Read Writ (2013) 26:139–161
DOI 10.1007/s11145-012-9359-6

Auditory processing interventions and developmental dyslexia: a comparison of phonemic and rhythmic approaches

Jennifer M. Thomson · Victoria Leong · Usha Goswami

Abstract The purpose of this study was to compare the efficacy of two auditory processing interventions for developmental dyslexia, one based on rhythm and one based on phonetic training. Thirty-three children with dyslexia participated and were assigned to one of three groups (a) a novel rhythmic processing intervention designed to highlight auditory rhythmic information in non-speech and speech stimuli; (b) a commercially-available phoneme discrimination intervention; and (c) a no-intervention control. The intervention lasted for 6 weeks. Both interventions yielded equivalent and significant gains on measures of phonological awareness (at both rhyme and phoneme levels), with large effect sizes at the phoneme level. Both programs had medium effect sizes on literacy outcome measures, although gains were non-significant when compared to the controls. The data suggest that rhythmic training has an important role to play in developing the phonological skills that are critical for efficient literacy acquisition. It is suggested that combining both prosodic/rhythmic and phonemic cues in auditory training programs may offer advantages for children with developmental dyslexia. This may be especially true for those who appear resistant to conventional phonics training methods.

Keywords Auditory processing · Developmental dyslexia · Intervention · Rhythm

---

J. M. Thomson (✉)
Harvard Graduate School of Education, 14 Appian Way, Cambridge, MA 02138, USA
e-mail: thomsoje@gse.harvard.edu

V. Leong · U. Goswami
University of Cambridge, Cambridge, UK

Introduction

Despite the advances made in our understanding of developmental dyslexia over recent decades, effective interventions remain elusive. Developmental dyslexia is usually defined by the presence of unexpected difficulties in accurate and fluent word recognition and accurate spelling, despite adequate instruction and an absence of overt sensory and neurological damage. A defining feature is difficulty in accessing or manipulating the sound-based, or phonological, representations for words. These phonological difficulties impede achieving automaticity in reading and spelling. The most effective current interventions are based on intensive, systematic phonics instruction (National Institute of Child Health & Human Development, 2000; Torgesen et al., 2001). When children are helped by these phonology-based interventions, it is assumed that explicit teaching of letter-sound correspondences acts to support a compromised sound system. However, response to intervention can be quite variable. Torgesen (2000) reports that 2–6% of children from the 16% most at risk of reading failure make minimal progress despite concentrated exposure to such instruction, while many others fail to catch-up successfully to age-appropriate levels. For these children, we currently do not have an established means of ensuring eventual reading success.

One important consideration with respect to failure to respond to treatment is whether any precursor skills must be in place for a phonics intervention to be effective. The ability successfully to learn letter-sound correspondences would appear to be dependent on multiple basic-level skills, including intact visual discrimination, verbal short-term memory and auditory perception. If a child does not have well-established precursor skills, it will be more difficult to respond to phonics instruction at a similar rate to their peers. Inevitably, this will result in an ever-increasing achievement gap. One precursor skill that has been investigated extensively in relation to the phonological deficit in dyslexia is basic auditory perception. The ability to perceive and segment the auditory speech stream is critical both for the creation of phonological representations of spoken words in a mental lexicon of word forms, and for learning how speech sound units link in a rule-governed manner to individual letters and groups of letters. Hence if auditory perceptual skills measured at school-age are poor, this is likely to contribute to a profile of poor phonological processing and impaired literacy (Goswami et al., 2002; McArthur, Ellis, Atkinson, & Coltheart, 2008; Witton et al., 1998).

A second important consideration with respect to failure to respond to treatment is whether the phonological system is compromised at levels other than the sub-syllabic level addressed by typical phonics interventions. Although the dominant assumption is that phonological training for dyslexia should focus on lexical representations for individual spoken words (and on how sub-syllabic units link to letters), developmental work shows the important role of suprasegmental phonology in developing well-specified representations for individual words. For example, sensitivity to speech rhythm is very important. In developmental phonology, one recent theoretical perspective is that phonological development depends on the infant storing language-specific phonotactic templates, or prosodies (e.g., CVCV, VCV), based on their specific experiences of adult input and their own babbling practices (Vihman & Croft, 2007). A phonotactic template is essentially a multi-syllabic phonological pattern. As such, it contains variations in sound intensity, pitch, duration and rhythm, which together constitute a unit, usually of meaning. A common template for English is a bi-syllabic pattern with stronger first syllable stress (a strong–weak stress template). The strong first syllable is typically louder, longer and higher in pitch than the second syllable. Familiar words that follow this pattern are *mummy*, *daddy*, *biscuit* and *baby*. Developmental phonologists like Vihman and Croft (2007) argue that babies' own babbling also conforms to these rhythmic patterns. Babies do not babble single-syllable words. So both phonological perception and production appear to converge on rhythmic templates that are longer than a single syllable.

The idea that the phonological system is richer than a set of lexical representations composed of syllables and phonemes has been made before, but it has not yet impacted dyslexia intervention research. For example, Port (2007) commented "it seems intuitively obvious that speech presents itself to our consciousness in the form of letter-like symbolic units. When we hear someone say *tomato*, we seem to hear it as a sequence of consonant and vowel sound units… [yet] there is virtually no evidence that supports the traditional view of linguistic representation" (Port, 2007, pp. 143–4). Port reviews this evidence in detail, and then proposes a theory of phonological representation based on a notion of rich phonology. According to Port's perspective, the mental lexicon in effect stores high-dimensional spectro-temporal auditory patterns. These high-dimensional auditory patterns would correspond to the phonotactic templates proposed by developmental phonologists, and to the speech envelopes for different words investigated by auditory scientists.

Basic auditory processing as a precursor skill

Given that a range of auditory cues are likely to contribute to the development of high-quality phonological representations and to successful phonological processing, and given that successful phonological processing may operate at both the segmental and the suprasegmental levels, our knowledge of which aspects of auditory perception will be most critical to the development of literacy is still rudimentary. For example, both brief, rapidly-occurring, spectro-temporal cues and the slower spectro-temporal modulations that are an important feature of the speech envelope have been the foci of intensive research. Tallal and her colleagues (Tallal, 1980, 2004) proposed that impaired processing of brief, rapidly presented sounds could underpin the phonological deficit in developmental dyslexia: the Rapid Auditory Processing Deficit (RAPD) theory. While a causal link between impaired perception of rapid spectro-temporal cues and impaired literacy appeared supported by early studies (De Martino, Espesser, Rey, & Habib, 2001; Reed, 1989; Tallal, 1980, 2004), more recent studies have suggested a more limited role for rapid auditory processing in developmental dyslexia (Heath & Hogben, 2004a, b). On the other hand, a growing literature attests to the presence of impaired amplitude envelope perception in developmental dyslexia, across languages with different phonological structures, and languages with different writing systems (e.g., English, Chinese, Spanish, Hungarian, Finnish, Dutch and French, see Goswami, Gerson, & Astruc, 2009; Goswami et al., 2002; Goswami, Fosker, Huss, Mead, & Szucs, 2011a, Goswami et al., 2011b; Hamalainen, Leppanen, Torppa, Muller, & Lyytinen, 2005; Hamalainen et al., 2009; Muneaux, Ziegler, Truc, Thomson & Goswami, 2004; Pasquini, Corriveau, & Goswami, 2007; Poelmans et al., 2011; Richardson, Thomson, Scott, & Goswami, 2004; Suranyi et al., 2009; Thomson, Fryer, Maltby, & Goswami, 2006).

The amplitude envelope in speech is likely to be important for phonological development because it is a key determinant of speech intelligibility (e.g., Drullman, Festen, & Plomp, 1994a, b; Shannon, Zeng, Kamath, & Wygonski, 1995). An explicit theoretical framework linking the perception of amplitude envelope structure to phonological development is offered by Goswami (2011). Her theoretical framework is based on the fact that the amplitude modulations in the envelope are one of the critical acoustic properties underlying syllable rate and speech rhythm. The amplitude envelope is the summation over time of the intensity fluctuations (amplitude modulations) in the different frequency channels that are present in the speech signal. The rate of onset of these intensity fluctuations is called rise time. Rise times are critical events in the speech signal, as they reflect the patterns of amplitude modulation that facilitate syllabic segmentation. They are also related to phonetic structure: a syllable beginning with a plosive (like BA) will onset rapidly and have a sharp rise time. A syllable beginning with a liquid (like WA) will onset more slowly and have a slower rise time. Hence, rise time perception is also important for the representation of phonetic structure (see Goswami et al., 2011a, b). Rise time is also a major determinant of the perception of speech rhythm. If rise times are varied in a nonspeech continuous tone, the perceptual impression is of a stronger or weaker rhythmic beat (Goswami et al., 2002).

Children with dyslexia in different languages show reliable and consistent impairments in perceiving accurately the rate of amplitude envelope onset, or *rise time*. Whereas brief, rapidly-occurring spectro-temporal cues are thought to be linked particularly to perceiving phonetic information in the speech stream (e.g., formant transitions, Tallal, 2004), slower spectro-temporal modulations and the amplitude envelope are linked to syllabic and prosodic structure, and to speech rhythm and intonational patterning (Greenberg, 2006). Stressed syllables have more salient rise times. Impaired auditory perception of slower temporal modulations and the amplitude envelope in speech is thus likely to be linked in particular to the perception of speech rhythm and syllable stress (Goswami, 2011; Leong, Hamalainen, Soltesz, & Goswami, 2010).

Rhythm, stress and the phonological system

These studies of auditory processing in dyslexia have led to renewed interest in the possibly causal role of rhythm-based processing for high-quality language acquisition and phonological development (Corriveau & Goswami, 2009; Nittrouer, 2006; Thomson & Goswami, 2010). It has long been known that human infants show sensitivity to speech rhythm, using rhythmic cues to segment syllables and words from the signal in order to build a lexicon of spoken word forms (e.g., Christophe, Mehler, & Sebastian-Galles, 2001; Jusczyk, Houston, & Newsome, 1999; Mehler et al., 1988). Infants are also aware of stress templates in their native language by as early as 4 months of age (Weber, Hahne, Friedrich, & Friederici, 2004). Sensitivity to the predominant stress patterns of a language is clearly important for extracting words and syllables from the speech stream, and therefore for phonological representation (Echols, 1996; Mattys & Jusczyk, 2001). Acoustically, all of these aspects of phonological processing implicate accurate rise time discrimination. As noted earlier, recent theories of infant phonology now foreground prosodic sensitivity (Pierrehumbert, 2003; Vihman & Croft, 2007), arguing that phonemic perception is dependent on prosodic context. If we apply these insights to improving phonological outcomes in dyslexia, it seems likely that prosodic sensitivity could be important for benefiting from phonics-based (phonemic) training. This raises the possibility that interventions based on general auditory rhythmic training may offer benefits for children with developmental dyslexia. In the following section we review current knowledge concerning the efficacy and generalizability of auditory training.

Studies of auditory training in dyslexia

In a typical auditory training paradigm listeners are presented with two or more sounds that vary systematically on a given acoustic parameter such as frequency, amplitude or duration. For example, to train duration discrimination, the listener might be asked to choose which of two sounds is longer or shorter in duration or to select the odd one out of several possibilities. Typically trials are presented in an adaptive format whereby the majority of trials are at an individual's edge of competence. Achieving a smaller *just noticeable difference* by the end of training is indicative of auditory learning. Auditory training studies have shown that gains in auditory acuity on a trained stimulus dimension can be rapid (within a single session) and significant (Moore, Halliday, & Amitay, 2009). It has also been established that auditory learning can occur irrespective of the initial level of an individual's performance. Nevertheless, better adult listeners will tend to remain better and poorer adult listeners will tend to remain relatively poorer, even after training (Moore & Amitay, 2007). The issue of transfer of learning to an untrained task is not well-understood. While transfer of gains between specific auditory parameters such as frequency and intensity are typically not observed in adult studies (Hawkey, Amitay, & Moore, 2004), auditory training has been found to impact higher-level cognitive skills such as memory (Mahncke et al., 2006). There is also interest in the potential of auditory training for improving literacy-related skills, the focus of the study reported here.

Most auditory training studies in the developmental reading literature have focused on training perception of rapid spectro-temporal cues. The most widely-cited intervention program of this type is Fast ForWord® (Scientific Learning Corporation, 1998). The Fast ForWord program grew out of RAPD theory, according to which deficits in perceiving brief and rapidly presented sounds impedes the establishment of stable speech sound representations. These deficits in turn are proposed to have a negative impact on the ability to map sounds systematically to letters, as required for literacy. Consequently, a key feature of Fast ForWord is adaptive training in discrimination of tones and phonemes in which the time interval between stimuli is systematically manipulated. The program also incorporates phonological and language games in which children are exposed to sounds that have been extended in time by 50% and amplified up to 20 dB (Nagarajan et al., 1998).

The stated aim of Fast ForWord is to increase the salience of the rapidly changing parts of speech and so facilitate more successful perception, however it should also be noted that Fast ForWord amplifies the amplitude modulations between three and 30 Hz in the narrowband filtered signal, thereby also enhancing amplitude envelope cues (McAnally, Hansen, Cornelissen, & Stein, 1997). Intensive applications of Fast ForWord (88–116 h) do appear to result in learning gains, both on the training tasks as well as on the untrained abilities of speech perception and language comprehension (Tallal et al., 1996). Nevertheless, both Fast ForWord and the RAPD hypothesis have been increasingly questioned by researchers. Attempts to validate the RAPD have been mixed, with studies failing to support the presence of deficits in perceiving either rapidly presented (Rosen & Manganari, 2001) or brief (Marshall, Snowling, & Bailey, 2001; Nittrouer, 1999; Waber et al., 2001) sounds. Stretching the formant transitions in syllables (or stretching the syllables in time) does not improve syllable perception in dyslexia, a necessary corollary of RAPD (Menell, McAnally, & Stein, 1999). Further, a meta-analysis found only weak evidence for an association between perception of single rapid/brief sounds and higher-level phonological and literacy skills (Farmer & Klein, 1995).

The Fast ForWord program by its very design has also been unable to shed light on the validity or otherwise of RAPD theory, due to the fact that so many aspects of auditory perception are trained concurrently. Children using Fast ForWord are trained to discriminate rapid tone sweeps and phonemes, and to process syllables, words and sentences, both with and without acoustic modification. Therefore, whether there is one key active ingredient of the program remains impossible to discern. The precise role of the auditory training component of the program is further questioned by large-scale, randomized-control trials (Cohen et al., 2005; Gillam et al., 2008) that have failed to demonstrate a significant remedial advantage for Fast ForWord over other language remediation programs that omit a rapid auditory component.

A recent study set out to train different aspects of Fast ForWord independently in an attempt to better understand the relationship between auditory training and gains in reading-related skills. McArthur et al. (2008) trained 28 children with specific reading or language difficulties with auditory training alone, varying the type of auditory training received. The children, who varied widely in age (6–16 years) underwent 6 weeks of individualized intervention in which they trained on either frequency discrimination, rapid auditory processing, vowel discrimination or consonant–vowel discrimination, depending on their performance thresholds upon initial testing. This 'auditory alone' program resulted in the trainees achieving age-typical thresholds on the trained dimensions. It also led to elevated spoken language and spelling scores, suggesting the possibility of transfer from basic auditory skills to more advanced linguistic skills.

Another study by Moore, Rosenberg, & Coleman, (2005) trained phonemic contrast discrimination exclusively. Eighteen children between the ages of 8 and 10 years were trained for 12 × 30 min sessions over 4 weeks using an adaptive software program, Phonomena®, while a parallel group participated in regular classroom activities. At the end of the training period the intervention group showed significant gains in word discrimination and phonological awareness, which were maintained at a 5–6 week follow-up. This study did not assess literacy outcomes.

The current study

The current study set out to make a novel contribution to the extant knowledge base by examining the efficacy of a dyslexia intervention program directly targeting rhythmic perception. Derived from the rise time hypothesis of auditory sensory difficulties in dyslexia (Goswami et al., 2002; Goswami, 2011) and the associated rhythmic perceptual difficulties that have been found to accompany rise time deficits (Thomson et al., 2006; Thomson & Goswami, 2008), an auditory training program was devised that trained rise time discrimination directly and also trained perception of non-speech rhythms and of metrical stress patterns in speech via a drumming game and a reiterative speech paradigm. In order to control the degree of change in rise time with enough specificity, the intervention largely employed non-speech tone stimuli in which the amplitude envelope alone varied within tasks. The effects of the rise time intervention were compared to the commercially available phoneme-based intervention, Phonomena®, as well as to a no-intervention control group. Phonomena® was chosen as a control for (a) its parallel focus on a specific skill at the phonemic level and (b) its comparable mode of computer presentation and adaptive design.

The rhythmic intervention was predicted to have direct, positive effects on children's auditory rise time perception. To explore possible transfer to other auditory measures, children's intensity and duration perception were also assessed before and after the intervention period. To explore whether linguistic benefits would be found, phonological processing and literacy measures were administered before and after the intervention.

Method

Participants

All those children with dyslexia who were participating in a longitudinal study and who consented to an intervention comprised the two training groups,[1] supplemented by extra children who were known to the first author through her speech and

---

[1] A requirement of the funder was that all the children in the longitudinal study were offered an intervention of some form. Therefore, we could not create a control group of dyslexic children from within the longitudinal study. Those children with dyslexia in the longitudinal study who consented to intervention ($n = 10$) were randomly assigned to the two training groups and extra children with dyslexia ($n = 23$) were then recruited to increase the training group sizes and to act as unseen controls.

language therapy work. Additional dyslexic children were recruited to form a matched unseen control group. Thirty-three children with dyslexia participated overall. They were divided between (a) a rhythmic processing intervention group, $n = 9$; mean age 9 years, 4 months; SD 15 months, henceforth RHYTHM; (b) a phoneme discrimination intervention group, $n = 12$, mean age 9 years, 5 months; SD 17 months, henceforth PHON; and (c) a no-intervention control group, $n = 12$, mean age 9 years, 4 months; SD 9 months, henceforth CONTROL. All children's first language was English and they attended schools in Southern England. Children were initially selected by their class teachers, undergoing further psychometric assessment with the researchers. Teachers were asked to identify children who struggled with reading in the context of average or above average intelligence (>85 IQ on the Wechsler Intelligence Scale for Children; WISC III, short-form, as verified by post-selection assessment), normal sensory ability and no documented neurological damage, no other diagnoses (e.g., Attention Deficit Hyperactivity Disorder), or exposure to social or educational deprivation. A Speech and Language Therapist determined that no children included in the study had significant speech or language difficulties. The majority of participants were of Caucasian decent.

Participant characteristics are shown in Table 1. Table 1 also shows the performance of the most similar-age typically-developing children drawn from the same longitudinal study that children with dyslexia were drawn from (Thomson & Goswami, 2008), to allow comparison of relative ability levels, where possible.

Table 1 Mean (SD) performance on baseline measures by intervention group

Group	RHYTHM	PHON	CONTROL	TYPICAL
n	9	12	12	11
Age	9;4 (15 months)	9;5 (17 months)	9;4 (9 months)	9;5 (8 months)
Expressive vocabulary	11.56 (1.9)	11.25 (2.6)	11.25 (4.3)	12.8 (3.7)
Non-verbal ability	9.67 (4.2)	9.58 (4.0)	9.92 (3.1)	12.1 (2.7)
Phonological short-term memory (PSTM)	96.00 (10.5)	93.92 (13.1)	111.08 (18.3)	105.3 (16.1)
Rapid naming (speed in s)	37.58 (4.3)	34.83 (11.2)	35.17 (7.6)	33.2 (3.7)
Rhyme oddity (out of 20)	13.6 (3.36)	14.4 (3.78)	–	16.8 (3.0)
PhAB rhyme	101.11 (5.0)	102.00 (16.0)	94.50 (11.9)	–
PhAB spoonerisms	100.00 (7.1)	97.00 (9.5)	100.25 (11.8)	–
Word reading	91.44 (8.2)	88.42 (13.7)	90.75 (13.6)	115.0 (11.4)
Non-word reading	83.22 (11.1)	87.17 (8.5)	89.67 (9.3)	111.2 (13.2)
Spelling	88.33 (4.9)	87.42 (7.7)	87.17 (6.0)	115.3 (15.4)

Scores from age-matched typically-developing children are provided for comparative purposes. All scores except rapid naming and rhyme oddity are reported as standard scores

None of the typically-developing group took part in the intervention. Ethical approval for the study was given by the Cambridge Psychology Research Ethics Committee, Cambridge University.

As shown in Table 1, the three experimental groups did not differ significantly from each other in age, reading, spelling, phonological awareness or rapid automatized naming baseline measures, as verified by Kruskal–Wallis 1-way ANOVAs; non-parametric tests were employed in the light of the small group sizes. The groups also did not differ in verbal or non-verbal ability (mean verbal ability = 11.3, SD = 3.1, $\chi^2 = 0.52$, $p = 0.77$; mean non-verbal ability = 9.73, SD = 3.6, $\chi^2 = 0.18$, $p = 0.92$). The mean standard scores for spelling and decoding across the three groups were below 90. There was a significant group difference on a measure of phonological short-term memory (PSTM), $\chi^2 = 7.03$, $p = 0.03$, with post hoc tests indicating that the PHON and CONTROL groups differed significantly from each other (mean standard scores 93.92 vs. 111.1), with the CONTROL group demonstrating higher PSTM performance. The RHYTHM group had an intermediate mean score of 96, which was not significantly different from the PHON or the CONTROL groups.

Baseline measures

Academic ability tests

Expressive vocabulary Children's expressive vocabulary was assessed with the Vocabulary subtest of the WISC-III (Wechsler, 1992). In this subtest children are required to give oral definitions to a selection of words, increasing in complexity. The Vocabulary and Block Design subtests of the WISC-III yielded a standard score of 10 and SD of 3.

Non-verbal ability Non-verbal ability was assessed with the Block Design of the WISC-III (Wechsler, 1992). Children are required to copy small geometric designs with four or nine plastic cubes, increasing in complexity.

The following literacy tests were administered to the experimental groups both immediately pre- and post-intervention. While standard scores are reported in Table 1 to characterize the sample, raw scores are reported and used in the analysis of change over time. Because some children moved from one standardization age range to another during the intervention period while others did not, use of standard score could mask or distort degrees of absolute performance difference.

Reading Reading was assessed using the Test of Word Reading Efficiency, Form A (TOWRE; Torgesen, Wagner, & Rashotte, 1999). This test has two subtests: Sight Word Efficiency (SWE) and Phonemic Decoding Efficiency (PDE), which feature lists of single real words and nonwords respectively. Children are required to read as many words or non-words as they can in 45 s. The test yields a standard score mean of 100 and SD of 15. The raw score comprises the absolute number of words read in 45 s. This test has an A & B version, which were administered in the pre- and post-intervention assessments respectively. The alternate form reliability coefficients for forms A and B are $r = 0.93$ for the Sight Word Efficiency and $r = 0.94$ for the Phonemic Decoding Efficiency subtests respectively.

Spelling Spelling was assessed using the Wide Range Achievement Test, Blue Spelling Test (WRAT-III, Wilkinson & Robertson, 2004). This is an untimed measure in which the child is asked to spell words of increasing difficulty that are read aloud by the examiner. The test yields a standard score mean of 100 and SD of 15. The raw score comprises the absolute number of words spelt correctly. It has a Blue and Tan version, which were administered in the pre- and post-intervention assessments respectively. The alternate form reliability coefficients for the Blue and Tan forms are $r = 0.93$.

Phonological processing measures

As noted, to demonstrate that the dyslexic participants did show severe deficits, Table 1 includes for comparison purposes data from a group of typically-developing control children matched in age to the children with dyslexia. These typical controls (hereafter TYPICAL) were from the ongoing longitudinal study (Thomson & Goswami, 2008) and had also received the memory and rapid automatized naming (RAN) tasks, but had not received the PhAB. They had however received a rhyme oddity measure of phonological awareness, as had the children with dyslexia who were drawn from the longitudinal study, and these scores are shown in Table 1. The memory and oddity rhyme tasks were presented using digitized speech created from a native female speaker of standard Southern British English. The children listened to the words through headphones and their responses were recorded using a minidisc recorder. Practice trials were always given. The PhAB was given orally by the experimenter in accordance with the instructions.

Phonological short-term memory (PSTM) task The Nonword Recall subtest of the Working Memory Test Battery for Children (WMTBC) was administered (Pickering & Gathercole, 2001). This test required children to recall and repeat a list of monosyllabic nonwords. List length increased as the trials progressed. Six trials were included in each block, and testing was halted when three or more trials were incorrect within a block. The raw score is the number of trials that were correctly recalled, which also yielded a standard score of 100 and SD of 15, reported here.

Rapid automatized naming task (RAN) The children had to name four familiar pictures under timed conditions. The pictures were repeated in a random order, with ten presentations of each stimulus item (total of 40 pictures—five rows of eight). Two sets of pictures were presented and children's mean speed across the two sets was used in the analysis (Set A: fire, cup, bird, leaf; Set B: gate, wheel, shop, tie).

Phonological awareness task (rhyme oddity) This task measured rhyme awareness using an oddity format (e.g., kick, pick, tip), see Thomson and Goswami (2008). Children listened to the computer speaking 3 words in a semi-random order and were asked to select the word that did not rhyme with the other 2 words. The presentation order of the words and thus the position of the target word was counterbalanced across groups. Trials were presented in 2 fixed random orders. The task comprised 20 trials, and a score of 1 was given for each correct answer.

Standardized phonological awareness Two subtests of the Phonological Assessment Battery (PhAB; Frederickson, Frith & Reason, 1997) were administered to the experimental groups only. In the Rhyme subtest children listened to sets of three words and had to select the words that sounded the same at the end (e.g., *dog*, *man*, *fog*). The subtest has 21 items. To assess phoneme-level skills the Spoonerisms subtest was administered. The Spoonerisms task consisted of two parts. In part 1, children were asked to replace the first sound of a word with a new sound (e.g., *make* with a/t/gives *take*). In the second part children were asked to exchange initial sounds in two words/nonwords (e.g., *big pip* gives *pig bip*). The subtest had 20 items and raw scores were out of 30. Standard scores yield a mean of 100 and SD of 15.

Auditory processing measures

Participants received a short hearing screen using an audiometer. Sounds were presented in both the left or right ear at a range of frequencies (250, 500, 1,000, 2,000, 4,000, 8,000 Hz), and all subjects were sensitive to sounds at the 20 dB SPL level. The remaining three psychoacoustic measures (Rise Time, Duration, Intensity) utilized the *Dinosaur game* threshold estimation program originally created by Dorothy Bishop (University of Oxford, UK) and adapted by the first author. The Dinosaur game uses a two-interval forced choice (2IFC) paradigm with a 500 ms inter-stimulus interval (ISI). Stimuli were presented binaurally through headphones at 73 dB SPL with the exception of the intensity discrimination task, in which intensity of presentation varied. Children's responses were recorded on the keyboard by the experimenter. In all tasks using the Dinosaur program, the child heard two cartoon characters make a sound, and was asked to choose which character produced the target sound, according to the different instructions below. Feedback was given after every trial throughout the course of the experiment. The Dinosaur program used the more virulent form of PEST (Parameter Settings by Sequential Estimation; Findlay, 1978) to staircase adaptively through the stimulus set based on the subject's previous answer. A maximum of 40 trials were presented in any one task. The threshold score achieved was based on the 75% correct point for the last four reversals. Across tasks, a higher threshold value represents a poorer performance. For all tasks, children were first given training trials consisting of the standard tone and the tone that was most audibly different from the standard tone. Training trials were repeated until children were correct on 4 out of 5 trials.

Amplitude rise time discrimination task This task measures children's ability to discriminate between the rate of onset (rise time) of different sound envelopes and is often called the Two Rise task (e.g., Goswami et al., 2011b). Perceptually, variation of the rise time of these sounds is experienced as degree of rhythmic beat. In this task, children were presented with two amplitude modulated sounds of equal modulation frequency and duration, but with different rise times. Their job was to decide which of the two sounds had a sharper beat (shorter rise time). The task used a continuum of 40 stimuli created using a sinusoidal carrier at 500 Hz amplitude-modulated at the rate of 0.7 Hz (depth of 50%). The standard reference stimuli always had the longest rise time value (300 ms). Each stimulus was 3,750 ms long (2.5 cycles). The child's task was to decide which dinosaur made a sound with a sharper beat. The concept of beat sharpness was reinforced visually/motorically by the researcher contrasting sharp hand taps on the table with a more gentle brushing contact. See Fig. 2.

Duration discrimination task This task measures children's ability to perceive how long sounds are. Children were presented with two tones varying in duration. The child's job was to decide which sound was longer. The task used a continuum of 40 stimuli created using a sinusoidal carrier at 500 Hz. The standard stimulus was 400 ms with the continuum increasing up to 600 ms.

Intensity discrimination task This task measures children's ability to perceive how loud sounds are. A continuum of forty 500 Hz stimuli was constructed by varying the intensity of the steady state logarithmically, values within a range of 30 dB. Each stimulus tone had linear onset and offset envelopes (50 ms) and fixed steady state duration of 700 ms. The stimulus with 29.25 dB steady state was used as a standard. Children were presented with the standard stimulus alongside another stimulus from the continuum and asked to choose the stimulus that was quietest.

Intervention procedure and tasks

Both groups receiving an active intervention were seen on a 1:1 basis for 30 min, once a week for 6 weeks. This length of time and intensity is representative of equivalent 1:1 interventions offered in schools by special needs teachers or other educational professionals in the United Kingdom. All intervention sessions were carried out by the same researcher (JMT). No children were receiving any other type of intervention for their reading disability at the time this study occurred.

Rhythm intervention, RHYTHM

The rhythm intervention included both speech and non-speech tasks and followed a set procedure in each session. The session started with 5 min of warm-up rhythmic activities, including rhythm copying on djembe drums and a rhythm synchronization game. In this game, two words of varied syllable length were introduced, for example, *hill* and *river*. The child and researcher each practiced a different four word sequence, e.g., *hill*, *hill*, *river*, *hill* or *hill*, *river*, *river*, *hill* and then tried to keep together when repeatedly saying or clapping their respective lines. The following 25 min were spent on computer-based activities, which involved a rotation of three activities. The first activity was the adaptive amplitude rise time discrimination task described above. The second activity, the DeeDee task, was adapted from Whalley and Hansen (2006) and used a reiterative speech technique (following Kitzen, 2001; cf. Whalley & Hansen, 2006; see also Goswami, Gerson, & Astruc, 2010). Each syllable of a phrase was replaced by the reiterative syllable *dee* in order to eliminate distinctive phonetic information while retaining the stress, rhythm and intonational pattern of the original phrase. Children saw a picture depicting a well-known movie or book title (pretested for familiarity). Two *DeeDee* phrases were then heard, one of which matched the stress, rhythm and intonation of the title. Children chose whether the first or second phrase matched the target. For example, for the target *Harry Potter*, the match would be *DEEdee DEEdee*. The activity presented 20 items per session. The third task was an amplitude rise time synchrony game. Children heard two sets of three tones. Both sets featured sine wave tones of 200 ms (500 Hz frequency). In Set A the sounds were equidistant (200 ms apart; total length of string = 1,000 ms), hence the rhythmic spacing was perfectly periodic. In Set B the middle tone was somewhere on the continuum between the first and last tone (continuum size = 80 steps; total string length = 1,000 ms), hence the rhythm was irregular. Children turned a bi-directional dial which controlled the temporal position of the middle tone in Set B, with the aim of making Set B sound the same as Set A. When the child determined that Set A and Set B were identical the activity finished and the adult carrying out the session gave quantitative feedback on the accuracy of the child's final decision, based on computer output data. Initially the rise time of all tones was 50 ms; in later sessions a longer rise time (150 ms) was used across tones for children achieving a criterion threshold of accuracy on the shorter rise time stimuli (see Figs. 1, 2 for examples of stimuli).

Phoneme discrimination intervention, PHON

The commercially available Phonomena® program was used for the phoneme discrimination intervention. This is an adaptive AXB game featuring eleven sets of digitised syllable pairs. Syllable-pair sound continua of 94 sounds were generated using linear prediction analysis and re-synthesis. A single game of 60 trials featured sounds from one of these sets. Children heard the dinosaur tutor utter a syllable, with two cavemen trying to copy him in turn. Children chose which caveman produced a sound that matched the tutor and were given immediate feedback on the accuracy of their decision. Complete details about the program can be found in Moore et al. (2005). At the end of each sound game, a short non-sound related arcade style game followed as a reward/break. The next run of the adaptive listening activity would feature a different syllable pair. For participating children, the sequence of activity was most like continuously playing the adaptive rise time discrimination game. However, although the phonemic training lacked the variety

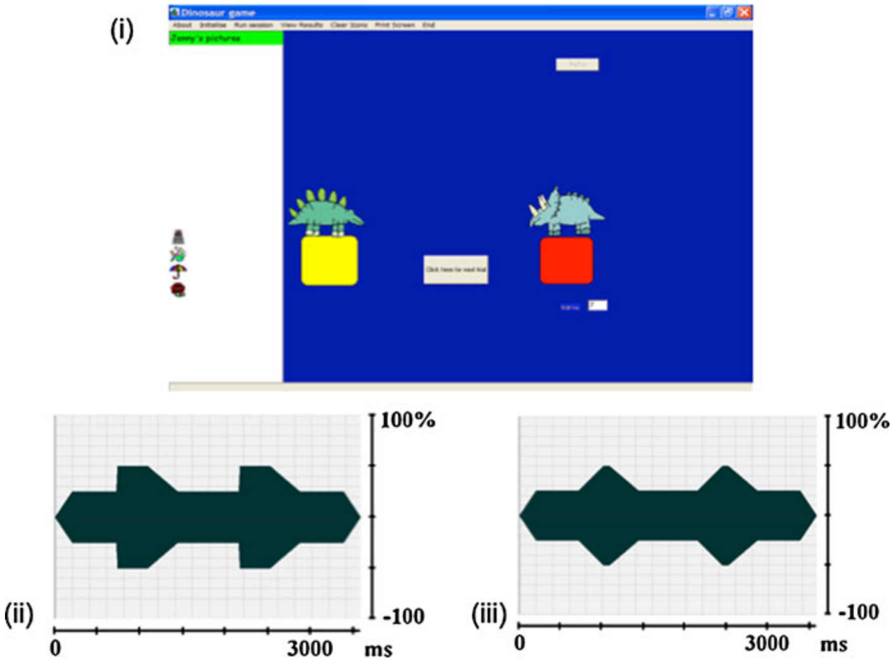

Fig. 1 Amplitude rise time discrimination task. Screen shot of the task (see (**i**)) and schematics of two stimuli. The amplitude modulated tone in (**ii**) has a sharp rise time (15 ms) on each modulation, while in (**iii**) it is slower (300 ms)

characterizing the rhythm-based training, the commercial arcade-like reward helped to maintain children's concentration.

Results

Exploratory analysis of children's scores across measures showed that in the majority of the assessed variables the distributions of scores within each group deviated significantly from a normal distribution. Therefore, the analyses presented are based on non-parametric tests.

Kruskal–Wallis 1-way ANOVAs were carried out to ensure that the three groups did not differ significantly from each other in pre-intervention auditory processing. While there were no significant differences in rise time and duration perception, there was a significant group difference on the intensity discrimination measure, $\chi^2 = 7.59, p = 0.023$. Post hoc inspection revealed that the CONTROL group had a significantly higher mean threshold (i.e., poorer discrimination) than the other two groups; see Table 2.

In order to examine changes in auditory, phonological and literacy performance as a function of group a series of Wilcoxon Signed Rank tests were carried out. See Tables 3, 4, and 5 for summaries of the pretest–posttest results.

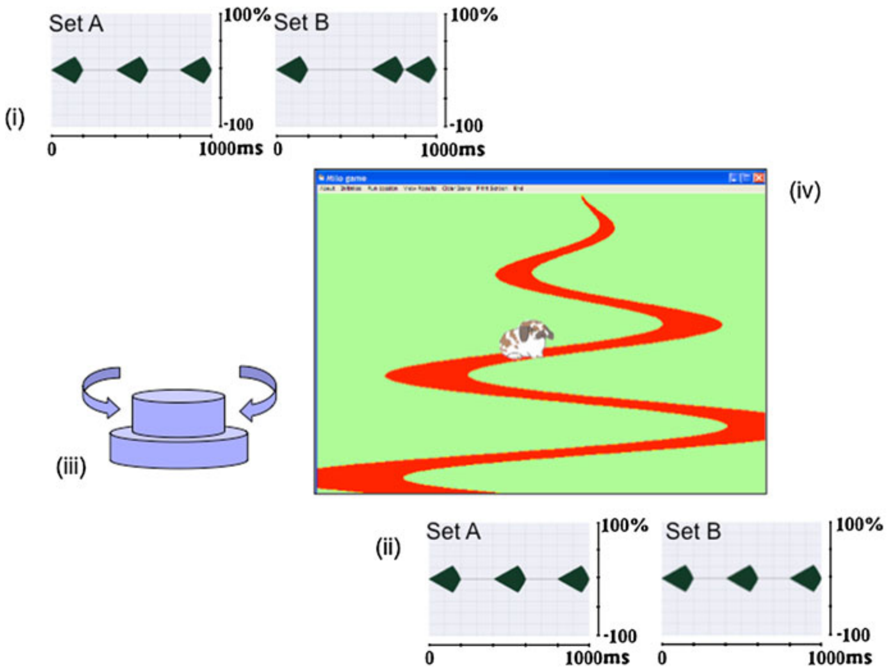

Fig. 2 Amplitude rise time synchrony game. Children heard two sets of three tones. Initially (see (**i**)) in Set A the sounds were equidistant and in Set B the middle tone was somewhere on the continuum between the first and last tone. Children turned a bi-directional dial (see (**iii**)) which controlled the temporal position of the middle tone in Set B, with the aim of making Set B sound the same as Set A (see (**ii**)). As the dial was turned, a rabbit moved up and down the path (see (**iv**)), to provide visual reinforcement

Table 2 Mean (SD) performance thresholds on psychoacoustic baseline measures by intervention group

Group	RHYTHM	PHON	CONTROL	TYPICAL
Rise time in ms	262.3 (63.8)	259.3 (77.3)	230.3 (132.4)	189.5 (119.0)
Intensity in dB	15.8 (7.8)	15.6 (7.4)	23.6 (5.8)	6.1 (4.7)
Duration in ms	99.4 (40.0)	98.2 (32.5)	95.9 (49.5)	64.6 (29.0)

Effect sizes were also used to investigate whether the observed gains in auditory, phonological and literacy performance made by the RHYTHM and PHON groups were larger than the gains made by the CONTROL group. See Tables 3 and 4. The effect sizes were calculated by first computing gain scores for each group (T2–T1), and then subtracting the mean gain score for the CONTROL group from the mean gain score for each of the experimental groups (RHYTHM, PHON). This relative gain (relative to controls) was divided by the SD of the gain for the CONTROL group to yield the effect size (see Hatcher, 2000).

RHYTHM intervention

Of the three literacy measures (word reading, nonword reading and spelling), the children receiving the RHYTHM intervention made statistically significant gains in spelling, $z = -2.39$, $p < 0.05$, $d = 0.61$, with medium effect sizes also present for gains in word ($d = 0.63$) and non-word ($d = 0.46$) reading as compared to the CONTROL group. The RHYTHM group made significant gains on the two phonological measures, rhyme perception ($z = -2.39$, $p < 0.05$, $d = 0.44$) and Spoonerisms ($z = -2.03$, $p < 0.05$, $d = 0.98$). Of the three auditory perception assessments, measuring rise time, intensity and duration discrimination respectively, the RHYTHM group made significant performance gains only in rise time discrimination, $z = -2.07$, $p < 0.05$, $d = 0.58$. Figure 3 shows the individual gains on the rise time discrimination task (note that a lower numerical threshold score indicates a better performance).

PHON intervention

The PHON group also made statistically significant gains in spelling ($z = -3.02$, $p < 0.01$), but not reading. However, as with the RHYTHM group, medium effect sizes were observed for gains in word ($d = 0.65$) and nonword reading ($d = 0.50$) as compared to the CONTROL group gains (see Table 4). In addition, the PHON group made performance gains in rhyme perception ($z = -2.41$, $p < 0.05$, $d = 0.51$) and Spoonerisms ($z = -3.09$, $p < 0.01$, $d = 1.38$). There were no gains observed for any of the auditory perception measures.

CONTROL intervention

The CONTROL group demonstrated statistically significant gains on one measure only, spelling, $z = -2.68$, $p < 0.01$. The improvement in intensity threshold was at the level of significance, $z = -1.96$, $p = 0.05$. As will be recalled, the CONTROL group had significantly elevated intensity thresholds at the beginning of the study.

Discussion

Here we designed a novel auditory training program for children with developmental dyslexia, aimed at remediating the rise time/rhythmic processing deficits suggested by earlier studies of auditory processing in dyslexia (Goswami et al., 2002, 2009, 2011, b; Hamalainen et al., 2005; 2009; Muneaux et al., 2004; Pasquini et al., 2007; Poelmans et al., 2011; Richardson et al., 2004; Suranyi et al., 2009; Thomson et al., 2006; Thomson & Goswami, 2008, 2010). The efficacy of this type of auditory training was tested in a short-term intervention study and compared to a standard phonemic training auditory intervention whose efficacy is already documented (Moore et al., 2005). To control for spontaneous development during the time period of the intervention, an untreated control dyslexic group was also utilized. Comparisons of improvement by group showed that both the rhythmic

Table 3 RHYTHM group: summary table of pretest and posttest raw scores on auditory, phonological and literacy measures

Behavioural variable	RHYTHM intervention		Wilcoxon Paired rank test		Effect size
	Pre	Post	*Z* score	*p*	*d*
Word reading	49.67 (12.44)	52.44 (11.26)	−1.69	0.09	0.63
Non-word reading	14.78 (9.48)	15.11 (7.66)	−0.18	0.86	0.46
Spelling	22.33 (2.06)	24.22 (2.99)	−2.39	0.02*	0.61
PhAB rhyme	16.78 (2.28)	18.78 (2.28)	−2.39	0.02*	0.44
PhAB spoonerisms	14.11 (6.54)	17.44 (7.38)	−2.03	0.04*	0.98
Rise time in ms	262.3 (63.8)	232.9 (96.6)	−2.07	0.04*	0.58
Duration in ms	99.4 (40.0)	104.9 (47.2)	−0.53	0.59	0.10
Intensity in dB	15.8 (7.8)	12.8 (5.4)	−1.01	0.31	0.39

Standard deviations are shown in parentheses. All phonological and literacy measures are reported as raw scores. Asterisks represent significant change as indicated by Wilcoxon Signed ranks tests

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

Table 4 PHON group: summary table of pretest and posttest raw scores on auditory, phonological and literacy measures

Behavioural variable	PHON intervention		Wilcoxon Paired rank test		Effect sizes
	Pre	Post	*Z* score	*p*	*d*
Word reading	46.08 (19.01)	48.92 (16.81)	−1.83	0.07	0.65
Non-word reading	16.92 (10.88)	17.42 (8.18)	−0.55	0.58	0.50
Spelling	22.17 (1.99)	23.92 (2.75)	−3.02	0.003**	0.47
PhAB rhyme	15.42 (5.74)	17.58 (5.09)	−2.41	0.02*	0.51
PhAB spoonerisms	13.08 (7.33)	17.50 (8.48)	−3.09	0.002**	1.38
Rise time in ms	259.3 (77.3)	257.0 (87.3)	−0.08	0.94	0.09
Duration in ms	98.2 (32.5)	77.0 (32.5)	−1.65	0.09	0.29
Intensity in dB	15.6 (7.4)	12.0 (4.6)	−0.94	0.35	0.29

Asterisks represent significant change as indicated by Wilcoxon Signed ranks tests

intervention (RHYTHM) and the phonemic intervention (PHON) led to significant gains in phonological awareness, with medium to large effect sizes. Although the RHYTHM intervention in theory addressed the syllabic level and the PHON intervention in theory addressed the phonemic level, both groups showed gains at both psycholinguistic grain sizes of rhyme and phoneme. In line with the view that phonological awareness is a single construct over developmental time (Anthony & Lonigan, 2004), both interventions had non-specific effects on phonological development.

In contrast, the interventions did have specific effects on the development of basic auditory processing. The RHYTHM intervention trained rise time discrimination, and the RHYTHM group showed significant gains in perceiving rise time

Table 5 CONTROL group: summary table of pretest and posttest raw scores on auditory, phonological and literacy measures

Behavioural variable	CONTROL		Wilcoxon Paired rank test	
	Pre	Post	*Z* score	*p*
Word reading	48.00 (15.97)	48.25 (17.27)	−0.27	0.79
Non-word reading	18.75 (9.64)	17.25 (8.69)	−1.23	0.22
Spelling	22.17 (2.21)	23.42 (2.31)	−2.68	0.007**
PhAB rhyme	14.08 (5.45)	15.08 (5.87)	−1.34	0.18
PhAB spoonerisms	14.17 (7.21)	14.83 (6.93)	−0.634	0.53
Rise time in ms	230.3 (132.4)	224.7 (147.5)	−1.26	0.21
Duration in ms	95.9 (49.5)	94.7 (42.5)	−0.28	0.78
Intensity in dB	23.6 (5.8)	18.0 (6.8)	−1.96	0.05

Asterisks represent significant change as indicated by Wilcoxon Signed ranks tests

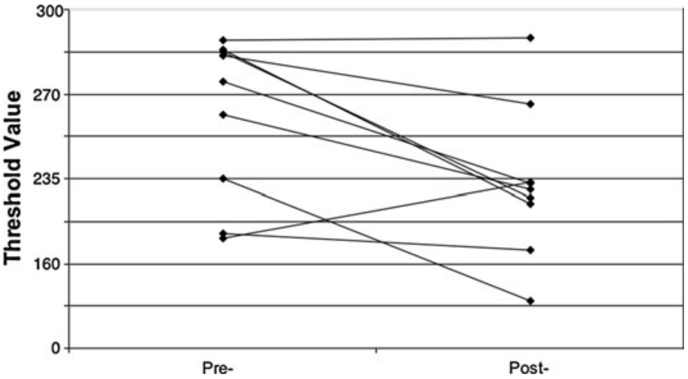

Fig. 3 Threshold change (in ms; stimuli use a logarithmic scale) in rise time discrimination for individual participants in the RHYTHM training group at pre- and post-intervention assessments

(medium effect size) that were not shown by the PHON group. As shown in Fig. 3, these gains were consistent across almost all participants. Neither intervention trained duration nor intensity discrimination, and neither intervention group showed significant gains for these auditory dimensions, ruling out the possibility that the gain in rise time discrimination shown by the RHYTHM group was a non-specific effect of practicing an auditory threshold task. The specificity of these auditory training effects is in line with prior investigations (Hawkey et al., 2004). Neither intervention trained literacy directly, and neither intervention group showed statistically significant improvements in reading or in the phonological decoding of nonwords. However, when effect sizes were used to compare the interventions, then both the RHYTHM and PHON groups showed medium effect sizes for literacy outcomes. The intervention period was only 6 weeks, hence significant literacy gains may have accrued with longer training. Future studies would benefit from both a longer period of intervention as well as a larger sample size. As all three groups, including the untreated control group, showed significant gains in spelling over the course of the intervention, the spelling improvement could reflect particular aspects of the spelling curriculum being taught at that particular point in the school year (literacy teaching is standardized in the United Kingdom via the National Literacy Strategy).

The results of this short-term intervention study are thus straightforward. Auditory training provided in a one-on-one intervention had a significant beneficial effect on phonological skills, whether the training was aimed at improving suprasegmental aspects of linguistic processing, as in the RHYTHM intervention designed for this study, or was aimed at improving segmental (phonemic) aspects of linguistic processing, as in the control intervention Phonomena®. Theoretically, the efficacy of the RHYTHM intervention supports the importance of prosodic sensitivity in developing awareness of the phonological grain sizes required for effective literacy development (rhyme and phoneme, see also Goswami et al., 2010). It also supports theoretical approaches to phonological development in infancy that emphasise the inter-dependence of phonemic and prosodic information (e.g., Pierrehumbert, 2003; Vihman & Croft, 2007). Such interdependence could suggest that a combined rhythmic and phonemic intervention would be more effective for children with dyslexia than offering either kind of training in isolation. However, this is an empirical question requiring further study.

In the current study, the independent effects of direct instruction on periodic patterning (e.g., the djembe drums), on matching motor rhythms to speech rhythms (e.g., the clapping game *hill*, *river*, *river*, *hill*), on discriminating rise time and using it in rhythm production, and on matching DeeDee syllables to real speech targets, cannot be disentangled. In our view, all are likely to have contributed to the success of the intervention. Certainly, in previous studies it has been shown that individual differences in these components of rhythmic and prosodic sensitivity are significant predictors of reading and phonological development (e.g., nonspeech rhythmic entrainment, Thomson & Goswami, 2008; the DeeDee task, Goswami et al., 2010). It has also shown recently that metrical music perception is impaired in developmental dyslexia. Children with dyslexia find it more difficult than controls to match short rhythmic sequences of musical notes, and the severity of impairment is related to reading and phonological development (Huss, Verney, Fosker, Mead, & Goswami, 2011). All of these data attest to the potential benefits that may accrue when including prosodic, metrical and stress/rhythm-based tasks in a program of remediation for developmental dyslexia (see also Overy, Nicolson, Fawcett, & Clarke, 2003). Significant variety could be introduced into such programs, as music-based and non-speech rhythmic tasks may train the same basic auditory processing skills that are required for the efficient segmentation and representation of speech (see Goswami, 2011).

Finally, it would be of interest to investigate the efficacy of rhythmic interventions for developmental dyslexia in non-alphabetic orthographies. As the primary perceptual linguistic unit across languages is the syllable (Greenberg, 2006), it seems likely that interventions based on rhythm and prosody would be also beneficial for children with dyslexia who are learning to read non-alphabetic scripts like Chinese and Japanese. Phonological development in Chinese for example is also linked to the auditory processing of rise time (Goswami et al., 2011b; Wang, Huss, Hamalainen, & Goswami, 2011). Tone awareness is the strongest phonological predictor of reading development in Chinese (McBride-Chang & Ho, 2005; McBride-Chang et al., 2008; Shu, Peng, & McBride-Chang, 2008), and individual differences in rise time discrimination are strongly linked to individual differences in tone awareness (Goswami et al., 2011b; Wang et al., 2011; relationships with morphological awareness have not been studied). As tone is a characteristic of the entire Chinese syllable (i.e., it is a suprasegmental cue), the design of interventions based on rhythm and prosodic patterning may offer previously unsuspected benefits for phonological development and literacy acquisition across all languages, not simply for languages that operate orthographically at the phoneme level.

Acknowledgments We would like to thank the staff and students of the participating schools in East Anglia, UK. This study was funded by the Economic and Social Research Council (ESRC), grant RES-000-23-0475, awarded to UG, while support to UG for writing this paper came from the Leverhulme Trust.

References

Anthony, J. L., & Lonigan, C. J. (2004). The nature of phonological awareness: Converging evidence from four studies of preschool and early grade school children. *Journal of Educational Psychology, 96*, 43–55.

Christophe, A., Mehler, J., & Sebastian-Galles, N. (2001). Perception of prosodic boundary correlates by newborn infants. *Infancy, 2*, 385–394.

Cohen, W., Hodson, A., O'Hare, A., Boyle, J., Durrani, T., & McCartney, E. (2005). Effects of computer-based intervention through acoustically modified speech (Fast ForWord) in severe mixed receptive-expressive language impairment: Outcomes from a randomized controlled trial. *Journal of Speech, Language, and Hearing Research, 48*, 715–729.

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

De Martino, S., Espesser, R., Rey, V., & Habib, M. (2001). The "temporal processing deficit" hypothesis in dyslexia: New experimental evidence. *Brain and Cognition, 46*, 104–108.

Drullman, R., Festen, J. M., & Plomp, R. (1994a). Effect of reducing slow temporal modulations on speech reception. *Journal of the Acoustical Society of America, 95*, 2670–2680.

Drullman, R., Festen, J. M., & Plomp, R. (1994b). Effect of temporal envelope smearing on speech reception. *Journal of the Acoustical Society of America, 95*, 1053–1064.

Echols, C. H. (1996). A role for stress in early speech segmentation. In J. L. Morgan & K. Demuth (Eds.), *Signal to Syntax: Bootstrapping from speech to grammar in early acquisition* (pp. 151–170). Mahwah, NJ: Lawrence Erlbaum Associates.

Farmer, M. E., & Klein, R. M. (1995). The evidence for a temporal processing deficit linked to dyslexia: A review. *Psychonomic Bulletin & Review, 2*, 460–493.

Findlay, J. M. (1978). Estimates on probability functions: A more virulent PEST. *Perception and Psychophysics, 23*, 181–185.

Frederickson, N., Frith, U., & Reason, R. (1997). *Phonological assessment battery* (Standardised ed.). Windsor, UK: NFER Nelson.

Gillam, R. B., Loeb, D. F., Hoffman, L. M., Bohman, T., Champlin, C. A., Thibodeau, L., et al. (2008). The efficacy of Fast ForWord Language intervention in school-age children with language impairment: A randomized controlled trial. *Journal of Speech, Language, and Hearing Research, 51*, 97–119.

Goswami, U. (2011). A temporal sampling framework for developmental dyslexia. *Trends in Cognitive Sciences, 15*, 3–10.

Goswami, U., Fosker, T., Huss, M., Mead, N., & Szucs, D. (2011a). Rise time and formant transition duration in the discrimination of speech sounds: The BA-WA distinction in developmental dyslexia. *Developmental Science, 14*, 34–43.

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

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

Goswami, U., Wang, H. L. S., Cruz, A., Fosker, T., Mead, N., & Huss, M. (2011b). Language-universal sensory deficits in developmental dyslexia: English, Spanish, and Chinese. *Journal of Cognitive Neuroscience, 23*, 325–337.

Greenberg, S. (2006). A multi-tier framework for understanding spoken language. In S. Greenberg & W. A. Ainsworth (Eds.), *Listening to speech: An auditory perspective* (pp. 411–433). Mahwah, NJ: Lawrence Erlbaum Associates Publishers.

Hamalainen, J., Leppanen, P., Eklund, K., Thomson, J. M., Richardson, U., Guttorm, T., et al. (2009). 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.

Hamalainen, J., Leppanen, P. H., Torppa, M., Muller, K., & Lyytinen, H. (2005). Detection of sound rise time by adults with dyslexia. *Brain and Language, 94*, 32–42.

Hatcher, P. J. (2000). Reading intervention need not be negligible: Response to Cossu (1999). *Reading and Writing, 13*(3), 349–355.

Hawkey, D. J. C., Amitay, S., & Moore, D. R. (2004). Early and rapid perceptual learning. *Nature Neuroscience, 7*, 1055–1056.

Heath, S. M., & Hogben, J. H. (2004a). Cost-effective prediction of reading difficulties. *Journal of Speech, Language, and Hearing Research, 47*, 751–765.

Heath, S. M., & Hogben, J. H. (2004b). The reliability and validity of tasks measuring perception of rapid sequences in children with dyslexia. *Journal of Child Psychology and Psychiatry, 45*, 1275–1287.

Huss, M., Verney, J. P., Fosker, T., Mead, N., & Goswami, U. (2011). Music, rhythm, rise time perception and developmental dyslexia: Perception of musical meter predicts reading and phonology. *Cortex, 47*, 674–689.

Jusczyk, P. W., Houston, D. M., & Newsome, M. (1999). The beginnings of word segmentation in English-learning infants. *Cognitive Psychology, 39*, 159–207.

Kitzen, K. R. (2001). 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 Abstrcts International*, *6*(2), 0460A.

Leong, V., Hamalainen, J., Soltesz, F., & Goswami, U. (2010). Rise time perception and detection of syllable stress in adults with developmental dyslexia. Unpublished manuscript submitted for publication.

Mahncke, H., Connor, B., Appelman, J., Ahsanuddin, O., Hardy, J., Wood, R., et al. (2006). Memoery enhancement in healthy older adults using a brain plasticity-based training program: A randomized controlled study. *Proceedings of the National Academy of Sciences of the United States of America, 103*, 12523–12528.

Marshall, C. M., Snowling, M. J., & Bailey, P. J. (2001). Rapid auditory processing and phonological ability in normal readers and readers with dyslexia. *Journal of Speech, Language, and Hearing Research, 44*, 925–940.

Mattys, S. L., & Jusczyk, P. W. (2001). Do infants segment words or recurring contiguous patterns? *Journal of Experimental Psychology: Human Perception and Performance, 27*, 644–655.

McAnally, K. I., Hansen, P. C., Cornelissen, P. L., & Stein, J. F. (1997). Effect of time and frequency manipulation on syllable perception in developmental dyslexics. *Journal of Speech, Language and Hearing Research, 40*, 912–924.

McArthur, G. M., Ellis, D., Atkinson, C. M., & Coltheart, M. (2008). Auditory processing deficits in children with reading and language impairments: Can they (and should they) be treated? *Cognition, 107*, 946–977.

McBride-Chang, C., & Ho, C. S.-H. (2005). Predictors of beginning reading in Chinese and English: A 2-year longitudinal study of Chinese Kindergartners. *Scientific Studies of Reading, 9*, 117–144.

McBride-Chang, C., Tong, X., Shu, H., Wong, A. M. Y., Leung, K.-W., & Tardif, T. (2008). Syllable, phoneme, and tone: Psycholinguistic units in early Chinese and English word recognition. *Scientific Studies of Reading, 12*, 171–194.

Mehler, J., Jusczyk, P., Lambertz, G., Halsted, N., Bertoncini, J., & Amiel-Tison, C. (1988). A precursor of language acquisition in young infants. *Cognition, 29*, 143–178.

Menell, P., McAnally, K. I., & Stein, J. F. (1999). Psychophysical sensitivity and physiological response to amplitude modulation in adult dyslexic listeners. *Journal of Speech, Language and Hearing Research, 42*, 797–803.

Moore, D. R., & Amitay, S. (2007). Auditory training: Rules and applications. *Seminars in Hearing, 28*, 99–109.

Moore, D. R., Halliday, L. F., & Amitay, S. (2009). Use of auditory learning to manage listening problems in children. *Philosophical Transactions of the Royal Society of London: B Biological Sciences, 364*, 409–420.

Moore, D. R., Rosenberg, J. F., & Coleman, J. S. (2005). Discrimination training of phonemic contrasts enhances phonological processing in mainstream school children. *Brain and Language, 94*, 72–85.

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

Nagarajan, S. S., Wang, X., Merzenich, M. M., Schreiner, C. E., Johnston, P., Jenkins, W. M., et al. (1998). Speech modifications algorithms used for training language learning-impaired children. *IEEE Transactions on Rehabilitation Engineering, 6*, 257–268.

NICHD. (2000). *Report of the National Reading Panel. Teaching children to read: An evidence-based assessment of the scientific research literature on reading and its implications for reading instruction: Reports of the sub-groups*. Washington, DC: U.S. Government Printing Office.

Nittrouer, S. (1999). Do temporal processing deficits cause phonological processing problems? *Journal of Speech, Language and Hearing Research, 42*, 925–942.

Nittrouer, S. (2006). Children hear the forest. *Journal of the Acoustical Society of America, 120*, 1799–1802.

Overy, K., Nicolson, R. I., Fawcett, A. J., & Clarke, E. F. (2003). Dyslexia and music: Measuring musical timing skills. *Dyslexia, 9*, 18–36.

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

Pickering, S., & Gathercole, S. E. (2001). *Working memory test battery for children (WMTB-C)*. London, UK: The Psychological Corporation.

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

Poelmans, H., Luts, H., Vandermosten, M., Boets, B., Ghesquière, P., & Wouters, J. (2011). Reduced sensitivity to slow-rate dynamic auditory information in children with dyslexia. *Research in Developmental Disabilities, 32*, 2810–2819.

Port, R. (2007). How are words stored in memory? Beyond phones and phonemes. *New Ideas in Psychology, 25*, 143–170.

Reed, M. A. (1989). Speech perception and the discrimination of brief auditory cues in reading disabled children. *Journal of Experimental Child Psychology, 48*, 270–292.

Richardson, U., Thomson, J. M., Scott, S. K., & Goswami, U. (2004). Auditory processing skills and phonological representation in dyslexic children. *Dyslexia, 10*, 215–233.

Rosen, S., & Manganari, E. (2001). Is there a relationship between speech and nonspeech auditory processing in children with dyslexia? *Journal of Speech Language and Hearing Research, 44*, 720–736.

Scientific Learning Corporation. (1998). Retrieved from: http://www.scilearn.com/products/index.php.

Shannon, R. V., Zeng, F.-G., Kamath, V., & Wygonski, J. (1995). Speech recognition with primarily temporal cues. *Science, 270*, 303–304.

Shu, H., Peng, H., & McBride-Chang, C. (2008). Phonological awareness in young Chinese children. *Developmental Science, 11*, 171–181.

Suranyi, Z., Csepe, V., Richardson, U., Thomson, J. M., Honbolygo, F., & Goswami, U. (2009). Sensitivity to rhythmic parameters in dyslexic children: A comparison of Hungarian and English. *Reading and Writing: An Interdisciplinary Journal, 22*, 41–56.

Tallal, P. (1980). Auditory temporal perception, phonics, and reading disabilities in children. *Brain and Language, 9*, 182–198.

Tallal, P. (2004). Improving language and literacy is a matter of time. *Nature Reviews Neuroscience, 5*, 721–728.

Tallal, P., Miller, S. L., Bedi, G., Byma, G., Wang, X., Nagarajan, S. S., et al. (1996). Language comprehension in language-learning impaired children improved with acoustically modified speech. *Science, 271*, 81–84.

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

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

Thomson, J. M., & Goswami, U. (2010). Learning novel phonological representations in developmental dyslexia: Associations with basic auditory processing of rise time and phonological awareness. *Reading and Writing: An Interdisciplinary Journal, 23*, 453–473.

Torgesen, J. K. (2000). Individual differences in response to early interventions in reading: The lingering problem of treatment resisters. *Learning Disabilities Research & Practice, 15*, 55–64.

Torgesen, J. K., Alexander, A. W., Wagner, R. K., Rashotte, C. A., Voeller, K. K., & Conway, T. (2001). Intensive remedial instruction for children with severe reading disabilities: Immediate and long-term outcomes from two instructional approaches. *Journal of Learning Disabilities, 34*(33–58), 78.

Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (1999). *Test of word reading efficiency (TOWRE)*. Austin, TX: Pro-Ed.

Vihman, M., & Croft, W. (2007). Phonological development: Toward a 'radical' templatic phonology. *Linguistics, 45*, 683–725.

Waber, D. P., Weiler, M. D., Wolff, P. H., Bellinger, D., Marcus, D. J., Ariel, R., et al. (2001). Processing of rapid auditory stimuli in school-age children referred for evaluation of learning disorders. *Child Development, 72*, 37–49.

Wang, H.-L. S., Huss, M., Hamalainen, J., & Goswami, U. (2011). Basic auditory processing and developmental dyslexia in Chinese. *Reading and Writing: An Interdisciplinary Journal*.

Weber, C., Hahne, A., Friedrich, M., & Friederici, A. D. (2004). Discrimination of word stress in early infant perception: Electrophysiological evidence. *Cognitive Brain Research, 18*, 149–161.

Wechsler, D. (1992). *Wechsler intelligence scales for children—III, UK*. Kent, UK: The Psychological Corporation.

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

Wilkinson, G., & Robertson, G. (2004). *Wide Range Acheivement Test*. Lutz, FL: Psychological Assessment Resources.

Witton, C., Talcott, J. B., Hansen, P. C., Richardson, A. J., Griffiths, T. D., Rees, A., et al. (1998). Sensitivity to dynamic auditory and visual stimuli predicts nonword reading ability in both dyslexic and normal readers. *Current Biology, 8*, 791–797.