CORTEX XXX (2010) 1–16

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/cortex

Research report

Music, rhythm, rise time perception and developmental dyslexia: Perception of musical meter predicts reading and phonology

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

Centre for Neuroscience in Education, University of Cambridge, Cambridge, U.K.

ARTICLE INFO

Article history:
Received 19 August 2009
Reviewed 5 October 2009
Revised 11 January 2010
Accepted 26 May 2010
Action editor J-F Demonet
Published online xxx

Keywords:
Dyslexia
Music
Rhythm
Phonology
Reading

ABSTRACT

Introduction: Rhythm organises musical events into patterns and forms, and rhythm perception in music is usually studied by using metrical tasks. Metrical structure also plays an organisational function in the phonology of language, via speech prosody, and there is evidence for rhythmic perceptual difficulties in developmental dyslexia. Here we investigate the hypothesis that the accurate perception of musical metrical structure is related to basic auditory perception of rise time, and also to phonological and literacy development in children.

Methods: A battery of behavioural tasks was devised to explore relations between musical metrical perception, auditory perception of amplitude envelope structure, phonological awareness (PA) and reading in a sample of 64 typically-developing children and children with developmental dyslexia.

Results: We show that individual differences in the perception of amplitude envelope rise time are linked to musical metrical sensitivity, and that musical metrical sensitivity predicts PA and reading development, accounting for over 60% of variance in reading along with age and I.Q. Even the simplest metrical task, based on a duple metrical structure, was performed significantly more poorly by the children with dyslexia.

Conclusions: The accurate perception of metrical structure may be critical for phonological development and consequently for the development of literacy. Difficulties in metrical processing are associated with basic auditory rise time processing difficulties, suggesting a primary sensory impairment in developmental dyslexia in tracking the lower-frequency modulations in the speech envelope.

Metrical perception is important for both speech and music. Both music and speech unfold in time, and the rhythm or periodicity with which strong and weak beats recur is central to the sequential organisation of sounds in both domains. This is referred to as meter in music and as syllable stress in speech. In music the place and role of different notes in the overall sequential pattern are important, with both rhythm and pitch acting as "musical syntax" (Thaut, 2005). This is analogous to prosodic structure in language, which has been described as a "phonological grammar" (Port, 2003). Both

---

* *Corresponding author*. Centre for Neuroscience in Education, 184 Hills Road, Cambridge CB2 8PQ, U.K.
E-mail address: ucg10@cam.ac.uk (U. Goswami).

0010-9452/$ – see front matter © 2010 Elsevier Srl. All rights reserved.
doi:10.1016/j.cortex.2010.07.010

Please cite this article in press as: Huss M, et al., Music, rhythm, rise time perception and developmental dyslexia: Perception of musical meter predicts reading and phonology, Cortex (2010), doi:10.1016/j.cortex.2010.07.010

rhythm and pitch contribute to the perception of speech prosody (Marie et al., 2009), and the position of syllables and the stress and pitch contour placed on different syllables contribute to the extent to which a language has easily-defined prominences or accents (see Arvaniti, 2009). Developmental inefficiencies in basic auditory processing might be expected to affect both language development and the development of musical abilities. Current data from children with developmental language impairments [specific language impairment (SLI) and developmental dyslexia] suggest a particular role for inefficiencies in processing acoustic cues to rhythm, although so far this has only been shown in the language domain (e.g., Corriveau et al., 2007; Goswami et al., 2002).

Rhythm in music reflects at least two core aspects of temporal organisation, periodicity or metrical structure, and the patterning of musical events into similarly-structured groupings, or phrase structure. In language, speech rhythm has a similar organisational role, reflecting syllable, word and clausal boundaries. The important energy fluctuations in the speech signal are rhythmic not in terms of being perfectly periodic (they are not), but in terms of the motor constraints inherent in producing syllables (Chandrasekaran et al., 2009). For example, long and short syllables often follow each other, as do stressed and unstressed syllables. According to Cutler's "rhythmic segmentation hypothesis" (e.g., Cutler 1996), listeners adopt the unit of metrical organisation prevalent in their language as a prelexical cue to word boundaries (e.g., the foot in English, the syllable in French or Spanish, the mora in Japanese). Developmentally, therefore, accurate metrical perception should be important for phonological learning (for example, by enabling the accurate segmentation of syllables and words from the speech stream, Echols, 1996). Here, we assume that there may be very basic auditory processes that are used in perceiving both music and language, which enable the extraction of metrical structure and rhythm (see Goswami, in press; Corriveau and Goswami, 2009). Building on prior work showing that individual differences in sensitivity to basic auditory cues to rhythm, in particular sound rise time, affect literacy development via phonological development, we explore the related possibility that individual differences in auditory sensitivity to these cues may also affect metrical perception. Further, as rhythmic structure is more overt in music than in language, we are interested in the possibility that musical interventions could be of benefit in developmental language disorders such as developmental dyslexia (Forgeard et al., 2008; Overy, 2000, 2003). We therefore also examine relations between musical metrical perception, phonological processing of language, and literacy acquisition (see also Wood, 2006).

The theoretical framework underpinning our approach can be described as a rhythmic timing hypothesis of developmental language impairments. Following a series of studies of children's auditory perception of amplitude envelope structure, in particular, rise time (e.g., Corriveau et al., 2007; Corriveau and Goswami, 2009; Goswami et al., 2002, 2010c; Richardson et al., 2004; Thomson and Goswami, 2008), we proposed that while amusic brains can be described as being "out of tune but in time" (Hyde and Peretz, 2004), the brains of children with developmental dyslexia or SLI may be brains that are "in tune but out of time" (e.g., Corriveau and Goswami, 2009; Goswami, in press; Thomson and Goswami, 2008). Accurate perception of sound rise time is known to be critical for rhythmic timing via the "perceptual centres" or "P-centres" literature (Hoequist, 1983; Morton et al., 1976). When deliberately speaking to a rhythm, even for languages from different rhythm classes (e.g., English, Spanish, Japanese, see Hoequist, 1983), the speaker times the rise time of each syllable (Scott, 1998). Similarly, adults hear alternating syllables like "ba" and "la" as non-rhythmic in timing when syllable onset–onset times are isochronous. This is because, across languages, listeners attend to syllable-internal events called "P-centres" or "stress beats" to determine speech rhythm, and not to the physical onsets of the syllables. Even babies are sensitive to the P-centres of syllables (Fowler et al., 1986). Rise time is also the critical auditory cue for rhythmic timing in music (Gordon, 1986; Vos and Rasch, 1981). We have proposed that impaired auditory rise time skills may underpin the phonological deficit that is pervasive in developmental dyslexia across languages, via a primary difficulty with the accurate syllabic segmentation of speech (Goswami et al., 2002; Goswami et al., 2010a).

In our auditory work with children, we have been comparing typically-developing children's processing of the rise time, duration, intensity and frequency of non-speech tone-like stimuli with that of children with developmental dyslexia or SLI. To date, we and others have found that the primary auditory difficulties for both children and adults with reading or language problems appear to involve the accurate perception of basic cues to auditory rhythmic timing, such as rise time and duration, and the correlate of rise time, amplitude modulation depth (Corriveau et al., 2007; Goswami et al., 2002, 2010c; Hämäläinen et al., 2005, 2009; Lorenzi et al., 2000; Muneaux et al., 2004; Pasquini et al., 2007; Richardson et al., 2004; Rocheron et al., 2002; Surányi et al., 2009; Thomson et al., 2006). Further, individual differences in rise time processing are linked to individual differences in phonological awareness (PA) tasks such as rhyme awareness and phoneme segmentation (e.g., Muneaux et al., 2004; Pasquini et al., 2007; Richardson et al., 2004; Surányi et al., 2009). One plausible reason for this robust relationship between auditory rhythmic cues and PA could be the important role of prosodic factors in children's phonological development (e.g., Goswami et al., 2010c; Pierrehumbert, 2003; Vihman and Croft, 2007). Rise time perception is fundamental to prosodic perception, as it is the key cue to stress accent or syllable prominence in speech (e.g., Greenberg, 1999). Infant studies show that prosodic perception is fundamental to phonological development (Johnson and Tyler, 2010; Pierrehumbert, 2003; Vihman and Croft, 2007). Children who have difficulties with the accurate perception of rise time should show reduced awareness of syllable stress and speech prosody, hampering the development of a well-specified phonological system.

Prosody is a term used in linguistic theory to cover all aspects of grouping, rhythm and prominence in spoken language, from sub-parts of the syllable up through the organisation of words in the phrase (Lehiste, 1970; Pierrehumbert, 2003). Indeed, many linguists propose that the units of prosodic organisation are arranged into a hierarchical structure, so that, for instance, syllables form feet

Please cite this article in press as: Huss M, et al., Music, rhythm, rise time perception and developmental dyslexia: Perception of musical meter predicts reading and phonology, Cortex (2010), doi:10.1016/j.cortex.2010.07.010

(strong and weak syllables), feet form words, and words form intonational phrases. By analogy, units of musical organisation are also arranged in a hierarchical structure, as the temporal distribution of musical notes and their organisation into groupings impose order in musical perception. However, in speech, rhythm does not equate to timing, as metrical structure (the alternation of strong and weak beats) must be taken into account, with grouping and relative prominence determining the perceptual experience of speech rhythm (Arvaniti, 2009). Accordingly, and as illustrated by Goswami (in press), the cognitive model proposed to explain amusia by Peretz and Coltheart (2003) provides an interesting theoretical framework for considering developmental dyslexia and SLI (see adaptation of model shown in Corriveau and Goswami, 2009). In the Peretz and Coltheart (2003) model, acoustic processing follows two "streams", a pitch organisation stream (proposed to be impaired in amusia) and a temporal organisation stream (proposed to be preserved in amusia). The temporal organisation stream includes rhythm analysis, meter analysis and tapping skills, and (we have suggested) is intimately linked to the development of the phonological lexicon (e.g., Corriveau and Goswami, 2009). In our research, we find consistently that the skills that are preserved in amusia are impaired in children with language and literacy problems (see also Waber et al., 2000; Wolff, 2002; Wolff et al., 1990). For example, children with developmental dyslexia and with SLI are impaired at tapping to a rhythm, and in perceiving tempo (e.g., Corriveau and Goswami, 2009; Thomson and Goswami, 2008). The 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 (e.g., Thomson and Goswami, 2008), even though children with developmental dyslexia and with SLI are also impaired in simple pitch perception (e.g., Baldeweg et al., 1999; Goswami et al., 2010b; Lachmann et al., 2005), and phonological training can improve pitch perception (Santos et al., 2007).

Nevertheless, to date, musical perception in dyslexia has been largely explored in relation to pitch (see Kraus et al., 2009, for a recent relevant review). The exception has been the work of Overy and Winner with children with dyslexia (Forgeard et al., 2008; Overy, 2000, 2003; Overy et al., 2003). For example, Overy et al. (2003) devised a series of tests of rhythmic timing and administered them to a group of 15 children with dyslexia aged 7–11 years and 11 age-matched controls. The tasks included copying a short rhythm on a keyboard, reporting whether two rhythms were the same or different, copying different tempi via tapping, discriminating different tempi and tapping to the beat of a song ("Happy Birthday"). Additional tasks measured rapid auditory processing skills and pitch skills. Overy et al. found that the only tasks to show group differences were the rapid auditory processing task and a task of timbre discrimination, despite the use of 1-tailed statistical tests. No significant differences in the tests of rhythm and meter were found at all. This was disappointing given their hypotheses, as a pilot study with an unselected class of 7-year-old children had suggested that the poorest readers in the class were impaired on similar musical timing tasks (Overy, 2000, 2003).

As Overy et al. (2003) noted, one reason for the absence of group differences in the dyslexia study could have been small sample size ($N = 15$). Another could be that a number of the tasks involved relatively few trials (e.g. the tapping tasks involved only 8 beats). Although some interesting correlations were reported, for example between spelling development and tapping out the beat of "Happy Birthday", the correlations were not corrected for age or I.Q., making them difficult to interpret. Forgeard et al. (2008) reported briefly on four behavioural studies of musical processing by children, two of which involved children with dyslexia. In one study, 31 children with dyslexia aged 10 years were given same-different judgement tasks of pitch and rhythm processing based on 5-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, 5 of the children with dyslexia were compared to 10 children without dyslexia. A significant group difference was found for the rhythm tasks and also the pitch (melodic discrimination) tasks. The data for dyslexia reported by Overy, Winner and colleagues are thus suggestive with respect to rhythm, but not conclusive.

In contrast, and as reviewed above, our own recent studies reliably find that children and adults with dyslexia or with SLI are impaired in tempo perception, auditory rhythmic perception, and tapping to a beat (Corriveau et al., 2007; Corriveau and Goswami, 2009; Goswami et al., 2002; Pasquini et al., 2007; Richardson et al., 2004, Thomson et al., 2006; Thomson and Goswami, 2008; see also Waber et al., 2000; Wolff, 2002; Wolff et al., 1990). Here, we set out to devise a task exploring in detail children's perception of musical meter. The second author, a musician with over 20 years of experience in working with young children, devised a series of simple metrical arrangements based on 3 repetitions of 2–5 notes played on real instruments (using Sibelius). The sequences varied in terms of musical takt and accent, in both 4 time and 3 time. The children listened to pairs of these sequences, and had to decide whether in each case the metrical arrangement was the same or different. We expected that children with dyslexia would be impaired significantly in this simple task, at least for the more complex metrical manipulations. We also expected that individual differences in the metrical task would be related to individual differences in auditory rhythmic perception, and consequently, that metrical perception might be related to phonological development and reading development, and perhaps also to general language development. Accordingly, we also gave our participants standardised tests of reading, spelling and receptive language, and tests of auditory sensitivity (to sound rise time, sound intensity, sound frequency and sound duration), PA and phonological short-term memory (PSTM).

1. Method

1.1. Participants

Sixty-four children aged between 8 and 13 years participated in this study. These children were taking part in a longitudinal study of developmental dyslexia, and comprised an unselected group of the total cohort who were available to complete the musical meter task (for a description of the larger cohort from which the participants were drawn, see Goswami et al., 2010b). Although this resulted in unequal group sizes, analysis of variance (ANOVA) is robust to such variation and the reported results were also confirmed using non-parametric tests. The auditory threshold tasks described below represent a subset of auditory thresholds tasks that have been delivered to the participating children at yearly intervals. All children are extremely familiar with the tasks, ruling out task difficulty as a basis for group differences. At the test point reported here, the children had been participating in the study for 3 years (test phase 3). 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 IQ above 85, and English as the first language spoken at home were included. 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 HL range.

Thirty-three of the children (17 males; mean age 10 years 5 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. Sixteen age-matched control children (chronological age – CA control group; 9 males; mean age 10 years 6 months) and 15 reading-level matched control children (reading level – RL control group; 4 males; mean age 8 years 4 months) were recruited from the same schools as the dyslexics. As shown in Table 1, the CA controls differed by 24 standard points and by 3 years 3 months in average reading age from the children with dyslexia (both significant differences), whereas the RL controls differed by 23 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) was not significant, whereas the difference in standard score was. Participant details are shown in Table 1.

1.2. Tasks

1.2.1. 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 and Vocabulary. I.Q. scores were prorated following the procedure adopted by Sattler (1982). Literacy skills were re-assessed at the current test point using the British Ability Scales (BAS) (Elliott, et al., 1996). A measure of receptive vocabulary, the British Picture Vocabulary Scales (BPVS), was also re-administered (Dunn et al., 1982).

1.2.2. PA measure

A rhyme oddity task using digitized speech created from a native female speaker of standard Southern British English was utilised. The children listened to sets of three words through headphones, and had to select the one that did not rhyme (e.g. gap, nap, Jack). Trials were presented in 2 fixed random orders. The task comprised 20 trials, 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.

1.2.3. PSTM measure

The memory task was also based on digitized speech from the same female speaker, and consisted of 16 trials of four spoken monosyllables. The children were required listen to each set of 4 words and then repeat them back to the experimenter.

Table 1 – Participant details.

Group	Dyslexic	CA controls	RL controls	$F(2,61)$
Chronological age (months)[a]	125.2	126.2	99.9	23.2***
(SD)	(14.1)	(14.3)	(6.3)	
Reading age (months)[b]	99.0	137.6	107.7	21.9***
(SD)	(18.7)	(22.1)	(17.3)	
WISC short-form I.Q.	107.6	109.6	110.0	.212
(SD)	(15.8)	(10.3)	(11.1)	
Reading standard score[c]	84.5	108.9	107.3	35.2***
(SD)	(10.5)	(10.8)	(13.3)	
Spelling standard score[c]	81.1	101.9	105.7	39.0***
(SD)	(8.2)	(10.0)	(14.3)	
BPVS standard score	105.5	108.1	107.0	.272
(SD)	(12.0)	(13.9)	(9.0)	

***$p < .001$.
a Dyslexic = CA, different from RL.
b Dyslexic = RL, different from CA.
c Dyslexic worse than CA and RL.

Table 2 – Group performance on the phonological and auditory tasks, with parametric statistics for dyslexics versus CA controls ($N = 49$).

Group	Dyslexic	CA control	RL control	$F(1,48)$
PA % correct[a]	62.1	81.3	62.7	19.98***
(SD)	(14)	(13)	(16)	
PSTM, % correct	42.6	50.6	40.9	16.62***
(SD)	(7)	(6)	(6)	
Auditory threshold				
1 Rise in msec[a]	105.9	36.4	95.0	9.71**
(SD)	(73.0)	(14.8)	(70.1)	
2 Rise in msec[a]	250.6	185.3	246.5	12.52**
(SD)	(151.7)	(129.9)	(172.9)	
Rise Duration Rove in msec[a]	113.4	31.8	105.9	13.13**
(SD)	(76.3)	(11.7)	(84.9)	
Duration in msec	97.6	89.6	107.6	.40
(SD)	(43.1)	(48.8)	(44.6)	
Frequency in semitones[a]	1.4	.6	1.0	15.99***
(SD)	(.5)	(.5)	(.6)	
Intensity in dB[a]	2.7	2.1	2.5	4.36*
(SD)	(.6)	(.3)	(.7)	

***$p < .001$, **$p < .01$, *$p < .05$.
a Dyslexic worse than CA.

Please cite this article in press as: Huss M, et al., Music, rhythm, rise time perception and developmental dyslexia: Perception of musical meter predicts reading and phonology, Cortex (2010), doi:10.1016/j.cortex.2010.07.010

Children listened to the stimuli through sound attenuating headphones. Responses were registered by digital voice recorder and scored in terms of the number of words recalled correctly. Performance (% correct) is shown in Table 2. Percentage scores were used in the analyses.

1.2.4. *Perception of musical meter*

This task comprised 36 trials of different metrical arrangements of a series of notes with an underlying pulse rate of 500 msec (120 bpm), each series being delivered twice within one trial. Eighteen of the trials delivered the identical series of notes twice ("same" trials), and 18 delivered two slightly different series of notes ("different" trials), created by making the accented note longer in the second delivery. All of the "different" trials are provided as Fig. 1. The sound files were created using Sibelius Version 4 from a sound set produced by Native Instruments (Kontakt Gold). As the sounds were sampled sounds from a vibraphone, they contained all the associated harmonic complexities. The pitch of the musical notes was G (392 Hz). Each series was based on between 2 and 5 notes repeated 3 times, to keep short-term memory (STM) demands low. Trial length was approximately equated across variations in the number of notes by using half notes (see Fig. 1). Twenty trials (10 same, 10 different) were in 4/4 time and 16 trials (8 same, 8 different) were in 3/4 time, with accent conveyed by increasing the intensity of the relevant note in the sequence (by 5 dB). This more intense note was the first note in the series for 20 trials, the second note in the series for 10 trials, and the third note in the series for 6 trials. This meant that the tone arrangements also varied in terms of musical accent (which could be on the first, second or third note in a bar). The change in metrical structure was either caused by adding 100 msec to the accented notes (short duration change, 9 "different" trials) or by adding 166 msec to the accented notes (long duration change, 9 "different" trials). The longer changes (166 msec) were expected to be perceptually more salient. 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 in which sequences expected to be perceptually easier were delivered first. However, as will be seen, the planned variation in rhythmic complexity did not have an effect on children's performance.

1.2.5. *Psychoacoustic tasks*

The psychoacoustic stimuli were presented binaurally through headphones at 75 dB SPL. Earphone sensitivity was calculated using a Zwislocki coupler in one ear of a KEMAR manikin (Burkhard and Sachs, 1975). 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 first author. The amended Dinosaur programme used an adaptive staircase procedure (Levitt, 1971) with a combined 2-up 1-down and 3-up 1-down procedure; after 2 reversals, the 2-up 1-down staircase procedure changes into 3-up 1-down. The step size halves after the 4th and 6th reversal. A test run typically terminates after 8 response reversals or alternatively after the maximum possible 40 trials. Four attention trials were randomly presented during each test run, using the maximum contrast of the respective stimuli in each auditory task. Analysis of these trials confirmed that attention was not different between groups in the auditory tasks. The threshold score achieved was calculated using the mean of the last four reversals. As rise time sensitivity was the theoretical focus of the larger longitudinal study from which the current data set is drawn, there were 3 measures of rise time sensitivity. In our cross-language studies, the 1 Rise task has been the most sensitive predictor of dyslexia across languages (e.g., Surányi et al., 2009; Goswami et al., 2010a). Schematic depiction of the 1 Rise and 2 Rise stimuli are provided as Fig. 2.

1.2.5.1. Amplitude envelope onset (rise time) task (1 Rise). This was a rise time discrimination task in AXB format. Three 800 msec tones were presented on each trial, with 500 msec 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 logarithmically 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). The child then participated in five practice trials. Feedback was given after every trial by the computer software. During the practice period this was accompanied by further verbal explanation and reinforcement by the researcher.

1.2.5.2. Rise time from a carrier task (2 Rise). For this 2IFC task a continuum of 40 stimuli was created using a sinusoidal carrier at 500 Hz amplitude-modulated at the rate of .7 Hz (depth of 50 per cent). Children were required to discriminate amplitude changes with different rates of onset within sounds comprising two amplitude envelopes rising from a steady state. Each stimulus was 3573 msec long (2.5 cycles), presented with an inter-stimulus interval (ISI) of 500 msec. Rise time was again varied logarithmically from 15–300 msec and fall time was fixed at 350 msec. The longest rise time sound was the standard sound, and children were asked to choose the dinosaur who made the sound that had the sharper beat (i.e., the shorter rise time).

1.2.5.3. Rise Duration Rove task. This was exactly as the 1 Rise task, except that the duration of each stimulus varied randomly across the experiment. This was done by randomly roving the duration of the steady state portion of the stimulus from 450 msec to 735 msec. If an amplitude envelope is always 800 msec long with a 50 msec fall time (as in the 1 Rise task), and the rise time is either 15 msec or 300 msec, then the steady state portion of the first stimulus will be 735 msec whereas for the second it will be 450 msec. It is thus possible that children could discriminate between the rise time stimuli on the basis of the difference in steady state duration. By roving duration we eliminated this alternative cue.

1.2.5.4. Frequency task. This was a frequency discrimination task delivered in an AXB format with 500 msec ISI between tones. The standard was a pure tone of 500 Hz presented at 75 dB SPL,

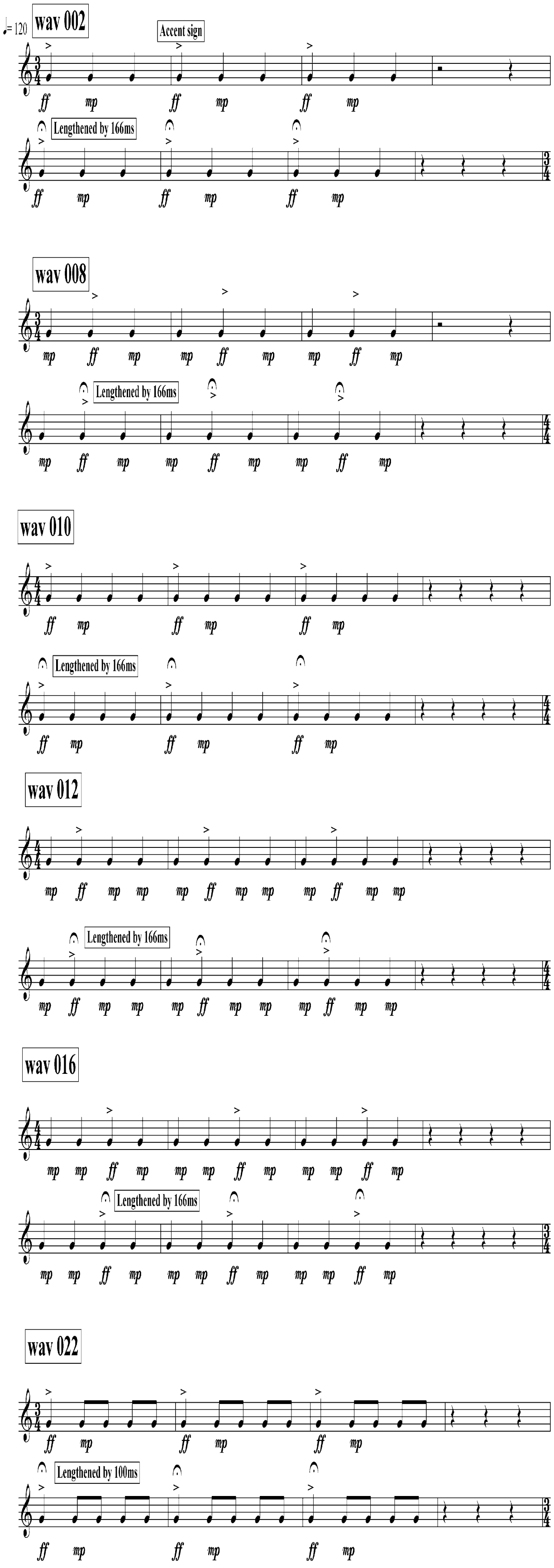

Fig. 1 – Depiction of all of the musical arrangements used as the "different" trials in the musical metrical perception task. Each arrangement was recorded with an underlying pulse rate of 500 msec. The more intense beat in a sequence is marked "＞", and the position and extra length of the lengthened accented beat are also marked. Wav file numbers correspond to file names in the online supporting materials.

Please cite this article in press as: Huss M, et al., Music, rhythm, rise time perception and developmental dyslexia: Perception of musical meter predicts reading and phonology, Cortex (2010), doi:10.1016/j.cortex.2010.07.010
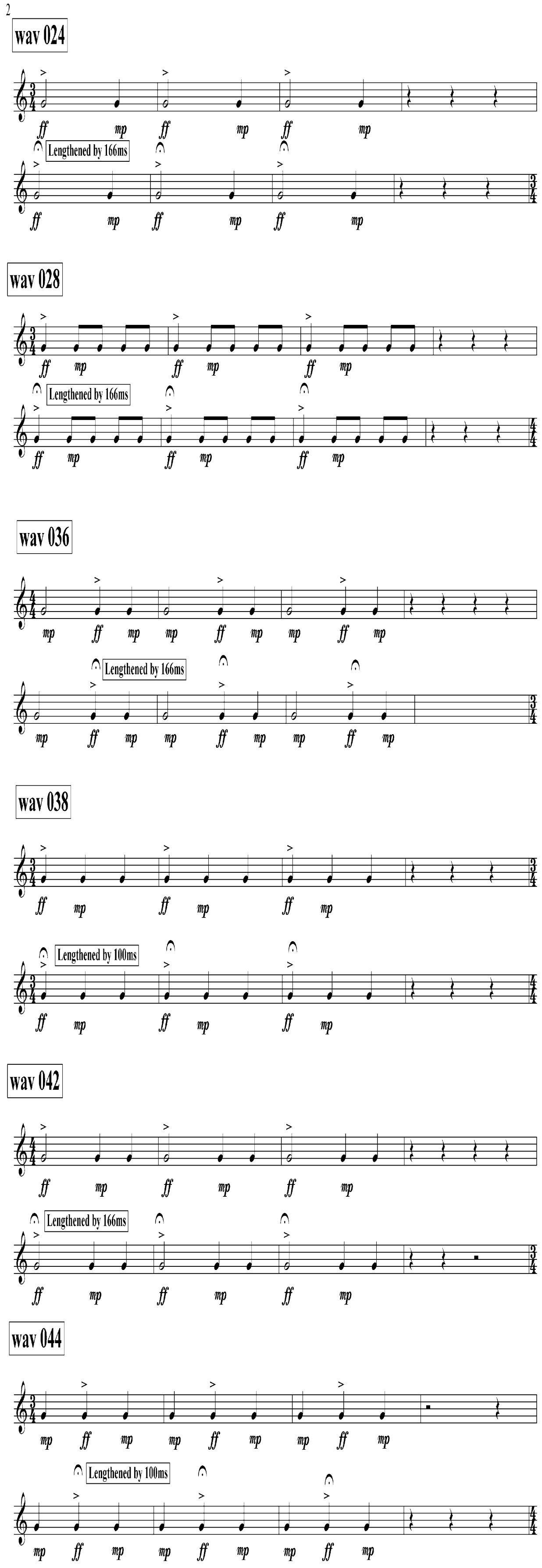
Fig. 1 (continued).

Please cite this article in press as: Huss M, et al., Music, rhythm, rise time perception and developmental dyslexia: Perception of musical meter predicts reading and phonology, Cortex (2010), doi:10.1016/j.cortex.2010.07.010
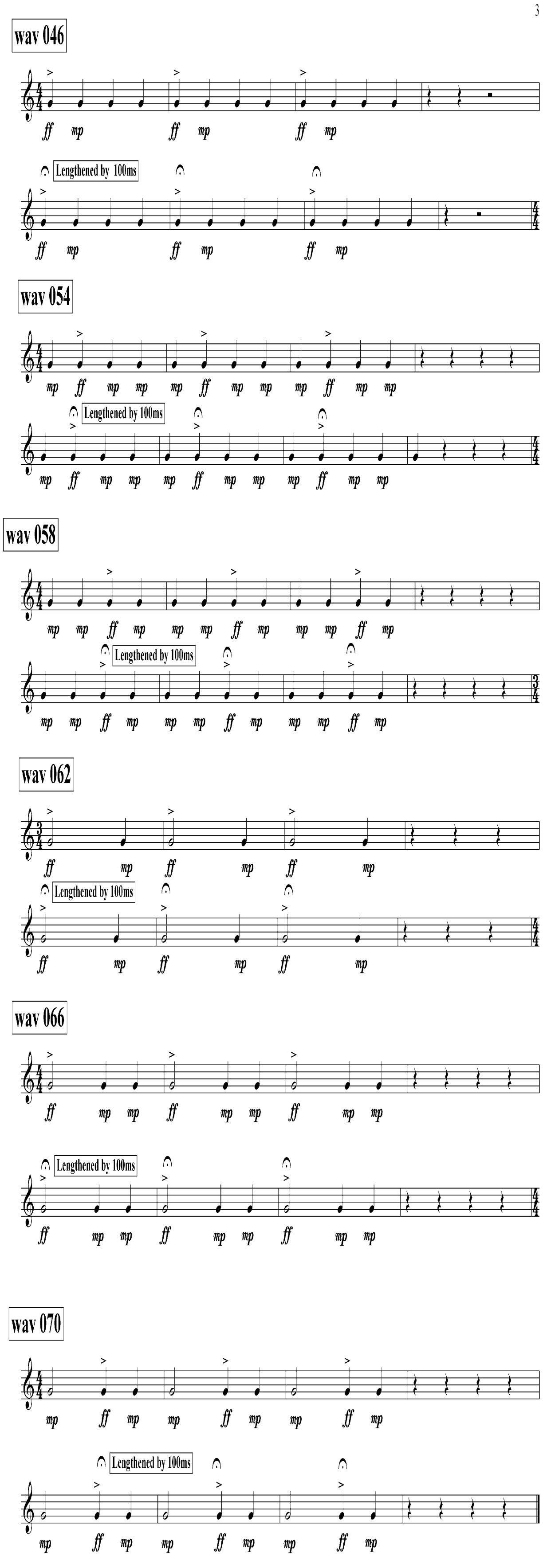
Fig. 1 (continued).

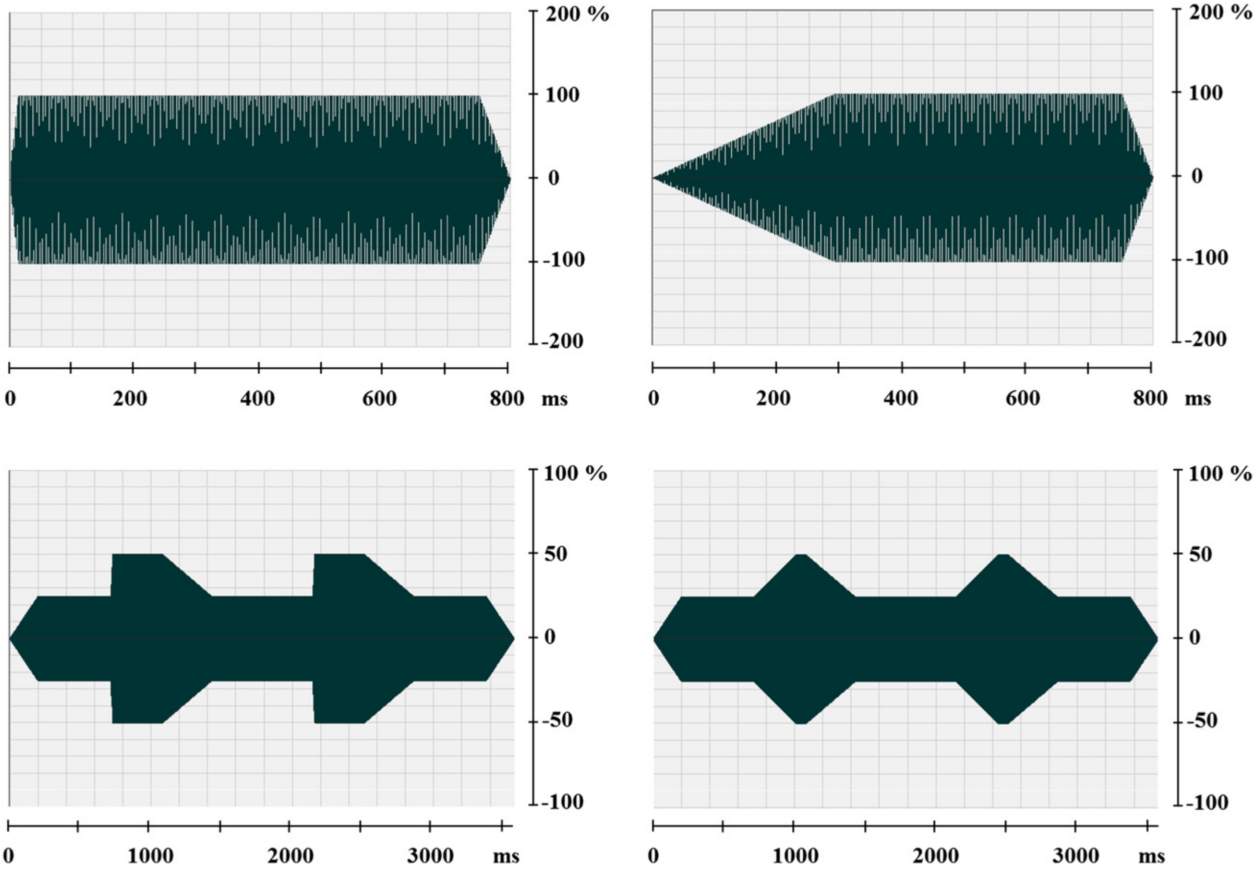

Fig. 2 – Schematic depiction of amplitude envelopes used in the 1 Rise and 2 Rise tasks.

which had a duration of 200 msec. The maximum pitch difference between the stimuli presented in this task was 3 semitones. Children were introduced to three cartoon elephants. It was explained that each elephant would make a sound and the child had to decide which elephant's sound was higher.

1.2.5.5. 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 400 msec and a frequency of 500 Hz, presented at 75 dB SPL. The duration of the third tone ranged logarithmically from 400 msec to 600 msec. Children were introduced to three cartoon sheep. It was explained that each would make a sound, and the child's job was to decide which sound was longer.

1.2.5.6. Intensity task. This was a 2IFC intensity discrimination task with 500 msec ISI between tones. The standard was a pure tone with a duration of 200 msec and a frequency of 500 Hz presented at 75 dB SPL. The intensity of the second tone ranged from 55 to 75 dB SPL. Children were introduced to two cartoon mice. It was explained that each would make a sound, and the child's job was to decide which sound was softer.

2. Results

Auditory discrimination and metrical perceptual data were explored by group to check that assumptions of normality were met. The statistical package for the social sciences (SPSS) boxplot function was used to check for outliers, and any data points lying farther than 3 interquartile ranges from the further edge of the box were removed. There were no outliers in the task measuring the perception of musical meter. Five outlier scores were identified and removed for the auditory processing tasks (1 CA control score for 1 Rise, 2 CA control scores for Rise Duration Rove, 1 dyslexic and 1 CA control score for intensity). Group data for the standardised tasks are provided in Table 1, for the experimental tasks in Table 2, and for the musical metrical perception task in Table 3.

As would be expected given previous work (Table 2), the children with dyslexia were significantly less sensitive to auditory rise time than their CA controls. There has been some debate in the literature concerning the appropriate control group to use in statistical comparisons with children with dyslexia when studying sensory tasks. One strong view has been that only comparison with age-matched controls is appropriate (e.g., Ramus et al., 2006, "a reading age [and therefore younger] control group could only have poorer sensorimotor performance", p. 266; see also White et al., 2006). However, it is also possible that learning to read could itself affect auditory sensory processing (see Goswami et al., 2010c). As learning print-sound correspondences helps to clarify the phonological representations of words in the mental lexicon (see Ziegler and Goswami, 2005), better-specified phonological representations could also impact auditory sensory processing. Therefore, comparisons with younger reading-level

Please cite this article in press as: Huss M, et al., Music, rhythm, rise time perception and developmental dyslexia: Perception of musical meter predicts reading and phonology, Cortex (2010), doi:10.1016/j.cortex.2010.07.010

Table 3 – Group performance in the perception of musical meter task, with parametric statistics for dyslexics versus CA controls ($N = 49$).

Task	Dyslexic	CA controls	RL controls	$F(1,48)$
Number correct[a] (out of 36)	22.6	30.2	23.5	39.2***
(SD)	(4.49)	(2.54)	(4.61)	
4/4 Time[a,b] (max = 20)	11.7	16.8	12.7	32.4***
(SD)	(3.47)	(1.28)	(2.61)	
3/4 Time[a] (max = 16)	10.9	13.4	10.9	19.9***
(SD)	(1.94)	(1.50)	(2.36)	
Accent on first note[a,b] (max 20)	13.2	17.3	13.3	28.9***
(SD)	(2.81)	(1.57)	(3.13)	
Accent on 2nd/3rd note[a,b] (max 16)	9.4	12.9	10.2	28.3***
(SD)	(2.45)	(1.39)	(2.27)	
2-note sequence[a] (max = 4)	2.4	3.6	2.4	23.1***
(SD)	(.89)	(.63)	(.83)	
3-note sequence[a] (max = 16)	9.9	12.7	10.1	18.8***
(SD)	(2.22)	(1.74)	(2.63)	
4-note sequence[a,b] (max = 12)	7.4	10.8	8.5	35.8***
(SD)	(2.19)	(.75)	(1.77)	
5-note sequence (max = 4)	2.9	3.1	2.5	.87
(SD)	(.89)	(.81)	(1.06)	
Metrical change via long durational change[a] (max = 9)	6.2	7.7	6.4	10.1**
(SD)	(7.69)	(1.20)	(1.40)	
Metrical change via short durational change[a] (max = 9)	4.1	7.1	4.3	31.1***
(SD)	(2.05)	(.77)	(2.32)	

a Children with dyslexia significantly worse than CA controls.
b Brown–Forsythe test.

matched children are also of theoretical value. Here we adopt the strategy of basing our conclusions on statistical comparisons with the CA children only, but for each analysis we also ran ANOVAs based on all 3 participant groups (*F* values not shown in Table 2). The one-way ANOVAs comparing the children with dyslexia ($N = 33$) to their CA controls ($N = 16$) showed significantly higher thresholds in the 1 Rise, 2 Rise and Rise Duration Rove tasks. Thresholds for the 1 Rise and Rise Duration Rove tasks were extremely similar (suggesting that the discrimination is made on the basis of rise time in both cases, we have not yet created a roving duration version of the 2 Rise task). The children with dyslexia were also significantly less sensitive to frequency and intensity, and they also showed significantly poorer PA and PSTM than their CA controls. Interestingly, they were not impaired in perceiving the duration of simple tones. When all 3 groups of children were compared statistically, the children with dyslexia showed auditory thresholds equivalent to the younger RL controls for all the rise time tasks and for the frequency task. For the duration and intensity tasks, they were again equivalent to the RL controls, but were also statistically equivalent to the CA controls (duration, $p = .518$; intensity, $p = .052$).

Table 3 shows that in general the children with developmental dyslexia were also performing more poorly than the CA controls in the musical metrical task, and at a similar level to the younger RL controls. In order to explore the effects of the different metrical manipulations shown in Table 3 (4/4 time versus 3/4 time, accent position, notes per takt, whether the durational difference of the note causing the metrical disruption was short or long), the age-matched children (CA controls [$N = 16$] and children with dyslexia, [$N = 33$]) were again compared using a series of one-way ANOVAs. The dependent variable in each case was the number of trials answered correctly. In comparisons where homogeneity of variance assumptions was not met, the Brown–Forsythe test was used to evaluate group differences. The findings were straightforward – the children with dyslexia were significantly poorer for every manipulation (all *p*'s and corrected *p*'s < .001). The one exception was the 5-note sequences. For every variable shown in Table 3, the additional ANOVAs using all the children ($N = 64$) showed that RL group performance was statistically equivalent to that of the children with dyslexia. The only exception was for the 5-note tasks, which were very easy for all of the children and showed no statistical differences between the 3 participant groups.

Partial correlations between all the metrical manipulations and the literacy and phonology measures when age and I.Q. were controlled are provided in Table 4. Inspection of Table 4 for bolded values ($p < .001$) demonstrates that for each outcome measure excepting receptive vocabulary (i.e., for PA, reading, spelling, and phonological memory), the partial correlations are significant. This is the case when metrical perception is scored in terms of 4/4 time, 3/4 time, number of notes, accent, and when the metrical change depends on adding a short duration (100 msec). The exceptions are the 5-note sequences, the 2-note sequences, and when the metrical change depends on adding a long duration (166 msec). Overall, Table 4 suggests that total number correct is a representative measure of task performance. This measure was used as the dependent variable in the multiple regression analyses.

If poorer discrimination of metrical structure in musical sequences is indeed associated with difficulties in amplitude envelope onset perception, then individual differences in rise time sensitivity should predict performance in the metrical perception task. Accordingly, individual differences in

Please cite this article in press as: Huss M, et al., Music, rhythm, rise time perception and developmental dyslexia: Perception of musical meter predicts reading and phonology, Cortex (2010), doi:10.1016/j.cortex.2010.07.010

Table 4 – Pearson correlations between musical metrical tasks, phonology and literacy measures, controlling for age and I.Q., dyslexic and CA children.

Metrical task	Rhyme oddity	BAS reading	BAS spelling	BPVS	PSTM
Total correct	**.539**	**.731**	**.645**	.069	**.475**
4/4 time	**.545**	**.698**	**.628**	.046	**.463**
3/4 time	**.382**	**.607**	**.509**	.188	**.373**
Accent on 1st	**.488**	**.657**	**.604**	.080	**.408**
Accent on 2nd/3rd	**.490**	**.672**	**.566**	.104	**.458**
2-note sequence	.291	**.427**	**.473**	.021	.169
3-note sequence	**.432**	**.645**	**.582**	.061	**.407**
4-note sequence	**.573**	**.733**	**.633**	.073	**.501**
5-note sequence	.153	.145	.026	.225	.176
Change via long duration	.273	.356	.273	.082	.221
Change via short duration	**.432**	**.590**	**.558**	.101	**.475**

Note: Correlations in bold indicate $p < .01$ with df 45.

performance in the 1 Rise, 2 Rise and Rise Duration Rove tasks were all expected to be related to individual differences in metrical performance. Also of interest was whether individual differences in duration discrimination, frequency discrimination and intensity discrimination would be predictive of metrical performance. As will be recalled, meter was conveyed by increasing the intensity of one note (the accented note), and metrical structure was altered in the "different" trials by increasing the temporal duration of this accented note. The multiple regression analyses were run for the age-matched children (CA and dyslexic, $N = 49$) using a series of three-step fixed entry equations, controlling first for age (step 1) and then I.Q. (step 2). The third step was the childrens' auditory discrimination thresholds in the respective auditory tasks. Results are shown in Table 5. As can be seen, all 3 measures of rise time processing explained significant unique variance in the perception of musical meter task, with the 2 Rise measure showing the strongest connection (24% of unique variance explained, compared to 19% for the 1 Rise measure and 21% for the Rise Duration Rove measure). Individual differences in the discrimination of duration did not explain significant variance in the perception of musical meter, despite the fact that metrical structure was altered by varying durational cues. Sensitivity to frequency and intensity were also significant predictors of metrical performance, explaining 23% and 11% of unique variance in the perception of musical meter task respectively.

Table 5 – Unique variance (R^2 change) in metrical musical perception (total correct out of 36) explained by the basic auditory processing measures in 3-step fixed entry regression equations.

Step	Beta	R^2 change
1. Age	.270	.073
2. IQ	.091	.008
3. 1 Rise	−.465	.192**
3. 2 Rise	−.494	.239***
3. Rise Duration Rove	−.475	.209**
3. Duration	−.096	.008
3. Frequency	−.554	.225***
3. Intensity	−.347	.109*

$^{***}p < .001$, $^{**}p < .01$,$^{*}p < .05$. Beta = standardized Beta coefficient; R^2 change = unique variance accounted for at each step of the three-step fixed entry multiple regression equations; I.Q. = WISC I.Q. short form.

The three different rise time measures are likely to be tapping the same auditory mechanism, whereas the frequency discrimination measure is not. To explore the independence of these auditory tasks with respect to metrical perception, a final regression equation was constructed in which the auditory thresholds for rise time (2 Rise task), frequency, duration and intensity were entered together at Step 3. This entry method enables direct comparison of the importance of each aspect of basic auditory processing to the perception of musical meter. The results are shown in Table 6. As can be seen, overall the auditory measures contributed 38% of unique variance to the metrical perception task. The only measures to retain individual significance in this equation were the 2 Rise and intensity measures (standardised Beta −.353 and −.287 respectively, p's < .05). Theoretically, this suggests that performance in the metrical task was related to the child's ability to detect meter per se (i.e., to discriminate the more intense beats, which conveyed the meter, and to discriminate the rhythmic timing of the beats, dependent on rise time). However, these results should be treated as indicative only, as we cannot be sure that the auditory tasks are tapping independent neural mechanisms.

Inspection of the correlation matrix (Table 4) reminds us that performance in the perception of musical meter task was also related to STM ability, as would be expected. Therefore, the relationship between the discrimination of metrical structure in musical sequences and basic auditory processing of rise time, intensity and frequency was also explored in three 4-step fixed entry multiple regression equations (not shown in Table 6), controlling first for age (step 1), then I.Q. (step 2), and then STM (step 3). The fourth step was the childrens' auditory discrimination threshold for either frequency, intensity or rise time (2 Rise). In each case, the auditory measure still accounted for significant unique variance in the perception of musical meter task (rise time, 13% of unique variance, $p = .003$; frequency, also 13% of unique variance, $p = .003$; intensity, 8% of unique variance, $p = .033$). Hence the regression equations show that the relations between

Table 6 – Predictors of metrical musical perception (total correct out of 36) explained by sound rise time, duration, frequency and intensity in a block entry multiple regression equation.

Step	Beta	t	Sig
1. Age	.270	1.86	.07
2. IQ	.091	.62	.536
3. 2 Rise	−.353	−2.48	.017*
3. Duration	.011	.09	.930
3. Frequency	−.284	−1.72	.094
3. Intensity	−.287	−2.23	.032*

$p < .05$. Beta = standardized Beta coefficient; $t = t$ statistic; Sig = significance level.

Please cite this article in press as: Huss M, et al., Music, rhythm, rise time perception and developmental dyslexia: Perception of musical meter predicts reading and phonology, Cortex (2010), doi:10.1016/j.cortex.2010.07.010

discrimination of sound rise time, sound frequency and sound intensity and the perception of musical meter are not caused by individual differences in age, I.Q. or memory.

The other main theoretical question was whether poorer discrimination of metrical structure in musical sequences would be associated with individual differences in the development of literacy, for example via a relationship with phonological skills. This was again investigated using the age-matched children (dyslexic and CA, $N = 49$) and three-step fixed entry multiple regression equations, this time entering childrens' performance in the musical meter task at step 3. The dependent variable in each equation was respectively reading development (BAS ability score), spelling development (BAS ability score), or PA (rhyme oddity). Results are shown in Table 7. As can be seen, the metrical task accounted for 42% of unique variance in reading, and 28% of unique variance in spelling. It also accounted for 28% of unique variance in PA. Interestingly, the metrical task did not account for any unique variance in receptive language development (not shown, although see absence of correlations in Table 4). This suggests that metrical perception is important for phonological development rather than overall language development.

Finally, the relationship between the discrimination of metrical structure in musical sequences and phonology and literacy development was also explored in 4-step fixed entry multiple regression equations, controlling first for age (step 1), then I.Q. (step 2), and then PA or STM (see Table 7). The fourth step in each case was the childrens' performance in the perception of musical meter task. In each case, the metrical measure still accounted for significant unique variance in progress in literacy (when controlling PA, reading, 16% of unique variance, $p = .000$; spelling, 12% of unique variance, $p = .000$; when controlling STM, reading, 18% of unique variance, $p = .000$; spelling, 15% of unique variance, $p = .000$). Performance in the perception of musical meter task is therefore very strongly associated with progress in literacy.

Table 7 – Unique variance (R^2 change) in phonological and literacy outcome measures explained by metrical musical perception in 3-step fixed entry multiple regression equations (7a), and by metrical musical perception when either PA is controlled in 4-step fixed entry multiple regression equations (7b) or STM is controlled (7c).

Step	Rhyme		Reading		Spelling	
	Beta	R^2 change	Beta	R^2 change	Beta	R^2 change
7a						
1. Age	.158	.025	.415	.172	.563	.317
2. IQ	.160	.026	.187	.035	.088	.008
3. Meter	.547	$.275^{***}$	.679	$.424^{***}$	.553	$.281^{***}$
7b						
3. PA	n/a		.590	$.331^{***}$	.457	$.198^{***}$
4. Meter	n/a		.502	$.164^{***}$	.427	$.119^{***}$
7c						
3. STM	.703	$.450^{***}$	.605	$.333^{***}$	.413	$.155^{**}$
4. Meter	.278	$.055^{*}$	.508	$.184^{***}$	.462	$.152^{***}$

$^{***}p < .001$, $^{**}p < .01$.
Beta = standardized Beta coefficient; R^2 change = unique variance accounted for at each step of the three- or four-step fixed entry multiple regression equations; I.Q. = WISC I.Q. short form; meter = musical metrical perception task.

3. Conclusions

We proposed here that very basic auditory processes such as accurate rise time detection may be required to extract periodic structure when perceiving both music and language. Further, we proposed that individual differences between children in these basic auditory processes may affect both the perception of metrical structure in music and the development of the language processing skills measured by PA tasks, which in turn would be expected to affect literacy acquisition. Consistent with this hypothesis, the simple task designed here to measure children's perception of musical meter was indeed found to be associated with individual differences in rise time and intensity detection. It was also a remarkably strong predictor of reading and spelling development. This relationship may reflect the importance of the perception of metrical structure for phonological development in children (Goswami et al., 2010c; Wood, 2006; Wood and Terrell, 1998). We found here that all the different ways of assessing metrical perception using our task showed equivalent performance when comparing the (younger) RL control children and the children with dyslexia. These groups also showed equivalent performance in the auditory processing, PA and reading tasks. This may suggest that individual differences in metrical perception act as a rate-limiting factor on reading development, via links with PA. Further, at the test point reported here, the auditory perceptual skills of the younger RL children and of the children with dyslexia were equivalent, consistent with Ramus et al.'s statement ("a reading age [and therefore younger] control group could only have poorer sensorimotor performance", p. 266, Ramus et al., 2006). On the other hand, the data reported here are from one time point (phase 3) in an ongoing longitudinal study. We are currently in our fourth phase of data collection, and it is notable that rise time thresholds are now significantly *more* sensitive in the RL controls than in the children with dyslexia. In fact, the RL controls are as sensitive as the CA controls, even though their reading is not equivalent. Hence younger children do not always have poorer sensorimotor performance. We are also re-administering the perception of musical meter task to check longitudinal associations, however those data are not yet available.

The cross-sectional associations reported here suggest that the perception of metrical structure is closely tied to phonological development, proposed here to be related via prosody. The ability to perceive "stress beats" (strong and weak syllables) should be impaired in dyslexia on a rise time hypothesis, and we showed recently that highly compensated dyslexic adults were indeed impaired in perceiving syllable stress compared to typically-reading controls (Cheah et al., 2009). Accuracy in judging stress was uniquely linked to individual differences in rise time discrimination. The task was to decide whether one word was wrongly stressed in a pair of words like "mi/LIT/ary"–"MI/litary". Further, in work with children we have shown that individual differences in rise time

Please cite this article in press as: Huss M, et al., Music, rhythm, rise time perception and developmental dyslexia: Perception of musical meter predicts reading and phonology, Cortex (2010), doi:10.1016/j.cortex.2010.07.010

discrimination are a significant predictor of performance in reiterative speech tasks (Goswami et al., 2010c). In reiterative speech, each syllable in a word is converted into the same syllable, thereby removing most phonetic information while retaining the stress and rhythm patterns of the original words and phrases (Kitzen, 2001; Nakatani and Schaffer, 1978; Whalley and Hansen, 2006). When children hear “famous” names as reiterative speech (e.g., ‘Harry Potter’ is DEEdee-DEEdee [strong weak strong weak]), those with dyslexia are significantly poorer in recognising the target names, suggestive of impaired prosodic sensitivity.

It is notable that rhythm perception tasks based on strong and weak beats, such as the musical metrical perception task used here, require children to attend to the temporal positions of the beats. As noted by Kotz et al. (2009), the auditory perception of periodicity and meter is also important for auditory syntactic processing, perhaps because beat perception enables the brain to set up predictable sensory cues to syntactic structure. Kotz et al. link their beat-based hypothesis to the dynamic attending theory of Large and Jones (1999), according to which beat regularity enables anticipatory attending, narrowing the attentional window and improving auditory perception (e.g., Jones et al., 2002). Kotz et al. (2009) reported that when patients with basal ganglia lesions (which impair beat perception) were given isochronous auditory primes, their syntactic processing of spoken sentences improved. In our own work on rhythm and tempo, we have demonstrated that children with developmental dyslexia and with SLI both show deficits in maintaining the beat in rhythmic entrainment tasks (see Corriveau and Goswami, 2009; Thomson and Goswami, 2008). All children anticipate the beat, but children with developmental language impairments do so very erratically. As entrainment in these studies was measured by using long sequences of beats (40 or more, with entrainment periods of 20 sec for the children with dyslexia and of 30 sec for the children with SLI), it does not seem to be the case that children with language impairments need more time to entrain their oscillators (following dynamic attending theory, Large and Jones, 1999). Rather, their brains may not set up a reliable internal representation of the beat at all.

In the current study, the musical metrical perception task accounted for 28% of unique variance in PA, after controlling for age and I.Q ($p < .0001$). The musical metrical perception task continued to account for significant unique variance when STM was additionally controlled (6%, $p < .05$). This makes it unlikely that the associations reported arose because of general factors such as memory or attention. It is also notable that the metrical sequences with more notes (which theoretically comprise a higher memory load) were sometimes easier than the metrical sequences with fewer notes. Indeed, the simplest 2-note sequence showed highly significant differences between children with dyslexia and CA controls, while the 5-note sequence did not. Such findings suggest that individual differences in sensitivity to metrical structure rather than individual differences in memory or attention are specifically associated with individual differences in the quality of the phonological lexicon. The data also suggest that prosodic development and phonological development are intimately connected to individual differences in sensitivity to rise time, and not to individual differences in pitch perception. While pitch perception is clearly important for prosodic performance, it may not play a critical role in developmental language disorders. Indeed, in a recent meta-analysis of studies measuring performance in non-speech auditory processing tasks in dyslexia and associations with reading (Hämäläinen et al., in press), Hämäläinen et al. reported that amplitude modulation and rise time discrimination were linked to developmental dyslexia in 100% of the studies that they reviewed, whereas pitch discrimination was linked to developmental dyslexia in 57% of studies. It appears that, via developmental associations with both prosody and phonology, sensitivity to auditory cues to speech rhythm such as rise time play a causal role in individual differences in the acquisition of literacy (see also Fraser et al., 2010; Corriveau et al., 2010).

Liberman (1975) originally pointed out the importance of metrical organisation in complex human behaviour. He proposed that speech, music and dance all conformed to the “metrical organisation hypothesis” that all temporally-ordered human behaviour is metrically organised. Recently, it was shown that babies as young as 5 months move rhythmically in time with music (Zentner and Eerola, 2010). Further, experiencing rhythmic movement affects infants’ auditory perception of ambiguous rhythms (Phillips-Silver and Trainor, 2005). In Phillips-Silver and Trainor’s study, babies listened to a snare drum producing an ambiguous rhythm (3 unaccented beats). They were then bounced on their parents’ laps in either duple or triple time. When consequently presented with two unambiguous rhythms on the drum (duple or triple time), they showed a listening preference for the rhythm that matched the beats on which they had been bounced. Analogous effects were demonstrated for adults who were asked to copy rhythmic bending and stretching movements in either marching time (duple time) or Waltz time (triple time, see Phillips-Silver and Trainor, 2007).

These cross-modal multisensory effects are particularly interesting with respect to the possibilities that they suggest for developmental remediation. When individual action components are rhythmically co-ordinated, they are constrained in their relative timing – the degrees of freedom in the system are reduced (see Cummins and Port, 1998, for experimental data from speech production). This suggests that rhythmic co-ordination activities in children, for example singing or dancing to music, or making large motor movements in response to the stress beats of syllables, or clapping out the rhythms in metrical poetry or nursery rhymes, may have previously unsuspected benefits for language development. Musical training is already known to have measurable effects on language development, particularly with respect to pitch tasks (Magne et al., 2006; Wong et al., 2007; Kraus et al., 2009; Moreno et al., 2009). The same may be true for rhythm. Musical activities are also fun for children. As motivation and engagement are important for successful learning by young children, the pleasurable aspects of music-making and dancing mean that rhythmic co-ordination skills may be particularly well-learned when motor and auditory rhythms are combined. Indeed, Thaut (2005) has speculated that children in all cultures may engage spontaneously in activities that integrate singing and movement, dancing and rhyming, because such activities “train the brain” in aspects of temporal structure and organisation that are central to cognitive, motor and emotional development.

The ideas noted here with respect to music education and remediation of language/reading difficulties have been suggested before (e.g., Jacques-Dalcroze, 1980; Kodály, 1974; Overy, 2000, 2003), but the literature is surprisingly patchy. One reason may be that the biological significance of different rhythmic rates has not been studied systematically. There is converging evidence that a temporal rate of 500 msec is biologically privileged (hence a pulse rate of 500 msec was adopted for the metrical task developed here). For example, stressed syllables occur at approximately 500 msec intervals (Arvaniti, 2009). When adults read aloud from text, they show a bias for inter-stress intervals which are multiples of a 500 msec unit (Fant and Kruckenberg, 1996). When adults are asked to tap spontaneously to different types of music, they converge on the rate of 500 msec (Moelants, 2002). McAuley et al. (2006) demonstrated that children aged 8 years and above also showed spontaneous tapping rates centred around 500 msec (younger children preferred slightly faster rates). When mothers sing "playsongs" to their infants, the average tempo is 498 msec (Trainor et al., 1997). Spontaneous applause that is rhythmically synchronized converges on a 493 msec average (Neda et al., 2000). We have also found that typically-developing 4- and 5-year-old children can best keep time when singing nursery rhymes with an underlying pulse of 500 msec, and that performance at this particular rate is associated with the development of rhyme and syllable awareness (Verney, 2009). Biologically, these convergent findings suggest that an underlying pulse of 500 msec emerges because of physiological factors, factors which may be impaired in developmental language disorders. Recently, Schwartz et al. (2003) analysed the statistical structure of the naturally-occurring periodic structures in human speech, identifying the probability distribution for amplitude–frequency combinations across a number of languages. They found concentrations of power (amplitude maxima) at integer multiples of the fundamental frequency of a speech sound (not the vocal tract formants). They also showed that the probability distribution derived from speech predicted the chromatic scale that forms the basis of Western musical composition. Accordingly, they suggested that musical universals reflect a probabilistic process underlying the perception of periodic auditory stimuli. An insensitivity to the auditory parameters (such as rise time) that are critical for the perception of auditory periodicity provides one explanation for the intimate links between metrical musical perception, phonology and literacy demonstrated here. Rhythmic perception and production would be expected to affect the development of both language and literacy in children, across languages from different rhythm classes (Goswami et al., 2010a). The current study provides some evidence in support of this hypothesis.

Acknowledgements

We would like to thank the head teachers, teachers, children and parents of all our participants. This research was supported by funding from the Medical Research Council, grant G0400574, and a Major Research Fellowship from the Leverhulme Trust to Usha Goswami. The funders had no input into study design, data collection or analysis, report writing nor choice of journal. Requests for reprints should be addressed to Usha Goswami or Martina Huss, Centre for Neuroscience in Education, 184 Hills Rd, Cambridge CB2 8PQ, U.K.

Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.cortex.2010.07.010.

REFERENCES

Arvaniti A. Rhythm, timing and the timing of rhythm. *Phonetica*, 66: 46–63, 2009.

Baldeweg T, Richardson A, Watkins S, Foale C, and Gruzelier J. Impaired auditory frequency discrimination in dyslexia detected with mismatch evoked potentials. *Annals of Neurology*, 45: 495–503, 1999.

Burkhard MD and Sachs RM. Anthropometric manikin for acoustic research. *Journal of the Acoustical Society of America*, 58 (1): 214–222, 1975.

Chandrasekaran C, Trubanova A, Stillittano S, Caplier A, and Ghazanfar AA. The natural statistics of audiovisual speech. *PloS Computational Biology*, 5(7). published online, July 2009.

Cheah V, Hämäläinen J, Soltesz F, and Goswami U. *Amplitude Envelope Perception and Sensitivity to Prosodic Stress in Developmental Dyslexia*. Poster presented at the 3rd International Conference on Auditory Cortex, 29 August–2 September, Magdeburg, Germany, 2009.

Corriveau K, Pasquini E, and Goswami U. Basic auditory processing skills and specific language impairment: A new look at an old hypothesis. *Journal of Speech, Language and Hearing Research*, 50: 1–20, 2007.

Corriveau K and Goswami U. Rhythmic motor entrainment in children with speech and language impairment: Tapping to the beat. *Cortex*, 45: 119–130, 2009.

Corriveau K, Goswami U, and Thomson J. Auditory processing and early literacy skills in a preschool and kindergarten population. *Journal of Learning Disabilities*, 43(4): 369–382, 2010.

Cummins F and Port R. Rhythmic constraints on stress timing in English. *Journal of Phonetics*, 26: 145–171, 1998.

Cutler A. Prosody and the word boundary problem. In Morgan JL and Demuth K (Eds), *Signal to Syntax: Bootstrapping from Speech to Grammar in Early Acquisition*. Mahwah, NJ: Lawrence Erlbaum, 1996: 87–99.

Dunn LM, Dunn LM, Whetton C, and Pintilie D. *British Picture Vocabulary Scale*. Windsor, UK: NFER-Nelson, 1982.

Echols CH. A role for stress in early speech segmentation. In Morgan JL and Demuth K (Eds), *Signal to Syntax: Bootstrapping from Speech to Grammar in Early Acquisition*. Mahwah, NJ: Lawrence Erlbaum Associates, 1996: 151–170.

Elliott CD, Smith P, and McCullogh K. *British Ability Scales*. 2nd ed. Windsor, UK: NFER-Nelson, 1996.

Fant G and Kruckenberg A. On the quantal nature of speech timing. In Bunnell HT and Idsardi W (Eds), *Proceedings of the 4th International Conference on Spoken Language Processing*. Wilmington, Delaware: Alfred du Pont Institute, 1996: 2036–2039.

Forgeard M, Schlaug G, Norton A, Rosam C, Iyengar U, and Winner E. The relation between music and phonological processing in normal-reading children and children with dyslexia. *Music Perception*, 25: 383–390, 2008.

Please cite this article in press as: Huss M, et al., Music, rhythm, rise time perception and developmental dyslexia: Perception of musical meter predicts reading and phonology, Cortex (2010), doi:10.1016/j.cortex.2010.07.010

Fowler C, Smith MR, and Tassinary LG. Perception of syllable timing by prebabbling infants. *Journal of the Acoustical Society of America*, 79: 814–825, 1986.

Fraser J, Goswami U, and Conti-Ramsden G. Dyslexia and specific language impairment: The role of phonology and auditory processing. *Scientific Studies of Reading*, 14(1): 8–29, 2010.

Gordon JW. The perceptual attack time of musical tones. *Journal of the Acoustical Society of America*, 82: 88–105, 1986.

Goswami U. Language, music and children's brains: A rhythmic timing perspective on language and music as cognitive systems. In Rebuschat P et al. (Eds), *Language and Music as Cognitive Systems*. Oxford: Oxford University Press, in press.

Goswami U, Wang HLS, Cruz A, Fosker T, Mead N, and Huss M. Language-universal deficits in developmental dyslexia: English, Spanish and Chinese. *Journal of Cognitive Neuroscience*, February 2010a. published online.

Goswami U, Fosker T, Huss M, Mead N, and Szűcs D. Rise time and formant transition duration in the discrimination of speech sounds: The Ba–Wa distinction in developmental dyslexia. *Developmental Science*, March 2010b. published online.

Goswami U, Gerson D, and Astruc L. Amplitude envelope perception, phonology and prosodic sensitivity in children with developmental dyslexia. *Reading and Writing*, 23: 995–1019, 2010c.

Goswami U, Thomson J, Richardson U, Stainthorp R, Hughes D, Rosen S, et al. Amplitude envelope onsets and developmental dyslexia: A new hypothesis. *Proceedings of the National Academy of Sciences of the United States of America*, 99(16): 10911–10916, 2002.

Greenberg S. Speaking in shorthand – A syllable-centric perspective for understanding pronunciation variation. *Speech Communication*, 29: 159–176, 1999.

Hämäläinen J, Leppänen PHT, Torppa M, Muller K, and Lyytinen H. Detection of sound rise time by adults with dyslexia. *Brain and Language*, 94: 32–42, 2005.

Hämäläinen J, Leppänen PHT, Eklund K, Thomson J, Richardson U, Guttorm TK, et al. Common variance in amplitude envelope perception tasks and their impact on phoneme duration perception and reading and spelling in Finnish children with reading disabilities. *Applied Psycholinguistics*, 30: 511–530, 2009.

Hämäläinen JA, Salminen HK, and Leppänen PHT. Basic auditory processing deficits in dyslexia: Review of the behavioural, event-related potential and magnetoencephalographic evidence. *Journal of Learning Disabilities*, in press.

Hoequist CA. The perceptual centre and rhythm categories. *Language and Speech*, 26: 367–376, 1983.

Hyde KL and Peretz I. Brains that are out of tune but in time. *Psychological Science*, 15: 356–360, 2004.

Jacques-Dalcroze E. *Rhythm, Music and Education* [Rubinstein H, Trans.]. London: The Dalcroze Society Inc., 1980.

Johnson EK and Tyler MD. Testing the limits of statistical learning for word segmentation. *Developmental Science*, 13(2): 339–345, 2010.

Jones MR, Moynihan H, MacKenzie N, and Puente J. Temporal aspects of stimulus-driven attending in dynamic arrays. *Psychological Science*, 13: 313–319, 2002.

Kitzen KR. Prosodic sensitivity, morphological ability and reading ability in young adults with and without childhood histories of reading difficulty. (Doctoral dissertation, University of Columbia, 2001). *Dissertation Abstracts International*, 62 (02): 0460A, 2001.

Kodály Z. *The Selected Writings of Zoltán Kodály*. London: Boosey and Hawkes, 1974 [Lily Halápy and Fred Macnicol, Trans.].

Kotz SA, Schwartze M, and Schmidt-Kassow M. Non-motor basal ganglia functions: A review and proposal for a model of sensory predictability in auditory language perception. *Cortex*, 45: 982–990, 2009.

Kraus N, Skoe E, and Ashley R. Experience-induced malleability in neural encoding of pitch, timbre and timing: Implications for language and music. *Annals of the New York Academy of Sciences*, 1169: 543–567, 2009.

Lachmann T, Berti S, Kujala T, and Schroger E. Diagnostic subgroups of developmental dyslexia have different deficits in neural processing of tones and phonemes. *International Journal of Psychophysiology*, 56: 105–120, 2005.

Large E and Jones MR. The dynamics of attending: How we track time-varying events. *Psychological Review*, 106: 119–159, 1999.

Lehiste I. *Suprasegmentals*. Cambridge, Massachusetts/London, England: The M.I.T. Press, 1970.

Levitt H. Transformed up–down methods in psychoacoustics. *Journal of the Acoustical Society of America*, 49: 467–477, 1971.

Liberman M. *The Intonational System of English*. Ph.D. thesis, MIT Cambridge, MA, 1975. Published by Indiana University Linguistics Club, 1978.

Lorenzi C, Dumont A, and Fullgrabe C. Use of temporal envelope cues by children with developmental dyslexia. *Journal of Speech, Language and Hearing Research*, 43: 1367–1379, 2000.

Magne C, Schon D, and Besson M. Musician children detect pitch violation in both music and language better than nonmusician children: Behavioural and electrophysiological approaches. *Journal of Cognitive Neuroscience*, 18: 199–211, 2006.

Marie C, Magne C, and Besson M. Musicians and the metric structure of words. *Journal of Cognitive Neuroscience*, 2009.

McAuley JD, Jones MR, Holub S, Johnston HM, and Miller NS. The time of our lives: Life span development of timing and event tracking. *Journal of Experimental Psychology: General*, 135: 348–367, 2006.

Moelants D. Preferred tempo reconsidered. In Stevens C, Burnham D, McPherson G, Schubert E, and Renwick J (Eds), *Proceedings of the 7th International Conference on Music Perception and Cognition, Sydney*. Adelaide: Causal Productions, 2002: 580–583.

Moreno S, Marques C, Santos A, Santos M, Castro SL, and Besson M. Musical training influences linguistic abilities in 8-year-old children: More evidence for brain plasticity. *Cerebral Cortex*, 19: 712–723, 2009.

Morton J, Marcus SM, and Frankish C. Perceptual centres (P-centres). *Psychological Review*, 83: 405–408, 1976.

Muneaux M, Ziegler JC, Truc C, Thomson J, and Goswami U. Deficits in beat perception and dyslexia: Evidence from French. *NeuroReport*, 15(8): 1255–1259, 2004.

Nakatani LH and Schaffer JA. Hearing "words" without words: Prosodic cues for word perception. *Journal of the Acoustical Society of America*, 63(1): 234–245, 1978.

Neda Z, Ravasz E, Brechet Y, Vicsek T, and Barabasi AL. The sound of many hands clapping: Tumultuous applause can transform itself into waves of synchronized clapping. *Nature*, 403: 849–850, 2000.

Overy K. Dyslexia, temporal processing and music: The potential of music as an early learning aid for dyslexic children. *Psychology of Music*, 28: 218–229, 2000.

Overy K. From timing deficits to musical intervention. *Annals of the New York Academy of Sciences*, 999: 497–505, 2003.

Overy K, Nicolson RI, Fawcett AJ, and Clarke EF. Dyslexia and music: Measuring musical timing skills. *Dyslexia*, 9: 18–36, 2003.

Pasquini E, Corriveau K, and Goswami U. Auditory processing of amplitude envelope rise time in adults diagnosed with developmental dyslexia. *Scientific Studies of Reading*, 11: 259–286, 2007.

Peretz I and Coltheart M. Modularity of music processing. *Nature Neuroscience*, 6: 688–691, 2003.

Phillips-Silver J and Trainor LJ. Feeling the beat: Movement influences infants' rhythmic perception. *Science*, 308: 1430, 2005.

Phillips-Silver J and Trainor LJ. Hearing what the body feels: Auditory encoding of rhythmic entrainment. *Cognition*, 105: 533–546, 2007.

Please cite this article in press as: Huss M, et al., Music, rhythm, rise time perception and developmental dyslexia: Perception of musical meter predicts reading and phonology, Cortex (2010), doi:10.1016/j.cortex.2010.07.010

Pierrehumbert J. Phonetic diversity, statistical learning and acquisition of phonology. *Language and Speech*, 46: 115–154, 2003.

Port R. Meter and speech. *Journal of Phonetics*, 31: 599–611, 2003.

Ramus F, White S, and Frith U. Weighing the evidence between competing theories of dyslexia. *Developmental Science*, 9: 265–269, 2006.

Richardson U, Thomson J, Scott SK, and Goswami U. Suprasegmental auditory processing skills and phonological representation in dyslexic children. *Dyslexia*, 10(3): 215–233, 2004.

Rocheron I, Lorenzi C, Fullgrabe C, and Dumont A. Temporal envelope perception in dyslexic children. *NeuroReport*, 13(3): 1683–1687, 2002.

Santos A, Joly-Pottuz B, Moreno S, Habib M, and Besson M. Behavioural and event-related potentials evidence for pitch discrimination deficits in dyslexic children: Improvement after intensive phonic intervention. *Neuropsychologia*, 45: 1080–1090, 2007.

Sattler JM. *Assessment of Children's Intelligence and Special Abilities*. Boston: Allyn and Bacon, 1982.

Schwartz DA, Howe CQ, and Purves D. The statistical structure of human speech sounds predicts musical universals. *Journal of Neuroscience*, 23: 7160–7168, 2003.

Scott SK. The point of P-centres. *Psychological Research*, 61: 4–11, 1998.

Surányi Z, Csépe V, Richardson U, Thomson JM, Honbolygó F, and Goswami U. Sensitivity to rhythmic parameters in dyslexic children: A comparison of Hungarian and English. *Reading and Writing*, 22: 41–56, 2009.

Thaut MH. *Rhythm, Music and the Brain*. New York: Routledge, 2005.

Thomson JM and Goswami U. Rhythmic processing in children with developmental dyslexia: Auditory and motor rhythms link to reading and spelling. *Journal of Physiology – Paris*, 102: 120–129, 2008.

Thomson JM, Fryer B, Maltby J, and Goswami U. Auditory and motor rhythm awareness in adults with dyslexia. *Journal of Research in Reading*, 29(3): 334–348, 2006.

Trainor LJ, Clark ED, Huntley A, and Adams BA. The acoustic basis of preferences for infant-directed singing. *Infant Behaviour and Development*, 20: 383–396, 1997.

Verney JP. *Bongo Phonics!* University of Cambridge, Faculty of Education, Unpublished Ph.D. upgrade dissertation, 2009.

Vihman M and Croft W. Phonological development: Towards a "radical" templatic phonology. *Linguistics*, 45: 683–725, 2007.

Vos J and Rasch RA. The perceptual onset of musical tones. *Perception and Psychophysics*, 29: 323–335, 1981.

Waber DP, Weiler MD, Bellinger DC, Marcus DJ, Forbes PW, Wypij D, et al. Diminished motor timing control in children referred for diagnosis of learning problems. *Developmental Neuropsychology*, 17(2): 181–197, 2000.

Wechsler D. *Intelligence Scale for Children (WISC – III)*. UK: The Psychological Corporation, 1992.

Whalley K and Hansen J. The role of prosodic sensitivity in children's reading development. *Journal of Research in Reading*, 29: 288–303, 2006.

White S, Milne E, Rosen S, Hansen P, Swettenham J, Frith U, et al. The role of sensorimotor impairments in dyslexia: A multiple case study. *Developmental Science*, 9: 237–269, 2006.

Wolff PH. Timing precision and rhythm in developmental dyslexia. *Reading and Writing: An Interdisciplinary Journal*, 15: 179–206, 2002.

Wolff PH, Michel GF, Ovrut M, and Drake C. Rating and timing precision of motor coordination in developmental dyslexia. *Developmental Psychology*, 26(3): 349–359, 1990.

Wong PCM, Skoe E, Russo NM, Dees T, and Kraus N. Musical experience shapes human brainstem encoding of linguistic pitch patterns. *Nature Neuroscience*, 10: 420–422, 2007.

Wood C. Metrical stress sensitivity in young children and its relationship to phonological awareness and reading. *Journal of Research in Reading*, 29: 270–287, 2006.

Wood C and Terrell C. Poor readers' ability to detect speech rhythm and perceive rapid speech. *British Journal of Developmental Psychology*, 16: 397–413, 1998.

Zentner M and Eerola T. Rhythmic engagement with music in infancy. *Proceedings of the National Academy of Sciences of the United States of America*, 107(13): 5768–5773, 2010.

Ziegler JC and Goswami U. Reading acquisition, developmental dyslexia, and skilled reading across languages: A psycholinguistic grain size theory. *Psychological Bulletin*, 131(1): 3–29, 2005.

Please cite this article in press as: Huss M, et al., Music, rhythm, rise time perception and developmental dyslexia: Perception of musical meter predicts reading and phonology, Cortex (2010), doi:10.1016/j.cortex.2010.07.010