Reduced sensitivity to slow-rate dynamic auditory information in children with dyslexia¹

Hanne Poelmans^{a,b}, Heleen Luts^{a,b}, Maaïke Vandermosten^{a,b}, Bart Boets^{a,b}, Pol Ghesquière^b
and Jan Wouters^a

^a*ExpORL, Department of Neurosciences, Katholieke Universiteit Leuven, Herestraat 49 PO Box 721, 3000 Leuven, Belgium*

^b*Parenting and Special Education Research Group, Katholieke Universiteit Leuven, A. Vesaliusstraat 2 PO Box 3765, 3000 Leuven, Belgium*

Corresponding author: Hanne Poelmans, O&N2, Herestraat 49 PO Box 721, 3000 Leuven, Belgium. Tel.: +32 16 33 04 95, Fax: +32 16 33 04 86, Hanne.Poelmans@med.kuleuven.be

¹ This article has been published as: Poelmans, H., Luts, H., Vandermosten, M., Boets, B., Ghesquière, P., Wouters, J. (2011). Reduced sensitivity to slow-rate dynamic auditory information in children with dyslexia. *Research in Developmental Disabilities*, 32 (6), 2810-2819.

Abstract

The aetiology of developmental dyslexia remains widely debated. An appealing theory postulates that the reading and spelling problems in individuals with dyslexia originate from reduced sensitivity to slow-rate dynamic auditory cues. This low-level auditory deficit is thought to provoke a cascade of effects, including inaccurate speech perception and eventually unspecified phoneme representations. The present study investigated sensitivity to frequency modulation and amplitude rise time, speech-in-noise perception and phonological awareness in 11-year-old children with dyslexia and a matched normal-reading control children. Group comparisons demonstrated that children with dyslexia were less sensitive than normal-reading children to slow-rate dynamic auditory processing, speech-in-noise perception, phonological awareness and literacy abilities. Correlations were found between slow-rate dynamic auditory processing and phonological awareness, and speech-in-noise perception and reading. Yet, no significant correlation between slow-rate dynamic auditory processing and speech-in-noise perception was obtained. Together, these results indicate that children with dyslexia have difficulties with slow-rate dynamic auditory processing and speech-in-noise perception and that these problems persist until sixth grade.

Introduction

Developmental dyslexia is characterized by a specific disability in learning to read and write despite adequate intelligence, education and intense remedial effort (Vellutino et al., 2004). It is well established that the majority of individuals with dyslexia demonstrate difficulties in the use and representation of phonological information (Snowling, 2000). A crucial step in the development of phonological representations is the awareness that every speech sound corresponds to a written symbol. Consequently if individuals with dyslexia perceive speech differently than normal-reading individuals, mapping speech sounds onto their corresponding symbols will become more challenging.

The most commonly used measure to assess speech sound processing in individuals with dyslexia is categorical perception. Categorical perception tasks demonstrated that the phoneme categories of individuals with dyslexia are less defined compared to normal-reading individuals (e.g. Vandermosten et al., 2010; for a review, see Vandermosten et al., 2011). However, reported effects were often subtle in that a deficit was only found in a subset of participants with dyslexia (e.g. Adlard & Hazan, 1998; Manis et al., 1997) or group differences were restricted to a specific task (e.g. Maassen et al., 2001) or to specific speech conditions (e.g. Blomert & Mitterer, 2004; Cornelissen et al., 1996).

Yet, the finding of only a subtle categorical perception deficit in individuals with dyslexia may be attributed to the fact that categorical perception is typically evaluated in quiet listening conditions. Given that speech signals contain redundant auditory information, speech identification performance in quiet can be achieved based on several auditory cues. By presenting speech signals in adverse listening conditions, auditory information becomes less reliable, resulting in speech sound identification based on a reduced amount of auditory cues. It is therefore possible that speech perception in noise is a more sensitive condition to provoke a deficit in individuals with dyslexia. Speech-in-noise perception has previously been investigated in individuals with dyslexia, but results are rather diverse. A number of studies found impaired speech-in-noise perception abilities in individuals with dyslexia (e.g. Bradlow et al., 2003; Chandrasekaran et al., 2009; Wible et al., 2002; Ziegler et al., 2009), suggesting that a core deficit in dyslexia is the inability to extract crucial auditory information from a complex or noisy signal. However, not all studies were able to support this hypothesis (Hazan et al., 2009).

The question is now whether this speech perception deficit is specific to processing speech sounds or whether it stems from deviant perception of low-level auditory cues that constitute speech sounds. Originally, it was proposed that individuals with dyslexia have

difficulties processing brief and rapidly successive acoustic cues (Tallal, 1980). Though more recently, the importance of “dynamic” (i.e. “changing over time”) auditory information processing in relation to dyslexia has received more attention (for a review, see McArthur & Bishop, 2001). Dynamic auditory cues such as amplitude- (AM) and frequency modulations (FM) are extensively present in speech signals. In particular slowly-varying auditory cues, with modulations between 2 and 20 Hz, provide important information about phonemic and syllabic transitions, and contribute largely to speech intelligibility (Drullman et al., 1994; Shannon et al., 1995). Consequently, imprecise processing of these slow-rate modulations can negatively affect the perception of spoken language and can withhold the development of precise phonological representations (Nitttrouer, 2006).

Detection of slow-rate modulations was often found impaired in individuals with dyslexia (McAnally & Stein, 1997; Witton et al., 1998; Menell et al., 1999; e.g. Lorenzi et al., 2000; Rocheron et al., 2002; Witton et al., 2002; Stuart et al., 2006). Yet, not all studies were able to replicate these findings (Hill et al., 1999; e.g. Edwards et al., 2004). Nevertheless, a strong relation between slow-rate modulation detection performance and phonological abilities has been found in school-aged children (Witton et al., 1998; Witton et al., 2002; Stuart et al., 2006; Talcott et al., 1999) as well as in preschoolers (Boets et al., 2008; Boets et al., 2011). Another important slow-rate auditory cue for speech perception is sound rise time (i.e. the rate of change of the amplitude envelope at the onset of a syllable) (Goswami et al., 2002). In natural speech, sound rise times comprise a combination of dynamic cues, such as changes in intensity, duration, and fundamental frequency, which are important for analyzing prosodic patterns in speech (Goswami et al., 2010) but also for phoneme discrimination (Goswami et al., 2011b). Atypical processing of sound rise time results in the distorted perception of syllable boundaries. Given that infants process spoken language based on its syllable structure, an inability to extract syllable-level information from the speech signal would result in the deficient representation of onset-rime and phoneme information, which both are crucial for literacy acquisition (e.g. Goswami et al., 2002; Ziegler & Goswami, 2005; Pasquini et al., 2007). Studies investigating sound rise time perception found indeed significantly poorer performance of individuals with dyslexia compared to normal-reading individuals (children: Richardson et al., 2004; adults: Hämäläinen et al., 2005; Pasquini et al., 2007). Additionally, rise time detection tasks were found to relate to reading, spelling, and phonological awareness abilities.

In sum, studies investigating slow-rate dynamic processing and speech-in-noise perception in individuals with dyslexia favour a deficit in both domains. However, only an

isolated study assessed both kinds of signals in the same population. Boets et al. (2011) showed retrospectively that preschool children who later on develop dyslexia were already impaired in slow-rate FM sensitivity and speech perception. These kindergarten measures were related to each other and uniquely predicted later growth in reading. In line with this study, the present study explored slow-rate dynamic auditory processing and speech-in-noise perception abilities in a group of sixth grade children.

The aim of this study was twofold. First, we aimed to investigate the nature of the speech-in-noise perception deficit in children with dyslexia. By presenting sentences in stationary and in temporally fluctuating noise, we were able to explore the influence of the dynamic nature of masking noise on speech perception. If individuals with dyslexia are less sensitive to dynamic variations in auditory signals, reduced sentence intelligibility in the fluctuating noise can be expected. However, if inferior speech-in-noise perception in individuals with dyslexia is the result of an inability to extract relevant auditory information from noisy signals, reduced speech-in-noise perception is expected independent of which kind of noise is presented. Furthermore, as sentences-in-noise perception can be facilitated by top-down influences of semantic information, it can be assumed that a potential speech-in-noise perception deficit is more pronounced in a words-in-noise test. It can therefore be hypothesized that the reduction of possible top-down influences does not affect the presence (or absence) of a speech-in-noise perception deficit but may rather expose the magnitude of the deficit. Second, in order to investigate the presence of a slow-rate dynamic processing deficit in individuals with dyslexia, a 2 Hz FM-detection task and a rise time discrimination task were conducted. Both tasks tap aspects of slow-rate dynamic processing mechanisms and have repeatedly been proven to be among the most sensitive auditory tasks to identify dyslexia. However, thus far they have never been assessed in the same participants. If both tasks indeed measure the same process, we hypothesize deviant performance on both tasks in individuals with dyslexia.

Methods

Participants

Fifty-eight 11-year-old children, attending sixth grade of primary school, participated in the study. Children were selected from the sample of Boets et al. (2006) that was longitudinally followed-up. Children were originally divided based on their family risk for dyslexia (i.e. a high-risk group with at least one first degree relative with a formal diagnosis of dyslexia, and a low-risk group with no dyslexic relatives) (Boets et al., 2010).

Literacy achievement was assessed by a standardized word-reading (EMT: Brus & Voeten, 1973) and pseudoword-reading test (Klepel: Van den Bos et al., 1994), and a spelling test (Dudal, 1997), administered in first, third and sixth grade of primary school, resulting in nine literacy scores for each participant (3 literacy tests x 3 test moments). In line with current practice in Belgium and the Netherlands (Gersons-Wolfensberger & Ruijsenaars, 1997), the criterion to diagnose dyslexia took into account both the severity and the persistence of children's literacy problems. In sixth grade, thirteen of the children demonstrated severe literacy problems, defined as performance below the 10th percentile of the norm group on the same standardized literacy task on at least two consecutive test moments. Additionally, they performed below the 50th percentile on all literacy tasks at all test points. These children constitute the dyslexic group. The remaining 45 normal-reading children did not show any reading or spelling difficulties throughout primary school. Based on their family risk for dyslexia, these normal-reading children constitute two separate groups: a group of low-risk normal-reading children ($N=25$) and a group of high-risk normal-reading children ($N=20$).

All children were native Dutch speakers, without a history of brain damage, psychiatric symptoms or visual problems. Additionally, all participants had adequate nonverbal intelligence, defined by a standard score above 85 on Raven's progressive matrices (Raven et al., 1984) and adequate audiometric pure-tone hearing thresholds (i.e., 25 dB HL or less from 0.25 – 8.0 kHz) at the test ear.

Table 1 shows participant characteristics for the three groups in sixth grade. Groups did not differ in age, gender and nonverbal IQ (all $p > 0.224$). As defined, groups differed in sixth grade word-reading ($F(2, 55) = 22.60$; $p < 0.001$), pseudoword reading ($F(2, 55) = 27.23$; $p < 0.001$) and spelling abilities ($F(2, 55) = 29.66$; $p < 0.001$). Children with dyslexia performed significantly poorer than both normal-reading groups, who themselves did not differ from each other on any of the sixth grade literacy tasks.

Table 1 Sixth grade participant characteristics (M $\pm$ SD)

	Low-risk normal-reading (N = 25)	High-risk normal-reading (N = 20)	Dyslexic (N = 13)
Gender (f/m)	11/14	9/11	5/8
Age (years)	11.7 $\pm$ 0.3	11.6 $\pm$ 0.2	11.6 $\pm$ 0.3
Non-verbal IQ	111.9 $\pm$ 13.5	104.7 $\pm$ 16.6	108.1 $\pm$ 8.2
Word-reading ^a	99.2 $\pm$ 11.8	88.3 $\pm$ 17.0	67.3 $\pm$ 15.4
Pseudoword-reading ^a	108.0 $\pm$ 11.3	102.3 $\pm$ 10.9	79.2 $\pm$ 15.0
Spelling ^a	100.4 $\pm$ 10.9	93.8 $\pm$ 8.4	79.4 $\pm$ 9.0

^a Scores are standardized with population average (M = 100, SD = 15)

Experimental setup

All tasks were performed on a Dell Latitude E6500. The phonological awareness tasks were controlled by E-Prime (Schneider et al., 2002). The auditory and speech perception tasks were controlled by APEX software (Laneau et al., 2005; Francart et al., 2008). Stimuli were presented using an integrated audio PC-card and routed to an audiometer (Madsen OB622), in order to control the presentation level. The stimuli were presented monaurally to the right ear over calibrated TDH-39 headphones at 70 dB sound pressure level (SPL). All tests were administered individually in a quiet room in the children's school. The study was approved by the Committee of Medical Ethics of Clinical Research of KU Leuven. Parents of all children gave a written informed consent.

Tasks

Auditory processing tasks

Auditory processing was measured by tasks assessing FM-detection, rise time discrimination and intensity discrimination. Stimuli were generated in MATLAB R14 and saved as 16-bit wav-files (sample frequency 44100 Hz). Thresholds were estimated by means of a one-up, two-down adaptive staircase procedure, which targets the threshold corresponding to 70.7 % correct responses (Levitt, 1971). In all tasks, a threshold run was terminated after eight reversals and the threshold was calculated as the average of the last four reversals. Each participant completed three threshold runs for every experiment and the average of the best two runs was calculated for each task. Prior to data collection, participants were given a short period of practice, comprising supra-threshold trials, to familiarize them with the stimuli and the tasks.

FM-detection

Participants were required to detect a 2 Hz sinusoidal frequency modulation of a 1 kHz carrier tone with varying modulation depth in an adaptive three-alternative forced-choice “odd-one-out” paradigm. Participants were asked to determine which of the three stimuli sounded different from the other two. The detection threshold was defined as the minimum depth of frequency deviation (in Hz) required to detect the modulation. Modulation depth of the target stimulus decreased with a factor 1.2 from 100 Hz towards 11 Hz. From a frequency deviation of 11 Hz, a step size of 1 Hz was used. The reference stimulus was a pure tone of 1 kHz. The length of both the reference and the target stimulus was 1000 ms including 50 ms cosine-gated onset and offset. The inter-stimulus-interval (ISI) was 350 ms.

Sound rise time discrimination

Rise time sensitivity was measured by an adaptive two-alternative forced-choice AXB paradigm. In each trial three stimuli were presented. The middle stimulus was used as a fixed reference stimulus. Children were asked to identify the stimulus that differed from the reference stimulus. Stimuli consisted of speech-weighted noises with linear amplitude rise times. The stationary speech-weighted noise was identical to the stationary noise used in the speech-in-noise tests for sentences. Rise times varied logarithmically between 15 ms and 300 ms in 40 steps. The total duration of the stimuli was fixed to 800 ms, including a linear fall time of 75 ms. The stimulus with the shortest rise time (15 ms) was used as the reference stimulus in every trial. The ISI was 350 ms. Discrimination thresholds were defined as the minimal difference in rise time required to discriminate between the reference and the target stimulus.

Intensity discrimination

The intensity discrimination task was identical to the rise time discrimination task. A two-alternative forced-choice AXB paradigm was used to measure intensity discrimination thresholds. In each trial, the middle of three stimuli was used as a fixed reference stimulus. Children were asked to identify the stimulus that was different from the reference stimulus. Stimuli consisted of speech-weighted noise with a total duration of 800 ms, including a linear rise time and fall time of 75 ms each. The most silent stimulus (70 dB SPL) was used as the reference stimulus in every trial. Intensity varied linearly between 70 dB SPL and 80 dB SPL in 40 steps of 0.25 dB SPL each. The ISI was 350 ms. Discrimination thresholds were defined as the minimal intensity difference (in dB SPL) required to discriminate between the reference

and the target stimulus. The intensity discrimination task was designed as a control task for two reasons. First, this task controls for cognitive demands related to the experimental task procedure. Second, the intensity discrimination task controls for the possible influence of intensity discrimination ability on the performance of the rise time discrimination task.

Speech-in-noise perception

Speech-in-noise intelligibility was assessed for phonemes and sentences. In both tests, the level of the background noise was fixed at 70 dB SPL, whereas the speech level varied. Speech and noise were presented through Sennheiser HDA 200 headphones to the right ear.

Words-in-noise perception

This test assessed the perception of CVC words presented in noise. The CVC words were obtained from Flemish recordings of the NVA list, consisting of 15 sublists of 33 target phonemes spoken by a male speaker (Wouters et al., 1994). The stationary speech-weighted noise of the NVA was used as masking noise. Before administering the six experimental word lists, a practice list was conducted at 0 dB signal-to-noise ratio (SNR). Subsequently, 3 x 2 lists were presented at SNRs of -4 dB, -7 dB and -10 dB. Participants were instructed to repeat every perceived phoneme when the entire word was not perceived. The percentage of correctly perceived phonemes was then calculated for each list and averaged over the two lists presented at identical SNRs. For every participant, a logistic function relating the percentage correct responses to SNR level was fitted to the data and the Speech Reception Threshold (SRT, i.e. the signal-to-noise ratio at which 50% of phonemes is correctly perceived) was calculated.

Sentences-in-noise perception

Speech-in-noise intelligibility for sentences was assessed for a stationary speech-weighted noise and for a fluctuating ICRA noise (Dreschler et al., 2001). Speech material for both conditions consisted of Flemish sentences, available as the Leuven Intelligibility Sentence Test (LIST), spoken by a female speaker (van Wieringen & Wouters, 2008). In the stationary noise condition, sentences were presented in a stationary speech-weighted noise, derived from white noise that was spectrally weighted to the average spectrum of the spoken LIST-sentences. In the fluctuating noise condition, LIST-sentences were presented in a fluctuating ICRA5-250 noise. This noise was a modified version of the ICRA5 noise with a maximum pause length of 250 ms (Wagener et al., 2006). For both conditions, three lists of 10 sentences

were presented. SRTs were determined adaptively by means of a one-up, one-down paradigm with a step size of 2 dB. A response was considered correct if all the key words of the sentence were repeated correctly. After determining the level of the (imaginary) 11th item, the SRT was calculated on the basis of the last six levels (see van Wieringen & Wouters, 2008, for details). The two best SRTs out of the three lists of the same noise condition were averaged to compute a mean SRT for each noise condition.

Phonological Awareness

Phonological awareness (PA) was assessed by a phoneme deletion and a spoonerisms task.

Phoneme deletion

The phoneme deletion task consisted of three blocks of eight pseudowords. Every trial contained a spoken pseudoword followed by a single phoneme. Participants had to name the remaining pseudoword after omission of this target phoneme. Before every block, two practice items were present. The first block involved the deletion of the second phoneme of a one-syllable pseudoword with onset cluster. The second block required the deletion of the penultimate phoneme of a one-syllable pseudoword with offset cluster. In the last block, the middle phoneme of a two-syllable pseudoword had to be deleted. Performance on this task was assessed by the number of correct responses (max: 24).

Spoonerisms

The spoonerisms task also consisted of three blocks of eight (pseudo)word pairs. In every trial two (pseudo)words were presented. Participants were asked to exchange the initial letters of both (pseudo)words. Each block was preceded by two practice items. The first block involved two words with a single consonant onset. The second block comprised two words with a consonant cluster onset. In the last block, two pseudowords with a single consonant onset were presented. Performance was assessed by the number of correct responded (pseudo)words (max: 48).

Statistical analyses

Statistical analyses were performed with SPSS. Only on the words-in-noise test did one normal-reading child show outlying performance (> 3 SD of its group mean). Data from this participant were left out of the words-in-noise analyses. All statistical tests were two-tailed ($\alpha = 0.05$). Reported p-values were Bonferroni corrected when necessary.

Results

No differences between low-risk and high-risk normal-reading children

We first investigated the presence of any differences in performance between the normal-reading children at high versus low family risk. A univariate ANOVA showed that groups did not differ for phoneme deletion ($F(1, 43) = 0.06$; $p = 0.808$), spoonerisms ($F(1, 43) = 0.27$; $p = 0.607$), FM sensitivity ($F(1, 43) = 0.21$; $p = 0.646$), rise time discrimination ($F(1, 43) = 0.17$; $p = 0.680$) or intensity discrimination ($F(1, 43) = 0.05$; $p = 0.827$). A repeated measures ANOVA for speech-in-noise intelligibility, with stimulus type (sentences fluctuating versus sentences stationary versus words stationary) as within-subject factor and group (low-risk normal-reading versus high-risk normal-reading) as between-subject factor, revealed no main effect of group ($F(1, 42) = 1.24$; $p = 0.272$), nor a significant noise type $\times$ group interaction ($F(2, 84) = 0.07$; $p = 0.926$). Since the normal-reading children at high versus low family risk did not differ from each other on any of the measures for literacy, phonology, auditory processing and speech perception, both groups were collapsed into one normal-reading group, in order to compare performance with those of children with dyslexia.

Performance of dyslexic versus normal-reading children

Table 2 provides summary statistics for phonological processing, auditory processing and speech perception in the normal reading and dyslexic reading children. Children with dyslexia demonstrated significantly poorer performance on phoneme deletion ($F(1, 56) = 29.47$; $p < 0.001$) and spoonerisms ($F(1, 56) = 33.06$; $p < 0.001$). Significantly poorer performance was also observed for FM-detection ($F(1, 56) = 9.92$; $p = 0.003$) and rise time discrimination ($F(1, 56) = 5.80$; $p = 0.019$). In contrast, no group difference was found for the intensity discrimination task ($F(1, 56) = 2.68$; $p = 0.107$).

Table 2 Average performance on low-level auditory processing and speech-in-noise perception tasks

	Normal-reading (<i>N</i> =45)		Dyslexic (<i>N</i> =13)	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Phoneme deletion	19.5	2.7	13.6	5.4
Spoonerisms	38.0	6.2	24.1	11.6
FM-detection (Hz)	5.2	1.9	7.5	3.2
Rise time discrimination ^a (step)	22.4	7.9	16.6	6.9
Rise time discrimination ^b (ms)	70.1	50.1	104.0	61.8
Intensity discrimination ^a (step)	32.7	3.4	30.8	4.4
Intensity discrimination ^c (dB)	1.8	0.8	2.3	1.1
Sentences in stationary noise (SRT)	-7.3	1.1	-6.7	0.8
Sentences in fluctuating noise (SRT)	-12.1	1.8	-11.3	1.8
Words in stationary noise ^d (SRT)	-8.6	1.6	-7.9	1.1

^a Stimulus number (max: 40)

^b Rise times reliably distinguished from the standard stimulus (15 ms rise time)

^c Just noticeable difference (JND) in dB SPL

^d *N* = 57; data of one normal-reading child were excluded because of outlying performance

A repeated measures ANOVA for speech-in-noise intelligibility revealed a main effect of group ($F(1, 55) = 5.87$; $p = 0.019$), a main effect of stimulus type ($F(2, 110) = 108.62$; $p < 0.001$), but no stimulus type x group interaction ($F(2, 110) = 0.12$; $p = 0.892$). As shown in Figure 1, children with dyslexia performed significantly slightly poorer than normal-reading children (mean difference: 0.7 dB, SE: 0.3 dB), independent of the dynamic nature of the added noise or the used speech material. As expected for sentences-in-noise perception, SRTs for the fluctuating noise condition were better than SRTs for the stationary noise condition (mean difference: 4.7 dB, SE: 0.3 dB, $p < 0.001$). This effect was equal for both groups.

Figure 1 Average speech-in-noise intelligibility performance for sentences and words for normal-reading children (dark bars) and children with dyslexia (light bars). Error bars indicate ± 1 standard error of the mean.

Relations between slow-rate auditory processing, speech perception, phonological awareness and literacy measures

Because group differences were found on measures for slow-rate auditory processing, speech-in-noise perception, phonological awareness and reading, correlations between these measures was examined. Comparable to Hazan, Messaoud-Galusi, Rosen, Nouwens, and Shakespeare (2009), composite z-scores were calculated by converting performance measures of all tasks to whole-group z-scores. Z-scores for FM-detection and SRTs of speech-in-noise perception for words and sentences were multiplied by -1 to obtain comparable performance. Composite scores were then calculated to compare performance on reading tasks, phonological awareness, speech-in-noise perception and slow-rate dynamic auditory processing. For each participant, a **READING** score was calculated by averaging z-scores for word-reading and pseudoword-reading tasks, a **PHONOLOGY** score was calculated by averaging z-scores for phoneme deletion and spoonerisms tasks, a **SPEECH-IN-NOISE** score was calculated as the mean of the z-scores of words in stationary, sentences in stationary and sentences in fluctuating noise and a **DYNAMIC** score was calculated by averaging z-scores for FM-detection and rise time discrimination tasks. As expected, normal-reading children and children with dyslexia also differed on the **READING** ($F(1, 56) = 49.39$; $p < 0.001$), **PHONOLOGY** ($F(1, 56) = 43.51$; $p < 0.001$), **SPEECH-IN-NOISE** ($F(1, 56) = 6.00$; $p = 0.017$) and **DYNAMIC** ($F(1, 56) = 11.05$; $p = 0.002$) composite scores.

Table 3 Whole-sample Pearson correlations between slow-rate auditory processing, speech-in-noise perception, phonological awareness and reading (N=58)

	DYNAMIC	READING	PHONOLOGY
DYNAMIC		0.22	0.38**
SPEECH-IN-NOISE ^a	0.24	0.38**	0.22

^a $N = 57$; data of one normal-reading child were excluded because of outlying performance

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

Pearson correlation coefficients were calculated to investigate the interrelations between the studied variables. Table 3 shows that speech-in-noise perception correlates with reading abilities, but not with phonological awareness. The reverse pattern can be seen for slow-rate dynamic processing, correlating significantly with phonological abilities, but not with reading. Finally, no significant correlation between speech-in-noise perception and slow-rate dynamic processing was found. To verify inflation of correlations due to extreme samples, these relations were also investigated for the normal-reading group alone. Even within this subsample, the correlation between speech-in-noise perception and reading ($r = 0.30$, $p = 0.050$, $N = 44$) and between slow-rate dynamic processing and phonology ($r = 0.29$, $p = 0.051$, $N = 45$) were close to significance. Comparable to the whole-sample correlations, no significant correlations between speech-in-noise perception and slow-rate dynamic processing ($r = 0.17$, $p = 0.278$, $N = 44$), reading and slow-rate dynamic processing ($r = 0.09$, $p = 0.544$, $N = 45$) and between speech-in-noise perception and phonology ($r = 0.05$, $p = 0.731$, $N = 44$) were found in the normal-reading group alone.

Discussion

It is well established that phonological processing abilities are related to literacy development and that individuals with dyslexia show a phonological processing deficit (Snowling, 2000). Currently it is under debate whether this phonological processing deficit stems from a specific deficit in processing speech sounds or whether it originates from reduced sensitivity to slow-rate dynamic auditory information. The present study investigated sensitivity to several slow-rate dynamic cues and speech perception measures in relation to skills characterizing developmental dyslexia (i.e. phonological processing, reading and spelling). Performance of sixth grade children was examined to study to what extent auditory processing and speech perception difficulties are still manifest in children with dyslexia at the end of primary school. The present study demonstrated that children with dyslexia are less sensitive to slow-rate dynamic information, investigated by sound rise time perception and FM sensitivity, than

normal-reading children, whereas sensitivity to intensity did not differ between groups. Sound rise time sensitivity has been shown to be a sensitive measure to discriminate between individuals with and without dyslexia. Studies found atypical sound rise time processing in adults (Hämäläinen et al., 2005; Corriveau et al., 2007) and children with dyslexia (Goswami et al., 2002; Richardson et al., 2004; Muneaux et al., 2004; Georgiou et al., 2010) and demonstrated associations between rise time sensitivity and a variety of phonological awareness tasks. Furthermore, sound rise time has been shown to discriminate between normal-reading children and children with dyslexia in several languages (English, Spanish, Chinese: Goswami et al., 2011a; Greek: Georgiou et al., 2010; Finnish: Hämäläinen et al., 2009; Hungarian: Suranyi et al., 2009; French: Muneaux et al., 2004). The present study is the first to demonstrate this effect in Dutch-speaking children, supporting the assumption that decreased sound rise time sensitivity is a language-universal characteristic of dyslexia (Goswami et al., 2011a). Additionally, sensitivity to sound rise time was evaluated in the simplest but most realistic conditions. Whereas all other rise time studies used a pure tone carrier signal, the present study applied a speech-weighted noise signal as carrier signal. The benefit of this complex carrier noise is that it contains important frequencies of real speech and therefore activates a broader frequency region in the auditory system compared to pure tones. While pilot tests demonstrated floor performance in some children for pure tone rise time stimuli, the application of a speech-weighted noise carrier resulted in reliable performance for all children (excluding ceiling or floor effects). This ensured that all children were able to perform the task and allowed to make a qualitative comparison of rise time sensitivity in both participant groups.

The present findings reinforce previous studies in that findings are consistent across age, stimuli and language. In addition to rise time perception difficulties, children with dyslexia also demonstrated reduced sensitivity to slow-rate FM. Comparable to studies investigating sound rise time, FM detection performance previously discriminated between individuals with and without dyslexia. Group differences have been reported in adults (Witton et al., 2000) and children (Talcott et al., 2000; Boets et al., 2006) and FM has been shown to be related to pseudoword-reading and phonological awareness (Witton et al., 1998; Boets et al., 2008; Boets et al., 2011; Witton et al., 2002; Stuart et al., 2006; Talcott et al., 1999). Studies investigating sound rise time and FM sensitivity independently demonstrated poorer performance in individuals with dyslexia. The present study extends previous research in that rise time and FM sensitivity were examined in the same group of children with and without dyslexia. This within-group comparison demonstrated that individuals with dyslexia

performed poorer on slow-rate dynamic auditory tasks, independent of whether stimuli comprised a change in frequency (FM) or a change in amplitude (sound rise time) over time. Moreover, as no group difference was found for the intensity discrimination task, these results indicate that the auditory processing problems in dyslexia arise from a specific impairment in the ability to process slowly-varying auditory information, independent of the nature of the variation.

Because accurate processing of slow-rate auditory cues is an important aspect of speech perception, impaired processing of these cues would inevitably lead to speech intelligibility problems. Indeed, previous studies demonstrated a speech-in-noise perception deficit in reading-disabled individuals (Chermak et al., 1989; Ramirez & Mann, 2005; Cornelissen et al., 1996), however results were not always clear (Hazan et al., 2009). The present study found evidence in favour of a (subtle) speech-in-noise perception deficit in children with dyslexia. Contrary to our expectations, this deficit occurred independent of the dynamic nature of the noise or semantic influence of the speech material. Based on the hypothesis that individuals with dyslexia are less sensitive to slow-rate dynamic variations, we expected a larger difference between normal-reading children and children with dyslexia for sentences presented in fluctuating noise compared to sentences presented in stationary noise. However, children with dyslexia benefited equally as normal-reading children from the dips in the background noise.

Comparable to the present results, Ziegler, Pech-Georgel, George, and Lorenzi (2009) demonstrated with a variety of amplitude-modulated noise conditions that children with dyslexia have a normal masking-release (i.e. better performance in fluctuating than in stationary noise), but that they are in general impaired in identifying speech in the presence of noise. Similarly, they demonstrated inferior performance of children with dyslexia when speech was degraded by eliminating temporal fine-structure cues without using external noise. From these results, the authors suggested that children with dyslexia have normal sensitivity to dynamic information but that their speech-in-noise perception problems are rather characterized by a lack of speech robustness in adverse situations. The present results partly confirmed this hypothesis. Indeed, children with dyslexia demonstrated poorer speech-in-noise perception performance, favouring the hypothesis that they suffer a lack of speech robustness in adverse situations. However, the fact that normal-reading children and children with dyslexia benefitted equally from the dynamic nature of fluctuating noise does not necessarily imply that children with dyslexia are unimpaired in processing slow-rate dynamic information. Speech is a complex signal containing several auditory cues that can lead to

speech identification. It is possible that the presence of dips in the fluctuating noise still allowed a significant degree of speech recovery based on unimpaired auditory cues. Therefore, the possibility that the speech-in-noise perception problem stems from decreased sensitivity to slow-rate dynamic auditory cues cannot be confirmed nor excluded based on these data.

The finding of poorer performance of children with dyslexia on tasks assessing slow-rate dynamic sensitivity and speech-in-noise perception favour the hypothesis of a low-level auditory processing deficit as the cause of impaired phonological awareness in individuals with dyslexia. However, the present study could not provide clear evidence for this hypothesis.

First, correlational analyses could not demonstrate a link between slow-rate dynamic processing and speech-in-noise perception. Yet, both measures correlated respectively with phonological awareness and reading ability, supporting the possibility that both deficits independently relate to reading-related measures. However, this seems unlikely considering that slow-rate dynamic cues are prominent features of speech signals. A more likely explanation is that in 11-year old children the link between these variables is simply not evident (or even not present) anymore. Infants are born with a certain auditory sensitivity based on which they fine-tune their sensitivity to important acoustic cues in their native language (Kuhl, 2004). If in some children auditory development is impaired, speech perception abilities can be affected already early in life. It is possible that by the time these children learn to read, the original relation between auditory sensitivity and speech perception is already concealed because of different developmental influences on both levels.

Alternatively, after formal reading instruction, top-down processes can also influence perception at all these domains (Mayo et al., 2003). Therefore, to make strong conclusions about the relation between slow-rate dynamic auditory processing abilities, speech perception, phonological awareness and literacy development a longitudinal design, starting at an early, pre-reading age is necessary. Indeed, longitudinal evidence for a causal, bottom-up influence of auditory processing and speech perception on later literacy skills has previously been obtained in preschool children. Recently, Boets et al. (2011) found that FM-detection and speech-in-noise perception in kindergarten contributed to subsequent growth in reading ability, even after controlling for phonological abilities and letter knowledge. Additionally, Corriveau, Goswami, and Thomson (2010) found that both sound rise time perception and sensitivity to a frequency change over time predicted phonological awareness abilities in a

normally developing sample, suggesting that a general sensitivity to dynamic auditory cues is important for literacy development.

Even though the present study could not obtain clear evidence supporting relations between slow-rate dynamic auditory processing and speech perception, it was demonstrated that after six years of reading education, children with dyslexia displayed atypical performance on both measures. Additionally, slow-rate dynamic auditory processing and speech perception correlated to phonological awareness and literacy abilities, confirming their link to reading-related abilities. These results indicate that the low-level auditory processing problems of children with dyslexia are persistent and possibly not entirely susceptible to remediation or compensation.

Acknowledgments

The research was financed by the fund for Scientific Research Flanders (grant G.0331.08 and G.0216.02) and a grant of the Research Council of Katholieke Universiteit Leuven (OT/07/034). Maaike Vandermosten is a junior research fellow of the Research Foundation Flanders. Bart Boets is a post-doctoral research fellow of the Research Foundation Flanders. We are grateful to all children, parents, teachers and schools that participated in this study. Special thanks are due to Sarah To, Véronique Celis, Lotte Boulet, Nathalie Charlier and Loes Lodewijckx for their assistance in data acquisition.

References

- Adlard, A. & Hazan, V. (1998). Speech perception in children with specific reading difficulties (dyslexia). *Quarterly Journal of Experimental Psychology Section A-Human Experimental Psychology*, 51, 153-177.
- Blomert, L. & Mitterer, H. (2004). The fragile nature of the speech-perception deficit in dyslexia: Natural vs. synthetic speech. *Brain and Language*, 89, 21-26.
- Boets, B., De Smedt, B., Cleuren, L., Vandewalle, E., Wouters, J., & Ghesquière, P. (2010). Towards a further characterization of phonological and literacy problems in Dutch-speaking children with dyslexia. *British Journal of Developmental Psychology*, 28, 5-31.
- Boets, B., Vandermosten, M., Poelmans, H., Luts, H., Wouters, J., & Ghesquière, P. (2011). Preschool impairments in auditory processing and speech perception uniquely predict future reading problems. *Research in developmental disabilities*, 32, 560-570.

Boets, B., Wouters, J., van Wieringen, A., De Smedt, B., & Ghesquière, P. (2008). Modelling relations between sensory processing, speech perception, orthographic and phonological ability, and literacy achievement. *Brain and Language*, 106, 29-40.

Boets, B., Wouters, J., van Wieringen, A., & Ghesquière, P. (2006). Auditory temporal information processing in preschool children at family risk for dyslexia: Relations with phonological abilities and developing literacy skills. *Brain and Language*, 97, 64-79.

Bradlow, A. R., Kraus, N., & Hayes, E. (2003). Speaking clearly for children with learning disabilities: Sentence perception in noise. *Journal of Speech Language and Hearing Research*, 46, 80-97.

Brus, B. T. & Voeten, M. J. M. (1973). *Een minuut test, vorm A en B*. Nijmegen, The Netherlands: Berkhout.

Chandrasekaran, B., Hornickel, J., Skoe, E., Nicol, T., & Kraus, N. (2009). Context-dependent encoding in the human auditory brainstem relates to hearing speech in noise: implications for developmental dyslexia. *Neuron*, 64, 311-319.

Chermak, G. D., Vonhof, M. R., & Bendel, R. B. (1989). Word identification performance in the presence of competing speech and noise in learning disabled adults. *Ear and Hearing*, 10, 90-93.

Cornelissen, P. L., Hansen, P. C., Bradley, L., & Stein, J. F. (1996). Analysis of perceptual confusions between nine sets of consonant-vowel sounds in normal and dyslexic adults. *Cognition*, 59, 275-306.

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.

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

Dreschler, W. A., Verschuure, H., Ludvigsen, C., & Westermann, S. (2001). ICRA noises: Artificial noise signals with speech-like spectral and temporal properties for hearing instrument assessment. *Audiology*, 40, 148-157.

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

Dudal, P. (1997). *Leerlingvolgsysteem VCLB (CSBO). Spelling: Toetsen 1-2-3. Basisboek en kopieerbundel [Student trajectory system. Spelling: Grade 1-2-3. Manual]*. Leuven, Belgium: Garant.

Edwards, V. T., Giaschi, D. E., Dougherty, R. F., Edgell, D., Bjornson, B. H., Lyons, C. et al. (2004). Psychophysical indexes of temporal processing abnormalities in children with developmental dyslexia. *Developmental Neuropsychology*, 25, 321-354.

Francart, T., van Wieringen, A., & Wouters, J. (2008). APEX 3: a multi-purpose test platform for auditory psychophysical experiments. *Journal of Neuroscience Methods*, 172, 283-293.

Georgiou, G. K., Protopapas, A., Papadopoulos, A. T., Skaloumbakas, C., & Parrila, R. (2010). Auditory temporal processing and dyslexia in an orthographically consistent language. *Cortex*, 46, 1330-1344.

Gersons-Wolfensberger, D. C. & Ruijsenaars, W. A. (1997). Definition and treatment of dyslexia: a report by the Committee on Dyslexia of the Health Council of The Netherlands. *Journal of Learning Disabilities*, 30, 209-213.

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

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

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

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

Hazan, V., Messaoud-Galusi, S., Rosen, S., Nouwens, S., & Shakespeare, B. (2009). Speech perception abilities of adults with dyslexia: Is there any evidence for a true deficit? *Journal of Speech Language and Hearing Research*, 52, 1510-1529.

Hill, N. I., Bailey, P. J., Griffiths, Y. M., & Snowling, M. J. (1999). Frequency acuity and binaural masking release in dyslexic listeners. *Journal of the Acoustical Society of America*, 106, L53-L58.

Kuhl, P. K. (2004). Early language acquisition: cracking the speech code. *Nat Rev Neurosci*, 5, 831-843.

Laneau, J., Boets, B., Moonen, M., van Wieringen, A., & Wouters, J. (2005). A flexible auditory research platform using acoustic or electric stimuli for adults and young children. *Journal of Neuroscience Methods*, 142, 131-136.

- Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *Journal of the Acoustical Society of America*, 49, 467-477.
- Lorenzi, C., Dumont, A., & Fullgrabe, C. (2000). Use of temporal envelope cues by children with developmental dyslexia. *Journal of Speech Language and Hearing Research*, 43, 1367-1379.
- Maassen, B., Groenen, P., Crul, T., Assman-Hulsmans, C., & Gabreels, F. (2001). Identification and discrimination of voicing and place-of-articulation in developmental dyslexia. *Clinical Linguistics & Phonetics*, 15, 319-339.
- Manis, F. R., McBrideChang, C., Seidenberg, M. S., Keating, P., Doi, L. M., Munson, B. et al. (1997). Are speech perception deficits associated with developmental dyslexia? *Journal of Experimental Child Psychology*, 66, 211-235.
- Mayo, C., Scobbie, J. M., Hewlett, N., & Waters, D. (2003). The influence of phonemic awareness development on acoustic cue weighting strategies in children's speech perception. *Journal of Speech Language and Hearing Research*, 46, 1184-1196.
- McAnally, K. I. & Stein, J. F. (1997). Scalp potentials evoked by amplitude-modulated tones in dyslexia. *Journal of Speech Language and Hearing Research*, 40, 939-945.
- McArthur, G. M. & Bishop, D. V. (2001). Auditory perceptual processing in people with reading and oral language impairments: current issues and recommendations. *Dyslexia*, 7, 150-170.
- Menell, P., McAnally, K. I., & Stein, J. F. (1999). Psychophysical sensitivity and physiological response to amplitude modulation in adult dyslexic listeners. *Journal of Speech Language and Hearing Research*, 42, 797-803.
- Muneaux, M., Ziegler, J. C., Truc, C., Thomson, J., & Goswami, U. (2004). Deficits in beat perception and dyslexia: evidence from French. *Neuroreport*, 15, 1255-1259.
- Nittrouer, S. (2006). Children hear the forest (L). *Journal of the Acoustical Society of America*, 120, 1799-1802.
- 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.
- Ramirez, J. & Mann, V. (2005). Using auditory-visual speech to probe the basis of noise-impaired consonant-vowel perception in dyslexia and auditory neuropathy. *Journal of the Acoustical Society of America*, 118, 1122-1133.
- Raven, J. C., Court, J. H., & Raven, J. (1984). *Manual for Raven's Progressive Matrices and Vocabulary Scales*. London, United Kingdom: Lewis.
- Richardson, U., Thomson, J. M., Scott, S. K., & Goswami, U. (2004). Auditory processing skills and phonological representation in dyslexic children. *Dyslexia*, 10, 215-233.
- Rocheron, I., Lorenzi, C., Fullgrabe, C., & Dumont, A. (2002). Temporal envelope perception in dyslexic children. *Neuroreport*, 13, 1683-1687.

Schneider, W., Eschman, A., & Zuccolotto, A. (2002). *E-Prime User's Guide*. Pittsburgh: Psychology Software Tools Inc.

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

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

Stuart, G. W., McAnally, K. I., McKay, A., Johnston, M., & Castles, A. (2006). A test of the magnocellular deficit theory of dyslexia in an adult sample. *Cognitive Neuropsychology*, 23, 1215-1229.

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

Talcott, J. B., Witton, C., McClean, M., Hansen, P. C., Rees, A., Green, G. G. R. et al. (1999). Can sensitivity to auditory frequency modulation predict children's phonological and reading skills? *Neuroreport*, 10, 2045-2050.

Talcott, J. B., Witton, C., Mclean, M. F., Hansen, P. C., Rees, A., Green, G. G. R. et al. (2000). Dynamic sensory sensitivity and children's word decoding skills. *Proceedings of the National Academy of Sciences of the United States of America*, 97, 2952-2957.

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

Van den Bos, K. P., Spelberg, H. C. L., Scheepstra, A. J. M., & De Vries, J. R. (1994). *De Klepel. Vorm A en B. Een test voor de leesvaardigheid van pseudowoorden. Verantwoording, handleiding, diagnostiek en behandeling*. Nijmegen, The Netherlands: Berkhout.

van Wieringen, A. & Wouters, J. (2008). LIST and LINT: Sentences and numbers for quantifying speech understanding in severely impaired listeners for Flanders and the Netherlands. *International Journal of Audiology*, 47, 348-355.

Vandermosten, M., Boets, B., Luts, H., Poelmans, H., Golestani, N., Wouters, J. et al. (2010). Adults with dyslexia are impaired in categorizing speech and nonspeech sounds on the basis of temporal cues. *Proceedings of the National Academy of Sciences of the United States of America*, 107, 10389-10394.

Vandermosten, M., Boets, B., Luts, H., Poelmans, H., Golestani, N., Wouters, J. et al. (2011). Impairments in speech and nonspeech sound categorization in children with dyslexia are driven by temporal processing difficulties. *Research in developmental disabilities*, 32, 593-603.

Vellutino, F. R., Fletcher, J. M., Snowling, M. J., & Scanlon, D. M. (2004). Specific reading disability (dyslexia): what have we learned in the past four decades? *Journal of Child Psychology and Psychiatry*, 45, 2-40.

Wagener, K. C., Brand, T., & Kollmeier, B. (2006). The role of silent intervals for sentence intelligibility in fluctuating noise in hearing-impaired listeners. *International Journal of Audiology*, 45, 26-33.

- Wible, B., Nicol, T., & Kraus, N. (2002). Abnormal neural encoding of repeated speech stimuli in noise in children with learning problems. *Clinical Neurophysiology*, 113, 485-494.
- Witton, C., Stein, J. F., Stoodley, C. J., Rosner, B. S., & Talcott, J. B. (2002). Separate influences of acoustic AM and FM sensitivity on the phonological decoding skills of impaired and normal readers. *Journal of Cognitive Neuroscience*, 14, 866-874.
- Witton, C., Talcott, J. B., Hansen, P. C., Richardson, A. J., Griffiths, T. D., Rees, A. et al. (1998). Sensitivity to dynamic auditory and visual stimuli predicts nonword reading ability in both dyslexic and normal readers. *Current Biology*, 8, 791-797.
- Witton, C., Talcott, J. B., Stoodley, C. J., & Stein, J. F. (2000). Frequency modulation, amplitude modulation and phonological ability in developmental dyslexia. *British Journal of Audiology*, 34, 123-124.
- Wouters, J., Damman, W., & Bosman, A. J. (1994). Vlaamse opname van woordenlijsten van spraakaudiometrie. *Logopedie*, 7, 28-33.
- Ziegler, J. C. & Goswami, U. (2005). Reading acquisition, developmental dyslexia, and skilled reading across languages: A psycholinguistic grain size theory. *Psychological Bulletin*, 131, 3-29.
- Ziegler, J. C., Pech-Georgel, C., George, F., & Lorenzi, C. (2009). Speech-perception-in-noise deficits in dyslexia. *Developmental Science*, 12, 732-745.