Journal of Memory and Language 69 (2013) 1–17

Contents lists available at SciVerse ScienceDirect

Journal of Memory and Language

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

Impaired perception of syllable stress in children with dyslexia: A longitudinal study

Usha Goswami *, Natasha Mead, Tim Fosker, Martina Huss, Lisa Barnes, Victoria Leong

Centre for Neuroscience in Education, University of Cambridge, UK

ARTICLE INFO

Article history:
Received 31 May 2012
revision received 5 March 2013
Available online 6 April 2013

Keywords:
Prosodic awareness
Syllable stress
Dyslexia
Auditory processing

ABSTRACT

Prosodic patterning is a key structural element of spoken language. However, the potential role of prosodic awareness in the phonological difficulties that characterise children with developmental dyslexia has been little studied. Here we report the first longitudinal study of sensitivity to syllable stress in children with dyslexia, enabling the exploration of predictive factors. An initial cohort of 104 children was recruited. In Experiment 1 (mean age 9 years), participants received a reiterative speech task (DeeDee task) and in Experiment 2 (4 years later, mean age 13 years), they received a direct stress perception task. The children with dyslexia were compared to both younger reading-level matched controls (aged 7 years initially) and to age-matched controls. Children with dyslexia showed impaired sensitivity to syllable stress compared to both reading-level and age-matched controls when aged 9 years, and to age-matched controls only when aged 13 years. The longitudinal predictors of sensitivity to syllable stress were investigated, controlling for prosodic sensitivity at Time 1 as the autoregressor. Measures of auditory sensory processing and sub-lexical phonological awareness were unique longitudinal predictors. Prosodic sensitivity in children was also a significant longitudinal predictor of reading development, accounting for independent variance from sub-lexical phonological sensitivity (rhyme awareness).

Introduction

The phonology of oral language has both prosodic and phonetic structure, and both levels of phonology play a key role in language acquisition. For example, infants use rhythmic stress patterning to help segment the speech stream into words and syllables, and show categorical perception, distinguishing phonetic boundaries (such as the ba/pa boundary) soon after birth (Kuhl, 2004, for review). Individual differences in phonological processing measured in pre-reading children predict written language acquisition (e.g., Bradley & Bryant, 1983), and children who experience specific difficulties in acquiring written language skills (children with developmental dyslexia) are characterised across languages by phonological processing difficulties (Snowling, 2000; Ziegler & Goswami, 2005). Nevertheless, despite the central role of prosodic structure in language acquisition and also memory (Rubin, 1995), the phonological difficulties experienced by children with developmental dyslexia have not been studied in terms of prosodic awareness until fairly recently (e.g., Holliman, Wood & Sheehy, 2012; Goswami, Gerson, & Astruc, 2010; Wood & Terrell, 1998). Here, we present the first longitudinal study of prosodic awareness in children with developmental dyslexia.

One aim of the current study was to provide an assessment of phonological processing in dyslexia that explored both the prosodic and sub-lexical levels of awareness in the same children. Accordingly, we investigated both the development of sensitivity to syllable stress, and also sub-lexical phonological processing (rhyme and phoneme awareness). Sub-lexical difficulties have been demonstrated in children with dyslexia across languages and

* Corresponding author. Address: Centre for Neuroscience in Education, Department of Experimental Psychology, Downing Street, Cambridge CB2 3EB, UK. Fax: +44 1223 333564.

E-mail address: ucg10@cam.ac.uk (U. Goswami).

0749-596X/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.jml.2013.03.001

orthographies. For example, dyslexic children are relatively poor at making decisions about whether words rhyme with each other (“cat” “hat”), are relatively poor at counting syllables in words (“caterpillar”, four syllables), and show relatively poor skills in tasks requiring the detection or manipulation of phonemes in words, such as phoneme deletion tasks (e.g., “say ‘bice’ without the /b/”; see Ziegler & Goswami, 2005, for a comprehensive review). A second aim was to investigate developmental relations between phonological processing and auditory sensory processing. Logically, it is possible that sub-lexical phonological difficulties and prosodic difficulties both stem from underlying difficulties in basic auditory processing. In particular, we were interested in the possible role of sensitivity to amplitude envelope structure as a cross-language sensory deficit in developmental dyslexia related to phonology (Goswami et al., 2011). Rise times (the time required to reach peak signal intensity) in the amplitude envelope are associated with syllables, and stressed syllables have larger rise times. Peak signal intensity is reached with the syllable nucleus, providing a cue to the onset-rime division of the syllable. Hence a difficulty in the accurate perception of rise times could cause difficulties in childhood with the efficient processing of both prosodic and sub-lexical phonology (Goswami, 2011). It is also possible that auditory and phonological deficits are distinct developmentally, and that both contribute independently to the impaired development of reading.

The possibility that impaired auditory perceptual processing in childhood helps to explain the phonological “deficit” in developmental dyslexia has been the focus of recent cross-sectional and longitudinal studies (e.g., Boets, Ghesquière, van Wieringen, & Wouters, 2007; Boets et al., 2011; Goswami, Wang, et al., 2011; White et al., 2006). Efficient auditory sensory processing is likely to be an important prerequisite to developing well-specified phonological representations for words, as babies are born with auditory processing abilities but without a spoken language system. Efficient auditory processing of rhythmic stress patterns may be particularly important developmentally for high-quality phonological development, as rhythmic stress patterns can be perceived while inside the womb. Therefore, even quite small initial differences in auditory sensitivity to rise time during infancy could affect the perception of rhythmic stress patterns, leading developmentally to phonological difficulties at both prosodic and sub-lexical levels as language representations are acquired (Power, Mead, Barnes, & Goswami, 2012). It has also been suggested that the effects of individual differences in auditory processing on literacy acquisition may be developmentally restricted to a certain time window (Boets et al., 2011), or may be unrelated to phonological development for the majority of dyslexics (White et al., 2006). Therefore, it is theoretically possible that differences in auditory sensitivity are unrelated to difficulties in acquiring lexical stress patterns, which might arise instead from differences in the quality of children’s phonological representations (this would be one perspective from phonological theory, see also the theoretical perspective offered by Goswami and Leong (in press)). Nevertheless, auditory abilities measured in infancy predict later reading acquisition (Guttorm et al., 2005; Lyytinen et al., 2004), and preschool differences in basic auditory sensitivity (to amplitude envelope rise time but not frequency glides) predict later phonological awareness in school-aged children. Further, although children with developmental dyslexia usually demonstrate intact performance on hearing screens using an audiometer, and also appear fluent in their use of spoken language, subtle differences in speech *production* can be measured as early as 2–3 years of age (Smith, Lambrecht Smith, Locke, & Bennett, 2008). Smith et al. (2008) reported that children who later had reading difficulties had speech timing difficulties in early childhood, producing significantly fewer syllables per second (e.g., 4.8 at age 3 compared to 7.1 for non-risk children) and pausing for longer between articulations. This production difference is consistent with data reported by Marshall and van der Lely (2009), who found that older children with dyslexia were impaired in producing consonant clusters in unstressed syllables in a nonword repetition task.

Relations between auditory sensory processing and dyslexia have been investigated by a large number of studies measuring many different auditory parameters (for reviews, see Farmer & Klein, 1995; McArthur & Bishop, 2001; Schulte-Körne & Bruder, 2010; Studdert-Kennedy & Mody, 1995). The most recent and comprehensive review (Hämäläinen, Salminen, & Leppänen, 2012) concluded that group differences (dyslexic versus control) were most consistent for the sound parameters of amplitude rise time, duration, frequency and frequency modulation (FM) at slower rates (<60 Hz). Amplitude rise time is thought to be a measure of perceptual sensitivity to the amplitude modulation structure of the speech envelope (Goswami & Leong, in press). Rhythmic structure in the envelope is given by regular modulations of signal energy over time, which for speech peak at a rate of 4–6 Hz, the “syllable rate” (Greenberg, Carvey, Hitchcock, & Chang, 2003). The onsets of successive modulations in the amplitude envelope and their rates of change (rise times) are critical linguistic perceptual events, as they typically signal the onset of new syllables. Rise times are larger when a syllable is stressed. Hämäläinen et al. (2012) reported significant group differences between dyslexics and controls for 100% of the rise time studies that they reviewed, 75% of the duration studies, 75% of the frequency discrimination studies, and 92% of the FM studies. The mean weighted effect size for rise time over 11 studies was 0.8, the mean weighted effect size for duration over 9 studies was 0.9, the mean weighted effect size for frequency over 25 studies was 0.7, and the mean weighted effect size for frequency modulation over 11 studies was 0.6. Hence the mean effect sizes for duration, frequency and rise time were large effect sizes. Brain event-related potential (ERP) studies were also reviewed, enabling assessment of possible auditory processing differences between groups when task demands were absent (e.g., active attention, motivation, following instructions). Hämäläinen et al. (2012) concluded that in general the ERP data were consistent with the behavioural data in revealing significant group differences, with some inconsistencies (e.g., for Finnish, the same children showed a group difference for rise time with ERP measurements, but not with behavioural [auditory threshold] measurements; Hämäläinen, Leppänen, Guttorm, & Lyytinen, 2008; Hämäläinen et al., 2009). Hämäläinen et al. (2012) also noted that when auditory deficits were present in dyslexia, they did not seem to diminish with age.

Our theoretical focus in the current paper is on amplitude rise time perception, as we have proposed that reduced sensitivity to rise time in infancy and childhood should impair children's awareness of speech prosody, syllable stress and speech rhythm (e.g., Corriveau, Pasquini, & Goswami, 2007; Goswami, 2011; Power et al., 2012). Here we investigate the connection between rise time and prosodic awareness directly, by measuring basic auditory processing of rise time using three different measures to derive a global measure of rise time sensitivity, and exploring possible longitudinal connections to sensitivity to syllable stress. We also measured children's sensitivity to the intensity, frequency and duration of nonspeech sounds (tones). Sensitivity to sound duration and frequency were also important in the review of auditory processing in dyslexia by Hämäläinen et al. (2012), while intensity provides a control measure for the attentional demands of the basic auditory processing task used here (as simple intensity discrimination is not usually impaired in children with dyslexia, see Richardson, Thomson, Scott, & Goswami, 2004). Classic theories of stress perception indicate that differences in the loudness, pitch and length of syllables are critical for discriminating stress (Fry, 1955). However, amplitude rise time (the time taken to reach maximum signal intensity) should be another important cue to stress perception, as it is related to syllable prominence (Greenberg, 2006). Intensity fluctuations in the amplitude envelope signal speech rate, carry stress and tonal contrasts, and reflect prosodic and intonational information (see Giraud & Poeppel, 2012; Goswami & Leong, in press; Zion-Golumbic, Poeppel, & Schroeder, 2012). Developmentally therefore, impaired sensitivity to amplitude modulation and amplitude envelope rise times should impair the ability to recover syllabic and prosodic structure from the speech signal. These predicted impairments for dyslexic children with syllable stress and speech prosody should be found in addition to the well-documented sub-lexical phonological impairments reported in developmental dyslexia.

Currently, there are only a few studies of sensitivity to syllable stress in children and adults with developmental dyslexia, and there are no longitudinal studies with children. For example, studies using reiterative speech tasks have produced data consistent with the prediction that the perception of syllable stress should be impaired in dyslexia. Kitzen (2001) first adapted the reiterant speech technique used in aphasia studies (Nakatani & Schaffer, 1978) for use with dyslexic adults. In reiterant speech, each syllable in a word is converted into the same syllable (here DEE), hence removing most phonetic information while retaining the stress and rhythm patterns of the original words and phrases. Kitzen converted film and story titles into "DeeDees", so that (for example) 'Casablanca' became DEEdeeDEEdee (STRONG weak STRONG weak or SWSW). Participants with dyslexia heard a tape-recorded DeeDee sequence while viewing three alternative (written) choices, for example 'Casablanca', 'Omega Man' and 'The Godfather'. Kitzen found that the participants with dyslexia were significantly poorer in the DeeDee task than age-matched controls. Performance in the DeeDee measure was significantly associated with syllable and phoneme segmentation skills, word reading abilities and reading comprehension. In logistic regression analyses carried out to predict group membership (dyslexic versus control), the DeeDee measure was a highly significant predictor of group status (along with syllable segmentation and rapid naming measures). All three measures together predicted group membership with 97% accuracy (phoneme segmentation was not a significant predictor).

Interpretation of the adult dyslexia findings is hampered by the fact that the DeeDee measure involved written stimuli and thus required the dyslexic particpants to read. Goswami et al. (2010) hence adapted the DeeDee task for use with dyslexic children by designing an oral version (based also on Whalley and Hansen (2006), who designed a DeeDee task for typically-developing children). Goswami et al. (2010) created two novel DeeDee measures, one based on celebrity names (e.g., *David Beckham*) and one based on film and book titles (e.g., *Harry Potter*). In the first task, the words were "spoken in DeeDees", and hence retained the metrical phrase-level structure of the originals. In the second task, this phrase-level information was removed by utilising four synthesised tokens, "DEE" and "dee" in initial and final position, which served to emphasise syllable stress (strong or weak). The selected film and book titles were then created by combining the synthetic "Dees" in the appropriate strong–weak syllable sequence. Goswami et al. (2010) reported that both tasks were performed more poorly by 12-year-old children with developmental dyslexia than by 12-year-old controls. Individual differences in DeeDee performance were associated with individual differences in auditory sensitivity to rise time, frequency and simple intensity, and the DeeDee measures were significant concurrent predictors of individual differences in reading, spelling and nonword reading. Further, the DeeDee task accounted for independent variance in these measures from a sub-lexical phonological task (rhyme awareness). This suggests that children with dyslexia have phonological impairments at both the sub-lexical and prosodic levels, and that both levels of phonology matter for their progress in learning to read and to spell.

Nevertheless, the DeeDee task is an indirect measure of sensitivity to syllable stress, as participants have to derive an abstract representation of the stress patterning of a particular utterance and match this to a DeeDee sequence. Participants do not have to perceive the stress patterns in the utterance directly. Accordingly, Leong, Hämäläinen, Soltész, and Goswami (2011) designed a direct syllable stress perception task based on 4-syllable words that had either first syllable primary stress (2000 rhythmic stress pattern) or second syllable primary stress (0200 rhythmic stress pattern). Participants were required to make a same-different judgement about pairs of words that either shared a rhythmic stress pattern (e.g., both 2000) or did not (e.g., 0200 versus 2000). Adults with dyslexia showed significantly lower sensitivity to syllable stress (d' measure) than adults without a reading impairment in this task, even when the task comprised the same word repeated twice (e.g., ''DIFF*iculty*–*di*FFI*culty*'' [different trial]). Given that comparison of the same item repeated twice does not require access to the stored rhythmic stress pattern in the mental lexicon, and that participants were highly compensated dyslexics attending university, Leong et al.'s study suggests an acoustic difficulty with stress perception in developmental dyslexia. Individual differences in stress sensitivity among the adult participants were indeed uniquely related to individual differences in auditory sensitivity to amplitude envelope rise time.

This raises interesting questions concerning the nature of the developmental trajectory. Theoretically, Leong et al. (2011) assumed that the auditory processing difficulties for rise time identified in these well-compensated dyslexic adults had been present throughout development, and had affected the perception of syllable stress. However, studies of auditory processing and syllable stress perception in infancy and childhood are required to test this theoretical assumption. Studies with infants using EEG measures show that sensitivity to the rhythmic stress templates that predominate in the native language is present and measurable at 4 months of age (e.g., Weber, Hahne, Friedrich, & Friederici, 2004). The rhythm of stress placement aids infants with segmentation of the speech stream (e.g., Echols, 1996), presumably in turn supporting the acquisition of lexical stress, so that lexical stress placement is learned as part of the phonological representation of a particular word (e.g., Curtin, 2010; Klein, 1984). Clearly, for the adult participants tested by Leong et al. (2011), both the 2000 and 0200 rhythmic stress patterns should have been highly familiar, and indeed performance did not differ for the two types of rhythmic stress pattern. The case for children is unknown. Although English is a free-stressed language, in which prominence may occur on different syllables and may also fall at different positions when the same syllable occurs in different words (as in ''orNATE'' for the isolated word versus ''ORnate BALcony'' for continuous speech), for 4-syllable words the most frequent rhythmic stress pattern is primary stress on the second syllable (0200). In Leong et al.'s (2011) analysis of over 2500 4-syllable words drawn from the CELEX database, 44% of words (like *maternity* and *ridiculous)* conformed to this 0200 rhythmic stress pattern. The remainder of 4-syllable words largely received primary stress on the first syllable (designated 2000, 24%), as in *difficulty* and *military*, or on the third syllable (28%), as in *comprehensive* and *interaction*. The latter also had secondary stress on the first syllable (1020 rhythmic stress pattern), hence were not included in Leong et al.'s experiments.

During language development, therefore, English-speaking children may acquire robust 0200 rhythmic stress patterns before robust 2000 rhythmic stress patterns, as the 0200 patterns are both more frequent during passive language exposure and are also likely to be more frequent in the child's oral vocabulary. On average 44% of the 4-syllable words that children are exposed to passively and that they add to their lexicons should conform to the 0200 template. In contrast, 2000 rhythmic stress patterns will be encountered less frequently by the child (on average, 24% of the time) and will also be added to the lexicon less frequently. By hypothesis, dyslexic children with impaired auditory rise time perception will develop poorer rhythmic stress patterns (or may require more learning time to acquire adequate rhythmic stress patterns, as they have pre-existing acoustic difficulties). If children with dyslexia have auditory difficulties, then they may even perform more poorly in stress perception tasks than *younger* children matched for reading level. Their rhythmic stress patterns may be neither age-appropriate nor reading level-appropriate.

The reading level match design has been important in helping to identify causal factors in reading research (Bryant & Goswami, 1986). The assumption underlying the reading-level match design is that if children with dyslexia perform more poorly than reading-level matched children who are 2 or 3 years younger than they are and who have a lower mental age, this may indicate a causal deficit (see also Goswami, 2003; a training study is then required to establish causality). Indeed, early studies of dyslexia demonstrated poorer performance in sub-lexical phonological tasks in comparison to reading level controls (e.g., Bradley & Bryant, 1978; rhyme awareness task). These studies led educators to accept that developmental dyslexia involved a ''core phonological deficit'', consequently children with dyslexia who have a statement of special educational needs may now receive intensive phonological remediation (at least, in the United Kingdom). This in turn can improve dyslexic performance in phonological tasks, so that group differences using a reading-level match design are no longer found. Nevertheless, this phonological remediation currently does not involve prosodic phonology, hence a reading-level match design may be sensitive to prosodic impairment. Further, in a recent study of musical beat perception, we found that children with dyslexia were significantly poorer than younger reading-level matched controls for both musical rhythm perception and amplitude rise time discrimination (Goswami, Huss, Mead, Fosker, & Verney, 2012).

Of course, learning to read may in itself help children with auditory impairments to specify prosodic phonology. Stress is not marked in the English orthography, in contrast to orthographies like Greek, nevertheless there are some implicit orthographic cues to syllable stress in English such as consonant doubling (e.g. *discuss* versus *discus*, see Kelly, Morris, & Verrekia, 1998). Sensitivity to such implicit cues in English-speaking children and the degree of reading experience required to benefit from them has not yet been studied. If reading experience helps children with auditory impairments to specify prosody, then children with developmental dyslexia should perform at a similar level to reading-level matched control children in stress perception tasks simply because they are matched for real word reading ability. On the other hand, the hypothetical support for prosodic awareness provided by learning to read may require some years of reading experience to affect the mental lexicon. Hence a group difference between children with dyslexia and reading-level matched controls may be measurable only early in development. This is why longitudinal developmental studies are so important. Note that learning to read *does* seem to help children with dyslexia to specify sub-lexical phonology, as the orthography helps to specify the *exact* sounds in different words, particularly in languages with transparent spelling systems, and this was revealed by longitudinal work (see Wimmer, 1993; Ziegler & Goswami, 2005). For example, a sub-lexical phonological deficit in dyslexia in German-speaking children is only measurable right at the beginning of learning to read (unless response time rather than accuracy is the dependent measure). Therefore, if stress perception is aided by implicit orthographic learning, then children with dyslexia may perform as well as younger reading-level matched children in stress perception tasks after some years of reading experience.

In the longitudinal study reported here, we gathered data relevant to these developmental questions. We administered two different stress perception tasks to children with and without dyslexia, the DeeDee task used by Goswami et al. (2010) and the 4-syllable word stress perception task used by Leong et al. (2011). The DeeDee measure selected was the "Films" task, in which synthesised Dee tokens were combined into strong–weak patterns, making syllable stress the key acoustic cue to successful performance. Measures of basic auditory processing, sub-lexical phonological awareness and reading were also administered, as well as a measure of phonological short-term memory. This experimental design enabled us to compare the development of sub-lexical (rhyme and phoneme awareness) and prosodic (syllable stress) aspects of phonology in our child participants. In line with our rise time theory (Goswami, 2011; Goswami & Leong, in press), we expected that basic auditory processing would show significant relations with phonological processing, at both the prosodic and sub-lexical levels. We also expected that prosodic awareness would be impaired in children with developmental dyslexia, and that prosodic sensitivity would show continuity at the level of individual differences between test points 1 and 2.

Experiment 1: reiterative speech

Method

Participants

One hundred and four children participated in this study. The children were all taking part in a longitudinal study of developmental dyslexia which is still ongoing (e.g., Goswami, Fosker, Huss, Mead, & Szűcs, 2011; Goswami, Wang, et al., 2011; the data reported here as Experiment 1 were collected in Year 2 of the ongoing study, in 2007). Children were recruited via learning support teachers, and only children who had no additional learning difficulties (e.g. dyspraxia, ADHD, autistic spectrum disorder, specific language impairment [SLI]), a nonverbal IQ above 85, and English as the first language spoken at home were included. The absence of additional learning difficulties was based on school reports, discussion with parents, and our own testing. All children 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, 1000, 2000, 4000, 8000 Hz), and all children were sensitive to sounds within the 20 dB HL range. The children included in this report are all the children out of the cohort initially tested who had data for the DeeDee task used in Experiment 1 ($N = 104$). During Year 2 of the study, a wide range of tasks were administered (some of which are reported here), and each child was seen for an average of 8 test sessions lasting half an hour each. There was no drop-out during the year; all children completed all sessions. Tasks were administered using one of two semi-randomised orders.

Forty-three of the children (27 male; mean age at first test point = 9 years 6 months) either had a statement of developmental dyslexia from their local education authority, or showed severe literacy and phonological deficits according to our own test battery. Children were assessed experimentally using the British Ability Scales (BASs) standardized tests of reading and spelling, and were included in the study if they scored at least 1 standard deviation below the test norm of 100 on at least one of the two reading measures used when the study began (BAS and TOWRE, the Test of Word Reading Efficiency). Thirty-six age-matched typically-developing control children were recruited, as well as 25 younger typically-developing children who were matched for reading level to the children with dyslexia. Participant details are shown in Table 1. As can be seen, by this point in the longitudinal study the age-matched controls differed in reading from the children with dyslexia by 27 standard points and 36 months (3 years). The reading-level matched controls differed from the children with dyslexia by 24 standard points in reading, but were equated for average reading age in months (91.2 versus 94.8 months).

Tasks

Standardised ability tests. All children had completed four subscales of the Wechsler Intelligence Scale for Children at the beginning of the study (*WISC*-III; (Wechsler, 1992): Block Design, Picture Arrangement, Similarities and Vocabulary (these four scales yield a short-form IQ). They also

Table 1
Participant characteristics by group for Experiment 1.

	Dyslexic $N = 43$	CA $N = 36$	RL $N = 25$	$F(2,101)$
Age in Months[a]	114.3 (12.9)	112.4 (12.3)	90.0 (6.3)	40.1***
Reading *BAS* SS[b]	83.3 (8.6)	110.7 (13.5)	107.1 (11.7)	67.9***
Reading age in months[c]	91.2 (14.5)	127.1 (26.5)	94.8 (11.2)	39.4***
Spelling *BAS* SS[b]	84.1 (9.7)	105.6 (11.4)	106.4 (10.3)	54.7***
WISC FSIQ	105.4 (14.4)	110.9 (12.7)	105.0 (10.8)	2.2
WISC Pic Arr	12.9 (4.3)	12.6 (3.9)	13.1 (4.2)	0.09

Note: Standard deviations in parentheses.
Note: CA, age-matched controls; RL, reading-level matched controls; DYS, dyslexics.
*** $p < .0001$.
[a] CA = DYS > RL.
[b] CA = RL > DYS.
[c] RL = DYS < CA.

completed the Picture Arrangement subscale (non-verbal) of the WISC at the current test point. Group performance for these assessments are shown in Table 1. Literacy skills were assessed at the current test point using the British Ability Scales Reading and Spelling subtests (Elliott, Smith, & McCulloch, 1996), also shown in Table 1. The children with dyslexia had significant deficits in both single word reading and spelling.

Phonological measures. An experimental rhyme oddity task and an experimental measure of phonological short-term memory based on single words were administered. The tasks used digitized speech created from a native female speaker of standard Southern British English. In the rhyme oddity task, the children listened to sets of three words and had to select the nonrhyme (e.g., gap, nap, Jack). Trials were presented in 3 fixed random orders. The task comprised 20 trials. Performance (% correct) by group is shown in Table 2. Scores out of 20 were used in the analyses. In the phonological short-term memory task, the children listened to sets of monosyllabic words without any shared phonemes (e.g., *jet*, *gang*, *rod*, *chip*) and were asked to repeat them back in an identical order. There were 18 trials each comprising 4 items. Responses were registered by digital voice recorder and scored in terms of the number of items recalled correctly. Performance (% correct) is shown in Table 2. Number of items recalled correctly were used in the analyses. In each case, practice trials were given before the phonological task.

Prosodic sensitivity (DeeDee) task. The DeeDee task was based on one of the experimental tasks used by Goswami et al. (2010, 'Films' task), in which names familiar from children's films and books were presented using the reiterated syllable "dee". Four synthesized Dee tokens (stressed [DEE] and unstressed [dee] in initial versus final position) were created that incorporated no cues to phrasal-level constituents. These were then combined into the appropriate sequence for each film or book title used. For example, if the target was "Harry Potter", the child heard "DEE dee DEE dee". Accuracy thus depended on matching syllable stress to the child's stored rhythmic stress pattern for this target (which should be SWSW). During a pretest, childrens' familiarity with the target stimuli was first ascertained. The children looked at a booklet of pictures that represented the different films and books being used with the experimenter, and named those that they knew. Median knowledge of the titles was 84%. Children were told the names of pictures they did not recognise. The experimental DeeDee task comprising 20 trials was then delivered by computer, with the child listening through headphones in a two alternative forced choice paradigm. The child saw the picture representing the target phrase (e.g., a picture of Harry Potter), and then pressed a button to listen to two DeeDee phrases. One matched the target picture, and the child's task was to choose the DeeDee sequence that they thought matched the picture. Further details are provided in Goswami et al. (2010). Performance in the experimental task was scored as total number correct. The Guttman split-half coefficient for this version of the DeeDee task was 0.52.

Auditory processing. Psychoacoustic tasks assessing auditory thresholds for sound rise time, frequency, duration and intensity in AXB or 2IFC formats were used to assess basic sensory processing (developed by MH). 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 & Sachs, 1975), and all testing laptops and headphones were calibrated. The tasks used a cartoon "Dinosaur" threshold estimation interface originally created by Dorothy Bishop (Oxford University), in which cartoon dinosaurs make different sounds. A novel adaptive staircase procedure (Levitt, 1971) using a combined 2-down 1-up and 3-down 1-up procedure was used with a test run terminating after eight response reversals or the maximum possible 40 trials. In a 2-down 1-up procedure, the stimulus value decreases by 2 steps after a successful response and increases by 1 step after an unsuccessful response; in a 3-down 1-up procedure, the stimulus value decreases by 3 steps after a successful response and

Table 2
Mean performance by group in Experiment 1: DeeDee task, phonological and auditory processing (standard deviations in parentheses).

	Dyslexic $N = 43$	*CA* $N = 36$	*RL* $N = 25$	$F(2,101)$
DeeDee number correct out of 20[a]	9.9 (1.9)	12.7 (2.6)	11.5 (2.3)	14.9*** [b]
Oddity rhyme% correct [c]	58 (16)	74 (17)	61 (16)	10.2***
PSTM% correct [c]	81 (4)	89 (8)	78 (12)	10.6***
1 Rise[c]	15.06 (9.8)	7.69 (3.8)	13.98 (7.8)	9.8*** [B]
2 Rise[c]	24.15 (9.9)	16.89 (9.0)	26.25 (8.5)	8.7***
Rise intensity rove[c]	24.79 (10.0)	17.72 (11.0)	25.78 (9.3)	6.2**
Duration[c]	23.0 (8.1)	17.7 (8.2)	22.0 (9.8)	3.9*
Frequency[c]	24.4 (11.5)	15.1 (11.4)	25.8 (9.6)	9.3***
Intensity	6.8 (2.9)	6.7 (3.3)	7.3 (3.6)	0.2

Note: CA, age-matched controls; RL, reading-level matched controls; DYS, dyslexic; PSTM, phonological short-term memory.
[a] *DYS* < worse than *CA* and *RL*.
[b] The Welch statistic is shown for the DeeDee and 1 Rise comparisons. Standard deviations in parentheses.
[c] *DYS* worse than *CA*.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

increases by 1 step after an unsuccessful response. The threshold was calculated using the measures from the last four reversals. This indicated the smallest difference between stimuli at which the participant could still discriminate with a 79.4% accuracy rate. The children were assessed individually in a quiet room within their school or at home. In the cartoon dinosaur tasks, the children were instructed to focus on a stimulus contrast (e.g. stimulus duration) by using verbal descriptions and five practice trials. Both verbal responses and pointing to a pictured dinosaur were accepted as responses, the experimenter entered the child's response and trials were not repeated. As sensitivity to amplitude envelope structure is a focus of our work, three measures of rise time sensitivity were included. These were a '1 Rise' task, a '2 Rise' task, and a 1 Rise task with intensity roving (Rise Rove). Each task was given twice, in order to increase threshold reliability (see Boets et al., 2011). Measures of sensitivity to simple duration, frequency and intensity were also given. Prior to data analysis, for each measure, the data were explored by group using box plots as well as measures of kurtosis and skew, to check that assumptions of normality were met. Any data points lying farther than 3 interquartile ranges from the nearer edge of the box were removed, resulting in 2 control (age-matched) scores being removed for the 1 Rise measure and 1 control (age-matched) and 1 dyslexic score being removed for the simple intensity measure.[1]

- *1 Rise task*. Three 800 ms tones were presented with 500 ms ISI. The second tone was always a standard tone, with a 15 ms linear rise time envelope, 735 ms steady state, and a 50 ms linear fall time (AXB paradigm). Either the first or third tone was identical to this standard, whereas the third or first tone varied the linear rise time envelope along a continuum, with the longest rise time being 300 ms. The child had to select the sound that was different. A schematic depiction of the stimuli is provided as Fig. 1.
- *2 Rise task*. This task used a long stimulus with amplitude modulations within it. Forty stimuli of 3573 ms (2.5 cycles) in duration were created using a sinusoidal carrier at 500 Hz amplitude modulated at the rate of 0.7 Hz (depth of 50 percent). A square wave was the basis of the underlying envelope modulation. Given the long stimuli, presentation format was 2IFC. Rise time was varied from 15 ms to 300 ms with a fixed linear fall time of 350 ms. The longest rise time was the standard. The child was asked to choose the sound with the sharper beat. This was the sound with the shorter rise time. A schematic depiction of the stimuli is provided as Fig. 1.

Rise Rove Task. This was identical to the 1 Rise task (AXB delivery), except that the intensity of the sounds varied randomly between 65 and 75 dB, so that intensity was not a complementary cue to rise time.

Duration task. A continuum of 40 stimuli was created using pure tones. Presentation format was AXB. The duration of the standard tone, presented second, was 400 ms. The first or third tone could be identical to this standard, and either the third or first tone was longer than the standard, ranging up to 600 ms. Each tone was presented at 500 Hz with a 50 ms rise and fall. Children chose the cartoon sheep which made the longest sound.

Frequency task. A continuum of 40 stimuli was created using pure tones, each with a duration of 200 ms. Presentation format was AXB. The frequency of the standard tone, presented second, was 500 Hz. The first or third tone could be identical to this standard, and either the third or first tone was higher in frequency than the standard, ranging up to 512 Hz. Children were asked to choose the cartoon elephant that made the highest sound.

Intensity task. A continuum of 40 stimuli was created using pure tones. Presentation format was 2IFC. The standard was a pure tone with a frequency of 500 Hz and a duration of 200 ms. Intensity of the variable tone ranged from 55 to 75 dB SPL. Each tone was presented with a 50 ms rise and fall. Children chose the cartoon mouse which made the quieter sound.

Results

Means and standard deviations by group are shown in Table 2. As predicted, the children with dyslexia showed impairments in detecting syllable stress. Indeed, the data suggest that the children with developmental dyslexia found the DeeDee task more difficult than *both* age-matched controls and younger reading-level matched controls. Group performance was investigated using a one-way ANOVA by Group, using the number of correct responses as the dependent variable. The main effect of Group was significant, $F(2,104) = 14.85$, $p < .001$, $\eta^2 = .227$. The Levene statistic showed that the homogeneity of variance assumption was violated, hence the Welch statistic was used. The main effect of Group was still significant, $F(2,56.6) = 14.9$, $p < .001$. Post-hoc comparison of group means using Games-Howell post hoc tests showed that the children with dyslexia performed at a significantly poorer level than *both* control groups (DYS < age-matched controls, $p < .001$; DYS < reading-level matched controls, $p = .018$), who did not differ. Hence at this relatively young age (9 years), children with dyslexia were poorer at matching a DeeDee sequence to a rhythmic stress pattern than younger children (reading-level matched controls, 7-year-olds). One-sample *t*-tests revealed that the children with dyslexia, but not the reading-level matched nor age-matched control children, were performing at chance level in the DeeDee task (dyslexics: $t = 0.32$, ns; reading-level matched controls $t = 3.2$, $p < .01$; age-matched controls

[1] There were also some missing data points due to illness or other absence: 1 missing age-matched control score for 1 Rise, 5 missing scores for 2 Rise (1 reading-level control, 2 dyslexics, 2 age-matched controls), 1 missing score for Rise Rove (age-matched child), 3 missing scores for duration (1 dyslexic, 2 age-matched controls), 2 missing scores for frequency (2 dyslexics) and 5 missing scores for intensity (2 reading-level controls, 2 dyslexics, 1 age-matched control). In addition, the distribution for frequency tended towards bimodality. Therefore, frequency was recoded as a dichotomous variable, using thresholds either less than or greater than 1.18 semitones as the cut-off (as in Goswami, Wang, et al., 2011).

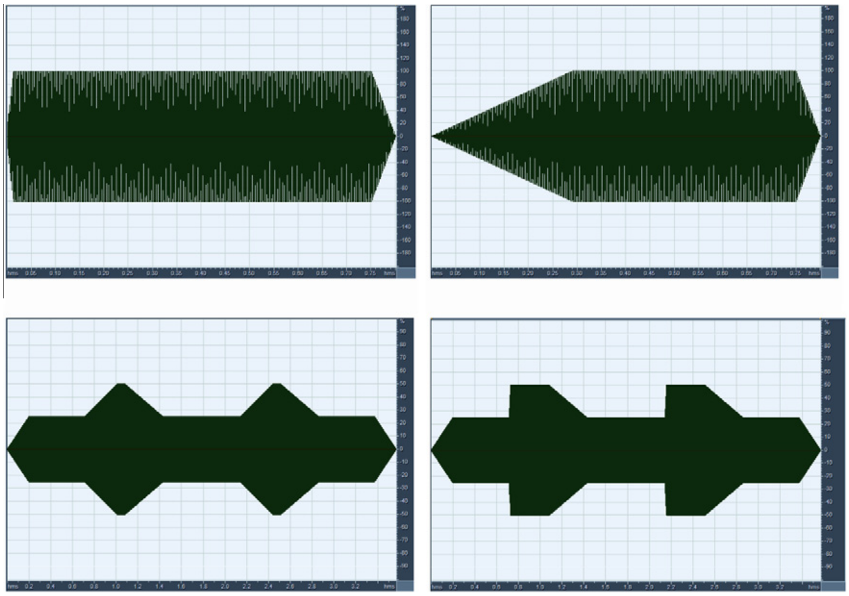

Fig. 1. Schematic depictions of the end points for the 1 Rise (upper panel) and 2 Rise (lower panel) stimuli. Amplitude is plotted on the *y* axis and time is plotted on the *x* axis.

$t = 6.2$, $p < .001$). Nevertheless, our impressions during testing were that the children with dyslexia were trying hard in the task, remaining motivated, and asking questions like "Can I do this by counting syllables?". Further, some of the children with dyslexia also received the Barkley scale for attention difficulties ($N = 22$, inattention scale; Barkley, 1998). There was no relation between inattention scores and performance in the DeeDee task ($r = -0.06$). Our impression was that the children with dyslexia found it very difficult to accurately hear the rhythmic patterns.

In contrast to the DeeDee task, for the other phonological processing measures the children with dyslexia had equivalent phonological processing skills to the younger reading-level matched controls (see Table 2; rhyme oddity, phonological short-term memory). The data therefore suggest that the core phonological "deficit" in dyslexia is particularly marked for prosodic sensitivity in comparison to word-level and sub-lexical phonology, at least at the age of 9 years. With respect to our first research question, therefore, sensitivity to syllable stress appears to be more impaired in our dyslexic sample in comparison to younger reading-level matched controls than sub-lexical phonological sensitivity (rhyme awareness).

Group data for the auditory processing tasks is also shown in Table 2[2]. The table shows that significant group effects were found for all the rise time measures, and for sensitivity to simple frequency and duration (but not to simple intensity). Post-hoc inspection of group differences showed that the children with dyslexia were performing at a similar level to the younger reading-level matched group for the rise time, frequency and duration measures, but showed significantly higher (=worse) thresholds in comparison to the age-matched controls. Nevertheless, auditory processing was continuously distributed in the sample[3]. Our second research question was whether auditory processing of rise time would show a particular connection with prosodic awareness in children. In order to explore whether individual differences in auditory sensory processing were related to individual differences in prosodic processing, 3-step fixed order multiple regression equations were computed ($N = 104$ children) taking the number of DeeDee trials answered correctly as the dependent variable. Each equation entered age at step 1 and IQ at the current test point at step 2, to account for age and IQ differences between children, and then entered an auditory processing measure at step 3. As preliminary regression analyses showed that the 3 measures of rise time were all significant predictors of prosodic awareness, and as Cronbach's Alpha for the 3 measures was 0.73, a global measure of sensitivity to amplitude rise time (Global Rise) was created for use in these analyses. Each threshold was converted to a Z score, and these *Z* scores were combined into the Global Rise measure. The results of the resulting 3-step regression analyses are shown in the top half of Table 3. As can be seen in the Table, all of the auditory measures were significant concurrent predictors of individual differences in the DeeDee task, including the intensity measure, which had not shown group differences (see Table 2). The largest absolute amount of unique variance was accounted for by the Global Rise measure (15%). At this developmental time point, therefore, all the auditory parameters assessed were concurrent predictors

[2] Homogeneity of variance assumptions were met for all tasks except the 1 Rise task, for which the Welch *F* statistic was used with Games-Howell post hoc tests.

[3] At time 1 (reading age 7 years), 51% of the dyslexics scored above (worse than) the 5th percentile of control (age-matched) performance for the global rise measure, 26% for the duration measure, 62% for the frequency measure, and 10% for the intensity measure.

Table 3
Stepwise regressions showing the unique variance in the DeeDee task versus rhyme awareness accounted for by the different auditory processing measures and concurrent phonological abilities (standardized Beta and R^2change).

Step	DeeDee		Rhyme oddity	
	Beta	R^2change	Beta	R^2change
1. Age	−.040	.002	.246	.061*
2. *WISC* IQ	.124	.015	.135	.018
3. Global Rise	−.426	.152***	−.468	.183***
3. Duration	−.300	.089**	−.377	.141***
3. Intensity	−.208	.043*	−.124	.015
3. Frequency	−.294	.085**	−.315	.098**
3. PA[a]	.404	.150***	.378	.141***
4. Global rise after PA	−.296	.059*	−.362	.093**
4. Duration after PA	.174	.025	.290	.076**
4. Frequency after PA	−.186	.031	−.224	.045*
4. PA[a] after global rise	.278	.057*	.247	.051*

[a] PA, Rhyme oddity when DeeDee is the DV, and DeeDee when rhyme oddity is the DV.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

of sensitivity to syllable stress. Finally, a 3-step fixed order multiple regression was run for the DeeDee task entering rhyme oddity performance at Step 3 as a predictor. As can be seen in Table 3, sub-lexical phonological sensitivity was also a significant predictor of prosodic sensitivity, accounting for 15% of unique variance.

In order to also assess the role of auditory sensory processing in sub-lexical phonological development, parallel sets of equations were computed using the number of trials answered correctly in the rhyme oddity task as the dependent variable. These analyses are also shown in Table 3. Inspection of the table shows that the same auditory measures were significant predictors of sub-lexical phonological awareness, except for intensity. In terms of the absolute amount of variance accounted for, sensitivity to rise time again accounted for the most unique variance (18%). Therefore, individual differences in children's sensitivity to sound rise time, duration and frequency were significant concurrent predictors of phonological sensitivity at *both* the prosodic (DeeDee task) and sub-lexical (rhyme oddity task) levels. We next explored whether auditory sensitivity would be a significant concurrent predictor of phonological sensitivity after controlling for concurrent phonological abilities. Six 4-step fixed order multiple regression equations were computed, three using DeeDee performance as the dependent variable and three using rhyme oddity as the dependent variable. Each equation entered age at step 1 and IQ at step 2, a phonological measure at step 3 (rhyme oddity or DeeDee respectively, depending on the DV), and then the threshold for either Global Rise, duration or frequency at step 4. In addition, a pair of analogous 4-step fixed entry multiple regression equations were run in which auditory processing (Global Rise) was entered at step 3, and phonological awareness at step 4.

As shown in Table 3, auditory processing of rise time remained a significant predictor of prosodic sensitivity when entered after sub-lexical phonological awareness in these rigorous equations, whereas auditory processing of frequency and duration did not. Similarly, sub-lexical phonological awareness remained a significant predictor of prosodic sensitivity after auditory processing was controlled at step 3. For rhyme oddity, all of the auditory measures were independent predictors of individual differences when entered after prosodic awareness, and prosodic awareness remained a significant predictor when entered after auditory processing (Global Rise). Therefore, in concurrent analyses, individual differences in auditory sensitivity to rise time accounted for individual differences in *both* prosodic and sub-lexical phonological awareness even *after* phonological sensitivity was controlled, and vice versa. In order to explore whether auditory processing of rise time would be a significant *longitudinal* predictor of prosodic phonological sensitivity, longitudinal relations were assessed in Experiment 2.

Discussion

In the current study, we were able to compare both prosodic and sub-lexical (rhyme) phonological sensitivity in children with developmental dyslexia aged 9 years, and to explore possible relations with individual differences in basic auditory processing of nonspeech sounds. Regarding prosodic versus sub-lexical phonological sensitivity, the data suggested that the prosodic impairments in dyslexia were even more marked than the impairments with sub-lexical phonology. While the children with dyslexia were as successful at making sub-lexical phonological judgements (rhyme judgements) as the younger reading-level matched children aged on average 7 years (58% and 61% correct respectively), for prosodic judgements this was not the case. The children with dyslexia made significantly fewer (50%) correct judgments about syllable stress than the reading-level matched children (58%), performing at chance level. Indeed, the younger reading-level matched control children were as successful at making accurate DeeDee judgements as the age-matched controls (64% correct). The children with dyslexia were trying hard in the DeeDee task, and in other work we have found that the DeeDee task is useful for training children with dyslexia to hear syllable stress and speech rhythm (Bhide, Power, & Goswami, in press; Thomson, Leong, & Goswami, 2012). Given that the younger reading-level matched children were cognitively less mature than the children with dyslexia, it seems to be the perception of syllable stress *per se* that is the source of dyslexic difficulties and not the cognitive load imposed by the task. The data suggest that insensitivity to prosodic structure may be a causal factor in developmental dyslexia in English.

One developmental source of the insensitivity to prosodic structure found in children with dyslexia may be sensory difficulties in basic auditory processing. Although the strongest test of this developmental hypothesis would be a longitudinal study conducted with infants at risk for dyslexia, such as that reported by Smith et al. (2008), even the relatively old dyslexic children studied here showed auditory processing deficits. When relations between basic auditory sensory processing and the development of prosodic phonology were explored in our sample, individual differences in sensitivity to sound rise time, duration and frequency were *all* related to individual differences in prosodic awareness. Global sensitivity to rise time predicted 15% of unique variance in prosodic sensitivity when entered after age and NVIQ, consistent with Greenberg's theory about the role of rise time in syllable prominence (Greenberg, 2006). Frequency and duration discrimination also accounted for significant amounts of unique variance in the prosodic measure (9% in each case). Further, the auditory processing of rise time retained significant predictive power for prosodic awareness even after age, non-verbal IQ and phonological processing (sub-lexical rhyme awareness) were controlled in the statistical analyses. Basic auditory processing of frequency and duration no longer predicted unique variance in the prosodic task after controlling for phonological sensitivity in these analyses. In turn, phonological sensitivity (rhyme awareness) remained a significant predictor of prosodic awareness after rise time processing was controlled. The equations suggest that auditory sensitivity to rise time and sub-lexical phonological awareness make independent contributions to children's sensitivity to syllable stress.

Regarding the other auditory variables studied, the importance of frequency discrimination for stress judgements revealed by the 3-step multiple regression analyses is consistent with classical theories of stress perception (e.g., Fry, 1955), which accorded fundamental frequency a key role. In classical theories, duration and intensity (amplitude) were thought to play secondary roles in stress perception. However, more recent investigations with adults using natural speech have shown that amplitude and duration cues play a stronger role in prosodic prominence than fundamental frequency (Choi, Hasegawa-Johnson, & Cole, 2005; Greenberg, 1999; Kochanski, Grabe, Coleman, & Rosner, 2005). In the more stringent 4-step regression analyses conducted here, in which phonological abilities were controlled before exploring the predictive power of basic auditory processing, only the rise time measure continued to explain significant unique variance in stress perception. This suggests that sensitivity to changes in amplitude rise time is the auditory factor most intimately connected to the perceptual experience of syllable stress (see Goswami & Leong, in press, for a theoretical explanation based on amplitude modulation phase hierarchies). However, the longitudinal auditory predictors of development in prosodic sensitivity could differ from the concurrent predictors.

Individual differences in basic auditory processing were also significant predictors of sub-lexical phonological awareness (rhyme oddity task). Global sensitivity to rise time predicted 18% of unique variance in rhyme awareness when entered after age and NVIQ, while sensitivity to sound duration predicted 14% of unique variance and sensitivity to sound frequency predicted 10% of unique variance. Further, all three auditory processing measures retained significant predictive power for rhyme awareness even after age, non-verbal IQ and phonological processing (prosodic awareness) were controlled in more stringent statistical analyses. Therefore, even for the relatively old children studied here, individual differences in basic auditory processing were unique concurrent predictors of performance in classic sublexical phonological awareness tasks. This suggests that early in the developmental trajectory, at least up to a reading level of around 7 years, basic auditory processing is an important determinant of individual differences in both prosodic and sub-lexical phonological awareness. Further, and in line with the proposed importance of sensitivity to amplitude modulation for phonological development (Goswami & Leong, in press), sensitivity to rise time was the only auditory measure to retain significant predictive strength for *both* prosodic and sub-lexical phonology.

Considering the specific relations found between the prosodic DeeDee measure and auditory processing in the current study, while rise time was also a significant concurrent predictor of individual differences in the DeeDee task in an earlier study of older children with dyslexia (12-year-olds; Goswami et al., 2010), the findings for frequency discrimination in the current study are different from the earlier DeeDee study. In that study, the strongest unique concurrent auditory predictor of individual differences in the DeeDee Films task was intensity discrimination, and frequency discrimination was not a significant predictor. In the current dataset, intensity discrimination is again a significant predictor of DeeDee performance, and so is frequency discrimination. It should be noted that both the intensity and frequency discrimination measures used by Goswami et al. (2010) were ABABA measures (e.g., loud–soft–loud–soft–loud; high–low–high–low–high). Therefore, children had to perceive *fluctuations* in intensity or frequency rather than a simple difference in intensity or frequency (as here). Further, the dyslexic children studied by Goswami et al. (2010) were 3 years older than those studied here. It is therefore possible that the strongest auditory correlates of stress perception vary with age. Nevertheless, the current data and the data reported by Goswami et al. (2010) for older dyslexic children are consistent regarding the roles of sensitivity to rise time and simple intensity for stress perception as measured by the DeeDee task. Given that rise time sensitivity but not frequency discrimination was a significant concurrent predictor of syllable stress perception in the dyslexic *adults* studied by Leong et al. (2011), longitudinal data may help to determine whether the auditory correlates of the perception of syllable stress change as children get older.

Experiment 2: syllable stress perception

Many of the children in Experiment 1 continued to participate in the ongoing longitudinal study of auditory processing in developmental dyslexia reported here, and so we were able to administer the direct measure of the perception of syllable stress devised by Leong et al. (2011) 4 years after the DeeDee measure. This enabled us to gain information about developmental trajectories. Given the severity of the stress perception deficit found in the children with dyslexia in Experiment 1, it was expected that judgements about syllable stress would still be impaired in the dyslexic children. As Leong et al. (2011) found that adults with dyslexia were impaired in both versions of the task (2000 rhythmic stress patterns, and 0200 rhythmic stress patterns), we expected that stress perception would be impaired with both types of item. Of interest was whether, as they got older, the children with dyslexia would improve in making stress judgements relative to the younger reading-level matched controls, for example because orthographic knowledge acquired through reading would support the specification of syllable stress (orthographic cues such as consonant doubling help to specify stress, e.g., *discus* versus *discuss*, Kelly et al., 1998). Also of interest was whether the longitudinal predictors of individual differences in prosodic sensitivity would be earlier auditory processing abilities, earlier metalinguistic abilities, or a combination of both factors.

Method

Participants

At the second test point reported in this paper, we were able to retest 64 of the original cohort of 104 children. We report data from 20 children with dyslexia, 28 age-matched controls, and 21 reading-level matched controls. Of the reading-level matched controls, 16 children were from the longitudinal study and 5 additional (new) participants were recruited for the current study, making 69 participants in total (see Table 4).

Tasks

Standardised measures. Reading was re-assessed at Time 2 using the British Ability Scales (BAS) test of single word reading (Elliott et al., 1996). One subtest of the Wechsler Intelligence Scale for Children (WISC-III, Picture Arrangement) had been given in the year prior to the current study and comprised the measure of general cognitive ability. Participant details are given in Table 4.

Table 4
Participant characteristics by group for Experiment 2.

	Dyslexic N = 20	CA N = 28	RL N = 21	$F(2,66)$
Age in months[a]	164.6	158.6	131.1	39.2***
	(13.7)	(15.4)	(8.5)	
Reading *BAS* SS[b]	82.4	109.6	101.9	22.4***
	(16.1)	(13.9)	(11.8)	
Reading age in months[c]	130.3	173.6	129.4	29.1***
	(29.0)	(22.5)	(18.0)	
WISC Pic Arr	14.9	14.6	13.4	0.7
	(3.6)	(3.4)	(5.0)	
Phoneme deletion % correct[d]	58.8	83.0	71.5	11.2***
	(19)	(17)	(17)	
PSTM[c]	42.5	56.2	42.6	7.1**
	(5)	(15)	(11)	
DeeDee performance, Experiment 1[e]	10.3	12.9	11.4	
	(2.3)	(2.4)	(2.0)	

Note: CA, age-matched controls; RL, reading-level matched controls, PSTM, phonological short-term memory.
[a] CA = DYS > RL.
[b] CA = RL > DYS.
[c] RL = DYS < CA.
[d] DYS < RL < CA.
[e] performance computed for 20 Dyslexics, 28 CA controls and 16 RL controls.
** $p < .01$.
*** $p < .001$.

Experimental phonological measures. A phoneme deletion task and an experimental measure of phonological short-term memory were administered. Phoneme deletion was substituted for rhyme oddity because it was thought that some of the older children might now be at ceiling with rhyme oddity. The tasks again used digitized speech created from a native female speaker of standard Southern British English. In the phoneme deletion task, the children listened to nonword stimuli and were asked to delete a target sound, e.g. "Please say 'starp' without the 'p'". The sounds to be deleted were either initial, medial or final phonemes, and in each case the deletion resulted in a real word. This was an adaptation by NM of a real word task originally devised by McDougall, Hulme, Ellis, and Monk (1994) and adapted by Pasquini, Corriveau, and Goswami (2007) for adults with dyslexia. The task comprised 20 trials. Performance (% correct) by group is shown in Table 4. In the phonological short-term memory task children were asked to recall sets of 4 monosyllabic nonwords, e.g. "sool, juff, teed, goak" in the correct order. There were 20 trials in total. Performance was scored in terms of the number of items recalled correctly (total = 80). Performance (% correct) by group is shown in Table 4.

Syllable stress perception task. This comprised one of the stress perception tasks originally devised for adults with dyslexia by Leong et al. (2011; the task that was easier for adults was selected). Participants listened to a 4-syllable word pronounced twice, and made a same-different judgement about stress. For example, for the word pair *DIfficulty* (SWWW)–*diFFIculty* (WSWW), a "different" judgement was required. The task was based on 10 4-syllable words with rhythmic stress templates that had first syllable stress (2000, such as *caterpillar* and *difficulty*) and 10 4-syllable words with lexical templates that had second syllable stress (0200, such as *maternity* and *ridiculous*). The words were selected on the basis of syllable structure (no consonant clusters in the first two syllables), spoken and written frequency and overall familiarity, and did not have alternative pronunciations. The two sets of lexical templates (2000, 0200) were matched as closely as possible for spoken and written frequencies. All items were produced naturally by a native female speaker of British English and recorded for computerised presentation using Audacity and Praat software. Two spoken tokens were recorded for each word. In one token, the speaker emphasised only the first syllable of the word (producing a SWWW stress pattern). In the other token, the speaker emphasised only the second syllable of the word (producing a WSWW stress pattern). Word pairs were then created for each trial by combining the two spoken tokens in all 4 possible ways, resulting in 80 trials overall. Further details of the task including the acoustic parameters of the stimuli are available in Leong et al. (2011).

Results

Participant data by group is shown in Table 4. Analyses confirmed that the dyslexic children who were retained were still matched for age and IQ with the retained age-matched controls, and for reading with the reading-level matched controls (using one-way ANOVAs, see Table 4). The performance of the retained children in the DeeDee task used in Experiment 1 is also provided for comparative purposes, and shows that the performance of the retained groups is almost identical to that of the 104 children tested earlier. Four years later all participants were very accurate in the direct stress perception task, performing at group levels above 90% correct. Therefore d' and criterion (c) values were calculated as a measure of sensitivity whilst controlling for bias. A Pearson's time-lagged correlation confirmed that the average d' score was significantly related to performance in the DeeDee task 4 years earlier, $r(63) = 0.33$, $p = .008$. Mean performance by group for making judgements about shared syllable stress for each stress location (2000, 0200) is shown in Table 5. The data suggest that now that they are older, the children with developmental dyslexia (average d' 3.76) are as good at making syllable stress judgements as the younger reading level matched controls (average d' 3.82). However, they are less sensitive to stress than the age-matched controls (average d' 4.20). There was no apparent difference between groups in bias toward giving a 'same' response (c values were similar between groups). A pair of repeated measures 3×2 ANOVAs were run to explore potential differences in sensitivity and bias, with Group as the between-subjects factor and stress location (2000, 0200) as the within-subjects factor, taking either d' or c as the dependent variable. The ANOVA for d' showed a significant main effect of Group, $F(2,66) = 3.6$, $p = .034$, $\eta\rho^2 = .641$, but no significant main effect of stress location, $F(1,66) = 0.23$, $p = .637$. However, there was a significant interaction between stress location and group, $F(2,66) = 3.3$, $p = .045$, $\eta\rho^2 = .601$. The ANOVA for c showed no significant effects.

To explore the source of the significant 2-way interaction for the d' measure, separate one-way ANOVAs by Group were run for each stress location. The ANOVA for second syllable stress (0200) was the only analysis to show a significant main effect of Group, $F(2,69) = 4.6$, $p < .05$, $\eta\rho^2 = .123$. The Levene statistic showed that the homogeneity of variance assumption was violated for second syllable stress (0200) stimuli, hence the Welch statistic was used, $F(2,35.7) = 5.4$, $p = .009$. Post-hoc inspection of group means (Games Howell statistic) showed that the dyslexics were significantly less sensitive to second syllable stress than the age-matched controls, $p = .037$, performing at a similar level to the reading-level matched controls. Hence for items which should have had well-established rhythmic stress patterns in the mental lexicon (4-syllable words with second syllable stress, which is the most frequent 4-syllable stress pattern in spoken English), the children with dyslexia did not show age-appropriate sensitivity to stress. This suggests that the stress perception difficulty in dyslexia is integrally related to the developing phonological representation, rather than being purely an acoustically-driven on-line difficulty.

Table 5
Mean performance by group in the stress perception task, Experiment 2 (d' and c scores).

	Dyslexic $N = 20$	*CA* $N = 28$	*RL* $N = 21$
First syllable stress d' (2000)	3.74 (0.12)	4.06 (0.10)	3.89 (0.12)
First syllable stress c (2000)	0.13 (0.25)	0.07 (0.21)	0.12 (0.26)
Second syllable stress d' (0200)	3.79 (0.14)	4.23 (0.12)	3.75 (0.14)
Second syllable stress c (0200)	0.11 (0.22)	0.09 (0.17)	0.10 (0.26)

Note: CA, age-matched controls; RL, reading-level matched controls.

Inspection of Table 4 also reveals that the children with dyslexia were now significantly worse than the younger reading-level matched control children in the sub-lexical phonology task. While they performed at a similar level to the reading-level matched controls in the phonological short-term memory task, they were significantly poorer than younger children in the phoneme deletion task (59% correct versus 72% correct for reading-level matched controls). Of particular theoretical interest in this study was whether individual differences in phonological processing between children would depend developmentally on earlier differences in metalinguistic skills or on earlier individual differences in acoustic sensitivity (or on a combination of both sensory and metaphonological ability). In order to explore whether individual differences in auditory sensory processing and metalinguistic skills present 4 years previously were related to individual differences in sensitivity to 0200 syllable stress, fixed order multiple regression equations were computed using only those children for whom longitudinal data were available ($N = 64$). In order to identify the unique longitudinal predictors of sensitivity to syllable stress, the multiple regression equations controlled for prosodic sensitivity at Time 1 (the DeeDee measure). Each equation had four steps: age was entered at step 1 and IQ at step 2, then the DeeDee measure from Experiment 1 was entered at Step 3 as the autoregressor, and then an auditory processing measure from Time 1 was entered at step 4. The results are shown in Table 6. If individual differences in basic auditory processing continue to affect the developmental trajectory for prosodic awareness, then the auditory measures should explain significant unique variance even after controlling for earlier metalinguistic abilities.

Inspection of Table 6 (first two columns) shows that all the measures of auditory sensitivity taken 4 years previously except for simple intensity were significant unique longitudinal predictors of sensitivity to syllable stress, even after earlier prosodic awareness was controlled. While the DeeDee task contributed significant unique variance to later syllable stress perception when entered at Step 3 as the autoregressor, the absolute amount of variance accounted for was only 6%. Much larger amounts of unique variance were accounted for by the auditory variables entered at Step 4, (earlier rise time sensitivity 14%, earlier duration sensitivity, 21%, and earlier sensitivity to frequency, 16%). Hence individual differences in basic auditory processing skills continued to exert an effect on phonological development 4 years later. Parallel equations were computed predicting individual differences in sublexical phonology (phoneme deletion), using rhyme oddity 4 years earlier as the autoregressor at Step 3. The results of these analyses are shown in columns 3 and 4 of Table 6. As can be seen from the table, the rise time measure (6%), the

Table 6
Stepwise regressions showing the unique variance in prosodic sensitivity (stress perception task, 0200 d'), phoneme deletion and reading (standard score) contributed by prosodic sensitivity (DeeDee task), basic auditory processing and rhyme awareness measured 4 years earlier (standardized Beta and R^2change).

Step	Syllable stress		Phoneme deletion		Reading SS	
	Beta	R^2change	Beta	R^2change	Beta	R^2change
1. Age	.121	.015	−.068	.005	−.289	.084*
2. *WISC* IQ	.353	.124**	.104	.011	.158	.025
3. PA [a]	.247	.060*	.484	.204***	.363	.129**
4. Global Rise	−.454	.144**	−.309	.062*	−.287	.058*
4. Duration	−.481	.206***	−.292	.069*	−.375	.125**
4. Frequency	−.414	.155**	.312	.085*	−.316	.090**
4. Intensity	−.093	.008	.075	.005	−.047	.002
4. PA [b]	.324	.077*	−.299	.008	.512	.192***
5. Global Rise	−.386	.092**	−.299	.055*	−.126	.010
5. Duration	−.431	.149***	−.284	.065*	−.253	.051*
5. Frequency	−.366	.114**	−.305	.079*	−.220	.041*

[a] PA at Step 3 refers to the DeeDee measure when syllable stress and reading are the DVs, and to rhyme oddity when Phoneme Deletion is the DV.
[b] PA at Step 4 refers to rhyme oddity when syllable stress and reading are the DVs, and to DeeDee when phoneme deletion is the DV.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

duration measure (7%) and the frequency measure (9%) all accounted for unique variance in phoneme deletion 4 years later, even after sub-lexical phonological awareness (rhyme oddity) was controlled as the autoregressor. In contrast to prosodic sensitivity, the auditory processing measures accounted for smaller absolute amounts of unique variance than the metaphonological measure.

The 4-step regressions suggest that *both* earlier metaphonological awareness and earlier auditory sensitivity contribute to the development of phonological processing in children. However, an even stronger test of the role of auditory skills would require *both* earlier sub-lexical and earlier prosodic awareness to be controlled prior to measuring this longitudinal relationship. The relevant 5-step multiple regression analyses are also shown in Table 6. In these equations, both rhyme oddity performance and DeeDee performance at time 1 were controlled before examining the longitudinal relationship between basic auditory processing of rise time, duration and frequency at time 1 to awareness of syllable stress and phoneme deletion measured 4 years later. Inspection of the table shows that all 3 auditory measures continued to contribute significant unique variance to both phonological measures even after these very strict controls. Therefore, individual differences in basic auditory processing make an important developmental contribution to phonological development at both the prosodic and sub-lexical levels. However, prosodic awareness (the DeeDee measure) did not contribute significant unique variance to children's later phoneme deletion skills after sub-lexical phonological awareness (rhyme oddity) was controlled.

Finally, there are no prior longitudinal studies involving children with dyslexia that predict reading development on the basis of earlier prosodic sensitivity. Therefore, parallel sets of both 4-step and 5-step multiple regression equations were computed with reading standard score at Time 2 as the dependent variable. These are also shown in Table 6. The 5-step equations showed that *both* earlier prosodic sensitivity (at step 3, 13% of unique variance) and earlier sub-lexical phonology (at step 4, 19% of unique variance) made independent contributions to reading development. Hence together these different measures of phonological sensitivity accounted for a third of the variance in reading development in this study. After controlling for both phonological measures in the 5-step regression equations, auditory sensitivity to *both* duration and frequency continued to contribute significant unique variance to reading (duration, 5%, frequency, 4%). Rise time sensitivity did not contribute significant unique variance when entered at step 5, suggesting that individual differences in rise time sensitivity were wholly accounted for by individual differences in the combination of prosodic and sub-lexical phonological skills. It is notable that although the reading measure was of children's single word decoding skills, and syllable stress is not marked in the English orthography, individual differences in sensitivity to syllable stress measured 4 years previously predicted significant unique variance in reading development.

Discussion

The direct stress perception task used in Experiment 2 provided evidence that the children with developmental dyslexia still had impairments in perceiving syllable stress despite four additional years of language development and reading instruction, but only in comparison to age-matched children (the age-matched control group). Now aged 13 years, the children with dyslexia were performing at the same level as the reading-level matched controls, now aged 11 years, in terms of their sensitivity (d') to the stress patterns of words with 0200 rhythmic stress patterns. For English 4-syllable words, the 0200 rhythmic stress pattern is the most frequent in the language, characterising almost half (44%) of the 4-syllable words in the CELEX database. For the less frequent 2000 rhythmic stress pattern, the 13-year-old children with dyslexia showed reduced sensitivity compared to age-matched controls (3.74 versus 4.06), but the difference was not statistically significant. As the adult dyslexics tested by Leong et al. (2011) showed impaired sensitivity to *both* types of 4-syllable rhythmic stress pattern (0200, 2000) compared to age-matched controls, this may imply that with further development, the dyslexics tested here would also show significantly poorer sensitivity for words with 2000 rhythmic stress patterns. For example, it is possible that by adulthood, *orthographic* experience has helped to specify rhythmic stress patterns in the mental lexicon. Orthographic experience will have been greater for the control adults tested by Leong et al. (2011) than for the dyslexic adults (as dyslexics tend to read less). Hence reduced orthographic learning may also explain the poorer sensitivity shown by dyslexic adults to words with 2000 rhythmic stress patterns in Leong et al.'s (2011) study. Further research is required to disentangle these possibilities.

The longitudinal multiple regression analyses conducted for Experiment 2 demonstrated that earlier developmental levels of *both* auditory sensitivity and metalinguistic sensitivity shaped the developmental trajectory for stress sensitivity. Consistent with our hypothesis about the importance of rise time perception for prosodic awareness, rise time sensitivity accounted for significant unique variance (9%) in stress sensitivity when both earlier prosodic sensitivity (DeeDee performance) and earlier sub-lexical phonological sensitivity (rhyme awareness) were controlled in 5-step multiple regression equations (in addition to age and non-verbal IQ). This is consistent with Greenberg's view that rise time is relevant for perceiving syllable prominence (Greenberg, 1999, 2006). Of the classical auditory measures related to syllable stress (frequency, duration and intensity), only earlier sensitivity to sound duration (15% of unique variance) and sound frequency (11% of unique variance) exerted significant developmental effects on later stress sensitivity. Sensitivity to overall sound intensity did not account for unique longitudinal variance. All three of the significant auditory predictors (rise time, duration and frequency) accounted for more unique longitudinal variance in stress sensitivity than earlier prosodic sensitivity (6% of unique variance) and earlier rhyme awareness (8% of unique variance). This suggests that individual differences in basic auditory processing exert particularly strong effects on prosodic awareness in children's phonological development. Further, the relatively small amount of absolute variance accounted for in the longitudinal stress sensitivity analyses by the DeeDee measure (6%) suggests that the two measures of syllable stress used here (DeeDee and direct stress perception) might measure different aspects of the awareness of syllable stress. One possibility is simply that the longitudinal relationship between the two stress sensitivity measures was attenuated because the DeeDee task had relatively low internal reliability (0.52). However, given that rhyme oddity also explained a relatively small amount of variance in later stress sensitivity when entered at Step 4 (8%) in comparison to the auditory measures (14%+), it may be that direct stress sensitivity is governed more closely by acoustic abilities, at least in English.

Indeed, the same three auditory measures also exerted longitudinal effects on individual differences in sublexical phonology in the 4-step multiple regression equations after controlling for age, NVIQ and earlier rhyme awareness (rise time, 6% of unique variance; frequency, 9% of unique variance; duration, 7% of unique variance). For sub-lexical phonological processing, however, earlier sub-lexical phonological awareness exerted a larger effect than basic auditory processing (rhyme awareness, 20% of unique longitudinal variance). All of the auditory predictors of phoneme deletion remained significant in the more stringent 5-step equations which also controlled for earlier prosodic awareness. Overall, therefore, the regressions showed that the same auditory measures predicted phonological development longitudinally at both the prosodic and sub-lexical levels. This indicates that auditory processing differences make an important contribution to the developmental trajectory for phonological awareness in children, although a training study is required to establish causality (see Thomson et al., 2012). When single word reading ability rather than phonological processing was the dependent variable in these longitudinal regressions, however, then both phonological measures accounted for more unique variance than the auditory measures. Together, the rhyme oddity and DeeDee tasks accounted for about a third of later variance in reading development. This finding is consistent with a developmental model in which early auditory abilities support the development of phonological processing abilities, which in turn support the development of reading.

General discussion

In two studies, children with developmental dyslexia showed impaired performance in stress perception tasks compared to children who did not have a reading difficulty. Earlier in development, when aged on average 9 years, the children with developmental dyslexia showed significantly poorer stress perception compared to *both* age-matched controls and younger reading-level matched children as measured by the DeeDee task. Four years later, at the age of 13 years, the children with dyslexia showed poorer stress perception as measured by the direct stress perception task in comparison to age-matched controls only. These longitudinal data show that prosodic awareness does develop in children with dyslexia, but does not develop age-appropriately. The change in relative sensitivity with age is unlikely to be a task-specific effect, as the 12-year-old dyslexic children studied by Goswami et al. (2010) were equivalent in the DeeDee task to younger reading-level matched controls (10-year-olds), yet significantly worse than age-matched controls (like the 13-year-old dyslexics tested here in the direct stress perception task). On the other hand, whereas the children with dyslexia tested here showed equivalent performance to the younger reading-level matched children in a sub-lexical phonology task when aged 9 years (rhyme oddity task), they were significantly poorer in a sub-lexical phonology task (phoneme deletion) compared to the reading-level matched controls 4 years later. Thus the apparent severity of the phonological deficit varies with different tasks at different ages.

The auditory measures taken in the current study were (apart from simple intensity) robust longitudinal predictors of sensitivity to both syllable stress and sub-lexical phonology, even when earlier metaphonological skills were controlled statistically. Basic auditory processing may thus play a stronger role in children's phonological development than has sometimes been thought to be the case. In the concurrent analyses, there was evidence to support the view that auditory processing of rise time played a special developmental role in sensitivity to syllable stress (see Table 3), however this was not the case in the longitudinal analyses, where rise time, duration and frequency all accounted for significant unique variance in stress sensitivity (see Table 6). Although not measured directly in the current study, it is possible that orthographic and morphological learning also contributed to the development of sensitivity to syllable stress in this cohort of children. Once children begin to read, they also learn spelling and morphological information that provides implicit cues to syllable stress placement (e.g., Arcuili, Monaghan, & Seva, 2010; Clin, Wade-Woolley, & Heggie, 2009). Consequently, both morphological awareness and stress sensitivity play a role in further reading development (e.g., Holliman, Wood, & Sheehy, 2008; Jarmulowicz, Hay, Taran, & Ethington, 2008). Importantly, these roles may vary with orthography. Some orthographies mark stress directly (e.g., Spanish, Greek), but (to our knowledge) stress processing by adults with dyslexia has yet to be examined in these orthographies. Other orthographies (like French) do not mark stress, but also make less use of stress in spoken language. In French, adults without dyslexia can show "stress deafness" in tasks using nonword stimuli (e.g., Dupoux, Pallier, Sebastian, & Mehler, 1997). Nevertheless, adults with dyslexia in the French language show significant deficits in stress perception with these nonword stimuli (Soroli, Szenkovits, & Ramus, 2010).

Finally, the current study provided unique *longitudinal* information regarding the associations between auditory processing, prosodic sensitivity, sub-lexical phonological awareness and literacy acquisition. A priori, it was expected that *both* auditory processing and metalinguistic skills should contribute to the development of prosodic awareness, and that *both* prosodic awareness and sub-lexical phonological awareness should contribute to the development of reading. The data were supportive of both of these theoretical assumptions. The data reported here suggest a developmental trajectory in which basic auditory processing skills are important for the early development of phonological skills, which in turn are important for the development of reading skills. In the current study, multiple regression equations exploring whether phonological sensitivity and auditory processing made independent or overlapping contributions to the further development of stress sensitivity and phoneme deletion showed that auditory processing made an independent contribution even *after* controlling for metalinguistic skills, and accounted for more unique variance than metalinguistic skills. Hence individual differences in auditory processing and phonological sensitivity both influenced the further development of prosodic awareness. Both auditory processing and phonological processing also contributed independent variance in the equations predicting reading development, but here metalinguistic skills accounted for the most unique variance. In conclusion, the longitudinal study reported here suggests that impaired auditory sensitivity to amplitude rise time, sound duration and frequency are all associated with the development of phonological awareness in children, at both prosodic and sub-lexical levels, and that the relationship between basic auditory processing and phonological development continues into the later school years. The data presented here thus support an intimate developmental relationship between auditory processing, phonological processing (both prosodic and sub-lexical) and the acquisition of literacy. Nevertheless, a study that begins in infancy is required in order to explore these proposed developmental trajectories in greater depth. Such a study could help to ascertain whether an auditory processing deficit completely mediates the relationships documented here between prosodic and sub-lexical phonological processing and reading development, or whether there are two independent deficits in dyslexia, an auditory deficit and a phonological deficit.

Acknowledgments

We would like to thank the head teachers, teachers, children and parents of the schools who participated in this study. This research was supported by funding from the Medical Research Council (MRC), Grants G0400574 and G0902375, awarded to Usha Goswami. Requests for reprints should be addressed to Usha Goswami, Centre for Neuroscience in Education, Downing Street, Cambridge CB2 3EB, UK.

References

Arcuili, J., Monaghan, P., & Seva, N. (2010). Learning to assign lexical stress during reading aloud: Corpus, behavioural and computational investigations. *Journal of Memory and Language, 63*, 180–196.

Barkley, R. A. (1998). *Attention-deficit hyperactivity disorder: A handbook for diagnosis and treatment* (2nd ed.). New York: Guildford Press.

Bhide, A., Power, A. J., & Goswami, U. (in press). A rhythmic musical intervention for poor readers: A comparison of efficacy with a letter-based intervention. *Mind, Brain & Education*.

Boets, B., Ghesquière, P., van Wieringen, A., & Wouters, J. (2007). Speech perception in preschoolers at family risk for dyslexia: Relations with low-level auditory processing and phonological ability. *Brain and Language, 101*, 19–30.

Boets, B., Vandermosten, M., Poelmans, H., Luts, H., Wouters, J., & Ghesquière, P. (2011). Preschool impairments in auditory processing and speech perception uniquely predict future readings problems. *Research in Developmental Disabilities, 32*, 560–570.

Bradley, L., & Bryant, P. E. (1978). Difficulties in auditory organisation as a possible cause of reading backwardness. *Nature, 271*, 746–747.

Bradley, L., & Bryant, P. E. (1983). Categorising sounds and learning to read – A causal connection. *Nature, 301*, 419–421.

Bryant, P. E., & Goswami, U. (1986). The strengths and weaknesses of the reading level design. *Psychological Bulletin, 100*, 101–103.

Burkhard, M. D., & Sachs, R. M. (1975). Anthropometric manikin for acoustic research. *Journal of the Acoustical Society of America, 58*(1), 214–222.

Choi, J.-Y., Hasegawa-Johnson, M., & Cole, J. (2005). Finding intonational boundaries using acoustic cues related to the voice source. *Journal of the Acoustical Society of America, 118*, 2579–2587.

Clin, E., Wade-Woolley, L., & Heggie, L. (2009). Prosodic sensitivity and morphological awareness in children's reading. *Journal of Experimental Child Psychology, 104*, 197–213.

Corriveau, K., Pasquini, E., & Goswami, U. (2007). Basic auditory processing skills and specific language impairment: A new look at an old hypothesis. *Journal of Speech, Language, and Hearing Research, 50*, 647–666.

Curtin, S. (2010). Young infants encode lexical stress in newly encountered words. *Journal of Experimental Child Psychology, 105*, 376–385.

Dupoux, E., Pallier, C., Sebastian, N., & Mehler, J. (1997). A distressing "deafness" in French? *Journal of Memory and Language, 36*, 406–421.

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.

Elliott, C. D., Smith, P., & McCulloch, K. (1996). *British ability scales II*. Windsor, UK: NFER-Nelson.

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.

Fry, D. B. (1955). Duration and intensity as physical correlates of linguistic stress. *Journal of the Acoustical Society of America, 27*, 765–768.

Giraud, A.-L., & Poeppel, D. (2012). Speech perception from a neurophysiological perspective. In D. Poeppel, T. Overath, A. N. Popper, & R. R. Fay (Eds.), *Human auditory cortex*. New York, NY: Springer.

Goswami, U. (2003). Why theories about developmental dyslexia require developmental designs. *Trends in Cognitive Sciences, 7*, 534–540.

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

Goswami, U., and Leong, V. (in press). Speech rhythm and temporal structure: Converging perspectives? *Laboratory Phonology.*

Goswami, U., Fosker, T., Huss, M., Mead, N., & Szűcs, D. (2011). 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, 23*, 995–1019.

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

Goswami, U., Huss, M., Mead, N., Fosker, T., & Verney, J. (2012). Perception of Patterns of Musical Beat Distribution in Phonological Developmental Dyslexia: Significant Longitudinal Relations with Word Reading and Reading Comprehension. *Cortex*. http://dx.doi.org/10.1016/j.cortex.2012.05.005.

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

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

Greenberg, S., Carvey, H., Hitchcock, L., & Chang, S. (2003). Temporal properties of spontaneous speech-a syllable-centric perspective. *Journal of Phonetics, 31*, 465–485.

Guttorm, T. K., Leppänen, P. H., Poikkeus, A. M., Eklund, K. M., Lyytinen, P., & Lyytinen, H. (2005). Brain event-related potentials (ERPs) measured at birth predict later language development in children with and without familial risk for dyslexia. *Cortex, 41*, 291–303.

Hämäläinen, J. A., Salminen, H. K., & Leppänen, P. H. T. (2012). Basic auditory processing deficits in dyslexia: Systematic review of the behavioural and event-related potential/field evidence. *Journal of Learning Disabilities*. http://dx.doi.org/10.1177/0022219411436213.

Hämäläinen, J. A., Leppänen, P. H. T., Eklund, K., Thomson, J., Richardson, U., Guttorm, T. K., 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.

Hämäläinen, J. A., Leppänen, P. H. T., Guttorm, T. K., & Lyytinen, H. (2008). Event-related potentials to pitch and rise time change in children with reading disabilities and typically reading children. *Clinical Neurophysiology, 119*, 100–115.

Holliman, A. J., Wood, C., & Sheehy, K. (2008). Sensitivity to speech rhythm explains individual differences in reading ability independently of phonological awareness. *British Journal of Developmental Psychology, 26*, 357–367.

Holliman, A. J., Wood, C., & Sheehy, K. (2012). A cross-sectional study of prosodic sensitivity and reading difficulties. *Journal of Research in Reading, 35*(1), 32–48.

Jarmulowicz, L., Hay, S. E., Taran, V. L., & Ethington, C. A. (2008). Fitting derivational morphophonology into a developmental model of reading. *Reading & Writing, 21*, 275–297.

Kelly, M. H., Morris, J., & Verrekia, L. (1998). Orthographic cues to lexical stress: Effects on naming and lexical decision. *Memory & Cognition, 26*, 822–832.

Kitzen, K. R. (2001). Prosodic sensitivity, morphological ability, and reading ability in young adults with and without childhood histories of reading difficulty. *Dissertation Abstracts International, 62*(02), 0460A.

Klein, H. B. (1984). Learning to stress: A case study. *Journal of Child Language, 11*, 375–390.

Kochanski, G., Grabe, E., Coleman, J., & Rosner, B. (2005). Loudness predicts prominence: Fundamental frequency lends little. *Journal of the Acoustical Society of America, 118*, 1038–1054.

Kuhl, P. K. (2004). Early language acquisition: Cracking the speech code. *Nature Reviews Neuroscience, 5*, 831–843.

Leong, V., Hämäläinen, J., Soltész, F., & Goswami, U. (2011). Rise time perception and detection of syllable stress in adults with developmental dyslexia. *Journal of Memory and Language, 64*, 59–73.

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

Lyytinen, H., Aro, Mm., Eklund, K., Erskine, J., Guttorm, T., et al. (2004). The development of children at familial risk for dyslexia: Birth to early school age. *Annals of Dyslexia, 54*(2), 184–220.

Marshall, C. R., & van der Lely, H. K. J. (2009). Effects of word position and stress on onset cluster production. *Language, 85*(1), 39–57.

McArthur, G. M., & Bishop, D. V. M. (2001). Auditory perceptual processing in people with reading and oral language impairments: Current issues and recommendations. *Dyslexia, 7*, 150–170.

McDougall, S., Hulme, C., Ellis, A., & Monk, A. (1994). Learning to read: The role of short-term memory and phonological skills. *Journal of Experimental Child Psychology, 58*, 112–133.

Nakatani, L. H., & Schaffer, J. A. (1978). Hearing "words" without words: Prosodic cues for word perception. *Journal of the Acoustical Society of America, 63*, 234–245.

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.

Power, A. J., Mead, N., Barnes, L., & Goswami, U. (2012). Neural entrainment to rhythmically-presented auditory, visual and audio-visual speech in children. *Frontiers in Psychology, 3*, 216. http://dx.doi.org/10.3389/fpsyg.2012.00216.

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

Rubin, D. C. (1995). *Memory in oral traditions: The cognitive psychology of epic, ballads, and counting-out rhymes*. Oxford, UK: Oxford University Press.

Schulte-Körne, G., & Bruder, J. (2010). Clinical neurophysiology of visual and auditory processing in dyslexia: A review. *Clinical Neurophysiology, 121*, 1794–1809.

Smith, A. B., Lambrecht Smith, S., Locke, J. L., & Bennett, J. (2008). A longitudinal study of speech timing in young children later found to have reading disability. *Journal of Speech, Language, and Hearing Research, 51*, 1300–1314.

Snowling, M. J. (2000). *Dyslexia* (2nd ed.). Oxford, UK: Blackwell.

Soroli, E., Szenkovits, G., & Ramus, F. (2010). Exploring dyslexics' phonological deficit III: Foreign speech perception and production. *Dyslexia, 16*, 318–340.

Studdert-Kennedy, M., & Mody, M. (1995). Auditory temporal perception deficits in the reading-impaired: A critical review of the evidence. *Psychonomic Bulletin and Review, 2*, 508–514.

Thomson, J., Leong, V., & Goswami, U. (2012). Auditory processing interventions and developmental dyslexia: A comparison of phonemic and rhythmic approaches. *Reading and Writing*. http://dx.doi.org/10.1007/s11145-012-9359-6.

Weber, C., Hahne, A., Friedrich, M., & Friederici, A. D. (2004). Discrimination of word stress in early infant perception: Electrophysiological evidence. *Cognitive Brain Research, 18*(2), 149–161.

Wechsler, D. (1992). *Wechsler intelligence scale for children (WISC-III)* (3rd ed.). 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.

White, S., Milne, E., Rosen, S., Hansen, P., Swettenham, J., Frith, U., et al. (2006). The role of sensorimotor impairments in dyslexia: A multiple case study of dyslexic children. *Developmental Science, 9*, 237–255.

Wimmer, H. (1993). Characteristics of developmental dyslexia in a regular writing system. *Applied Psycholinguistics, 14*, 1–33.

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

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

Zion-Golumbic, E. M., Poeppel, D., & Schroeder, C. E. (2012). Temporal context in speech processing and attentional stream selection: A behavioural and neural perspective. *Brain and Language*. http://dx.doi.org/10.1016/j.bandl.2011.12.010.