to a standard score with a mean of 100 and a standard deviation of 15.

2.3.4 Psychoacoustic Measures

These psychoacoustic tasks were designed to measure children's sensitivity to acoustic cues to speech rhythm and prosody, such as amplitude rise time, duration, and intensity. The auditory tasks utilized an AXB or 2IFC format in a “Dinosaur” software threshold estimation program. A visualization of the “Dinosaur” game is shown below in Figure 3.
This program was created by Dorothy Bishop (University of Oxford, 2001) and amended by Martina Huss (University of Cambridge). The reprogrammed version, used in this study, utilized an adaptive staircase procedure (Levitt, 1971). This procedure began with a combined two-down one-up and three-down one-up staircase; and after two reversals, the two-down one-up procedure changed into three-down one-up. The step size halved after the 4th and 6th reversal. Each child began with five practice trials and continued on to the game. The game terminated after the maximum possible 40 trials, or after eight response reversals. Feedback was given after every trial by the computer software. During the practice period this feedback was reinforced and explained further by the researcher. The inter-stimulus interval was 500 ms. The threshold score was calculated using the mean of the last four reversals. This calculation indicated the smallest acoustic difference between stimuli at which the child could still discriminate with a 79.4% accuracy rate. The lower the threshold score the child received, the better they performed the task.

Figure 3. “Dinosaur” program illustration.
A computer snapshot of a “Dinosaur” game level; this particular “Dino-game” is used for amplitude rise time threshold detection. Participants heard three tones, one emitted from each of the three dinosaur’s mouths. One of the three tones emitted had a different amplitude rise time, and the participants were instructed to select the dinosaur that emitted the different tone. Participants received a sticker ‘prize’ after every correct selection; stickers would accumulate during every trial on the left-hand side of the screen in the black outlined box.
The acoustic stimuli were presented binaurally through headphones at 75dB sound pressure level (SPL). A Zwislocki coupler in one ear of a Knowles Electronic Mannekin for Acoustic Research (KEMAR) manikin (Burkhard & Sachs, 1975) was used to calculate earphone sensitivity, and all testing laptops were calibrated.

2.3.4.1 Rise Time Discrimination Threshold

In the rise time discrimination task (AXB), children were tested for their sensitivity to the rate of amplitude change (rise time) occurring at the initial onset of a tone. Tones that have a fast rise time are perceived as having a strong beat, whereas tones that have a slow rise time are perceived as having a weak beat. In the task, children were presented with three cartoon dinosaurs standing on a red, white, or yellow box. Each dinosaur would generate a tone with one of the three tones sounding differently from the other two. The children were instructed to identify which of the dinosaurs standing on the red or yellow box emitted the tone with the different rise time. Children responded to the different tone by pressing a button on the keyboard that corresponded to the colored boxes. The task was completed twice and an average threshold was calculated.

Every tone had a duration of 800ms and a frequency (pitch) of 500Hz. In each trial, the standard tone had a 15ms linear rise time envelope, 735ms steady state, and 50ms linear fall time. The different tone had an onset rise time that varied logarithmically, with the longest rise time of 300ms.

2.3.4.2 Duration Discrimination Threshold

In the duration discrimination task (AXB), children were tested for their sensitivity to duration differences between tones. They were presented with three cartoon dinosaurs standing on a red, white, or yellow box. Each dinosaur would generate one tone. One of the three tones generated would have a different duration from the other two. The children were instructed to identify which of the dinosaurs standing on the red or yellow box emitted the tone with the different duration. Children responded to the different tone by pressing a button on the keyboard.

The standard was a pure tone of 125ms duration and 500Hz frequency. The duration of the different tone ranged logarithmically between 125 and 250ms. The children were instructed to choose the tone whose duration was of a different length by pressing a button on the keyboard that corresponded to the correct colored box.
2.3.4.3 Intensity Discrimination Threshold

In the intensity discrimination task (2IFC), children were tested for their sensitivity to intensity (loudness) differences between tones. The intensity game (2IFC) presented two dinosaurs, one standing on a red box, the other on a yellow. One dinosaur, the standard, would emit a pure tone with a duration of 200 ms and frequency of 500 Hz, at a loudness level of 75 dB. The other dinosaur would emit the same tone but at a lower amplitude (quieter sound). The children had to choose the dinosaur associated with the softer tone by pressing a button on the keyboard that corresponded to the correct colored box.

2.3.5 Participants' Profile

All literacy and phonological test scores for dyslexics were significantly lower than those of controls (all \( p \)-values < 0.05), as shown in Table 1. The groups were matched on age and IQ, however they did show significant differences in vocabulary and working memory. The working memory test is a phonological awareness task, thus a significant difference between groups was expected. For the psychoacoustic measures, there were no significant differences between groups in terms of sensitivity to rise time, duration, or intensity.
Table 1. Participant details and performance on literacy, phonological, and psychoacoustic tasks before intervention, with parametric statistics for dyslexics (DY) versus controls (CA).

<table>
<thead>
<tr>
<th></th>
<th>Dyslexics N = 17</th>
<th>Controls N = 22</th>
<th>F (1, 23) (MANOVA)</th>
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<tr>
<td>Age (months) [SD]</td>
<td>93.06 (9.16)</td>
<td>89.41 (8.43)</td>
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<td>General Ability Measures</td>
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<tr>
<td>BPVS SS (SD)</td>
<td>97.76 (18.90)</td>
<td>108.77 (13.59)</td>
<td>4.25* a</td>
</tr>
<tr>
<td>WMTB-C SS (SD)</td>
<td>96.06 (10.63)</td>
<td>108.45 (16.38)</td>
<td>6.66* b</td>
</tr>
<tr>
<td>Literacy Measures</td>
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</tr>
<tr>
<td>BAS reading SS (SD)</td>
<td>83.59 (7.75)</td>
<td>103.41 (11.86)</td>
<td>36.74***</td>
</tr>
<tr>
<td>BAS spelling SS (SD)</td>
<td>81.41 (7.08)</td>
<td>100.82 (12.69)</td>
<td>33.08***</td>
</tr>
<tr>
<td>TOWRE word reading SS (SD)</td>
<td>79.47 (9.19)</td>
<td>106.50 (14.91)</td>
<td>46.67***</td>
</tr>
<tr>
<td>TOWRE non-word reading SS (SD)</td>
<td>84.41 (6.76)</td>
<td>103.72 (12.79)</td>
<td>47.49***</td>
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<tr>
<td>Phonological Awareness Measures</td>
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<tr>
<td>PhAB rhyme oddity SS (SD)</td>
<td>91.35 (8.67)</td>
<td>102.32 (12.68)</td>
<td>10.88*** c</td>
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<tr>
<td>Psychoacoustic Measures</td>
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<td></td>
</tr>
<tr>
<td>Rise time discrimination threshold (ms) (SD)</td>
<td>192.10 (91.88)</td>
<td>227.12 (55.92)</td>
<td>2.06* d,e</td>
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<tr>
<td>Duration threshold (ms) (SD)</td>
<td>83.51 (30.74)</td>
<td>81.44 (25.78)</td>
<td>0.11</td>
</tr>
<tr>
<td>Intensity threshold (dB) (SD)</td>
<td>7.07 (4.08)</td>
<td>6.34 (4.29)</td>
<td>0.27</td>
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</tbody>
</table>

Note: SS = standard score.
***p < 0.001; **p < 0.01; *p < 0.05
a. p-value = 0.047
b. p-value = 0.014
c. p-value = 0.002
d. p-value = 0.160
e. Two children were removed from analysis for outlying psychoacoustic scores in the rise time tasks, one child was a dyslexic male, and the other was a control female.

The data are presented as mean (standard deviation). Both intervention groups were compared in a multivariate analysis of variance (MANOVA) and the resulting F-statistics are shown. The groups differ significantly on all literacy and phonologically related pre-test measures (all p-values < 0.05). Assumptions of normality were met for all standardized background measure scores (p > 0.05 for Kolmogorov-Smirnov test of normality). There were no outliers other than for two psychoacoustic rise time threshold scores (DY, CA). Outliers were defined as any data point beyond three interquartile ranges from the furthest edge of the box. The statistical package for the social sciences (SPSS) was used for all statistical calculations in this study.

2.4 Beat Perception Task

This novel beat perception task was modified from Huss et al. (2011) to isolate duration cues to rhythm, and to assess potential compensatory effects of pitch.

There were two conditions in the beat perception task: without pitch (“no-pitch”), and with pitch (“+pitch”). In each trial, children were presented with two sequences of four-beat
rhythmic tone sequences, and were asked to determine whether the two sequences were the same or different. In each pair of rhythmic sequences, the second four-beat group was either identical (standard) or different to the first four-beat group. That is, in half of the trials, one of the four beats in the second sequence was briefly delayed (e.g. AAAA - AAdAA), arriving 100ms late. As previous psychoacoustic duration tasks had measured the participants’ sensitivity to approximately 80ms, a duration of 100ms was chosen as the delay. In the no-pitch condition, every note was played at G4 (392Hz). In the +pitch condition, pitch variations were introduced to co-vary with the rhythm pattern of the sequence (i.e. to highlight target rhythmic deviations), as explained subsequently.

2.4.1 Beat distinction by distribution in time (“no-pitch”)

In this condition, a standard (‘same’) trial consisted of 2 groups of four notes, in which each note was identical in duration (300ms), intensity, rise time (15ms), and pitch (G4, 392Hz). Every note in the identical trials arrived on the 120bpm beat, creating a 4/4 metric time. The two groups of notes were separated by four beats of silence (= 2 seconds). In the ‘different’ trials, one note in the second group (the first, second, third, or fourth note) arrived 100ms after the 120bpm beat, but all notes remained 300ms in duration. The notes succeeding the off-beat note were in time (at 120bpm, as distinct from Huss et al., 2011). Examples of same and different beat patterns are shown in Figure 4 below. Sheet music of the full beat task stimuli materials can be found in Appendix A.

![Figure 4. No-pitch standard (‘same’) and delayed (‘different’) beat sequences.](image)

A sheet music depiction of the standard trial and a delay on 1st beat sequence trial for the no-pitch condition. The sequences were played over headphones using Audacity software, and were played on G4 (392Hz) at 120bpm, with each beat lasting 300ms. The first beat of the delayed sequence was played 100ms after the 120bpm beat, but remained 300ms in duration.
2.4.2 Beat distinction by pitch and distribution in time ("+pitch")

In the +pitch condition, both tone sequences in the pair contained one note at a higher pitch (one semitone higher at 415.305Hz) in the same relative location, where a 100ms delay could occur. This delay occurred in half of the trials (i.e. 'different' trials), at a location coinciding with the higher pitch cue (e.g. ABAA - ABdAA). For the other 50% of standard ('same') trials, pitch changes also occurred on the first, second, third, or fourth note (in the same position for both groups of notes), but no temporal delays were introduced. As before, all notes were identical in duration (300ms), intensity, and rise time (15ms). Non-delayed notes had a pitch of 392Hz (G4). The notes succeeding the delayed note were in time. Examples of same and different beat patterns are shown in Figure 5 below. Sheet music of the full beat task stimuli materials can be found in Appendix A.

1. Standard, pitch change on 1st Beat

![Sheet music depiction of standard trial](image1)

2. Delay on 1st Beat

![Sheet music depiction of delayed trial](image2)

**Figure 5.** +pitch standard ('same') and delayed ('different') beat sequences.

A sheet music depiction of the standard trial and a delay on 1st beat sequence trial for the +pitch condition. The sequences were played over headphones using Audacity software, and were played at 120bpm, with each beat lasting 300ms. The first beat of the delayed sequence was played 100ms after the 120bpm beat, but remained 300ms in duration. In these trials, the first note was a semitone above (415.305Hz) the rest of the three G4 notes (392Hz). In the delayed trial, the delayed note was paired with the pitch change.
2.4.3 Stimuli presentation

The stimuli were presented as one bunny and one kangaroo hopping. A depiction of the task is shown below in Figure 6.

![Beat perception game illustration](image)

**Figure 6. Beat perception game illustration.** Computer snapshot of a beat perception task trial; participants were instructed to choose whether the bunny and kangaroo hopped in the same or different pattern. The children listened to the hopping patterns first emitted from the bunny and then from the kangaroo. There were two buttons on the keyboard, one labelled “same,” the other, “different.” The participants pressed these keys in response to what they heard.

The bunny and kangaroo each represented one beat group. Children were asked to choose whether the kangaroo hopped in the same (standard trial) or different pattern (delayed trial) from the bunny. To describe the possible difference between the same and different hopping pattern, the children were told that if the kangaroo tripped, then it would hop in a different pattern from the bunny. Positive feedback was given after every six trials regardless of the child’s performance. The task was scored as a percent of the correct trials over the total number of trials.

A total of 48 trials were presented in each condition, of which 24 trials contained a delay and 24 trials did not. The order of presentation of trials was fully randomized. The beat perception tasks were delivered at the start and at the end of the music and Graphogame Rime interventions. This allowed the investigators to see whether the children improved in beat perception task performance. The experiment was programmed and presented using Presentation software on a Lenovo ThinkPad Edge E130 Intel Core i3-3217U laptop.
were created by Natalie Matthews using Audacity software and presented through headphones. The experimenters were Natalie Matthews, Angela Wilson, and Natasha Mead.

2.5 Intervention Procedure

As mentioned in the opening paragraph, children were participating in an on-going MRC intervention study with the Center for Neuroscience in Education. The intervention was administered over the course of three months. The children were seen twice a week, with slight variations depending on school availability. All children were given twenty intervention sessions in total. Two types of intervention were provided, a musical intervention or a Graphogame Rime intervention. Twenty-one children were assigned to the musical intervention (12 males, 9 dyslexics), and 18 children were assigned to the Graphogame intervention (12 males, 8 dyslexics). Participants from the same school were distributed between the two intervention groups. As shown in Table 2, the two intervention groups did not differ in age, general ability, literacy, phonological awareness, or psychoacoustic sensitivity before the intervention (all $p$-values > 0.05).
Table 2. Participant performance on literacy, phonological, and psychoacoustic tasks before intervention, with parametric statistics for musical (MC) versus Graphogame Rime (GG) intervention groups.

<table>
<thead>
<tr>
<th></th>
<th>Graphogame Group N = 18</th>
<th>Music Group N = 21</th>
<th>F (1, 23) (MANOVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (months) [standard deviation (SD)]</td>
<td>92.00 (8.38)</td>
<td>90.14 (9.31)</td>
<td>0.30</td>
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<tr>
<td><strong>General Ability Measures</strong></td>
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<td></td>
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<td>FSIQ SS (SD)</td>
<td>108.39 (14.44)</td>
<td>104.62 (16.54)</td>
<td>0.16</td>
</tr>
<tr>
<td>BPVS SS (SD)</td>
<td>101.17 (19.28)</td>
<td>106.38 (14.45)</td>
<td>0.43</td>
</tr>
<tr>
<td>WMTB-C SS (SD)</td>
<td>107.67 (16.05)</td>
<td>99.10 (13.83)</td>
<td>0.07</td>
</tr>
<tr>
<td><strong>Literacy Measures</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BAS reading SS (SD)</td>
<td>96.50 (14.06)</td>
<td>93.29 (14.53)</td>
<td>0.29</td>
</tr>
<tr>
<td>BAS spelling SS (SD)</td>
<td>93.72 (16.63)</td>
<td>91.19 (12.31)</td>
<td>0.21</td>
</tr>
<tr>
<td>TOWRE word reading SS (SD)</td>
<td>94.44 (15.04)</td>
<td>94.95 (21.42)</td>
<td>0.02</td>
</tr>
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<td>TOWRE non-word reading SS (SD)</td>
<td>95.94 (12.68)</td>
<td>93.14 (16.90)</td>
<td>0.15</td>
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<td><strong>Phonological Awareness Measures</strong></td>
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<tr>
<td>PhAB rhyme oddity SS (SD)</td>
<td>96.00 (12.87)</td>
<td>98.85 (11.91)</td>
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<td><strong>Psychoacoustic Measures</strong></td>
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</tr>
<tr>
<td>Rise time discrimination threshold (ms) (SD)</td>
<td>200.34 (83.97)</td>
<td>222.99 (64.85)</td>
<td>0.85a</td>
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<tr>
<td>Duration threshold (ms) (SD)</td>
<td>82.16 (30.95)</td>
<td>82.49 (25.33)</td>
<td>0.21</td>
</tr>
<tr>
<td>Intensity threshold (dB) (SD)</td>
<td>6.85 (4.42)</td>
<td>6.49 (4.03)</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Note: SS = standard score.

a. Two children (one dyslexic male, one control female) were removed from analysis for outlying rise time psychoacoustic scores, both children participated in the Music intervention.

The data are presented as mean (standard deviation). Both intervention groups were compared in a multivariate analysis of variance (MANOVA) and the resulting F-statistics and significances are shown. The groups do not significantly differ on any of the standardized background measures (all p-values > 0.05). Assumptions of normality were met for all standardized background measure scores (p > 0.05 for Kolmogorov-Smirnov test of normality). There were no outliers other than for two psychoacoustic rise time threshold scores (1DY, 1CA, both MC intervention). Outliers were defined as any data point beyond three interquartile ranges from the furthest edge of the box. The statistical package for the social sciences (SPSS) was used for all statistical calculations in this study.

In the musical intervention, children completed 4 – 6 musical tasks for sessions 1-10, and 6-8 musical tasks for sessions 11-20. In the Graphogame Rime intervention, children played the game and also tapped to a beat in every second session for all 20 sessions. Each music and Graphogame Rime session took approximately 20-30 minutes to complete. The musical intervention was instructor-mediated, but all activities in the musical intervention utilized a computer for stimuli presentation. Graphogame Rime was entirely played on a
laptop computer, but the experimenter assisted the children with difficult levels by providing explanation and encouragement throughout the task. All of the children received one-on-one sessions with the experimenter. The experimenters were Natalie Matthews, Angela Wilson, and Natasha Mead. All musical intervention tasks, with the exception of the “Syllable Stress and Rhythmic Command in Poetry” (section 2.5.1.7) and the “Dee-Dee Game” (section 2.5.1.8), were created by Natalie Matthews. Appendix B provides a schedule of all twenty sessions of the musical intervention.

2.5.1 Musical Intervention

The following tasks formed the musical intervention program:

2.5.1.1 Rhythmic Entrainment to Musical Tempos

The children heard click tracks at 60, 80, 100, 120, and 140bpm using Audacity software. The children were instructed to tap along to the tempo using the space bar of a computer keyboard. Each tempo was played for 35 beats, regardless of durational differences. The tempos, which they heard on every other day of intervention, were randomized. The subjects heard each tempo twice, once during the first 10 intervention sessions and again in the last 10 sessions. The timing of their taps was captured by Presentation software.

2.5.1.2 Rhythmic Entrainment to 120bpm

The children heard a 120bpm click track on Audacity software. The tempo was played for 35 beats. The participants heard the 120bpm tempo on every other day of intervention, opposite days to the rhythmic entrainment to musical tempos. The children were instructed to tap along to the tempo using the space bar of a computer keyboard. The timing of their taps was captured by Presentation software. This was the only task, other than the beat perception measure, that both children who received musical intervention and Graphogame Rime intervention performed.

2.5.1.3 Discrimination between Two Tempos

The participants heard eight beats of two different or two identical tempos. The first tempo set was separated by one second of silence from the second tempo set. The subjects were instructed to determine whether or not the beats were at the same speed. For the pairings of different tempos, as the intervention progressed, the difference between the tempos decreased, making each trial more difficult than the previous. The task was scored as whether the child responded correctly. If the child responded incorrectly, the investigator replayed the trial and encouraged hand clapping, drumming, or marching to help the child
feel the beat. The beats were played as click tracks using Audacity software to more easily distinguish the tempos.

2.5.1.4 Discrimination between Two Rhythmic Sequences

Two, four beat rhythmic sequences were played. The pair of rhythms was separated by four beats of silence. The rhythmic sequences were click tracks played at 120bpm (quarter note receives a 500ms duration) with Audacity software, to make the beats more distinct. The rhythmic sequences within a pair were either identical or different. The rhythmic sequences were adapted from Bhide et al. (2013). As the musical intervention progressed, the different rhythmic pairs became more difficult to distinguish. The children had to determine whether the two sequences were the same or different. The task was scored as whether the child responded correctly. If the child responded incorrectly, the investigator replayed the trial and hand clapped along to provide sharper, more percussion-like note distinctions. Stimulus materials can be found in Appendix C.

2.5.1.5 Vocal Imitation of a Rhythmic Sequence

Children heard a 4-8 beat rhythmic sequence. The beats were played at 120bpm (quarter note receives a 500ms duration) with Audacity software click tracks to make the notes more distinct. As the musical intervention progressed, the difficulty of the rhythmic sequences increased for sessions 2, 4, 6, 8, 10, 12, 14, 16, 18, and 20. For sessions 11, 13, 15, 17, and 19, the first five vocal imitation sessions were re-administered to determine whether the children had improved on the task and to provide further training. The rhythmic patterns were adapted from Bhide et al. (2013) and individually composed. After hearing the sequence, the children were encouraged to mimic the rhythm using the syllable “ta.” If necessary, the investigator helped them learn and practice the rhythmic sequence. The task was scored on a scale from one to five (1=incorrect number of notes; 2= correct number of notes, but very incorrect rhythm; 3= longer notes relatively longer, shorter notes relatively shorter, but rhythm still very incorrect; 4=rhythm almost correct; 5=rhythm completely correct). The child’s sung imitation of the rhythmic sequence was recorded digitally using a sound recorder so that the investigator could score with greater accuracy. Stimulus materials can be found in Appendix D.

2.5.1.6 Drumming and Marching to Instrumental Music

The children heard minute-long clips of instrumental dance music with highly salient rhythmic beats. The musical genre of the clips ranged from Salsa to Rhythm and Blues music. The songs were chosen for an up-beat, easy to follow tempo. The songs also were chosen to be without lyrics to avoid possible distractions from rhythm. These relatively
obscure instrumental clips were chosen over more mainstream music samples to avoid possible familiarity advantages some children may have had over others. Subjects heard the same clip in two consecutive sessions. In the first session, the children would drum along to the beat on bongo drums. During the following session the children would march along to the beat. For sessions 11-20, participants were instructed to march or drum more slow and then more quickly to their chosen original beat (half notes and eighth notes to a quarter note, 4/4 beat). Therefore, for sessions 11-20, the children were marching or drumming to the entire musical clip three times, each at a different speed. To explain the task, the researcher would model what drumming or marching to the beat entailed (drumming/marching to the beat allowed for whole, half, quarter, eighth note, etc. divisions of the beat) by drumming, or by marching to several seconds of the music clip. After modeling the task, the researcher would let the child drum or march to the music alone. If there was still any confusion, the investigator would demonstrate how to drum or march along to the beat for the entire duration of the one minute instrumental clip. Children’s performances were scored on a scale of one to five (1=could not perform the task; 2=made frequent mistakes while performing the task with the investigator; 3=made no mistakes with the investigator’s assistance, but was dependent upon her help; 4=made some mistakes, but was able to do it without assistance; 5=performed the task perfectly without assistance). Appendix B contains the track list.

2.5.1.7 Syllable Stress and Rhythmic Command in Poetry

This task emphasized rhythmic patterns via syllabic stress in poetry. In the first ten sessions, for every given poem, the experimenter played a recording of the poem to the participant. The woman narrating the poem was a native British English speaker (Southeastern English accent). Once the recording was played, the experimenter and child read the poem aloud together at a slower pace. The child and experimenter read the poem aloud once more, this time drumming to the syllabic rhythm of the poem on a bongo drum, using alternating hands for each beat. After the child heard the entire poem three times, the experimenter asked the child three questions to gauge the child’s rhythmic understanding of the poem.

The first question, designed to gauge syllable stress, asked the participant to listen to a segment of the poem in which a word was said with either the correct or incorrect syllable stress pattern. The child was instructed to determine which section contained the correct syllabic stress. For example, in the line “But now I am six, I'm as clever as clever” from the poem “Now we are six” by A.A. Milne, the word clever is correctly-stressed when pronounced CLEver, but incorrectly-stressed when pronounced cleVER.
The second question tested the child’s ability to detect the number of syllables in words. The participant was asked whether replacing a word in the poem with one of similar or opposite meaning, but different syllable length, would ruin the rhythm of the poem. If the replaced word had the same number of syllables, it also had an identical stress pattern. Only replaced words with different syllable numbers would disrupt the poem’s rhythm. For example, in the line “When I was three I was hardly me” from the poem “Now we are six,” if the experimenter replaced the word “hardly” with “definitely,” a word with a different number of syllables, the rhythm of the poem would be disrupted. If the word “hardly” was replaced with “barely,” a word with the same number of syllables and stress pattern, the rhythm of the poem would remain the same.

The third question sought to determine the child’s perception of the poem’s overall rhythm. Words in one line of the poem were rearranged such that the syllable stress pattern was altered. For example, in the line “When I was two I was nearly new” from the poem “Now we are six,” a rearranged version of that line would be “I was two when I was nearly new.” This rearranged version does not have the same rhythmic pattern as the original line from the poem. The section of the poem with the line of jumbled words was then compared to the same section with all words in original placement. The child was asked to identify which version of the poem contained the rhythm disruption. If the child answered any of the questions incorrectly the researcher would explain the correct answer and even have the child re-read aloud the chosen sections with drumming.

The poems increased in rhythmic difficulty and complexity, but all poems were still highly rhythmic and child-friendly. The task was scored on the number of correct questions answered. From sessions 11-20, poem memorization was integrated into the task. Please refer to Appendix E for the poems and questions.

### 2.5.1.8 Dee-Dee Game

The Dee-Dee game was used to improve children’s prosodic awareness; this was done by characterizing syllable stress in words as phonologically simplified “Dee-Dee” sounds, or 'reiterative speech.' The sound “dee” replaced every syllable. For example, HArry POtter, became DEEdee DEEdee. The participant was presented with pictures on a computer representing popular children’s fictional characters and movies. All children were familiar with the references, and if they were not, the researcher provided the name corresponding to the picture. The first stage of the Dee-Dee game required that the child select the correct syllable stress version of the character or film name without the Dee-Dee substitutions (e.g. HArry POtter vs. haRRY poTTER). Each time a picture was displayed, a correct and
incorrect syllable stressed name was played. The child was instructed to choose the name with the correct syllable stress. If they selected the incorrect syllable stress, the experimenter corrected the child and explained the correction. If the child selected the correct syllable stress, the experimenter also reinforced why their selection was correct.

The participants were given four sessions to familiarize themselves with the correct name-picture association and syllable stress selection. In each session they were given half of the total picture set so that they were exposed to all pictures in the game two times. After the four practice sessions, the children played the entire Dee-Dee game without the experimenter's assistance three times, once per session for three sessions. The Dee-Dee computer game played the Dee-Dee name of the picture twice, once with the correct syllable stress, and once without the correct syllable stress. For example, with a picture of Harry Potter, the computer played DEEdee DEEdee and deeDEE deeDEE, with the former Dee-Dee being the correct syllable stress. In order to select the correct answer, the child had to listen to the syllable stress pattern (Goswami et al., 2010a). The task was scored on the number of correct syllable stress selections made. A native English female speaker with a Southern British accent recorded all words and sounds played in the practice trials and game. Please refer to Appendix B for the schedule of when the practice trials and entire Dee-Dee game were administered.

2.5.2 Graphogame Intervention

Graphogame Rime is a child-friendly reading intervention computer game developed in Finnish by Heikki Lyytinen and Ulla Richardson (University of Jyvaskyla), and adapted for English by Fiona Kyle and Usha Goswami (University of Cambridge). The game taught phoneme-grapheme correspondences through the psycholinguistic grain size of the rime, aiming for the psycholinguistic level with the highest orthographic consistency.

The game utilized a dynamic element by adapting to the child’s ability level and set further levels in accordance with this ability. At the start of the game, it introduced participants to a small set of prototypical and consistent phonemes and corresponding graphemes, like “a” and “t.” As the player progressed, the game combined the small set of phonemes and graphemes into vowel-consonant (VC) rime units, like “at” and “it.” After introducing rimes, the game taught how onsets combined with rime families to make familiar CVC words, like m + at = cat, and t + in = tin. As the game advanced, CCVC and CVCC words and families that had more complex or less frequent rimes (e.g. –irt, -udge) were introduced. The game continued to introduce more phonemes and corresponding graphemes,
similarly building them up into words and eventually utilized more complex word structures, vowel diagraphs, and rhymes.

The game presented a series of targets in balls. The participants selected the target that matched the word they heard (Figure 7). The target sounds were recorded by a native English female speaker with a Northern British accent. Most levels were introduced by a visual demonstration of phoneme-grapheme correspondences to make the purpose more explicit. As the children progressed through the series of levels, they were awarded a ‘sticker’ game token on completion of each level. The program occasionally integrated new reading games to maintain the child’s interest. For example, some levels used a spacecraft icon to zap balls in constant motion, which contained the correct target sound. Other levels encouraged spelling skills, instructing participants to click on the letters or rime units in the correct order to form the word played.

**Figure 7. Graphogame Rime level illustration.**
Computer snapshot of a Graphogame Rime game level; participants heard the word “spite” and were instructed to select the ball that contained the word that corresponded to the one they heard.
Each level was played three times or until the child reached 80% accuracy. If the child failed to reach 80% accuracy by her/his first or second time playing the level, the program provided an individualized training level. This level selected targets unfamiliar to the child, and presented them with the familiar targets that the child struggled with. Once this level was completed, the previous level was played again.
3 RESULTS

3.1 Data pre-processing

Assumptions of normality were met for scores on the beat perception task \((p > 0.05)\) for Kolmogorov-Smirnov test of normality for both groups). Accordingly, parametric statistics were used for analysis. The statistical package for the social sciences (SPSS) boxplot function was used to check for outliers. Outliers were defined as any data point beyond three interquartile ranges from the furthest edge of the box. There were no outliers in the beat perception task. Two participants produced outlier scores in the psychoacoustic rise time threshold task and were removed from analyses involving rise time (see Methods, Tables 1 and 2, sections 2.3.5 and 2.5; 1 dyslexic male and 1 control female, both with musical intervention). SPSS was used for all statistical calculations in this study.

3.2 Hypotheses

(1) Dyslexic children (DY) would perform worse than controls (CA) in the no-pitch condition. In the +pitch condition, we expected performance of both groups to improve, particularly the dyslexic group, as theoretically pitch perception is unimpaired in developmental dyslexics (with an IQ above 85; Goswami, 2013; Kuppen et al., 2013). Therefore, we did not expect a significant difference for +pitch beat task performance between DY and CA.

(2) Both DY and CA’s beat perception performance would improve more after musical intervention (MC) than after Graphogame Rime intervention (GG).

(3) Individual differences in beat perception would relate to phonological awareness and reading measures for DY and CA, as observed in Huss et al. (2011).

(4) Performance in the beat perception task would be predicted by the children’s (both DY and CA) rise time sensitivity, rather than by other auditory measures, as also observed in Huss et al. (2011).

The results are presented in the order of the stated hypotheses.
3.3 Performance of DY and CA in no-pitch and +pitch conditions of the beat perception task

The mean performance of each group before and after intervention, for no-pitch and +pitch conditions is summarized in Figure 8 and Table 3. To assess differences in performance between dyslexic and control participants in the beat perception task, a 2 x 2 x 2 repeated measures ANOVA was conducted. In the ANOVA, Condition [2, +pitch and no-pitch] and Time [2, pre and post intervention] were within-subjects factors, and Group [2, DY (N=17) versus CA (N=22)] was the between-subjects factor. The assumption of sphericity (Mauchly’s test) was met for all comparisons.

There was a significant main effect of Condition (F (1, 37) = 46.86, p < 0.001), as all participants performed significantly better for +pitch than for no-pitch conditions. This is marked in Figure 8. However, there was no significant main effect of Time (F (1, 37) = 1.32, p = 0.26) and no significant interaction between Condition and Time (F (1, 37) = 0.15, p = 0.70). These results indicate that, contrary to prediction, both groups of children performed significantly better on the no-pitch task compared to the +pitch task, both before and after intervention. Also, there was no significant difference overall between pre and post intervention beat perception scores, with the same pattern observed in no-pitch and +pitch conditions.

In terms of group differences, there was a near significant main effect of Group, in which dyslexic children performed marginally worse than controls across all conditions (F (1, 37) = 3.66, p = 0.063). However, there were no significant interactions between Time and Group (F (1, 37) = 1.94, p = 0.17), Condition and Group (F (1, 37) = 0.31, p = 0.58), and Time, Condition, and Group (F (1, 37) = 1.16, p = 0.29). Therefore, dyslexics performed worse than controls overall, but their pattern of performance across conditions and time (pre-post) was identical to that of controls. That is, contrary to our expectations, dyslexics did not show a selective benefit in the +pitch condition, and DY performed only marginally worse than CA in the no-pitch condition. Given that DY were able to perform the task above chance without ceiling effects for both conditions, and perform almost as well as CA, duration perception is not likely an issue for rhythmic computation in dyslexia. Huss et al. (2011) and Goswami et al. (2012) were unable to isolate basic auditory cues in their task. Therefore, they could not attribute solely rise time, intensity, duration, or a specific combination of the auditory features to the effects they observed. Nor could they explain specifically why their DY exhibited significantly worse beat perception when compared to their CA. Given our results, it is likely that perception of duration-based patterns did not contribute to the
significant difference in beat perception between DY and CA found in the Huss et al. (2011) and Goswami et al. (2012) studies.

3.4 Effect of MC versus GG training on accurate beat perception

Next, the effect of music or Graphogame Rime intervention on beat perception performance was analyzed. These results, organized by intervention and group, are summarized in Figure 8 and Table 3. To determine whether there was a significant difference in performance between children who received a music intervention and those who received a Graphogame Rime intervention, a 2 x 2 x 2 repeated measures ANOVA was conducted. In the ANOVA, Condition [2, +pitch and no-pitch] and Time [2, pre and post intervention] were within-subjects factors, and Intervention [2, GG (N= 18) versus MC (N=21)] was the between-subjects factor. The assumption of sphericity (Mauchly’s test) was met for all comparisons.

As before, there was a strong main effect of Condition (F (1, 37) = 45.83, p < 0.001), in which children performed better on no-pitch than on +pitch trials. Again, there was no significant main effect of Time (F (1, 37) = 1.99, p = 0.17), and no significant interaction between Condition and Time (F (1, 37) = 0.07, p = 0.80).

However, there was no significant main effect of Intervention. Children who received GG training performed no worse than children who received MC training, across all conditions (F (1, 37) = 0.001, p = 0.97). There were also no significant interactions between Time and Intervention (F (1, 37) = 1.28, p = 0.27), Condition and Intervention (F (1, 37) = 0.04, p = 0.84), and Time, Condition, and Intervention (F (1, 37) = 0.02, p = 0.88).
Figure 8. Mean beat perception scores (by percent trials correct) for CA and DY groups, divided according to GG (top panel, A & B; CA N=10, DY N=8) and MC (bottom panel, C & D; CA N=12, DY N=9) interventions, and no-pitch (left panel, A & C) and +pitch (right panel, B & D) conditions. Error bars indicate the standard error. All +pitch scores were significantly lower than no-pitch scores \((p < 0.001)\) across both pre and post MC and GG interventions. Dyslexic participants scored worse than controls at near significance \((p = 0.063)\) for all tasks. Mean percent trials correct are displayed from 50% to 90% correct.
**Table 3.** Mean and standard deviations of beat perception scores (by percent trials correct), for CA and DY groups, divided according to pre and post MC and GG interventions and no-pitch and +pitch conditions.

<table>
<thead>
<tr>
<th></th>
<th>Pre-Intervention</th>
<th></th>
<th>Post-Intervention</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+Pitch</td>
<td>No-Pitch</td>
<td>+Pitch</td>
<td>No-Pitch</td>
</tr>
<tr>
<td></td>
<td>GG</td>
<td>MC</td>
<td>GG</td>
<td>MC</td>
</tr>
<tr>
<td>Controls</td>
<td>N</td>
<td>10</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Mean (%)</td>
<td>68.75</td>
<td>72.57</td>
<td>76.25</td>
</tr>
<tr>
<td></td>
<td>SD (%)</td>
<td>12.73</td>
<td>13.11</td>
<td>7.56</td>
</tr>
<tr>
<td>Dyslexics</td>
<td>N</td>
<td>8</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Mean (%)</td>
<td>65.15</td>
<td>62.96</td>
<td>73.50</td>
</tr>
<tr>
<td></td>
<td>SD (%)</td>
<td>18.13</td>
<td>9.19</td>
<td>17.49</td>
</tr>
</tbody>
</table>

The data are presented as mean and standard deviation (SD) of percent trials correct. Mean values correspond to those shown in Figure 8.

The lack of difference between beat perception scores following music and Graphogame Rime interventions was surprising. This could have been due to the variability in raw scores before the intervention, which could have been large enough to mask any signs of true improvement following the intervention. The variability in raw scores before and after intervention for all 39 participants is shown below in Figure 9.
Given the variability in raw scores before the intervention (Figure 9), we decided to calculate “improvement gain” scores, which effectively normalized the participants’ percent trials correct (scores) according to their initial (pre-intervention) beat perception accuracy. The improvement gain was calculated by subtracting each participant's post-intervention percent trials correct score from his/her pre-intervention percent trials correct score for each condition. We calculated the gains in improvement for the +pitch condition, no-pitch condition, and mean of +pitch and no-pitch conditions (Table 4). We hoped that by analyzing gains in improvement instead of raw scores, we could better access the children’s beat perception performance pre- and post-intervention.
These gain scores were then entered into a new 2 x 2 x 2 mixed-design repeated measures ANOVA, taking 'gain' scores (pre-to-post improvement) as the dependent variable rather than raw scores. In the ANOVA, Condition [2, +pitch and no-pitch] was the within-subjects factor. Group [2, CA (N= 22) versus DY (N= 17)] and Intervention [2, GG (N=18) versus MC (N=21)] were both entered as between-subjects factors. It was predicted that there would be greater gains post MC intervention, given that the beat perception task was a music-based task. Theoretically the MC intervention should have honed rhythm-based skills used in the beat task. The assumption of sphericity (Mauchly’s test) was met for all comparisons.

The results of the ANOVA indicated that there was no main effect of Condition (F (1, 35) = 0.16, p = 0.69), Group (F (1, 35) = 3.04, p = 0.09), or Intervention (F (1, 35) = 0.83, p = 0.37). These results indicated that there was no significant difference in score improvement between +pitch and no-pitch conditions, no significant difference in improvement between DY and CA groups, and no significant difference in score improvement overall between MC or GG intervention groups. However, there was a significant interaction between Group and Intervention, (F (1, 35) = 7.74, p = 0.009). This interaction, illustrated in Figure 10, indicates that for the GG intervention, control children improved in their beat perception significantly more than dyslexic children after intervention (p = 0.02 on Tukey HS post hoc test). This interaction is noticeable in Figure 9 (panels A and B). While all CA participants improved after GG intervention, with the exception of 2 children in the no-pitch and +pitch conditions, more than half of the DY performed worse after GG intervention (Figure 9). Conversely, dyslexic children appeared to benefit more than controls after MC intervention, although this difference between groups did not reach significance (p = 0.87 on Tukey HS post hoc test). This trend is also noticeable in Figure 9 (panels C and D), particularly in the +pitch condition (panel D), as 8 of 9 DY participants and only 7 of 12 CA participants improved post MC intervention. Regardless, the dyslexic children who received a MC intervention demonstrated equivalent improvement in beat perception to their respective controls. In summary, controls improved less with music training compared to Graphogame Rime training, and dyslexics improved as much with music training as they did with Graphogame Rime training, for beat perception performance.
Table 4. Mean and standard deviations of beat perception score improvement (by percent trials correct) for no-pitch and +pitch conditions, and mean +pitch and no-pitch conditions, post GG and MC interventions for DY and CA participants.

<table>
<thead>
<tr>
<th></th>
<th>+Pitch Intervention Improvement</th>
<th></th>
<th></th>
<th>Mean +Pitch and No-pitch Intervention Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GG</td>
<td>MC</td>
<td>GG</td>
<td>MC</td>
</tr>
<tr>
<td>Controls</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>10</td>
<td>12</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Mean (%)</td>
<td>8.59</td>
<td>-2.78</td>
<td>7.50</td>
<td>1.39</td>
</tr>
<tr>
<td>SD (%)</td>
<td>14.71</td>
<td>5.21</td>
<td>9.17</td>
<td>9.24</td>
</tr>
<tr>
<td>Dyslexics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>8</td>
<td>9</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Mean (%)</td>
<td>-2.13</td>
<td>4.86</td>
<td>-3.19</td>
<td>-1.33</td>
</tr>
<tr>
<td>SD (%)</td>
<td>9.11</td>
<td>9.02</td>
<td>8.99</td>
<td>18.02</td>
</tr>
</tbody>
</table>

The data are presented as *mean improvement* and standard deviation (SD) of percent trials correct. Gains in improvement were calculated by subtracting participants’ percent trials correct post-intervention from their percent trials correct pre-intervention, for each +pitch and no-pitch condition. The mean improvement for both conditions (fifth and sixth column) was calculated by subtracting the mean of combined conditions post-intervention from the mean of combined conditions pre-intervention. A negative percentage indicates a worsened performance score (decrease in percent trials selected correct) after intervention compared to before; a positive percentage indicates an improved percent score after intervention. Mean values for combined +/- pitch conditions (fifth and sixth column) correspond to those shown in Figure 10.
Figure 10. Mean and standard errors of combined +pitch and no-pitch condition beat perception score improvement (by percent trials correct) post-intervention, divided according to GG (CA N=10, DY N=8) and MC (CA N=12, DY N=9) interventions for DY and CA participants. Dyslexic participants improved significantly less than controls with GG intervention ($p = 0.009$), while dyslexic participants improved as much as controls with the MC intervention. Beat perception improvement is calculated by subtracting each participant's post-intervention percent trials correct score from the pre-intervention percent trials correct score for each condition. The participants’ percent improvements are separated by group and training, and then averaged. A negative percentage indicates a worsened performance score (decrease in percent trials selected correct) after intervention compared to before; a positive percentage indicates an improved percent score after intervention.
3.5 Can performance in the beat perception task predict phonological awareness and literacy skills?

From the prior literature (Huss et al., 2011; Goswami et al., 2012), it was expected that there would be associations between participants' performance on the beat perception task, and their phonological awareness and literacy skills. Accordingly, correlations between performance in the beat perception task (distinguished by +/- pitch conditions and GG/MC interventions) and general ability, literacy, phonological awareness, and psychoacoustic measures were computed. In addition, rhythmic entrainment to 2Hz (120 beats per minute) was also included as a dependent variable in the correlations. This entrainment task was included as a measure of synchronization accuracy. Correlations for mean improvement of beat perception performance were also computed. For this analysis, improvement in no-pitch and +pitch conditions were combined and averaged into a single score, as there was no significant difference between conditions in the previous ANOVA analysis ($p = 0.69$).

The resulting correlations are provided in Table 5. The values in bold ($p < 0.05$) demonstrate that, as expected, there are significant correlations between the beat perception task performance and literacy, phonological, psychoacoustic, and tapping measures. In general, there were stronger correlations found for post intervention beat performance and literacy, phonological, psychoacoustic, and tapping measures. There were also significant correlations between beat scores and IQ. A more comprehensive correlation table dividing no-pitch and +pitch conditions by GG and MC interventions is provided in Appendix F, and a table dividing GG and MC by DY and CA participants is provided in Appendix G.
Table 5. *Pearson bivariate correlations between beat perception, general ability, literacy, phonological awareness, psychoacoustic, and tapping measures across both dyslexic and control participants for (a) pre- and (c) post-intervention, as well as for (c) mean gains in improvement post-intervention.*

<table>
<thead>
<tr>
<th></th>
<th>a. Pre-Intervention</th>
<th>b. Post-Intervention</th>
<th>c. Mean improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No-pitch</td>
<td>+Pitch</td>
<td>No-pitch</td>
</tr>
<tr>
<td></td>
<td>N =39</td>
<td>N =39</td>
<td>N =39</td>
</tr>
<tr>
<td><strong>General Ability Measures</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FSIQ SS</td>
<td>0.39*</td>
<td>0.40*</td>
<td>0.40*</td>
</tr>
<tr>
<td>BPVS SS</td>
<td>0.28</td>
<td>0.12</td>
<td>0.38*</td>
</tr>
<tr>
<td>WMTB-C SS</td>
<td>0.15</td>
<td>0.02</td>
<td>0.24</td>
</tr>
<tr>
<td><strong>Literacy Measures</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BAS reading SS</td>
<td>0.29</td>
<td>0.29</td>
<td>0.51**</td>
</tr>
<tr>
<td>BAS spelling SS</td>
<td>0.21</td>
<td>0.14</td>
<td>0.48**</td>
</tr>
<tr>
<td>TOWRE word reading SS</td>
<td>0.03</td>
<td>0.23</td>
<td>0.29</td>
</tr>
<tr>
<td>TOWRE non-word reading SS</td>
<td>0.17</td>
<td>0.24</td>
<td>0.38*</td>
</tr>
<tr>
<td><strong>Phonological Awareness Measures</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PhAB rhyme oddity SS</td>
<td>0.43**</td>
<td>0.27</td>
<td>0.53**</td>
</tr>
<tr>
<td><strong>Psychoacoustic Measures</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rise time discrimination threshold</td>
<td>-0.37*</td>
<td>-0.19</td>
<td>-0.16</td>
</tr>
<tr>
<td>Duration threshold</td>
<td>-0.55**</td>
<td>-0.33*</td>
<td>-0.41**</td>
</tr>
<tr>
<td>Intensity threshold</td>
<td>-0.22</td>
<td>-0.14</td>
<td>-0.15</td>
</tr>
<tr>
<td><strong>2 Hz Tapping</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tapping ITI post intervention</td>
<td>0.37*</td>
<td>0.21</td>
<td>0.36*</td>
</tr>
<tr>
<td>Tapping Sync post intervention</td>
<td>0.42**</td>
<td>0.24</td>
<td>0.35*</td>
</tr>
</tbody>
</table>

SS = standard score.
Tapping ITI = tapping inter-tap interval.
Tapping Sync = tapping synchronization.
***p < 0.001; **p < 0.01; *p < 0.05
p values, if listed, are in parenthesis beside Pearson correlation value, e.g. Pearson correlation (p-value)

The Pearson correlations are 2-tailed, with correlations highlighted in bold. Negative correlations for basic auditory measures indicate lower thresholds; positive correlations indicate higher thresholds.

As participants’ IQ appeared to be an important factor influencing their performance in the beat perception task, stringent partial correlations were computed, controlling for age, IQ, and memory. As shown in Table 6, even when age, IQ, and memory were accounted for, significant correlations between beat perception, reading, phonology, and tapping still emerged, particularly for post-intervention beat perception performance. This suggests that, as predicted, beat perception is robustly related to reading and phonological skills.
Table 6. Pearson partial correlations between beat perception, literacy, phonological awareness, psychoacoustic, and tapping measures, controlling for age, IQ, and memory across both dyslexic and control participants for (a) pre- and (c) post-intervention, as well as for (c) mean gains in improvement post-intervention.

<table>
<thead>
<tr>
<th></th>
<th>a. Pre-Intervention</th>
<th>b. Post-Intervention</th>
<th>c. Mean improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No-pitch N =39</td>
<td>+Pitch N =39</td>
<td>No-pitch N =39</td>
</tr>
<tr>
<td><strong>Literacy Measures</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>BAS reading SS</td>
<td>0.16 0.16</td>
<td><em><em>0.41</em> 0.40</em>**</td>
<td>0.33 (0.06)</td>
</tr>
<tr>
<td>BAS spelling SS</td>
<td>0.07 0.07</td>
<td><em><em>0.39</em> 0.30</em>*</td>
<td><strong>0.37</strong>*</td>
</tr>
<tr>
<td>TOWRE word reading SS</td>
<td>0.03 0.20</td>
<td>0.30 0.23</td>
<td>0.20</td>
</tr>
<tr>
<td>TOWRE non-word reading SS</td>
<td>0.12 0.11</td>
<td><em><em>0.37</em> 0.40</em>**</td>
<td><strong>0.37</strong>*</td>
</tr>
<tr>
<td><strong>Phonological Awareness Measures</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PhAB rhyme oddity SS</td>
<td>0.25 0.08</td>
<td><em><em>0.35</em> 0.39</em>**</td>
<td>0.28 (0.12)</td>
</tr>
<tr>
<td><strong>Psychoacoustic Measures</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rise time discrimination threshold</td>
<td>-0.27 -0.13</td>
<td>-0.03 0.10</td>
<td><strong>0.34</strong>*</td>
</tr>
<tr>
<td>Duration threshold</td>
<td><strong>-0.55</strong>*-0.24**</td>
<td>-0.30 -0.26</td>
<td>0.19</td>
</tr>
<tr>
<td>Intensity threshold</td>
<td>-0.11 -0.11</td>
<td>-0.03 0.10</td>
<td>0.21</td>
</tr>
<tr>
<td><strong>2 Hz Tapping</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tapping ITI post intervention</td>
<td><em><em>0.35</em> 0.28</em>*</td>
<td><em><em>0.35</em> 0.40</em>**</td>
<td>0.05</td>
</tr>
<tr>
<td>Tapping Sync post intervention</td>
<td><strong>0.43</strong>* 0.35*</td>
<td><em><em>0.39</em> 0.53</em>**</td>
<td>0.07</td>
</tr>
</tbody>
</table>

SS = standard score.
Tapping ITI = tapping inter-tap interval.
Tapping Sync = tapping synchronization.
***p < 0.001; **p < 0.01; *p < 0.05
p values, if listed, are in parenthesis beside Pearson correlation value, e.g. Pearson correlation (p-value)

The Pearson correlations are 2-tailed, with correlations highlighted in bold. Negative correlations for basic auditory measures indicate lower thresholds; positive correlations indicate higher thresholds.

To assess whether individual differences in beat perception were able to predict performance on reading, spelling, and phonological awareness tasks, we conducted a multiple linear regression analysis. For each of three fixed-entry regression equations, the dependent variable was respectively reading (BAS reading, Table 6), spelling (BAS Spelling), or phonological awareness (PhAB rhyme oddity). TOWRE non-word reading also had a strong Pearson correlation strength (Table 6), so a regression analysis with TOWRE non-word reading as the dependent variable is provided in Appendix H. Standard scores were used for reading, spelling, and phonological awareness measures.

As shown in Table 7, the predictor variables of Age and IQ were first entered in a fixed order as Step 1 and 2 respectively for each equation. As the third step, post-intervention
beat performance was entered, taking the no-pitch condition (7a), the +pitch condition (7b),
or the mean improvement over no-pitch and +pitch conditions (7c). Post-intervention beat
perception was chosen over pre-intervention beat perception for its strength of Pearson
correlation with literacy and PA measures (Table 6). The results for the multiple linear
regression analysis run with pre-intervention beat perception as the predictor variable are
shown in Table 13, Appendix I. As predicted, there were no significant associations between
pre-intervention beat perception and reading, spelling, and PA (Table 13).

The post-intervention beat perception in the no-pitch condition accounted for 12% of
unique variance in reading, 13% of unique variance in spelling, and 11% of unique variance
in phonological awareness when controlling Age and IQ (Table 7a). The beat perception task
for the +pitch condition post-intervention accounted for 9% of unique variance in reading and
11% of unique variance in phonological awareness, but was not a significant predictor for
spelling (Table 7b). Mean improvement in beat perception accounted for 10% of unique
variance in reading and 14% of unique variance in spelling, but was not a significant
predictor for phonological awareness (Table 7c). Thus, individual differences in accurate beat
perception did predict phonological awareness and reading measures for DY and CA, as
observed in Huss et al. (2011).

Unlike the beat task used in Huss et al. (2011), our task isolated duration as the sole
varying percept, while controlling for rise time and intensity. Therefore, a high beat
perception score for our task indicated an acute perception of time-lagged 100ms differences
between beats. It did not measure differences in intensity or rise time. While Huss et al.
(2011) could not attribute solely duration, rise time, intensity, or a combination of the
percepts to any of the beat perception effects they observed, we can attribute duration-based
beat perception to the literacy and PA relation we observed.
Table 7. Unique variance ($R^2$ change) in phonological and literacy outcome measures explained by no-pitch musical beat perception (7a), +pitch beat perception (7b), and mean beat perception improvement (7c) post MC/GG interventions for DY and CA participants (N=39), in 3-step fixed entry multiple regression equations.

<table>
<thead>
<tr>
<th>Step</th>
<th>Reading</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>SE B</td>
<td>Beta</td>
<td>$R^2$ change</td>
<td>B</td>
<td>SE B</td>
<td>Beta</td>
<td>$R^2$ change</td>
<td>B</td>
<td>SE B</td>
<td>Beta</td>
</tr>
<tr>
<td>7a</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>1. Age</td>
<td>-0.06</td>
<td>0.23</td>
<td>-0.04</td>
<td>0.0001</td>
<td>0.14</td>
<td>0.26</td>
<td>0.09</td>
<td>0.008</td>
<td>0.30</td>
<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td>2. IQ</td>
<td>0.40</td>
<td>0.10</td>
<td>0.52</td>
<td>0.28***</td>
<td>0.33</td>
<td>0.15</td>
<td>0.36</td>
<td>0.12*</td>
<td>0.41</td>
<td>0.11</td>
<td>0.52</td>
</tr>
<tr>
<td>3. No-Pitch Post</td>
<td>0.43</td>
<td>0.16</td>
<td>0.38</td>
<td>0.12**</td>
<td>0.45</td>
<td>0.18</td>
<td>0.40</td>
<td>0.13**</td>
<td>0.36</td>
<td>0.14</td>
<td>0.37</td>
</tr>
<tr>
<td>7b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. +Pitch Post</td>
<td>0.37</td>
<td>0.17</td>
<td>0.34</td>
<td>0.09*</td>
<td>0.30</td>
<td>0.19</td>
<td>0.27</td>
<td>0.06 (0.13)</td>
<td>0.36</td>
<td>0.14</td>
<td>0.37</td>
</tr>
<tr>
<td>7c</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Mean Improvement</td>
<td>0.55</td>
<td>0.24</td>
<td>0.31</td>
<td>0.10*</td>
<td>0.68</td>
<td>0.26</td>
<td>0.38</td>
<td>0.14**</td>
<td>0.40</td>
<td>0.21</td>
<td>0.27</td>
</tr>
</tbody>
</table>

***p < 0.001, **p < 0.01, *p < 0.05

$p$ values, if listed, are in parenthesis beside Pearson correlation value, e.g. Pearson correlation ($p$-value)

$B$ = coefficient $b_n$ for predictor variables; $SE$ $B$ = standard error of $B$; $Beta$ = standardized Beta coefficient; $R^2$ change = unique variance accounted for at each step of the three-step fixed entry multiple regression equations; IQ = FSIQ from standardized background scores; No-Pitch Post = accurate monotone beat perception performance post MC/GG intervention; +Pitch Post = accurate two-tone beat perception performance post MC/GG intervention; Mean Improvement = average of +pitch and no-pitch beat perception ability scores post MC/GG intervention subtracted by average of +pitch and no-pitch beat perception ability scores pre MC/GG intervention.
3.6 Can sensitivity to rise time predict accurate performance in the beat perception task?

Given that previous literature supports an association between amplitude envelope onset perception and musical beat perception (Huss et al., 2011; Goswami et al., 2012), it was predicted that similar relationships would be found in this study. It was hypothesized that poor discrimination of beat structure in musical sequences would be associated with difficulties in rise time perception, and that individual differences in rise time sensitivity would predict performance in the beat perception task. Also, since the beat perception task varied temporal duration, it was of interest to examine whether individual differences in duration discrimination would be predictive of beat perception performance. Note that in the beat task, beat structure was altered in the delayed trials by introducing the delayed note 100ms after onset compared to neighboring notes. This was done to alter the rhythmic structure of the selected delayed beat without altering the rhythmic temporal structure of all notes following the delay. To test these hypotheses, a further set of multiple regression analyses were conducted. The dependent variables were respectively beat perception performance for the no-pitch condition pre-intervention, +pitch condition pre-intervention, and mean improvement over combined +/- pitch conditions. Pre-intervention beat perception and mean improvement were chosen, because of the strength of their Pearson correlations (Table 6; a regression analysis with post-intervention beat perception as the dependent variable is provided in Table 14, Appendix J). Pre-intervention data was collected at the same time-point as psychoacoustic measures. The independent predictors were sensitivity to auditory rise time, duration, and intensity. Intensity was the third psychoacoustic measure used in the standardized background measures, and we predicted no relation between intensity and beat task performance.

As before, the predictor variables of Age and IQ were first entered in a fixed order as Step 1 and 2 respectively for each equation. As the third step, psychoacoustic rise time, duration, or intensity thresholds were entered. The results of this analysis are shown in Table 8. There were no significant time-lagged associations between rise time and beat perception performance for no-pitch and +pitch conditions in the current study (Tables 8 and 14). Rise time was a marginally significant predictor for mean improvement (accounted for 10% variance, \( p = 0.056 \)). This suggests that higher auditory rise time thresholds are associated with greater improved beat perception scores after intervention. Although we did not find an association between rise time and every beat perception measure, our results still indicate a link between rise time and beat perception, which supports findings from previous literature.
(Huss et al., 2011; Goswami et al., 2012). Given that our beat perception task rigorously controlled for rise time and intensity, and that rise time was still significantly related to beat perception, our results provide support for the integral role of rise time in extracting overall beat structure.

Duration accounted for 18% of unique variance in beat perception for the no-pitch condition, pre-intervention (Table 8). Also, duration was a marginally significant predictor for beat perception in the no-pitch condition, post-intervention (accounted for 8% variance, \( p = 0.057 \); Table 14, Appendix J). Duration was not a significant predictor for +pitch beat perception and mean improvement. Since participants performed significantly worse on the +pitch beat tasks (Figure 8), their difficulty performing the task may have affected the lack of significance between duration and +pitch perception. Since duration was identically varied for both +/- pitch conditions, sensitivity to duration may have predicted a similar amount of variance for both conditions had participants properly performed the +pitch task.

It was predicted that individual differences in duration perception would relate to beat perception performance, because the beat task was altered by only varying durational cues. Previous studies have not found such a link between duration and beat perception (Huss et al., 2011; Goswami et al., 2012), because they failed to isolate duration from other basic auditory cues, and neglected to use the appropriate duration threshold. Our results underscore the importance of strictly controlling for basic auditory cues, as potentially significant associations with the independent variable may be masked by the presence of additional cues.

As expected, there was no significant association between intensity thresholds and the beat perception task.
Table 8. Unique variance ($R^2$ change) in no-pitch and +pitch conditions pre MC/GG interventions, and mean improvement beat perception performance for DY and CA participants (N=39), explained by the basic auditory processing measures of rise time, duration, and intensity in 3-step fixed entry regression equations.

<table>
<thead>
<tr>
<th>Step</th>
<th>No-Pitch Pre</th>
<th>+Pitch Pre</th>
<th>Mean Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>SE B</td>
<td>Beta</td>
</tr>
<tr>
<td>1. Age</td>
<td>0.36</td>
<td>0.23</td>
<td>0.26</td>
</tr>
<tr>
<td>2. IQ</td>
<td>0.28</td>
<td>0.13</td>
<td>0.34</td>
</tr>
<tr>
<td>3. Rise time</td>
<td>-0.05</td>
<td>0.03</td>
<td>-0.26</td>
</tr>
<tr>
<td>3. Duration</td>
<td>-0.21</td>
<td>0.07</td>
<td>-0.46</td>
</tr>
<tr>
<td>3. Intensity</td>
<td>-0.34</td>
<td>0.50</td>
<td>-0.11</td>
</tr>
</tbody>
</table>

** $p < 0.01$, * $p < 0.05$

$P$ values are listed for the psychoacoustic measures of rise time, duration, and intensity thresholds. They are listed in parenthesis beside Pearson correlation value, e.g. Pearson correlation ($p$-value)

B = coefficient $b_n$ for predictor variables; SE B = standard error of B; Beta = standardized Beta coefficient; $R^2$ change = unique variance accounted for at each step of the three-step fixed entry multiple regression equations; IQ = FSIQ from standardized background scores; No-Pitch Pre = accurate monotone beat perception performance pre MC/GG intervention; +Pitch Pre = accurate two-tone beat perception performance pre MC/GG intervention; Mean Improvement = average of +pitch and no-pitch beat perception ability scores post MC/GG intervention subtracted by average of +pitch and no-pitch beat perception ability scores pre MC/GG intervention.
Since the results in this study did not support as strong of a relationship between rise time and beat perception as in Huss et al. (2011), a final multiple regression analysis was conducted to determine whether our data supported a relation between rise time and reading, spelling, and PA; a relationship that has strong empirical support for typically developing children and children with developmental dyslexia (Richardson et al., 2004; Pasquini et al., 2007; Suranyi et al., 2009; Muneaux et al., 2004; Corriveau et al., 2007; Goswami et al., 2010a; Goswami, 2011, 2012).

For each of three fixed-entry regression equations, the dependent variable was respectively reading (BAS Spelling, chosen for strength of Pearson correlation, Table 6), spelling (BAS Spelling), or phonological awareness (PhAB rhyme oddity). Standard scores were used for reading, spelling, and phonological awareness measures.

As shown in Table 9, the predictor variables of Age and IQ were first entered in a fixed order as Step 1 and 2 respectively for each equation. As the third step, rise time threshold (9a), duration threshold (9b), or intensity threshold (9c) were entered. The results of this analysis are shown in Table 9a – c.

Although previous literature supports the relation between rise time and PA and literacy measures (Goswami et al., 2010a; Goswami, 2011, 2012), there were no significant associations between rise time and reading, spelling, and PA performance in the current sample. Also, there were no significant associations between duration thresholds, or intensity thresholds, and PA and literacy measures.
Table 9. Unique variance ($R^2$ change) in phonological and literacy outcome measures explained by basic auditory processing measures of rise time (9a), duration (9b), and intensity (9c) in 3-step fixed entry multiple regression equations for both DY and CA participants (N=39).

<table>
<thead>
<tr>
<th>Step</th>
<th>Reading</th>
<th>Spelling</th>
<th>Rhyme</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>SE B</td>
<td>Beta</td>
</tr>
<tr>
<td>9a</td>
<td>1. Age</td>
<td>-0.04</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>IQ</td>
<td>0.50</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>Rise time</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>9b</td>
<td>3. Duration</td>
<td>-0.06</td>
<td>0.08</td>
</tr>
<tr>
<td>9c</td>
<td>3. Intensity</td>
<td>-0.12</td>
<td>0.52</td>
</tr>
</tbody>
</table>

***$p < 0.001$, *$p < 0.05$

$p$ values are listed for the psychoacoustic measures of rise time, duration, and intensity thresholds. They are listed in parenthesis beside Pearson correlation value, e.g. Pearson correlation ($p$-value)

B = coefficient $b_n$ for predictor variables; SE B = standard error of B; Beta = standardized Beta coefficient; $R^2$ change = unique variance accounted for at each step of the three-step fixed entry multiple regression equations; IQ = FSIQ from standardized background scores.
4 DISCUSSION

This study explored the effects of pitch and musical training on the perception of beat distribution for typically developing children (controls) and children with developmental dyslexia. We proposed that dyslexic children, with average and above average IQs, are “in tune, but out of time,” and therefore as capable as controls of performing tasks with pitch. Although the beat perception task was temporally varied, we predicted that (1) dyslexic children would perform as well as controls with pitch change as an added cue, and perform worse than controls without pitch. (2) We expected that all children’s beat detection performance would improve after rhythm-based musical training, but not with language-based Graphogame Rime training. (3) We posited that individual differences in beat perception performance would predict phonological awareness and literacy skills; and that (4) basic auditory processes such as accurate rise time and duration detection would be related to both musical beat perception, and PA and literacy development.

4.1 Effect of pitch

Consistent with our hypothesis, dyslexic children (DY) performed marginally worse than controls (CA) in the beat perception task ($p = 0.063$), but contrary to prediction, their poorer performance was observed even with pitch as an added cue. Furthermore, both groups of children performed significantly better on the no-pitch task compared to the +pitch task ($p < 0.001$; Figure 8, section 3.4), both pre and post music (MC) and Graphogame Rime (GG) intervention.

The relatively young age of participants (average age ~7-years-old) and smaller sample size ($N = 39$) compared to the participants used in Huss et al. (2011; average age ~10 years-old, $N = 64$) and Goswami et al. (2012; average age ~11-years-old, $N = 88$), may have accounted for some of the variability seen in beat task scores for both the no-pitch and +pitch conditions (Table 3, section 3.4). The demands of the beat task were also substantial for these young children, given that there were 48 trials per condition. Had there been a larger sample size, perhaps the difference observed between DY and CA would be significant. Furthermore, adding an additional perceptual dimension like pitch may have rendered the task too complicated for the younger children, possibly in part accounting for the overall worse performance for the +pitch condition.

Although studies with younger participants than ours have shown significant associations between rhythm/pitch and PA and literacy development, the tasks used in those
For example, Anvari et al. (2002) found that with 4 and 5 year-old children, melody and harmony (complex pitch and rhythm-related features) correlated consistently with phonemic awareness and reading. Their tasks comprised of (1) same/different monotone rhythm discrimination, (2) same/different melody discrimination, (3) same/different chord discrimination, (4) rhythm production, and (5) chord versus single note discrimination. Of all 5 tasks, Anvari et al.’s task (1) was the most difficult. It is similar to that of our no-pitch beat perception task; however, Anvari et al., varied all basic auditory cues with their beat change. By varying rise time, intensity, and duration all at the same time, they provided more auditory cues to assist children in discriminating rhythmic differences. The remaining tasks in Anvari et al. (2002; tasks 2 - 5) varied all basic auditory cues, multiple perceptual cues, and incorporated cross-modal multisensory effects like physical rhythmic coordination, making rhythm or pitch perception easier for these young children. Similarly, Dege and Schwarzer (2011) integrated singing, drumming, dancing, and other cross-modal multisensory tasks into their experimental design. Dellatolas et al. (2011) utilized rhythmic tapping. Even for studies that investigated rhythm and pitch perception with children aged ~7 years and older (Overy, 2003; Forgeard et al., 2008; Douglas and Willatts, 1994), the tasks employed were perceptually easier than ours, because they provided participants with more than one auditory cue and information in more than one sensory modality. Because of the musically free and ecologically valid design of these studies, single basic auditory measures like rise time, or even percepts like pitch, cannot be solely attributed as causal in the significant relations found between the children’s music task performance and literacy skills and PA in the studies (Anvari et al., 2002; Dege & Schwarzer, 2011; Dellatolas et al., 2011; Overy, 2003; Forgeard et al., 2008; Douglas and Willatts, 1994). Given the markedly different task design in these studies compared to ours, we cannot properly compare results. To our knowledge, there are no task designs in previous literature that vary simultaneously both pitch and rhythmic percepts under a tightly controlled auditory environment, as done in the current study.

One strength of our study is the strictly controlled task design. Unlike previous musical rhythm and/or pitch-based studies (Goswami et al., 2012; Huss et al., 2011; Dege & Schwarzer, 2011; Dellatolas et al., 2009; Moreno et al., 2009; Forgeard et al., 2008; Overy, 2003; Anvari et al., 2002; Douglas and Willatts, 1994), our beat perception stimuli separately controlled each basic auditory feature, allowing for the independent alteration of each
acoustic cue. Also, we designed our task such that the alterations to beat structure would affect only the selected beat. Therefore, we were able to change only one acoustic feature on one beat within a rhythmic sequence. Because of our rigorous task design, we are able to attribute changes in duration, the sole auditory cue being varied, to a causal role in each of our results.

In both no-pitch and +pitch conditions of our study, the major rhythm-varying dimension was duration. We hoped that by adding pitch, it would not only act as an attentional cue, but also provide additional auditory informational input to support rhythm detection. The model put forward by Peretz & Coltheart (2003) for musical processing suggests that pitch and temporal content are organized and processed independently and in parallel. While tonal properties, including melodic contour and successive pitch intervals, are segregated into one processing stream, all temporal content, including beat and non-periodic rhythm, are processed in a separate stream. Thus, the +pitch condition for our young subjects may have increased the processing demands of the task, possibly leading to a perceptual overload. That is, children may have found it hard to attend to both rhythm and pitch concurrently.

The prosodic and phonological impairment observed in individuals with developmental dyslexia is strongly associated with impaired sensitivity to rise time, not to pitch perception (Goswami et al., 2012; Thomson & Goswami, 2008; Hamalainen et al., 2012). Recall that rise time is vital for the temporal segmentation of speech (Goswami, 2011), and important for the rhythmic perception of music (See Introduction sections 1.1.1 and 1.2.1; Thomson & Goswami, 2008; Wolff, 2002). Also, individual differences in sensitivity to rise time are linked to accurate rhythmic entrainment to a 2 Hz (120 beats per minute) beat, which was the rate at which our beats were played (Thomson & Goswami, 2008; Goswami, 2011). While pitch perception is an important component of prosody, it may not play as important a role in developmental language disorders. In a meta-analysis, Hamalainen et al. (2012) found that pitch discrimination was linked to developmental dyslexia in only 57% of the studies they reviewed measuring performance in non-speech auditory processing tasks in dyslexia and associations with reading. By contrast, amplitude modulation and rise time discrimination was associated with developmental dyslexia in 100% of the studies they reviewed (See Introduction section 1.1.2). Thus, we expected our dyslexic participants to be able to perceive the change in pitch and perhaps use the added perceptual information to detect the temporal difference in beat. Perhaps with older children, the addition of pitch would indeed assist in the detection of temporal beats.
Although dyslexics did not show a selective benefit in the +pitch condition, DY were still able to perform the task above chance without ceiling effects for both +/- pitch conditions. Furthermore, the participants in our study were, on average, 3 years younger than the participants in Huss et al. (2011), and our DY performed only marginally worse ($p = 0.063$) than our CA (Huss et al.’s DY performed significantly worse by $p < 0.001$). That is, our DY participants were only marginally worse at detecting temporal differences of 100ms in beat position compared to our CA children. Taken together, sensitivity to duration is not likely a primary contributor to the difficulties found in rhythmic beat computation in dyslexia.

Note that this finding does not eliminate duration perception from playing a role in beat perception, rather, this finding only suggests that duration perception did not cause the difference in performance observed between DY and CA in previous beat studies (e.g. Huss et al., 2011; Goswami et al., 2012). Our finding also indicates that Huss et al. (2011) and Goswami et al. (2012) were unable to isolate duration from the other basic auditory cues in their task. Although they claimed to have altered only duration, Huss et al. (2011) and Goswami et al. (2012) inadvertently varied rise time and intensity. Therefore, they could not attribute solely rise time, intensity, duration, or a specific combination of the auditory features to the beat effects they observed. Our findings narrow the auditory cues responsible for causing the significant difference in beat performance between DY and CA in Huss et al. (2011) and Goswami et al. (2012) down to rise time and intensity. The concurrent rise time changes with duration most likely explain Huss et al.’s and Goswami et al.’s highly significant association between rise time and beat perception performance, and the significant difference between DY and CA. Since impaired sensitivity to rise time is linked to dyslexia (Goswami et al., 2002; Corriveau et al., 2007; Hamalainen et al., 2012; Pasquini et al., 2007; Richardson et al., 2004; Thomson & Goswami, 2008), and rise time relates to improved performance in the current beat task (Table 6, section 3.5), it is probable that sensitivity to rise time, rather than intensity, primarily contributed to the significant difference in beat perception between DY and CA in Huss et al. (2011) and Goswami et al. (2012). If changes in rise time were included with changes in duration in our beat task, like in Huss et al. (2011) and Goswami et al. (2012), our DY would likely perform worse than our CA at greater significance.
4.2 Effect of intervention

After twenty sessions of 20-30 minutes of music or Graphogame Rime training per session, the dyslexic children who received a MC intervention demonstrated as great of an improvement in beat perception as their respective controls. It even appeared that dyslexic children benefited more than controls after receiving MC training (1.8% vs -0.7%), although this difference between groups did not reach significance ($p = 0.09$). However, for the GG intervention, dyslexic children showed the opposite trend, showing a mean decrement in performance (-2.7%) that was significantly different to the healthy improvement of 8% observed for controls ($p = 0.009$; Figure 10, section 3.4). While we had predicted greater gains for MC training for dyslexics, the negative effect of GG training on dyslexics' beat perception was not anticipated.

The musical intervention was based on non-linguistic rhythm, with the aim of linking beat structure in music and language. It was a modified version of that used in Bhide et al. (2013), which showed equivalent benefits for reading and phonological development compared to Graphogame Rime. The MC intervention included cross-modal, multisensory beat training, like marching, clapping, drumming, and singing to the beat of a song or rhythm. These auditory-motor activities have been shown to constrain individual’s relative timing, reducing degrees of freedom, and increasing accuracy of beat entrainment (Cummins & Port, 1998). Repeated practice of accurate beat entrainment may have enhanced the children’s ability to detect disturbances in the beat for the beat perception task post-intervention. As the MC intervention directly trained rhythmic entrainment and beat perception, and GG specifically trained reading and phonology, we expected beat perception to improve after the MC, but not the GG intervention. The results obtained with the dyslexic group followed this predicted trend. However, the robust improvement in beat perception observed in controls after GG training (but not MC training) was surprising.

For Graphogame Rime, control participants may have already mastered the larger phonological grain sizes (e.g. syllable stress units), and were able to utilize the GG intervention to elaborate their phonological representations at smaller grain sizes (e.g. phonemes). Granularity refers to the level of mappings between the sounds and symbols in a language, whether they are smaller or larger sized units. According to the Psycholinguistic Grain Size Theory (Ziegler & Goswami, 2005, 2006), reading development depends upon the abstraction of optimal mappings between orthographic units and phonology. Controls may have improved their beat perception after GG training by enhancing their temporal sensitivity to sound units at smaller grain sizes, which requires more fine-grained temporal acuity.
Although Graphogame Rime is a large grain task and is designed to benefit only reading and phonology, the game does involve smaller grain size elements like phonemes (e.g. “a” and “t”; refer to Methods section 2.5.2). These elements could have made CA more sensitive to the durational changes in general, thus benefiting them in the beat perception task. To learn how to read, a child must be able to find shared grain sizes in the orthography and phonology of their language that allow mapping between the two domains. The quality and grain size of phonological representations prior to reading plays a role in reading acquisition (Ziegler & Goswami, 2005; Perfetti, 1992; Wydell & Butterworth, 1999). Indeed, dyslexics exhibit deficits in the representation and use of phonological information across languages, and difficulties in phonological recoding at small grain sizes (Zeigler & Goswami, 2005; Snowling, 2000). Thus, the dyslexic children in our study, with reduced awareness of both small and large grain size, may have had more difficulty improving their fine-grained temporal acuity, as they had weaker pre-existing large grain skills to build upon. Training with GG appeared to have none, if not detrimental, effects on dyslexic children's beat perception (Figure 9 and 10, section 3.4), presumably because their underlying large-grained phonological representations were not sufficiently robust enough to perform the task, and GG only trained for reading and phonology. This predicts that for dyslexic children, training with music prior to GG training could produce more optimal effects.

It is also possible that while in school, the CA children, who have unimpaired PA, may have improved their rhythmic timing skills through training, from which DY did not benefit. The intervention took approximately one month to complete all twenty sessions. During this time, the schools provided a range of language- and music-based lessons that could have honed rhythmic skills for CA, but not necessarily for DY. This alternative is possible, because Graphogame Rime is designed to benefit only reading and phonology, and the current study is the first to report crossover effects to music.

4.3 Beat perception as a predictor of PA and literacy

As predicted, individual differences in beat perception were strongly associated with phonological and reading measures (Table 7, section 3.5). The beat perception task accounted for 11% of unique variance in phonological awareness, even after controlling for age and IQ ($p < 0.01$) in the no-pitch condition and 11% in the +pitch condition ($p < 0.01$). Furthermore, beat perception measures accounted for 31% of unique variance in reading measures and 27% of unique variance in spelling measures, controlling for age and IQ.
These predictions support those reported in previous beat perception studies (Huss et al., 2011; Goswami et al., 2012). This is notable because the auditory stimuli in our study were tightly controlled. As mentioned previously (Introduction, section 1.2.2), Huss et al. (2011) and Goswami et al. (2012) not only inadvertently altered the rise time and intensity of the elongated note, but also altered all basic auditory cues of the neighboring notes by using the Sibelius accent and fermata. Because sensitivity to auditory rise time and duration are associated with literacy and PA measures (Goswami et al., 2002; Corriveau et al., 2007; Hamalainen et al., 2012; Pasquini et al., 2007; Richardson et al., 2004; Thomson & Goswami, 2008), one would expect that Huss et al. (2011) and Goswami et al. (2012) would observe an association between their beat task and reading and PA measures. We modified their beat task to test strictly durational changes in beat structure. The current data suggest that musical beat perception, with only duration varied, is still closely associated with phonological and thereby literacy development via prosody.

Note that for all our regression analyses (Tables 7 - 9, 12 – 14) IQ is a significant predictor for beat perception, and for reading, spelling, and PA measures, even though the DY and CA groups were matched on IQ and age. Standardized scores were used for IQ, and all literacy and PA measures. This is an uncommon finding and could be attributed in part to the young age of our participants. Further research with younger children is required to understand the role of IQ in these measures.

In addition to the strong associations between beat perception, and phonological awareness and literacy measures, there were also significant correlations between beat perception and rise time, beat perception and duration, and beat perception and rhythmic entrainment, discussed later.

4.4 Rise time and beat perception

We observed an association between beat perception and rise time in the current study (Table 8, section 3.6). This finding is consistent with the literature that suggests sensitivity to auditory rise time is a unique predictor of both musical beat perception and written language development (Introduction, sections 1.1.1 and 1.2.1; Huss et al., 2011; Goswami et al., 2012). Here, rise time was a marginally significant predictor for mean improvement in the beat perception task (accounted for 10% variance, \( p = 0.056 \)). Although the association in the current study was modest, its presence was noteworthy since we controlled for rise time when creating the beat perception task. Our smaller sample size may have also been a factor. The positive correlation between rise time and mean improvement (Table 6, section 3.5; \( p < \)
0.05) indicated that the higher the rise time threshold, the greater the gain in beat perception improvement. Therefore, participants with higher rise time thresholds (lower sensitivity) improved more, or may have had more room to allow for improvement after intervention, than participants with lower rise time thresholds (high sensitivity).

Duration accounted for 18% of unique variance in beat perception for the no-pitch condition, pre-intervention (Table 8, section 3.6), and 8% of unique variance for the no-pitch condition, post-intervention (duration was a marginally significant predictor in this case, \( p = 0.057 \); Table 14, Appendix J). The significantly worse performance on +pitch beat tasks (Figure 8, section 3.4) likely contributed to the lack of association between duration and +pitch perception. Because duration was identically varied in both conditions, sensitivity to duration would have likely predicted a similar percent variance for both conditions had the +pitch task not been more difficult for our young participants. The lack of association between sensitivity to duration and +pitch beat perception also suggests that participants could not properly perform the +pitch task, that is, their performance of the +pitch task was not a true representation of their beat perception ability with the added cue of pitch.

The link between duration perception and performance on our beat task was predicted, because our beat perception task varied solely duration at participants’ measured duration thresholds (Table 1; section 2.3.5). Huss et al. (2011) and Goswami et al. (2012) did not find such a link between duration and beat perception, but their studies did not isolate duration as the sole auditory variable in their rhythm task, and did not vary duration at their participants’ thresholds. Our results indicate the importance of strictly controlling for all but one basic auditory cue when investigating beat perception in children, as associations may become masked by the presence of additional cues. Also, our results indicate that we were able to successfully isolate duration as the rhythm-producing variable because (1) our task enabled DY to perform nearly as well as CA (section 3.3), an effect that may not have occurred if rise time was not controlled for, and (2) duration predicted our duration-varied beat perception tasks, which was not the case with beat perception tasks in previous studies (Huss et al., 2011; Goswami et al., 2012).

The lack of relation between rise time and literacy and PA measures was unexpected (Table 9, section 3.6). Given the breadth of literature that supports the relationship between rise time and PA and reading (Goswami et al., 2002; Hamalainen et al., 2012), it is likely that some feature about our participants, for example their young age, may have impacted our rise time/literacy association measures.

Nevertheless, the link between rise time sensitivity and performance on our duration-
varied beat task indicates that rise time is an important factor in the perception of global rhythmic beat structure, when perceiving both music and language. These results support the “temporal sampling framework” proposed for developmental dyslexia, in which difficulties processing certain aspects of auditory temporal structure, specifically rise time discrimination, impair both musical processing and reading development in affected children (Goswami, 2011; Introduction sections 1.1, 1.2.1).

The temporal sampling framework suggests that music and language processing depend on the accurate temporal sampling of auditory input by the different firing rates of oscillating neural mechanisms. Theoretically these neural networks entrain their oscillations with the auditory input rhythms by aligning excitatory spikes with matching events in the input, like the peak amplitude of stressed syllables (Schroeder & Lakatos, 2009). For temporal sampling to facilitate rhythmic temporal perception, amplitude modulations at 0.5 - 4 or 4 - 8 Hz (theta and delta rhythms; Goswami, 2011) are important. These low frequency modulations are essential for the perception of both music- and language-based rhythm, providing cues to stressed and unstressed notes and beats. As mentioned earlier (Introduction, section 1.2.1), the alternation of strong and weak beats found in music and speech is central to the sequential organization of sounds in both domains (Arvaniti, 2009). Thus, despite music having periodic rhythm and language having non-periodic rhythm, the same neural networks are likely involved in processing beat distribution, as suggested by adult and infant data, and by the universal (2Hz) stressed syllabic rhythmic rates used by speakers across languages (Patel, 2008; Avartini, 2009; Goswami, 2012). This 2Hz rate (discussed in further detail in section 4.5) may support language acquisition by providing a foundation to which the developing brain may entrain, enabling individuals to anticipate important information in speech on the basis of acoustic patterning for arriving stressed syllables. For phonological development, infants may locate such syllable beats using rise time. With rise time sensitivity underpinning the expectancy framework, infants may consequently develop sensitivity to higher-order temporal structure for non-periodic and periodic rhythm, like aural differences in grouping and duration in language (Goswami, 2011). Given this developmental perspective (Goswami, 2011), impaired rise time and impaired global beat perception, as found in dyslexia (Huss et al., 2011; Goswami et al., 2012), may disrupt the efficient processing and accurate encoding of syllable stress in language, and affect the quality of phonological development. This developmental perspective fits the data reported in the current study, as individual differences in rise time were related to individual differences in beat distribution, and individual differences in beat perception were related to individual
differences in both phonological awareness and literacy measures.

4.5 Rhythmic entrainment and beat perception

Additionally, it is worth noting that there were strong correlations between rhythmic entrainment to a 2Hz beat (120 beats per minute, 500ms pulse rate; an intervention task) and performance in the beat perception task (Tables 5 and 6, section 3.5). Even when age and IQ were accounted for, significant correlations between 2Hz entrainment and beat perception remained for each condition, pre and post intervention. As both tapping and beat perception required individuals to attend to the temporal position of the beats, and both were set at 2Hz, this correlation between tasks was expected.

There is a growing body of evidence that suggests that 2Hz could be a biologically privileged rate. For example, when mothers sing to their infants, the average tempo is 120bpm (Trainor et al., 1997). When children 8 years and above and adults tap spontaneously to various kinds of music, they also converge at a 2Hz rate (McAuley et al., 2006). Similarly, spontaneous applause converges at 2Hz when it is rhythmically synchronized (Neda et al., 2000). Linguistic reviews of rhythmic processing have shown that, across languages, the occurrence of stressed syllables also occurs on average, at a 2 Hz rate (Arvaniti, 2009). These findings suggest that biologically, a 2Hz rate emerges because of physiological factors, which constrain the production of bodily motor movements; and these may be the same factors that are impaired in individuals with developmental language disorders. The inability or ability to perceive and entrain to this rate has been linked to sensitivity in basic auditory parameters such as rise time (Goswami, 2011; Schwartz et al., 2003). Rise time has also been suggested as the underlying perceptual link between musical beat perception, and phonology and literacy (Huss et al., 2011; Goswami et al., 2012).

4.6 Conclusion

This investigation strengthens the hypothesis that perception of musical beat patterns is related to phonological and literacy skills, and perceptual sensitivity to sound rise time may contribute uniquely to both musical beat perception and written language development. Additionally, our study indicates that musical interventions may be particularly beneficial for dyslexic children to improve beat perception. Further studies with a larger sample size and older participants (10+ years old) are needed to investigate whether adding pitch may benefit dyslexic children’s ability to perceive a temporal change in beat pattern, as the young children in this current study appeared to struggle to process or attend simultaneously to
information from two different auditory dimensions (pitch and rhythm). Also, simplification of the beat task by delaying only the 2nd or 3rd beat may refine the pitch manipulation. This is because delays on the 2nd or 3rd beat are the most perceptually obvious (Huss et al., 2011), and may make the isolation of the beat dimension more cognitively accessible. Additional future studies should investigate whether combining MC and GG interventions will improve beat perception more than MC or GG alone. Also, it would be interesting to study whether there is an added benefit for training MC before GG, or GG before MC, when combining interventions. Since training with GG appeared to have none, or even detrimental effects on dyslexic children's beat perception, training with music prior to GG training could produce more optimal effects for poor readers, as MC training could strengthen complementary auditory abilities for GG. If MC trains and GG refines large-grained temporal representations, then a combination of the two interventions may enable greater improvement of children’s large-grained phonological representations, and may even improve fine-grained temporal acuity for children at all reading-levels. It also may prove beneficial to evaluate which of the exercises in the musical intervention most improved musical beat perception, as improvements in beat perception are associated with improved phonological awareness and literacy development.
REFERENCES


APPENDIX A

Beat Perception Task, Sheet Music of Stimuli*

No-Pitch Trials:
1. Standard

2. Delay on 1st Beat

3. Delay on 2nd Beat

4. Delay on 3rd Beat

5. Delay on 4th Beat

+Pitch Trials:
1. Standard, pitch change on 1st Beat

2. Delay on 1st Beat
3. Standard, pitch change on 2nd Beat

4. Delay on 2nd Beat

5. Standard, pitch change on 3rd Beat

6. Delay on 3rd Beat

7. Standard, pitch change on 4th Beat

8. Delay on 4th Beat

*Note that the written sixteenth note rests are approximations of the delays. In the delivered trials, all delayed beats arrived exactly 100ms after the 120bpm beat. All beats, including delayed beats, were 300ms in duration. Stimuli were sine tones, created using Audacity software.
APPENDIX B

Schedule of Tasks for the Musical Intervention

Session 1
1. Beat Perception Task
2. Rhythmic Entrainment to 120bpm

Session 2
1. Drumming to Instrumental Music
   a. African Warm Up – Zumba
2. Marching to Instrumental Music
   a. African Warm Up – Zumba
3. Rhythmic Entrainment to Musical Tempos
   a. 60bpm
4. Discrimination between Two Tempos
   a. 90 vs. 130 bpm
5. Discrimination between Two Rhythmic Sequences
   a. #1
6. Syllabic Stress and Rhythmic Command in Poetry
   a. Now We Are Six

Session 3
1. Drumming to Instrumental Music
   a. Sous Le Soleil – Gotan Project
2. Rhythmic Entrainment to 120bpm
3. Discrimination between Two Tempos
   a. 70 vs. 70 bpm
4. Discrimination between Two Rhythmic Sequences
   a. #2
5. Vocal imitation of a rhythmic sequence
   a. #1
6. Dee-Dee Game Practice, 1st half of trials

Session 4
1. Marching to Instrumental Music
   a. Sous Le Soleil – Gotan Project
2. Rhythmic Entrainment to Musical Tempos
   a. 80 bpm
3. Vocal imitation of a rhythmic sequence
   a. #2
4. Syllabic Stress and Rhythmic Command in Poetry
   a. The Little Ducks
Session 5
1. Drumming to Instrumental Music
   a. Chinese Checkers – Booker T. & The MG’s
2. Rhythmic Entrainment to 120bpm
3. Discrimination between Two Tempos
   a. 85 vs. 55 bpm
4. Discrimination between Two Rhythmic Sequences
   a. #3
5. Dee-Dee Game Practice, 2nd half of trials

Session 6
1. Marching to Instrumental Music
   a. Chinese Checkers – Booker T. & The MG’s
2. Rhythmic Entrainment to Musical Tempos
   a. 100 bpm
3. Vocal imitation of a rhythmic sequence
   a. #3
4. Syllabic Stress and Rhythmic Command in Poetry
   a. I’d Rather have Fingers than Toes

Session 7
1. Drumming to Instrumental Music
   a. Blitz – Digitalism
2. Rhythmic Entrainment to 120bpm
3. Discrimination between Two Tempos
   a. 170 vs. 200 bpm
4. Discrimination between Two Rhythmic Sequences
   a. #4
5. Dee-Dee Game Practice, 1st half of trials

Session 8
1. Marching to Instrumental Music
   a. Blitz – Digitalism
2. Rhythmic Entrainment to Musical Tempos
   a. 120 bpm
3. Vocal imitation of a rhythmic sequence
   a. #4
4. Syllabic Stress and Rhythmic Command in Poetry
   a. Five Little Owls

Session 9
1. Drumming to Instrumental Music
   a. Tango Flamenco – Gipsy Kings
2. Rhythmic Entrainment to 120bpm
3. Discrimination between Two Tempos
   a. 140 vs. 140 bpm
4. Discrimination between Two Rhythmic Sequences
   a. #5
5. Dee-Dee Game Practice, 2nd half of trials
Session 10
1. Marching to Instrumental Music
   a. Tango Flamenco – Gipsy Kings
2. Rhythmic Entrainment to Musical Tempos
   a. 140 bpm
3. Vocal imitation of a rhythmic sequence
   a. #5
4. Syllabic Stress and Rhythmic Command in Poetry
   a. Duck Weather

Session 11
1. Drumming to Instrumental Music
   b. Slow Beat
   c. Fast Beat
2. Rhythmic Entrainment to 120bpm
3. Discrimination between Two Tempos
   a. 190 vs. 190 bpm
4. Discrimination between Two Rhythmic Sequences
   a. #6
5. Repeat of Vocal imitation of a rhythmic sequence
   a. #1
6. Dee-Dee Game Full

Session 12
1. Marching to Instrumental Music
   b. Slow Beat
   c. Fast Beat
2. Rhythmic Entrainment to Musical Tempos
   a. 60 bpm
3. Vocal imitation of a rhythmic sequence
   a. #6
4. Syllabic Stress and Rhythmic Command in Poetry
   a. The Crocodile and the Lady
   b. Memorization, 6 lines

Session 13
1. Drumming to Instrumental Music
   a. Diablo Rojo – Rodrigo y Gabriela
   b. Slow Beat
   c. Fast Beat
2. Rhythmic Entrainment to 120bpm
3. Discrimination between Two Tempos
   a. 65 vs. 85 bpm
4. Discrimination between Two Rhythmic Sequences
   a. #7
5. Repeat of Vocal imitation of a rhythmic sequence
   a. #2
6. Dee-Dee Game Full
Session 14
1. Marching to Instrumental Music
   a. Diablo Rojo – Rodrigo y Gabriela
   b. Slow Beat
   c. Fast Beat
2. Rhythmic Entrainment to Musical Tempos
   a. 80 bpm
3. Vocal imitation of a rhythmic sequence
   a. #7
4. Syllabic Stress and Rhythmic Command in Poetry
   a. Hand on the Bridge
   b. Memorization, 8 lines

Session 15
1. Drumming to Instrumental Music
   a. Hip Hug-Her – Booker T. & The MG’s
   b. Slow Beat
   c. Fast Beat
2. Rhythmic Entrainment to 120bpm
3. Discrimination between Two Tempos
   a. 65 vs. 65 bpm
4. Discrimination between Two Rhythmic Sequences
   a. #8
5. Repeat of Vocal imitation of a rhythmic sequence
   a. #3
6. Syllabic Stress and Rhythmic Command in Poetry
   a. Windy Nights
   b. Memorization, 6 lines

Session 16
1. Marching to Instrumental Music
   a. Hip Hug-Her – Booker T. & The MG’s
   b. Slow Beat
   c. Fast Beat
2. Rhythmic Entrainment to Musical Tempos
   a. 100 bpm
3. Vocal imitation of a rhythmic sequence
   a. #8
4. Syllabic Stress and Rhythmic Command in Poetry
   a. Free choice poem memorization, 6-8 lines
Session 17
1. Drumming to Instrumental Music
   a. Selber – Paul Kalkbrenner
   b. Slow Beat
   c. Fast Beat
2. Rhythmic Entrainment to 120bpm
3. Discrimination between Two Tempos
   a. 110 vs. 110 bpm
4. Discrimination between Two Rhythmic Sequences
   a. #9
5. Repeat of Vocal imitation of a rhythmic sequence
   a. #4
6. Syllabic Stress and Rhythmic Command in Poetry
   a. Bed in Summer, 8 lines

Session 18
1. Marching to Instrumental Music
   a. Selber – Paul Kalkbrenner
   b. Slow Beat
   c. Fast Beat
2. Rhythmic Entrainment to Musical Tempos
   a. 120 bpm
3. Vocal imitation of a rhythmic sequence
   a. #9
4. Syllabic Stress and Rhythmic Command in Poetry
   a. Free choice poem memorization, 6-8 lines

Session 19
1. Drumming to Instrumental Music
   a. Moorea – Gipsy Kings
   b. Slow Beat
   c. Fast Beat
2. Rhythmic Entrainment to 120bpm
3. Discrimination between Two Tempos
   a. 110 vs. 130 bpm
4. Discrimination between Two Rhythmic Sequences
   a. #10
5. Repeat of Vocal imitation of a rhythmic sequence
   a. #5
6. Syllabic Stress and Rhythmic Command in Poetry
   a. From a Railway Carriage
   b. Memorization, 4 lines
Session 20

1. Marching to Instrumental Music
   a. Moorea – Gipsy Kings
   b. Slow Beat
   c. Fast Beat
2. Rhythmic Entrainment to Musical Tempos
   a. 140 bpm
3. Vocal imitation of a rhythmic sequence
   a. #10
4. Beat Perception Task
APPENDIX C

*Discrimination between Two Rhythmic Sequences Task Sheet Music*

#1 (‘Different’ sequence trial)

\[
\begin{array}{c}
\frac{4}{4} \quad \boxed{\text{P} \quad \text{P} \quad \boxed{\text{1}} \quad \boxed{\text{P} \quad \text{P} \quad \boxed{\text{1}}}} \\
\end{array}
\]

#2 (‘Different’ sequence trial)

\[
\begin{array}{c}
\frac{4}{4} \quad \boxed{\text{P} \quad \text{P} \quad \boxed{\text{1}} \quad \boxed{\text{P} \quad \text{P} \quad \boxed{\text{1}}}} \\
\end{array}
\]

#3 (‘Same’ sequence trial)

\[
\begin{array}{c}
\frac{4}{4} \quad \boxed{\text{P} \quad \text{P} \quad \boxed{\text{1}} \quad \boxed{\text{P} \quad \text{P} \quad \boxed{\text{1}}}} \\
\end{array}
\]

#4 (‘Different’ sequence trial)

\[
\begin{array}{c}
\frac{4}{4} \quad \boxed{\text{P} \quad \text{P} \quad \boxed{\text{1}} \quad \boxed{\text{P} \quad \text{P} \quad \boxed{\text{1}}}} \\
\end{array}
\]

#5 (‘Different’ sequence trial)

\[
\begin{array}{c}
\frac{4}{4} \quad \boxed{\text{P} \quad \text{P} \quad \boxed{\text{1}} \quad \boxed{\text{P} \quad \text{P} \quad \boxed{\text{1}}}} \\
\end{array}
\]

#6 (‘Same’ sequence trial)

\[
\begin{array}{c}
\frac{4}{4} \quad \boxed{\text{P} \quad \text{P} \quad \boxed{\text{1}} \quad \boxed{\text{P} \quad \text{P} \quad \boxed{\text{1}}}} \\
\end{array}
\]

#7 (‘Different’ sequence trial)

\[
\begin{array}{c}
\frac{4}{4} \quad \boxed{\text{P} \quad \text{P} \quad \boxed{\text{1}} \quad \boxed{\text{P} \quad \text{P} \quad \boxed{\text{1}}}} \\
\end{array}
\]
#8 (‘Different’ sequence trial)

#9 (‘Same’ sequence trial)

#10 (‘Different’ sequence trial)
APPENDIX D

Vocal Imitation of a Rhythmic Sequence Task Sheet Music

#1
\[ \begin{array}{c}
\frac{4}{4} \\
\end{array} \]

#2
\[ \begin{array}{c}
\frac{4}{4} \\
\end{array} \]

#3
\[ \begin{array}{c}
\frac{4}{4} \\
\end{array} \]

#4
\[ \begin{array}{c}
\frac{4}{4} \\
\end{array} \]

#5
\[ \begin{array}{c}
\frac{4}{4} \\
\end{array} \]

#6
\[ \begin{array}{c}
\frac{4}{4} \\
\end{array} \]

#7
\[ \begin{array}{c}
\frac{4}{4} \\
\end{array} \]
APPENDIX E
Poems and Questions Used in the Syllabic Stress and Rhythmic Command in Poetry Task

1. **Now We Are Six** (By A.A. Milne)

When I was one I had just begun
When I was two I was nearly new

When I was three I was hardly me
When I was four I was not much more

When I was five I was just alive
But now I am six, I'm as clever as clever;

So I think I'll be six now for ever and ever.

1. Which is the right way of saying this word?—**CLEver** or cle**VER**?

2. Would the rhythm of the poem be messed up if I replaced the word “hardly” with “definitely”? (Read the poem from the beginning, with both versions)

3. Which way ruins the rhythm?
When I was one I had just begun
I was two when I was nearly new
OR
When I was one I had just begun
When I was two I was nearly new
2. **The Little Ducks** (Unknown Author)

Have you seen the little ducks
Swimming in the water?
Mother, father, baby ducks
Grand-mamma and daughter

Have you seen them dip their bills
Swimming in the water?
Mother, father, baby ducks,
Grand-mamma and daughter

Have you seen them flap their wings
Swimming in the water?
Mother, father, baby ducks
Grand-mamma and daughter.

1. Which is the right way of saying this word?—**GRAND**-mamma or grand-**MAM**ma?

2. Would the rhythm of the poem be messed up if I replaced the word “Grand-mamma” with “Aunt”? (Read the poem from the beginning, with both versions)

3. Which way ruins the rhythm?
Have you seen the little ducks
Swimming in the water?
Mother, father, baby ducks
Grand-mamma and daughter
OR
Have you seen the little ducks
Swimming in the water?
Mother, father, baby ducks
Daughter and Grand-mamma
3. **I’d Rather have Fingers than Toes** (Unknown Author)

I’d rather have fingers than toes  
I’d rather have eyes than a nose  
And as for my hair, I’m glad that its there  
I’ll be sorry, you bet, when it goes

For beauty I am not a star  
There are many more handsome by far  
In fact, I don’t mind it, for I am behind it,  
It’s the people in front get the jar.

1. Which is the right way of saying this word?—**RA**ther or ra**THER**?

2. Would the rhythm of the poem be messed up if I replaced the word “eyes” with “a bottom”? (Read the poem from the beginning, with both versions)

3. Which way ruins the rhythm?  
I’d rather have fingers than toes  
I’d rather have eyes than a nose  
And as for my hair, I’m glad that its there  
I’ll be sorry, when it goes, you bet!  
OR  
I’d rather have fingers than toes  
I’d rather have eyes than a nose  
And as for my hair, I’m glad that its there  
I’ll be sorry, you bet, when it goes
4. *Five Little Owls* (Unknown Author)

Five little owls in an old elm-tree  
Fluffy and puffy as owls could be  
Blinking and winking with big round eyes  
At the big round moon that hung in the skies

As I passed beneath I could hear one say  
“There’ll be mouse for supper today”  
Then all of them hooted, too-whit, too-whoo  
“Yes mouse for supper!” Hoo Hoo Hoo

1. Which is the right way of saying this word?—BEneath or beNEATH?

2. Would the rhythm of the poem be messed up if I replaced the word “winking” with “awake”? (Read the poem from the beginning, with both versions)

3. Which way ruins the rhythm?
Five little owls in an old elm-tree  
Fluffy and puffy as owls could be  
Blinking and winking with big round eyes  
At the big round moon that hung in the skies
OR  
Five little owls in an old elm-tree  
As owls could be, fluffy and puffy  
Blinking and winking with big round eyes  
At the big round moon that hung in the skies
5. **Duck Weather** (By Shirley Hughes)

Splishing, splashing in the rain
Up the street and back again
Stomping, stamping through the flood
We don't mind a bit of mud
Running pavements, gutters flowing
All the cars with wipers going
We don't care about the weather
Tramping hand in hand together
We don't mind a damp wet day
Sloshing puddles all the way
Splishing, splashing in the rain
Up the street and back again

1. Which is the right way of saying this word?— **FLOW**ing or flow**ING**?

2. Would the rhythm of the poem be messed up if I replaced the word “cars” with “vehicles”? (Read the poem from the beginning, with both versions)

3. Which way ruins the rhythm?
   Splishing, splashing in the rain
   Up the street and back again
   Stomping, stamping through the flood
   We don't mind a bit of mud
   OR
   Splishing, splashing in the rain
   Up the street and back again
   Stomping, stamping through the flood
   A bit of we don’t mind mud
6. *The Crocodile and the Lady* (Unknown Author)

She sailed away
On a lovely summer’s day
On the back of a crocodile.

“You see” said she
“He’s as tame as can be
I’ll float him down the Nile”.

The croc winked his eye
As she waved them all goodbye
Wearing a sunny smile

At the end of the ride
The lady was inside
And the smile on the crocodile.

1. Which is the right way of saying this word?— SUMmer or sumMER?

2. Would the rhythm of the poem be messed up if I replaced the word “Nile” with “River Cam”? (Read the poem from the beginning, with both versions)

3. Which way ruins the rhythm?
The croc winked his eye
All goodbye as she waved them
Wearing a sunny smile
Or
The croc winked his eye
As she waved them all goodbye
Wearing a sunny smile
7. **Hand On The Bridge** (By Michael Rosen)

Hand on the bridge,
Feel the rhythm of the train.
Hand on the window
Feel the rhythm of the rain.
Hand on your throat
Feel the rhythm of your talk
Hand on your leg
Feel the rhythm of your walk
Hand in the sea
Feel the rhythm of the tide
Hand on your heart
Feel the rhythm inside
Hand on the rhythm
Feel the rhythm of the rhyme
Hand on your life
Feel the rhythm of time
Hand on your life
Feel the rhythm of time
Hand on your life
Feel the rhythm of time.
8. *Windy Nights* (By Robert Louis Stevenson)
Whenever the moon and stars are set,
Whenever the wind is high,
All night long in the dark and wet,
A man goes riding by.
Late in the night when the fires are out,
Why does he gallop and gallop about?

Whenever the trees are crying aloud,
And ships are tossed at sea,
By, on the highway, low and loud,
By at the gallop goes he.
By at the gallop he goes, and then
By he comes back at the gallop again.

1. Which is the right way of saying this word? — **RIding** or ri**DING**?

2. Would the rhythm of the poem be messed up if I replaced the word “man” with “gentleman”? (Read the poem from the beginning, with both versions)

3. Which way ruins the rhythm?
Whenever the moon and stars are set,
Whenever the wind is high,
All night long in the dark and wet,
A man goes riding by.

OR

Whenever the moon and stars are set,
Is whenever the wind high,
All night long in the dark and wet,
A man goes riding by.
9. **Bed in Summer** (By Robert Louis Stevenson)

In winter I get up at night
And dress by yellow candlelight
In summer, quite the other way
I have to go to bed by day.

I have to go to bed and see
The birds still hopping on the tree
Or hear the grown-up people’s feet
Still going past me in the street.

And does it not seem hard to you
When all the sky is clear and blue
And I should like so much to play
To have to go to bed by day?

1. Which is the right way of saying this word?— **SUM**mer or **sumMER**?

2. Would the rhythm of the poem be messed up if I replaced the word “candlelight” with “moon”? (Read the poem from the beginning, with both versions)

3. Which way ruins the rhythm?
   I have to go to bed and see
   Still hopping on the tree the birds
   Or hear the grown-up people’s feet
   Still going past me in the street.
   OR
   I have to go to bed and see
   The birds still hopping on the tree
   Or hear the grown-up people’s feet
   Still going past me in the street.
10. **From a Railway Carriage** (By Robert Louis Stevenson)

Faster than fairies, faster than witches,
Bridges and houses, hedges and ditches;
And charging along like troops in a battle
All through the meadows the horses and cattle:
All of the sights of the hill and the plain
Fly as thick as driving rain;
And ever again, in the wink of an eye,
Painted stations whistle by.
Here is a child who clambers and scrambles,
All by himself and gathering brambles;
Here is a tramp who stands and gazes;
And here is the green for stringing the daisies!
Here is a cart runaway in the road
Lumping along with man and load;
And here is a mill, and there is a river:
Each a glimpse and gone forever!

1. Which is the right way of saying this word? — HORses or horSES?

2. Would the rhythm of the poem be messed up if I replaced the word “troops” with “people”? (Read the poem from the beginning, with both versions)

3. Which way ruins the rhythm?
Here is a child who clambers and scrambles,
All by himself and gathering brambles;
Here is a tramp who stands and gazes;
And here is the green for stringing the daisies!
OR
Here is a child who clambers and scrambles,
And all by himself gathering brambles;
Here is a tramp who stands and gazes;
And here is the green for stringing the daisies!
Table 10. Pearson bivariate correlations between beat perception, general ability, literacy, phonological awareness, psychoacoustic, and tapping measures across both dyslexic and control participants, arranged by condition (no-pitch/+pitch) and intervention (GG/MC).

<table>
<thead>
<tr>
<th>General Ability Measures</th>
<th>Pre Intervention</th>
<th>Post Intervention</th>
<th>Mean Improvement</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>No-Pitch</td>
<td>+Pitch</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GG</td>
<td>MC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N=18</td>
<td>N=21</td>
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<td>0.268</td>
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<tr>
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<td>0.410</td>
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<td></td>
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<tr>
<td>Literacy Measures</td>
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<tr>
<td>BAS reading SS</td>
<td></td>
<td>0.381</td>
<td>0.234</td>
</tr>
<tr>
<td>BAS spelling SS</td>
<td></td>
<td>0.276</td>
<td>0.159</td>
</tr>
<tr>
<td>TOWRE word reading SS</td>
<td></td>
<td>-0.006</td>
<td>0.055</td>
</tr>
<tr>
<td>TOWRE non-word reading SS</td>
<td></td>
<td>0.190</td>
<td>0.162</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phonological Awareness Measures</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PhAB rhyme oddity SS</td>
<td></td>
<td>0.470*</td>
<td>0.396</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Psychoacoustic Measures</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rise time discrimination threshold</td>
<td></td>
<td>-0.391</td>
<td>-0.400</td>
</tr>
<tr>
<td>Duration threshold</td>
<td></td>
<td>-0.755**</td>
<td>-0.365</td>
</tr>
<tr>
<td>Intensity threshold</td>
<td></td>
<td>-0.105</td>
<td>-0.323</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Hz Tapping</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tapping ITI post intervention</td>
<td></td>
<td>0.245</td>
<td>-0.038</td>
</tr>
<tr>
<td>Tapping Sync post intervention</td>
<td></td>
<td>-0.289</td>
<td>-0.241</td>
</tr>
</tbody>
</table>

SS = standard score.
Tapping ITI = tapping inter-tap interval.
Tapping Sync = tapping synchronization.

**p < 0.001; *p < 0.01; *p < 0.05

p values, if listed, are in parenthesis beside Pearson correlation value, e.g. Pearson correlation (p-value).

The Pearson correlations are 2-tailed, with correlations highlighted in bold.
## Table 11. Pearson bivariate correlations between beat perception, general ability, literacy, phonological awareness, psychoacoustic, and tapping measures, arranged by condition (no-pitch/+pitch), intervention (GG/MC), and group (DY/CA).

<table>
<thead>
<tr>
<th></th>
<th>Pre Intervention</th>
<th>Post Intervention</th>
<th>Mean Intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No-Pitch</td>
<td>+Pitch</td>
<td>No-Pitch</td>
</tr>
<tr>
<td></td>
<td>GG MC</td>
<td>GG-MC</td>
<td>GG-MC</td>
</tr>
<tr>
<td></td>
<td>DY CA</td>
<td>DY CA</td>
<td>DY CA</td>
</tr>
<tr>
<td></td>
<td>N=8 N=10 N=9 N=12</td>
<td>N=8 N=10 N=9 N=12</td>
<td>N=8 N=10 N=9 N=12</td>
</tr>
</tbody>
</table>

### General Ability Measures

|                                |                  |                  |                  |                  |                  |
|                                |                  |                  |                  |                  |                  |
|                                |                  |                  |                  |                  |                  |
|                                |                  |                  |                  |                  |                  |
|                                |                  |                  |                  |                  |                  |

### Literacy Measures

|                                |                  |                  |                  |                  |                  |
|                                |                  |                  |                  |                  |                  |
|                                |                  |                  |                  |                  |                  |
|                                |                  |                  |                  |                  |                  |
|                                |                  |                  |                  |                  |                  |

### Phonological Awareness Measures

|                                |                  |                  |                  |                  |                  |
|                                |                  |                  |                  |                  |                  |
|                                |                  |                  |                  |                  |                  |
|                                |                  |                  |                  |                  |                  |

### Psychoacoustic Measures

|                                |                  |                  |                  |                  |                  |
|                                |                  |                  |                  |                  |                  |
|                                |                  |                  |                  |                  |                  |
|                                |                  |                  |                  |                  |                  |

### 2 Hz Tapping

|                                |                  |                  |                  |                  |                  |
|                                |                  |                  |                  |                  |                  |
|                                |                  |                  |                  |                  |                  |
|                                |                  |                  |                  |                  |                  |

SS = standard score.
Tapping ITI = tapping inter-tap interval.
Tapping Sync = tapping synchronization.

**p < 0.01; *p < 0.05

a Mean improvement post GG for DY participants tapping phase pre intervention -0.836**, and -0.834* for post pitch improvement
b Improvement post +Pitch condition, after GG intervention for CA participants 0.674*
c Improvement post +Pitch condition, after GG intervention for CA participants 0.705*
d Improvement post +Pitch condition, after GG intervention for CA participants 0.696*
e Improvement post +Pitch condition, after GG intervention for CA participants for tapping phase 0.662*
f Improvement post +Pitch condition, after MC intervention for CA participants -0.782**

The Pearson correlations are 2-tailed, with correlations highlighted in bold.
APPENDIX H

**Table 12.** Unique variance ($R^2$ change) in reading (TOWRE non-word reading) outcome measures explained by no-pitch musical beat perception (12a), +pitch beat perception (12b), and mean beat perception improvement (12c) post MC/GG interventions in 3-step fixed entry multiple regression equations for DY and CA ($N=39$).

<table>
<thead>
<tr>
<th>Step</th>
<th>Reading</th>
<th>B</th>
<th>SE B</th>
<th>Beta</th>
<th>$R^2$ change</th>
</tr>
</thead>
<tbody>
<tr>
<td>12a</td>
<td>1. Age</td>
<td>-0.62</td>
<td>0.26</td>
<td>-0.39</td>
<td>0.14*</td>
</tr>
<tr>
<td></td>
<td>2. IQ</td>
<td>0.44</td>
<td>0.13</td>
<td>0.46</td>
<td>0.20**</td>
</tr>
<tr>
<td></td>
<td>3. No-Pitch Post</td>
<td>0.40</td>
<td>0.17</td>
<td>0.34</td>
<td>0.09*</td>
</tr>
<tr>
<td>12b</td>
<td>3. +Pitch Post</td>
<td>0.42</td>
<td>0.17</td>
<td>0.36</td>
<td>0.10*</td>
</tr>
<tr>
<td>12c</td>
<td>3. Mean Improvement</td>
<td>0.59</td>
<td>0.24</td>
<td>0.32</td>
<td>0.10*</td>
</tr>
</tbody>
</table>

**B** = coefficient $b_n$ for predictor variables; **SE B** = standard error of B; **Beta** = standardized Beta coefficient; **$R^2$ change** = unique variance accounted for at each step of the three-step fixed entry multiple regression equations; **IQ** = FSIQ from standardized background scores; **No-Pitch Post** = accurate monotone beat perception performance post MC/GG intervention; **+Pitch Post** = accurate two-tone beat perception performance post MC/GG intervention; **Mean Improvement** = average of +pitch and no-pitch beat perception ability scores post MC/GG intervention subtracted by average of +pitch and no-pitch beat perception ability scores pre MC/GG intervention.

**p < 0.01, *p < 0.05**
**APPENDIX I**

**Table 13.** Unique variance ($R^2$ change) in phonological and literacy outcome measures explained by no-pitch musical beat perception (13a) and +pitch beat perception (13b) pre MC/GG interventions for DY and CA participants (N=39), in 3-step fixed entry multiple regression equations.

| Step | Reading | | | Spelling | | | | Rhyme | | |
|------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
|      | B       | SE B    | Beta    | $R^2$ change | B       | SE B    | Beta    | $R^2$ change | B       | SE B    | Beta    | $R^2$ change |
| 13a  |         |         |         |         |         |         |         |         |         |         |         |         |
| 1. Age | -0.06   | 0.23    | -0.04   | 0.0001  | 0.14   | 0.26    | 0.09   | 0.008  | 0.30   | 0.22    | 0.22   | 0.05  |
| 2. IQ  | 0.40    | 0.10    | 0.52    | 0.28*** | 0.33   | 0.15    | 0.36   | 0.12*  | 0.41   | 0.11    | 0.52   | 0.25*** |
| 3. No-Pitch Pre | 0.15    | 0.17    | 0.14    | 0.02 (0.39) | 0.09 | 0.19 | 0.08 | 0.005 (0.64) | 0.23 | 0.14 | 0.25 | 0.05 (0.10) |
| 13b  |         |         |         |         |         |         |         |         |         |         |         |         |
| 3. +Pitch Pre | 0.10 | 0.17 | 0.09 | 0.01 (0.58) | -0.002 | 0.18 | -0.002 | 0.0001 (0.99) | 0.07 | 0.14 | 0.07 | 0.004 (0.65) |

***$p < 0.001$, *$p < 0.05$*  
$p$ values, if listed, are in parenthesis beside Pearson correlation value, e.g. Pearson correlation ($p$-value)

B = coefficient $b_n$ for predictor variables; SE B = standard error of B; Beta = standardized Beta coefficient; $R^2$ change = unique variance accounted for at each step of the three-step fixed entry multiple regression equations; IQ = FSIQ from standardized background scores; No-Pitch Pre = accurate monotone beat perception performance pre MC/GG intervention; +Pitch Pre = accurate two-tone beat perception performance pre MC/GG intervention.
### APPENDIX J

**Table 14.** Unique variance ($R^2$ change) in no-pitch and +pitch beat perception performance post MC/GG interventions for DY and CA participants (N=39), explained by the basic auditory processing measures of rise time, duration, and intensity in 3-step fixed entry regression equations.

<table>
<thead>
<tr>
<th>Step</th>
<th>No-Pitch Post</th>
<th></th>
<th></th>
<th></th>
<th>+Pitch Post</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>SE B</td>
<td>Beta</td>
<td>$R^2$ change</td>
<td></td>
<td>B</td>
<td>SE B</td>
<td>Beta</td>
</tr>
<tr>
<td>1. Age</td>
<td>0.26</td>
<td>0.23</td>
<td>0.19</td>
<td>0.04</td>
<td>0.42</td>
<td>0.22</td>
<td>0.30</td>
<td>0.09</td>
</tr>
<tr>
<td>2. IQ</td>
<td>0.32</td>
<td>0.13</td>
<td>0.40</td>
<td>0.15*</td>
<td>0.29</td>
<td>0.13</td>
<td>0.35</td>
<td>0.12*</td>
</tr>
<tr>
<td>3. Rise time</td>
<td>-0.01</td>
<td>0.03</td>
<td>-0.04</td>
<td>0.001 (0.83)</td>
<td>0.02</td>
<td>0.03</td>
<td>0.10</td>
<td>0.01 (0.57)</td>
</tr>
<tr>
<td>3. Duration</td>
<td>-0.14</td>
<td>0.07</td>
<td>-0.31</td>
<td>0.08 (0.057)</td>
<td>-0.11</td>
<td>0.07</td>
<td>-0.23</td>
<td>0.05 (0.14)</td>
</tr>
<tr>
<td>3. Intensity</td>
<td>-0.11</td>
<td>0.49</td>
<td>-0.04</td>
<td>0.001 (0.82)</td>
<td>0.26</td>
<td>0.48</td>
<td>0.09</td>
<td>0.007 (0.59)</td>
</tr>
</tbody>
</table>

*p < 0.05

$p$ values are listed for the psychoacoustic measures of rise time, duration, and intensity thresholds. They are listed in parenthesis beside Pearson correlation value, e.g. Pearson correlation ($p$-value)

$B = \text{coefficient } b_n \text{ for predictor variables; } \text{SE } B = \text{standard error of } B; \text{Beta} = \text{standardized Beta coefficient; } R^2 \text{ change} = \text{unique variance accounted for at each step of the three-step fixed entry multiple regression equations; } IQ = \text{FSIQ from standardized background scores; } \text{No-Pitch Post} = \text{accurate monotone beat perception performance post MC/GG intervention; } +\text{Pitch Post} = \text{accurate two-tone beat perception performance post MC/GG intervention.}$