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Research report

Perception of patterns of musical beat distribution in phonological developmental dyslexia: Significant longitudinal relations with word reading and reading comprehension

Usha Goswami*, Martina Huss, Natasha Mead, Tim Fosker and John P. Verney

Centre for Neuroscience in Education, University of Cambridge, UK

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ABSTRACT

Introduction: In a recent study, we reported that the accurate perception of beat structure in music ('perception of musical meter') accounted for over 40% of the variance in single word reading in children with and without dyslexia (Huss et al., 2011). Performance in the musical task was most strongly associated with the auditory processing of rise time, even though beat structure was varied by manipulating the duration of the musical notes.

Methods: Here we administered the same musical task a year later to 88 children with and without dyslexia, and used new auditory processing measures to provide a more comprehensive picture of the auditory correlates of the beat structure task. We also measured reading comprehension and nonword reading in addition to single word reading.

Results: One year later, the children with dyslexia performed more poorly in the musical task than *younger* children reading at the same level, indicating a severe perceptual deficit for musical beat patterns. They now also had significantly poorer perception of sound rise time than younger children. Longitudinal analyses showed that the musical beat structure 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.

Conclusions: The non-linguistic musical beat structure task is an important independent longitudinal and concurrent predictor of variance in reading attainment by children. The different longitudinal versus concurrent associations between musical beat perception and auditory processing suggest that individual differences in the perception of rhythmic timing are an important shared neural basis for individual differences in children in linguistic and musical processing.

1. Introduction

Potential associations between music and dyslexia have long intrigued researchers, but there are relatively few empirical studies. Two aspects of musical processing have been of particular interest, pitch perception (e.g., Besson et al., 2011; Loui et al., 2011) and rhythm perception (e.g., Overy et al., 2003; Forgeard et al., 2008; Huss et al., 2011). Our focus in the current

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* Corresponding author. Centre for Neuroscience in Education, Downing Street, Cambridge CB2 3EB, UK.
E-mail address: ucg10@cam.ac.uk (U. Goswami).

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study is on rhythm perception, because we have proposed that sensitivity to *metrical structure* is important in the development of both musical and language processing. Children with developmental dyslexia have auditory perceptual impairments in sound rise time perception that are hypothesised to affect their sensitivity to metrical structure (see Goswami, 2011, 2012, for recent reviews). According to the 'rise time hypothesis' (Goswami, 2011), developmental relationships between musical and linguistic processing depend in part on shared underlying neural processing of strong and weak beats and the patterns that they form. While beat and meter in music are periodic, metrical structure in language depends on the alternation of strong and weak syllables in order to avoid stress clashes, and so language has non-periodic metrical or prosodic structure related to the patterning of strong and weak syllable "beats". The patterns of stressed and unstressed syllables in language may thus be processed by the same neural mechanisms used for processing patterns of strong and weak beats in music, at least in childhood. Hence individual differences in phonological processing in language should be related to individual differences in non-linguistic musical tasks based on patterns of beat distribution. If this is the case, then interventions based on musical beat perception may be helpful for improving phonological processing in childhood, and thus reading development.

Nevertheless, perhaps surprisingly, earlier studies of musical rhythm in dyslexia have not shown strong relationships between rhythm perception and either phonology or reading. For example, Overy et al. (2003) devised a series of tests of rhythmic timing such as rhythm copying and tapping tasks, and administered them to a group of 15 children with dyslexia aged 7–11 years and 11 age-matched controls. No significant group differences were found in the different rhythm tasks, although the small sample size may have reduced the power of the study. Forgeard et al. (2008) reported briefly on four behavioural studies of musical processing by children, two of which involved children with dyslexia. In the first dyslexia study, 31 children with dyslexia aged 10 years were given same–different judgement tasks of rhythm processing based on five-tone sequences. Performance in the rhythm tasks came close to being associated with performance on a phoneme awareness task (p's = .10 and .08), but no significant relations were found with reading outcomes. In the second study, five children with dyslexia were compared to 10 children without dyslexia. A significant group difference was found for the rhythm tasks with this very small sample.

Similar mixed results have been found in studies of typically-developing child readers. For example, Anvari et al. (2002) gave 100 typically-developing 4- and 5-year-olds some musical tasks based on piano tones requiring either rhythm or pitch judgements (e.g., same/different rhythm discrimination, same/different melody discrimination) and explored correlations with phonological awareness (rhyme oddity, onset-rime blending and rhyme generation) and single word reading. For the 4-year-olds, all the musical tasks loaded on to a single factor in a principal components factor analysis, and this factor was significantly associated with both phonological awareness and single word reading. For the 5-year-olds, the musical tasks loaded on to two separate factors, a pitch perception factor and a rhythm perception factor. Although the rhythm perception factor was significantly associated with phonological awareness for 5-year-olds, it was not significantly related to single word reading. Anvari et al. (2002) concluded that the relationship between rhythm perception and reading was unclear. In contrast, a recent study involving German preschool children (5-year-olds) carried out by Degé and Schwarzer (2011) found significant links between rhythm *training* and phonological awareness. A total of 41 preschool children were assigned to either a phonological awareness training programme, a musical training programme, or a sports training programme (the sports training was the control intervention and was not expected to enhance phonological awareness). Training was given to small groups for 10 min daily, for a period of 20 weeks. The musical training programme included joint singing, joint drumming, rhythmic exercises, metrical training, dancing and rudimentary notation skills. Both the musical training group and the phonological training group showed significant gains in phonological awareness in comparison to the sports control group. Gains were specific to larger phonological units, namely rhymes and syllables, but not phonemes. Syllables and rhymes are the linguistic units highlighted by metrical rhythmic structure and the rise time hypothesis (see Goswami, 2011, 2012). Finally, a study of musical pitch versus rhythm carried out with 78 older typically-developing English-speaking children in Scotland (Douglas and Willatts, 1994; 8-year-olds) found significant correlations for the musical rhythm measures with reading and spelling, but not the musical pitch measures, once vocabulary development was partialled out in the analyses. Phonological awareness was not measured. Therefore, studies of typically-developing children do show some support for a link between musical rhythm perception, phonological processing, and progress in written language development.

Recently, strong support for a link between musical rhythm perception and reading was reported in a study of 10-year-old children with and without developmental dyslexia by Huss et al. (2011). They designed a novel musical perceptual task based on metrical rhythmic structure, which revealed significant associations between 'perception of musical meter', reading and phonology. Performance in the musical task along with age and I.Q. explained over 60% of the variance in concurrent single word reading in their sample of 64 children. The non-linguistic musical measure showed stronger associations with reading (predicting 42% of unique variance) than traditional phonological awareness measures (a rhyme awareness measure, which predicted 33% of unique variance). This suggests that Huss et al.'s musical task was measuring something of perceptual importance to the development of phonological awareness and reading. As reading development is tied so closely to the development of phonological awareness, Huss et al. (2011) suggested that the accurate perception of metrical structure was likely to underlie both musical and phonological (prosodic) processing. Nevertheless, it has been argued since that metrical structure itself was not varied in Huss et al.'s task. Meter per se did not change in the task (e.g., from binary to ternary[1]), rather the

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[1] We are grateful to an anonymous referee for this point.

duration of the accented notes was varied. These durational changes affected rhythmic temporal structure, as they altered the patterns of beat distribution. As Huss et al.'s musical task is perhaps better described as a measure of sensitivity to rhythmic temporal structure (the temporal patterns between the accented and unaccented beats), we refer to the same task in the current paper as a measure of 'sensitivity to patterns of beat distribution'.

Huss et al. (2011) reported that children with dyslexia were significantly poorer at perceiving changes in beat distribution compared to typically-reading same age controls [chronological age (CA) matched controls], but performed at the same level as younger children [reading-level (RL) matched controls]. Therefore, when the children with dyslexia were aged 10 years, performance in the musical task was associated with absolute RL (which was matched between the 10-year-olds with dyslexia and the 8-year-old without dyslexia, at approximately 8 years). The musical task comprised short "tunes" played on the note of G that were 6–15 notes in length, were in either 4/4 time or 3/4 time, were based on an isochronous beat structure of 2 Hz (120 bpm, 500 msec), and had different beat structures conveyed by increasing the intensity of the accented note in a bar. Individual differences in the musical task were most strongly associated with individual differences in auditory sensitivity to sound rise time, and also sound intensity. Individual differences in sensitivity to sound rise time, but not sound intensity, are also a significant associate of individual differences in phonological awareness and reading in children with and without dyslexia, across languages (English, Spanish, Chinese, French, Dutch, Finnish and Hungarian, see Goswami, 2011, Hämäläinen et al., 2012a, for reviews). Sensitivity to the pitch and duration of sounds did not explain unique variance in sensitivity to patterns of beat distribution in the block entry multiple regression analyses conducted by Huss et al. (2011), although individual differences in these auditory measures can be related to reading development (see Hämäläinen et al., 2012b). However, it is possible that the auditory measures of pitch and duration used by Huss et al. were not 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 msec long), while the durational changes in the musical task were relatively short (note durations were increased by either 100 msec or 166 msec).

In the current study, we follow up the participants in Huss et al. (2011) a year later, assessing developmental progress in the musical task and incorporating novel measures of pitch and duration perception that theoretically should be more relevant to the perception of patterns of beat distribution. We also test additional children, to give a larger sample for exploring concurrent relations between the beat distribution task and the different measures of basic auditory processing. Although the musical sequences in Huss et al.'s musical task all had the same underlying periodicity (2 Hz), the perturbations in beat structure would also have affected non-periodic rhythmic parameters like grouping. We therefore added novel auditory measures related to the perception of non-periodic rhythm (following Patel, 2008, who noted the importance of sensitivity to both rising pitch and duration). We used new short duration stimuli (125–250 msec) and new measures of sensitivity to rising and falling pitch, comparing these cues to acoustic cues to periodic rhythm (sound rise time, which underpins sensitivity to rhythmic timing and the perceptual centres of sounds, e.g., Gordon, 1987; Hoequist, 1983; Morton et al., 1976; Scott, 1998). Both rising pitch and duration should be important for perceptual grouping (Patel, 2008).

Finally, as the child participants were all taking part in a longitudinal study of developmental dyslexia, we were also able to explore relations between performance in the same musical task administered the previous year (by Huss et al., 2011) and development in reading a year later (i.e., at the time point assessed in the current study). If the non-linguistic musical task is able to predict longitudinal variance in reading development, that would support the theoretical view that musical interventions should be important for developing reading skills in children with dyslexia (e.g., Overy, 2003; Forgeard et al., 2008; Besson et al., 2011; Huss et al., 2011) as well as typically-developing children (e.g., Douglas and Willatts, 1994; Anvari et al., 2002; Degé and Schwarzer, 2011). By hypothesis, the beat perception task is measuring shared processing demands in music and language which relate to the awareness of *phonological structure* in language (particularly prosodic structure). The literature considering typical reading development considers prosodic awareness to be more important for the development of reading *comprehension* than of single word decoding (e.g., Miller and Schwanenflugel, 2008; Whalley and Hansen, 2006). On that perspective, individual differences in sensitivity to non-linguistic patterns of beat distribution in the musical task should be a strong predictor of development in reading comprehension as well as single word reading. Meanwhile, the broader perspective on the developmental links between rhythmic processing and phonology captured 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 sensitivity to non-linguistic patterns of beat distribution should also be a significant predictor of development in nonword reading, which is a relatively pure measure of phonological recoding to sound. To our knowledge, ours is the first *longitudinal* study to assess rhythmic musical processing as a predictor of individual differences in single word reading, reading comprehension and nonword reading.

2. Methods

2.1. *Participants*

Eighty-eight children aged between 8 and 14 years participated in this study, 59 of whom had also completed the musical task a year earlier (Huss et al., 2011). Thirty-eight of the children (21 males; mean age 11 years 6 months) 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. Note that in England children with a statement of dyslexia are entitled to phonological remediation. Twenty-five age-matched control children (CA control group; 14 males; mean age 11 years 5 months) and 25 RL matched control children (RL control group; 11 males; mean age 9 years 2 months) were recruited from the same schools as the dyslexics. As shown in Table 1, the CA controls differed by 27 standard points and by 3 years 11 months in average reading age from the children with dyslexia (both significant differences), whereas the RL controls differed by 20 standard points and 8 months in average reading age from the children with dyslexia. The difference in reading age between the dyslexics and the RL controls (who had been exactly matched at the beginning of the longitudinal study, 4 years previously) was not significant, but the difference in standard score was. Participant details are shown in Table 1.

All of the children were taking part in a longitudinal study of dyslexia, and comprised an unselected group of the total cohort who were available to complete the musical beat perception task (as the task was quite lengthy, not all schools were able to accommodate the extra testing session required). The test battery reported here was used in Year 4 of the ongoing study. As all children are extremely familiar with the auditory tasks, task difficulty is unlikely to be the basis for group differences. Only children who had no diagnosed additional learning difficulties (e.g., dyspraxia, attention deficit hyperactivity disorder – ADHD, autistic spectrum disorder, speech and language impairments), a nonverbal I.Q. above 85, and English as the first language spoken at home were included in the longitudinal study. All participants received a short hearing screen using an audiometer. Sounds were presented in both the left and right ear at a range of frequencies (250, 500, 1000, 2000, 4000, 8000 Hz), and all subjects were sensitive to sounds within the 20 dB hearing level (HL) range.

2.2. Tasks

2.2.1. Standardised ability tests

All children had completed four subscales of the Wechsler Intelligence Scale for Children in an earlier phase of the study (WISC-III; Wechsler, 1992: Block Design, Picture Arrangement, Similarities, Vocabulary). I.Q. scores were prorated following the procedure adopted by Sattler (1982). Nonverbal I.Q. was re-assessed at the current test point using the Picture Arrangement subscale from the WISC-III. Literacy skills were re-assessed at the current test point using the British Ability Scales (BAS) (Elliott et al., 1996), and the Test of Word Reading Efficiency (TOWRE) nonword scale (phonemic decoding efficiency - PDE; Torgesen et al., 1999). The Neale Analysis of Reading Ability, Revised (NARA-R, Neale, 1997), was also used in order to provide a standardised assessment of reading comprehension.

2.2.2. Phonological awareness measures

A *rhyme oddity* task using digitized speech created from a native female speaker of standard Southern British English was utilised (based on the version used for Huss et al., 2011). The children listened to sets of three words or nonwords through headphones, and had to select the one that did not rhyme (e.g., gap, nap, Jack; rizz, nizz, kiv). Trials were presented in three fixed random orders. The task comprised 20 trials, 10 with real words, 10 with nonwords, and a score of 1 was given for each correct answer. Performance (% correct) by group is shown in Table 2. Scores out of 20 were used in the analyses. A *phoneme deletion* measure was also used. In this task, digitized speech created from the same native female speaker of standard Southern British English was used to present 18 pseudowords (including three practice words), followed by a target phoneme contained in the pseudoword. Participants were asked to produce the pseudoword omitting the target phoneme (e.g., *Say "bice" without the "b"*; *Say "splow" without the "p"*). Phonemes were deleted from a variety of positions within the pseudoword (initial, medial, final), leaving a real word in each case. This was an abbreviated version of a deletion task from McDougall et al. (1994), used by Pasquini et al. (2007). Scores out of 15 were used in the analyses.

2.2.3. Phonological short-term memory measure (PSTM)

The memory task was also based on digitised speech from the same female speaker, and consisted of 20 trials of four spoken

Table 1 – Participant details: standardised and phonological tasks.

Group	Dyslexic N = 38	CA controls N = 25	RL controls N = 25	F(2,85)
CA (months)[a] [standard deviation (SD)]	138.1 (14.1)	136.8 (12.5)	109.8 (6.9)	48.3^{***}
Reading age (months)[b] (SD)	106.2 (19.4)	153.5 (23.9)	113.8 (19.1)	41.9^{***}
WISC short-form I.Q. SS[c] (SD)	103.7 (13.2)	105.7 (10.6)	105.0 (10.8)	.22
WISC Picture subscale[d] (SD)	14.1 (4.3)	13.3 (3.1)	13.8 (4.7)	.28
Reading SS[e] (SD)	83.3 (9.8)	110.6 (10.9)	103.6 (13.1)	51.7^{***}
Nonword reading SS[e] (SD)	86.2 (10.3)	110.7 (11.1)	103.0 (13.8)	37.3^{***}
Reading comprehension SS[f] (SD)	86.6 (12.8)	106.7 (13.1)	100.0 (10.3)	19.9^{***}
Rime oddity % correct[b] (SD)	69.5 (12)	81.7 (10)	71.4 (16)	7.3^{**}
Phoneme deletion % correct[b] (SD)	53.7 (19)	76.5 (15)	62.9 (21)	11.9^{***}
PSTM, % correct[b] (SD)	43.2 (12)	60.4 (17)	41.3 (13)	14.3^{***}

Note: DYS = dyslexic, SS = standard score.
$^{***}p < .001$; $^{**}p < .01$.
a DYS = CA, different from RL.
b DYS equivalent to RL, RL and DYS worse than CA.
c Administered at beginning of study, standard score = 100.
d Administered in current test phase, standard score = 10.
e DYS worse than RL, RL worse than CA.
f Dyslexic worse than CA and RL, CA = RL.

Table 2 – Group performance on the musical beat perception and auditory tasks.

Group	Dyslexic	CA control	RL control	F(2,85)[a]
Musical beat perception				
Number correct[b] (out of 24) (SD)	14.5 (3.7)	18.6 (3.0)	16.6 (3.6)	10.7***
4/4 Time[c] (max = 14) (SD)	8.6 (2.5)	11.2 (2.3)	9.9 (2.8)	7.9***
3/4 Time[c] (max = 10) (SD)	5.9 (1.9)	7.4 (1.7)	6.7 (1.8)	5.4***
Quarter note trials[d] (max 12) (SD)	7.6 (2.3)	9.8 (1.7)	9.1 (2.3)	8.6***
Mixed trials[c] (max 12) (SD)	6.9 (2.0)	8.8 (1.5)	7.4 (2.2)	7.5***
Accented note change 100 msec[d] (max = 14) (SD)	8.1 (2.7)	10.6 (2.2)	9.4 (2.3)	7.8***
Accented note change 166 msec[c] (max = 10) (SD)	6.4 (1.7)	8.1 (1.3)	7.1 (1.9)	7.7***
Auditory threshold				
1 Rise AXB in msec[d] (SD)	113.6 (79.6)	36.5 (12.4)	46.0 (21.2)	22.0***
1 Rise 2IFC in msec[c] (SD)	115.9 (789.2)	27.6 (3.0)	77.8 (53.8)	16.2***
Short Duration in msec[c] (SD)	45.5 (23.4)	30.3 (10.6)	37.8 (13.5)	4.8*
Frequency Rise in semitones[c] (SD)	2.7 (1.5)	1.5 (1.2)	1.9 (1.3)	4.6*
Frequency Fall in semitones (SD)	1.0 (.5)	.9 (.4)	.8 (.4)	2.2

a Some tasks show Brown–Forsythe statistic.
b Dyslexic worse than RL, RL worse than CA.
c Dyslexic worse than CA, Dyslexic equivalent to RL.
d Dyslexic worse than RL and CA ***$p < .001$, *$p < .05$.

monosyllables (all nonwords, e.g., rell, kide, tave, nug). The children were required listen to each set of four items and then repeat them back to the experimenter. Children listened to the stimuli through headphones. Responses were registered by digital voice recorder and scored in terms of the number of items recalled correctly. Performance (% correct) is shown in Table 2. Number of items recalled correctly were used in the analyses.

2.2.4. *Beat perception in music task (previously ‘perception of musical meter’ task)*

This task was a shortened version of the ‘musical meter’ task reported by Huss et al. (2011), comprising 24 instead of 36 trials of different beat structure arrangements of a series of notes with an underlying pulse rate of 500 msec (120 bpm). Twelve of the trials delivered the identical series of notes twice (“same” trials), and 12 delivered two slightly different series of notes (“different” trials), created by elongating the accented note by either 100 msec or 166 msec. All of the “different” trials are provided as Fig. 1. The “same” trials were the identical arrangements without a lengthening of the accented note. The sound files were created using Sibelius Version 4 from a sound set produced by Native Instruments (Kontakt Gold) hence the notes sounded musical with appropriate timbre and slow decay times. Fourteen trials (seven same, seven different) were in 4/4 time and 10 trials (five same, five different) were in 3/4 time. The delay in the rhythm structure was either short (100 msec, seven “different” trials) or long (166 msec, five “different” trials). The child's task in all cases was to make a same–different judgement: were the two “tunes” the same or different? Trials were delivered in a pseudo-random order. Further details can be found in Huss et al. (2011).

2.2.5. *Psychoacoustic tasks*

The psychoacoustic stimuli were presented binaurally through headphones at 75 dB sound pressure level (SPL). Earphone sensitivity was calculated using a Zwislocki coupler in one ear of a Knowles Electronic Mannekin for Acoustic Research (KEMAR) manikin (Burkhard and Sachs, 1975) and all laptops were calibrated. Children's responses were recorded on the keyboard by the experimenter. The auditory tasks used a child-friendly AXB or 2IFC “Dinosaur” threshold estimation program, originally created by Dorothy Bishop (Oxford University). The original tasks were reprogrammed for this study by the second author who also created all the novel auditory threshold measures. The amended Dinosaur programme used an adaptive staircase procedure (Levitt, 1971) with a combined two-down one-up and three-down one-up procedure; after two reversals, the two-down one-up staircase procedure changes into three-down one-up. The step size halves after the 4th and 6th reversal. In each task, the child would first participate in five practice trials. Feedback was given after every trial by the computer software. During the practice period this feedback was accompanied by further verbal explanation and reinforcement by the researcher. A test run typically terminated after eight response reversals or alternatively after the maximum possible 40 trials. The threshold score was calculated using the mean of the last four reversals. This indicated the smallest difference between stimuli at which the participant could still discriminate with a 79.4% accuracy rate.

2.2.5.1. AMPLITUDE ENVELOPE ONSET (RISE TIME) TASK (1 RISE AXB). This was a rise time discrimination task in AXB format, also used by Huss et al. (2011). Three 800 msec tones were presented on each trial, with 500 msec inter-stimulus intervals (ISIs). Two (standard) tones had a 15 msec linear rise time envelope, 735 msec steady state, and a 50 msec linear fall time. The third tone varied the linear onset rise time with the longest rise time being 300 msec. Children were introduced to three cartoon dinosaurs. It was explained that each dinosaur would make a sound and that the child's task was to decide which dinosaur's sound was different from the other two and had a softer rising sound (longer rise time).

Fig. 1 – Depiction of all of the musical arrangements used as the "different" trials in the metrical musical perception task, which were recorded with an underlying pulse rate of 500 msec. The more intense beat in a sequence is marked >, and the position and increased length of the note are also marked. Wav file numbers correspond to file names in the online supporting materials linked to Huss et al. (2011).

2.2.5.2. Rise time task, 2IFC format (1 Rise 2IFC). This task used the same stimuli as the 1 Rise AXB task, but presented them in a novel two-interval forced choice paradigm. The intention was to equate the cognitive demands with the musical task, which also required a forced choice between two alternatives. Children were asked to choose the dinosaur who made the sound that began more gently (the sound with the longer rise time).

Fig. 1 – (*continued*).

2.2.5.3. Frequency Rise task. The stimuli were linearly frequency-modulated tone glides, comprising upward sweeps at 40 different levels of frequency change. All stimuli had a linear rise and fall time of 50 msec and were 600 msec in duration. All the stimulus frequencies started at 900 Hz and increased linearly within each stimulus. The final stimulus frequency stopped variously at 1200 Hz–1700 Hz. Thus the rate of frequency change ranged between 500 Hz/sec and 1333 Hz/sec. In this AXB task, three pure tones were given and associated with three dolphin pictures. Children decided which dolphin produced a different sound from the standard.

2.2.5.4. Frequency Fall task. The sound stimuli were presented as linearly frequency-modulated tone glides, comprising downward sweeps at 40 different levels of frequency change. All stimuli had a linear rise and fall time of

50 msec and were 600 msec in duration. All the stimulus frequencies started at 900 Hz and decreased linearly within each stimulus. The final stimulus frequency stopped variously at 800 Hz–700 Hz. Thus the rate of frequency change ranged between 166.67 Hz/sec and 333.33 Hz/sec. In this AXB task, three pure tones were associated with three owl pictures. Children decided which owl produced a different sound from the standard.

2.2.5.5. Short Duration task. This was a duration discrimination task in AXB format. Three tones were presented on each trial, with 500 msec ISIs. The standard was a pure tone with a duration of 125 msec and a frequency of 500 Hz, presented at 75 dB SPL. The duration of the third tone ranged from 125 msec to 250 msec. Children were introduced to three cartoon animals (mice). It was explained that each would make a sound, and the child's job was to decide whose sound was longer.

3. Results

Auditory discrimination and musical perceptual data were explored by group to check that assumptions of normality were met. The Statistical Package for Social Sciences (SPSS) boxplot function was used to check for outliers, and any data points lying farther than three interquartile ranges from the further edge of the box were removed. There were no outliers in the experimental tasks measuring musical beat perception or phonology. Four outlier scores were identified and removed for the auditory processing tasks (one CA and one RL control score for one Rise AXB, two CA control scores for one Rise 2IFC). Homogeneity of variance assumptions were met for all standardised, phonological and musical tasks. In statistical comparisons where homogeneity of variance assumptions were not met (some of the auditory tasks), the Brown–Forsythe test and Games–Howell post hoc tests were used to evaluate the group differences reported below. Group data for the standardised tasks and phonological tasks are provided in Table 1, and for the musical and auditory tasks in Table 2.

Inspection of Table 2 reveals that, in contrast to a year previously, the children with dyslexia were now significantly less sensitive to beat structure in music and to auditory rise time (1 Rise AXB) than their (younger) RL controls. Even though the children with dyslexia were matched for I.Q. and real word reading with the younger children, for these auditory and perceptual tasks related to rhythmic timing, they were clearly progressing more slowly. The sample of children varied continuously in all the key measures of interest (reading, phonology, musical beat perception, see scatterplots in Figs. 2 and 3), and homogeneity of variance assumptions were met, therefore both control groups were included in the statistical analyses, which used one-way analysis of variances (ANOVAs) comparing the children with dyslexia ($N = 38$) to their CA controls ($N = 25$) and RL controls ($N = 25$). Table 2 shows that the children with developmental dyslexia always performed more poorly than the CA controls in the musical task, whichever measure of musical beat awareness was utilised. They were also significantly poorer compared to the younger RL controls in their overall performance in the task, and when making judgements about Quarter (crochet) trials and judgements involving disruptions of the beat structure by 100 msec. It is notable that a durational change of the accented note by 100 msec was within the auditory thresholds of the dyslexic children for duration as measured by the Short Duration task. Nevertheless, they were worse at perceiving

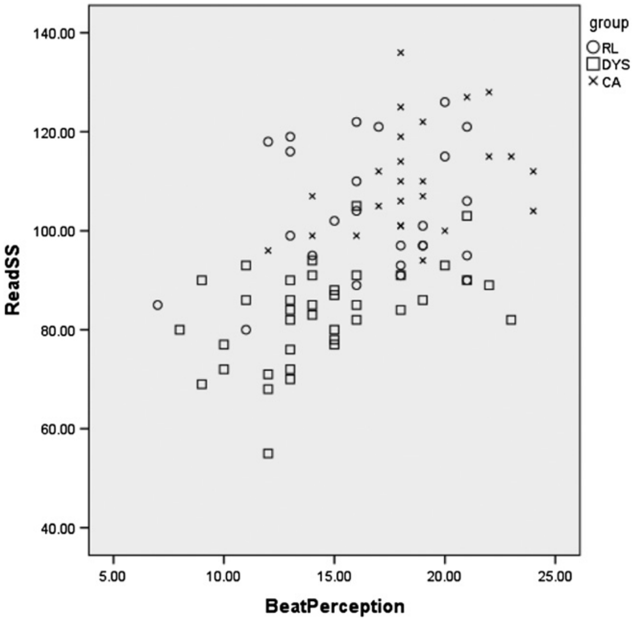

Fig. 2 – Scatterplot showing beat perception (number correct) plotted against reading standard score, with group membership indicated.

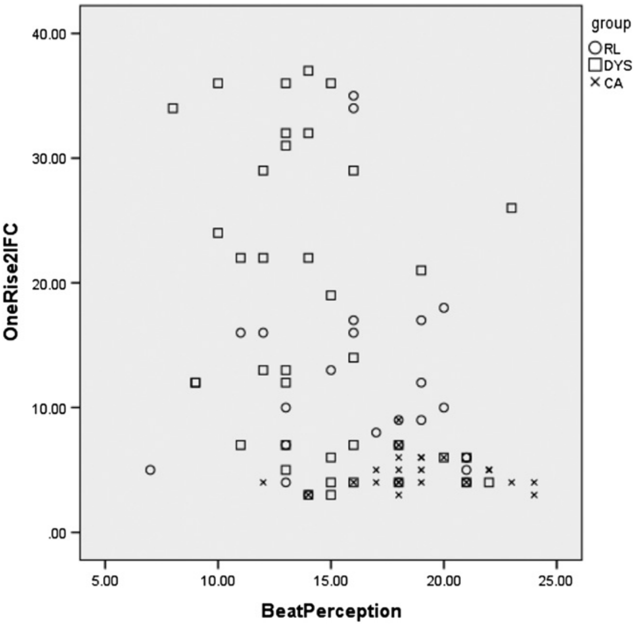

Fig. 3 – Scatterplot showing beat perception (number correct) plotted against rise time sensitivity (1 Rise 2IFC threshold as a wav file number, maximum = 40), with group membership indicated.

differences in beat structure based on a 100 msec disruption than the younger RL children.

Regarding the hypothesis-driven auditory measures, the children with dyslexia showed significantly higher thresholds than *both* CA and RL controls in the 1 Rise AXB task (see Table 2). Hence their auditory perception of rise time in this task was now also significantly poorer than that of younger children of the same reading age, suggesting a robust perceptual deficit. For the 1 Rise 2IFC, Short Duration and Frequency Rise tasks (see Table 2), the children with dyslexia performed at a statistically similar level to the younger RL controls but had significantly higher thresholds than the CA controls. Mean auditory thresholds for the Frequency Fall task did not show group differences, suggesting that auditory attention per se is not governing the patterns of group performance in the different auditory tasks. The children with dyslexia also showed significantly poorer sub-word phonological awareness (rhyme oddity and phoneme deletion, Table 1) and PSTM than their CA controls, but not compared to their RL controls. Therefore, over the course of a year (i.e., since the measurements reported by Huss et al., 2011), the children with dyslexia had fallen behind the younger RL controls in rise time sensitivity and in performance on the musical task, but had not fallen (statistically) behind the younger RL controls in the reading or phonological tasks, including phonological memory. Recall however that as many of the children with dyslexia in this study had educational statements, they were entitled to receive phonological remediation in school, which could explain why their sub-lexical phonological skills were equivalent to the RL controls.

To explore the relations between the different auditory processing measures and performance in the musical and language tasks, partial correlations between the musical beat perception task, the different auditory measures and the phonological and literacy measures when concurrent age and nonverbal I.Q. (WISC Picture subscale) were controlled were computed and are provided in Table 3. As noted, the auditory, reading and musical measures were continuously distributed in the sample (see Figs. 2 and 3), and so separate analyses for the dyslexic children only were not computed. Indeed, raw correlations for the children with dyslexia only or the typically-developing children only for the key measures were very similar but fell short of significance for one group or the other (e.g., 1 Rise 2IFC and musical task, $r = -.34$, $p = .034$ for the dyslexics, $r = -.22$, $p = .14$ for controls; musical task and reading comprehension standard score, $r = .34$, $p = .055$ for the dyslexics, $r = .42$, $p = .003$ for the controls). Applying a Bonferroni correction for multiple comparisons, p values smaller than .0031 were significant, significant correlations are shown in bold. Inspection of Table 3 for bolded values demonstrates that individual differences in the musical beat perception task were significantly related to individual differences in the literacy and phonology measures. Performance in the musical task was also significantly related to individual differences in rise time sensitivity (both rise time measures), and sensitivity to rising pitch (Frequency Rise). The rise time measures were also significantly related to most of the literacy and phonology outcomes, in contrast to most of the other auditory measures. The Frequency Rise and Short Duration measures were related to phoneme deletion and the Short Duration measure was related to reading comprehension.

In order to investigate which auditory parameters were most strongly associated with both concurrent and longitudinal performance in the musical beat perception task, multiple regression equations were computed using the whole sample, but including Group as an independent variable to account for any variability due to group (dyslexic, CA control, RL control). For the concurrent analyses, individual differences in performance in the rise time tasks were expected to be related to individual differences in musical beat perception, as in Huss et al. (2011). The novel auditory measures (discriminating short durations within the theta band, 125–250 msec; discriminating rises and falls in pitch) should also be related to musical beat perception if non-periodic rhythmic factors like grouping are related to task performance. The first set of multiple regression equations used a two-step fixed entry method, controlling first for Group (step 1) and then entering the childrens' auditory discrimination thresholds in the respective auditory tasks at step 2 (five equations). The dependent variable was performance on the musical task (number correct). Results are shown in the first two columns of Table 4. As can be seen, both measures of rise time processing explained significant unique variance in the musical beat perception task, with the 1 Rise 2IFC measure accounting for the larger amount of unique variance (13%, $p < .0001$). Consistent with Huss et al. (2011), individual differences in the discrimination of duration did not explain significant variance in the musical beat perception task (4% of unique variance), even though shorter durational judgements were now required. Sensitivity to Frequency Rise and

Table 3 – Concurrent partial correlations between the musical task, auditory processing, phonology and literacy measures, controlling for age and nonverbal I.Q.

	Metric task	Rhyme Odd.	Phon Deln	BAS read	BAS spell	TOWRE Nonw.	NARA Comp
Metric task		**.328**	**.412**	**.555**	**.428**	**.508**	**.523**
1 Rise AXB	**−.345**	**−.320**	−.216	**−.445**	**−.445**	**−.472**	**−.418**
1 Rise 2IFC	**−.406**	**−.366**	**−.325**	**−.401**	**−.351**	**−.404**	**−.415**
Short Dur	−.230	−.224	**−.374**	−.285	−.194	−.263	**−.330**
Freq Rise	**−.452**	−.281	**−.381**	−.276	−.233	−.186	−.151
Freq Fall	−.220	−.151	−.214	−.144	−.231	−.200	−.074

Note: Correlations in bold indicate $p < .0031$ with d.f. 83. Rhyme Odd. = Rhyme oddity task; Phon Deln = Phoneme deletion task; BAS = British Ability Scales standard score measure; Nonw. = nonword scale standard score (also called phoneme decoding efficiency - PDE); Comp = Comprehension standard score; Short Dur = Short Duration; Freq Rise = Frequency Rise; Freq Fall = Frequency Fall.

Table 4 – Unique variance (R^2change) in musical beat perception (total correct out of 24) explained by the concurrent basic auditory processing measures (columns 1 and 2) and by basic auditory processing measured a year previously (columns 3 and 4).

Step	Beta music concurrent	R^2change music concurrent	Beta music longit	R^2change music longit
1. Group	.205	.042+	.205	.042^
2. 1 Rise AXB	−.299	.089**	−.310	.089**
2. 1 Rise 2IFC	−.376	.133***	–	–
2. Short Duration	−.194	.037	–	–
2. Frequency Rise	−.422	.176***	–	–
2. Frequency Fall	−.220	.048*	–	–
2. Long duration (Huss et al., 2011)	–	–	−.287	.082**
2. Frequency (Huss et al., 2011)	–	–	−.276	.074**
2. Intensity (Huss et al., 2011)	–	–	−.115	.013

$^{***}p < .001$, $^{**}p < .01$, $^{*}p < .05$. $+p = .058$, $\hat{}p = .063$. Longit = longitudinal; Beta = standardized Beta coefficient; R^2change = unique variance accounted for at each step of the two-step fixed entry multiple regression equations.

Frequency Fall were also significant concurrent predictors of musical beat performance, but the largest amount of unique variance was predicted by Frequency Rise, which explained 18% of unique variance in the musical beat perception task ($p < .0001$).

The longitudinal auditory predictors of performance in the musical beat perception task were also explored using two-step multiple regression equations, controlling for Group as a first step, and then entering auditory performance a year previously at step 2 (four equations, for the 1 Rise AXB, simple frequency and intensity, and the long duration measures used by Huss et al., 2011)[2]. The dependent variable was performance in the musical beat perception task a year later. As shown in Table 4, all of the auditory measures were significant longitudinal predictors of musical beat perception except for intensity. The duration task, which had not shown significant concurrent relations with musical beat perception a year earlier, accounted for a significant 8% of unique variance longitudinally. The analyses suggest that rise time, duration and frequency discrimination are all important longitudinal predictors of individual differences in the musical beat perception task.

In a final set of multiple regression analyses, we investigated longitudinal prediction of reading by individual differences in the musical beat perception task. Theoretically, the beat perception task is tapping individual differences in sensitivity to the temporal structure of beat distribution, which is also related to phonological awareness. Therefore, longitudinal prediction of individual differences in phonological awareness (rhyme oddity and phoneme deletion) was also investigated. Three measures of written language skills were used, a standardized measure of single word reading (BAS single word reading), a standardized measure of nonword reading (phonological recoding to sound, TOWRE PDE), and a measure of reading comprehension (NARA standard score). The first set of equations controlled first for Group (step 1), and then entered performance in the musical beat perception task a year earlier at step 2 (Huss et al., 2011, hence overall there were 59 children in the longitudinal analyses). The results are shown in the first two rows of Table 5. As can be seen, for all the reading and phonology measures, performance in the musical beat structure task accounted for significant unique variance in the dependent variable. Associations were particularly strong for single word reading (31% of unique variance) and reading comprehension (43% of unique variance), suggesting that the task is related to the quality of *lexical* phonological representations. As a more stringent test of the contribution of musical beat perception to reading development and phonology, a second set of equations was run controlling for sub-lexical phonological awareness (rhyme awareness) before exploring the longitudinal contribution made by musical beat perception. These were three-step fixed entry equations, controlling first for Group at step 1, then entering phonological awareness measured a year earlier (rhyme oddity task) at step 2, and finally entering performance in the musical beat perception task measured a year earlier at step 3 (Huss et al., 2011). The results are shown in rows 3, 4 and 5 of Table 5. As can be seen, even when phonological awareness a year earlier was controlled, the musical beat perception measure was a significant predictor of all the reading measures. Both measures together (phonological awareness and musical beat perception) accounted for 56% of unique variance in reading comprehension, 37% of unique variance in single word reading, and 27% of unique variance in nonword reading. The musical beat perception measure also predicted a small amount of unique variance in phoneme deletion, but not in rhyme oddity. This is not surprising, as individual differences in rhyme oddity a year earlier were accounted for at step 2 of the equation (the autoregressor). Overall, the equations are consistent with the theoretical view that the musical beat perception task is a sensitive measure of auditory perceptual mechanisms that are important both for phonological development and for the development of written language skills (reading, nonword reading, reading comprehension).

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[2] The auditory data for those children tested by Huss et al. (2011) were rechecked prior to running the regression analyses, as RL controls were now included. We found two outliers for intensity (one RL, one DYS) and a distribution for frequency that was bimodal. Frequency was therefore recoded as a dichotomous variable, using thresholds either less than or greater than 1.18 semitones as the cut-off (as in Goswami et al., 2011).

Table 5 – Unique variance (R^2change) in phonological and literacy outcome measures explained by musical beat perception and phonological awareness a year earlier in fixed entry multiple regression equations controlling for Group.

Step	Rhyme		Phoneme		READ		TOWRE		R Comp	
	Beta	R^2change	Beta	R^2change	Beta	R^2change	Beta	R^2change	Beta	R^2change
1. Group	.269	.072*	.228	.052	.153	.023	.166	.027	.144	.021
2. Music Huss	.371	.116**	.469	.186**	.603	.307***	.473	.189**	.711	.427***
1. Group.	.269	.072*	.228	.052	.153	.023	.166	.027	.144	.021
2. PA Huss	.582	.311***	.444	.181**	.494	.224***	.465	.198***	.643	.380***
3. Music Huss	.133	.012	.330	.075*	.467	.150**	.323	.072*	.518	.184***

$^{***}p < .001$, $^{**}p < .01$, $^{*}p < .05$.

Beta = standardized Beta coefficient; R^2change = unique variance accounted for at each step of the fixed entry multiple regression equations; Music Huss = musical beat perception task given by Huss et al. (2011); Rhyme = Rhyme oddity task; PA = phonological awareness; Phoneme = Phoneme deletion task; READ = BAS reading standard score; TOWRE = nonword reading standard score; R Comp = NARA reading comprehension standard score.

4. Conclusions

This study explored whether musical beat perception is associated longitudinally with phonological and literacy development (Huss et al., 2011), measured the longitudinal auditory predictors of progress in the musical beat perception task, and also measured novel concurrent auditory predictors of individual differences in musical beat perception. We report the developmental progress of children with and without phonological developmental dyslexia over a period of 12 months. In conjunction with the data previously reported by Huss et al. (2011) for a sub-set of the same children a year earlier, the data show that perception of patterns of musical beat distribution is severely impaired in dyslexic children. Indeed, the musical beat perception task (formerly the ‘perception of musical meter task’, Huss et al., 2011) was performed more poorly by children with dyslexia aged 11 years than by younger RL-matched controls aged 9 years, suggesting a robust perceptual deficit. Individual differences in the musical beat perception task were also both concurrent and longitudinal predictors of individual differences in reading development, for single word reading, nonword reading and reading comprehension. Further, longitudinal multiple regression analyses provided evidence that the musical beat perception task is measuring auditory mechanisms related to reading skills that only partially overlap with those related to sub-lexical phonological awareness, as musical beat perception continued to predict significant unique variance in reading even after phonological awareness was accounted for statistically. For example, the data analyses showed that a further 18% of unique variance in reading comprehension was explained longitudinally by the musical beat perception task even after accounting for sub-lexical phonological awareness, which accounted longitudinally for 38% of unique variance in reading comprehension.

Given the current range of theoretical views concerning possible shared neural bases for processing music and language (e.g., Patel, 2008; Shahin et al., 2010; Besson et al., 2011; Strait and Kraus, 2011; Huss et al., 2011), it is of interest to explore the auditory sensory predictors of performance in the musical beat perception task. Exploration of the *longitudinal* auditory predictors of performance in the musical beat perception task identified sensitivity to sound rise time, duration and frequency as important predictors of individual differences. Exploration of *concurrent* auditory predictors identified sensitivity to rise time and rising and falling pitch as uniquely related to performance in the musical beat perception task. 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 musical beat perception measure may arise in part because certain aspects of auditory processing are related to both musical perception and phonological awareness, which is related to reading development (Anvari et al., 2002). The auditory measures that were significantly related to both musical perception and phonological awareness in partial correlation analyses were rise time and rising pitch. However, sensitivity to rising pitch was not related to reading development, whereas sensitivity to rise time was (single word reading, nonword reading, reading comprehension). Furthermore, the children with dyslexia now had significantly higher rise time thresholds than the *younger* RL controls, whereas a year earlier they had shown equivalent auditory sensitivity to rise time as these younger children. Taken together, the analyses identify perceptual sensitivity to sound rise time as a unique associate of both musical beat perception and written language development. Sensitivity to rise time appears to mediate performance in both types of task, supporting the theoretical view that difficulties in processing certain aspects of auditory temporal structure, for which rise time discrimination is a sensitive indicator, will impair both musical processing and reading development in affected children (the “temporal sampling” framework, see Goswami, 2011).

In the temporal sampling framework, it is proposed that both musical and language processing depend in part on accurate “temporal sampling” of auditory input by neural oscillatory mechanisms at different temporal rates. These neuroelectric oscillations are thought to align their excitable phases with matching events in the input such as the peak amplitude of stressed syllables, thereby entraining their oscillations with input rhythms. For perceiving rhythmic temporal structure in musical and speech inputs, successful sampling of amplitude modulations at lower frequencies (theta, 4–8 Hz, and delta, .5–4 Hz) is thought to be critical (see Goswami, 2011). These lower-frequency modulations underpin the perception of rhythm, namely the patterns of beat distribution in music (accented and unaccented notes) and language (stressed and unstressed syllables). Although periodicity in music is isochronous, whereas periodicity is anisochronous in language, this may not necessitate different neural networks for periodic versus non-periodic rhythm (as suggested on the basis of adult data by Patel, 2008). Indeed, earlier in development infants and children may used *shared* neural mechanisms to process *both* periodic and aperiodic patterns of beat distribution. Linguistic reviews of rhythmic processing have shown that, across languages, the occurrence of stressed syllables is approximately periodic, occurring on average every 500 msec (2 Hz, Arvaniti, 2009). Therefore, across languages, there may be a quasi-rhythmic temporal skeleton to which the infant brain may entrain, enabling infants to form temporal expectancies about when the next stressed syllable should occur on the basis of acoustic statistical regularities, and thereby supporting language acquisition (Hämäläinen et al., 2012a). In terms of phonological development, infants who are learning to process a given language may locate syllable beats on the basis of acoustic cues like rise time, using this temporal expectancy framework to develop sensitivity to higher-order temporal structure, such as the differences in the grouping and relative duration of sound elements in a language (non-periodic rhythm).

From this “entrainment” perspective (Goswami, 2011), relative insensitivity to patterns of beat distribution as found in dyslexia may impair the efficient processing and accurate encoding of syllable stress in language and thereby affect the quality of the phonological representations that develop in the child’s mental lexicon of word forms. This developmental perspective would fit the data reported here, as individual differences in sensitivity to patterns of beat distribution were related to individual differences in both phonological awareness and reading. However, difficulties in forming an internal representation of rhythmic timing would also affect the development of auditory attention, and there are a variety of attentional theories of dyslexia (see Lallier and Valdois, 2012, for a recent overview). Cognitive work on attention has discussed extensively the role of hypothetical oscillators in auditory attending (Large & Jones, 1999; Jones et al., 2002; see also Kotz and Schwartze, 2010), and auditory attention-based theories of dyslexia propose (for example) sluggish attentional shifting in dyslexia (e.g., Hari and Renvall, 2001; Facoetti et al., 2010a; Lallier et al., 2009, 2010). As noted by Goswami (2011), the temporal sampling framework would predict that inefficient auditory entrainment would necessarily affect auditory attention and attention shifting. According to dynamic attending theory (Jones et al., 2002), when an auditory event is anticipated at a regular and predictable rhythmic rate, the window of attention is narrowed and stimulus perception is enhanced. If basic entrainment processes are inefficient in dyslexia, this would affect temporal expectancies and impair attention shifting. Hence a conceptual framework for dyslexia based on temporal sampling can integrate attentional and phonological deficits into a single explanatory system.

Of course, it is also logically possible that an auditory attention problem has a specific effect on auditory processing in dyslexia, which affects the perception of sound rise time. However, auditory attention problems should affect all auditory perception tasks equally in dyslexic children (such as the discrimination of falling pitch, which here showed no group differences, or the duration discrimination task in Huss et al., 2011, which also showed no group differences). Regarding the current sample of children, some of whom were previously screened for attention difficulties using the Barkley scale (Barkley, 1998), we can report that there was no correlation between inattention scores and rise time perception [$r(46) = .023$, $p = .875$]. Furthermore, a recent developmental study of attention in pre-reading typically-developing English-speaking children as young as 3 years found no longitudinal predictive relations between measures of both sustained and selective attention and literacy development, even though relations were found for basic numeracy (Steele et al., in press). On the other hand, a recent study by Facoetti and colleagues of Italian children did find predictive relations between a preschool measure of visual attention and literacy acquisition (Facoetti et al., 2010b). Clearly, to test possible developmental inter-relationships between attention, auditory sensory processing, phonological and literacy development, systematic data are required using all the different auditory and attention tasks in the dyslexia literature (e.g., attention shifting, stream segregation, rise time and other measures) with the same children. Ideally these data would be collected before reading commences, in order to understand possible causal links with dyslexia.

In conclusion, the current data on auditory rise time discrimination and musical beat perception 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. A similar point has been made by Patel (2011), who has highlighted the important role of the amplitude envelope in musical perception. Patel (2011) notes that the envelope is an important cue to musical timbre, and that attack time in music (the rise time of a musical note) is critical for the perception of musical rhythm and timing. He thus argues that musical training in envelope processing might benefit the neural processing of speech envelopes as well. This seems a plausible proposal on the basis of the data reported here. The current data support the theoretical view that perception of patterns of beat distribution (rhythmic timing) is a key parameter in linking the processing of music by children to the processing of language. The data also suggest that a shared underlying sensory/neural mechanism may be auditory processing of rise time.

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