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Speech Recognition in Noise by Children with and without Dyslexia: How is it Related to Reading?

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ABSTRACT

Purpose: Developmental dyslexia is commonly viewed as a phonological deficit that makes it difficult to decode written language. But children with dyslexia typically exhibit other problems, as well, including poor speech recognition in noise. The purpose of this study was to examine whether the speech-in-noise problems of children with dyslexia are related to their reading problems, and if so, if a common underlying factor might explain both. The specific hypothesis examined was that a spectral processing disorder results in these children receiving smeared signals, which could explain both the diminished sensitivity to phonological structure – leading to reading problems – and the speech recognition in noise difficulties. The alternative hypothesis tested in this study was that children with dyslexia simply have broadly based language deficits.
Participants: Ninety-seven children between the ages of 7 years; 10 months and 12 years; 9 months participated: 46 with dyslexia and 51 without dyslexia.
Methods: Children were tested on two dependent measures: word reading and recognition in noise with two types of sentence materials: as unprocessed (UP) signals, and as spectrally smeared (SM) signals. Data were collected for four predictor variables: phonological awareness, vocabulary, grammatical knowledge, and digit span.
Results: Children with dyslexia showed deficits on both dependent and all predictor variables. Their scores for speech recognition in noise were poorer than those of children without dyslexia for both the UP and SM signals, but by equivalent amounts across signal conditions indicating that they were not disproportionately hindered by spectral distortion. Correlation analyses on scores from children with dyslexia showed that reading ability and speech-in-noise recognition were only mildly correlated, and each skill was related to different underlying abilities.
Conclusions: No substantial evidence was found to support the suggestion that the reading and speech recognition in noise problems of children with dyslexia arise from a single factor that could be defined as a spectral processing disorder. The reading and speech recognition in noise deficits of these children appeared to be largely independent.

What this paper adds?

Two clear trends are apparent across research studies into developmental dyslexia: (1) Children with dyslexia display a variety of deficits beyond just reading problems; and (2) These children appear to have subtle and as-yet unspecified perceptual processing problems that may account for their reading problems and other deficits. This paper adds to our understanding of these issues by

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examining reading skill and one other deficit commonly found for children with dyslexia: problems recognizing speech in noise. The mirror hypotheses were posed that either a common source of difficulty – a spectral processing disorder – could explain both the reading and speech-recognition-in-noise deficits, or the deficits of these children may be largely independent of each other, even if comorbid. This paper reveals that for children with dyslexia the degree of severity in reading deficit and difficulty recognizing speech in noise are largely uncorrelated, and dependent on different levels of linguistic structure, with word-internal phonological structure playing the most important role in reading and lexical structure playing the larger role in speech recognition in noise. Thus it must be concluded that these children have broadly based language deficits, that although often comorbid are not necessarily related.

1. Introduction

Dyslexia is conventionally defined as an impairment in reading, in spite of there having been ample educational opportunity to learn and no apparent sensory or cognitive obstacle to that learning (e.g., Lyon, Shaywitz, & Shaywitz, 2003; Snowling, 2000). Although accurate in description, this definition places the locus of the problem solely on difficulty with visual forms of language. It may reflect the historical roots of the clinical diagnosis, which can be traced back more than a century to a time when dyslexia was viewed as a visual disturbance (Hinshelwood, 1900, 1917; Orton, 1928; Stephenson, 1907). But this view of dyslexia came under scrutiny in the latter half of the twentieth century when psycholinguists discovered that individuals with dyslexia commonly have difficulty recognizing word-internal, or phonological, structure (e.g., Bradley & Bryant, 1983; Fox & Routh, 1980; Liberman, 1973; Liberman, Shankweiler, Orlando, Harris, & Berti, 1971; Shankweiler & Liberman, 1972). In fact, the prevalence of phonological deficits among individuals with dyslexia is so striking that the disorder has been described as arising from a core phonological deficit (e.g., Ramus et al., 2003; Snowling, 2000; Vellutino, Fletcher, Snowling, & Scanlon, 2004), thus supplanting visual disturbances as the ostensible crux of the problem. With attention displaced from visual processing as the locus of the disorder, the question might legitimately be asked of how this impairment would be characterized, if we were to encounter it anew today. Would it be defined as primarily a reading disability? Or would it be seen as a multifaceted language problem, with reading difficulty as just one component of a broader impairment?

The legitimacy of that question hinges on the fact that individuals with dyslexia display many deficits related to language processing, beyond just reading. Dyslexia has been associated with a higher prevalence of poor short-term memory for verbal materials (Brady, Shankweiler, & Mann, 1983; Mann & Liberman, 1984; Nittrouer & Miller, 1999; Shankweiler, Liberman, Mark, Fowler, & Fischer, 1979), slow lexical retrieval (Law, Vandermosten, Ghesquiére, & Wouters, 2014; Stanovich & Siegel, 1994; Súarez-Coalla & Cuetos, 2015; Swan & Goswami, 1997), diminished speech intelligibility (Catts, 1989; Lewis et al., 2011; Smith, Pennington, Boada, & Shriberg, 2005), and poor recognition of spoken language, especially under conditions of signal degradation (Brady, Shankweiler, & Mann, 1983; Dole, Hoen, & Meunier, 2012; Johnson, Pennington, Lowenstein, & Nittrouer, 2011; Nittrouer & Lowenstein, 2013; Ziegler, Pech-Georgel, George, & Lorenzi, 2009). The breadth of language-related difficulties demonstrated by individuals with dyslexia suggests that a broad approach needs to be taken to understanding the disorder. One component of that approach should involve investigating the interconnectedness of the separately measured deficits to see if all children with dyslexia exhibit the same pattern of deficit across language skills. A second component of the study of dyslexia should involve searching for a potential common source of deficit across language skills. The current study focused on the potential relationship between two deficits previously observed in children with dyslexia, poor reading abilities and poor speech recognition in noise, and on exploring a potential common source of both deficits.

1.1. Speech perception in noise by children with dyslexia

In 1983, Brady, Shankweiler, and Mann tested the hypothesis that dyslexia may have at its source perceptual-processing problems, which could explain the phonological deficit exhibited by so many children with dyslexia. Specifically, these authors used a paradigm described earlier by Rabbitt (1968), showing that broadband noise added to recorded digits impairs the recall of those digits, even when added at a level that does not impair recognition of the digits. Rabbitt's conclusion from individuals with typical language abilities was that any condition that hinders perceptual processing of the sensory input impairs language functioning. Brady and colleagues used that finding to suggest that children with dyslexia may have persistent perceptual processing difficulties that interfere with their abilities to discover phonological structure in the acoustic speech signal, which would give rise to the phonological deficits. This hypothesis was tested by asking children with and without dyslexia to repeat words in quiet and in noise at a 0 dB signal-to-noise ratio. In quiet, accuracy was similar across groups, but when those words were embedded in noise, children with dyslexia showed significantly greater diminishment in recognition than children without dyslexia. From this finding the authors concluded that children with dyslexia have perceptual processing problems that hinder their abilities to recover clear speech from noisy signals and to form phonological representations. These ill-defined phonological representations subsequently make it more difficult for listeners with dyslexia to learn to read. According to this account, problems with reading and problems with speech-in-noise recognition arise from a common source: perceptual processing difficulties.

Since that study was conducted, a fair number of other investigators have similarly observed that children with dyslexia exhibit difficulty recognizing speech in noise (Bradlow, Kraus, & Hayes, 2003; Calcus, Deltenre, Colin, & Kolinsky, 2017; Ziegler et al., 2009). However, a few investigators have failed to replicate this effect, reporting instead that children with and without dyslexia are affected similarly by noise (Messaoud-Galusi, Hazan, & Rosen, 2011; Nittrouer, Shune, & Lowenstein, 2011). One study (Boets et al., 2011) revealed impaired speech-in-noise recognition for children at familial risk of dyslexia in kindergarten, but no deficit in first grade. Thus, a generally accepted description of the speech recognition in noise problems of children with dyslexia continues to elude the field. Differences in outcomes across studies may be due to differences in materials used (nonsense syllables, words, or sentences) or to differences in the kinds of noise used (Gaussian noise, speech-shaped noise, or speech babble). Nonetheless, evidence for enhanced effects of noise masking on speech recognition by individuals with dyslexia has been sufficiently replicated to use it to support the idea that these individuals may have a perceptual processing problem, of some kind. Suggestions for exactly what that problem may be have largely focused on the temporal domain (Farmer & Klein, 1995). The most well-known proposal is one offered by Tallal and Merzenich, among others, suggesting that children with dyslexia have difficulty recognizing auditory information that is presented rapidly (McArthur & Bishop, 2001; Merzenich, Schreiner, Jenkins, & Wang, 1993; Merzenich et al., 1996; Tallal, 1980; 1984; Tallal, Miller, & Fitch, 1993), but that proposal has not met with uniform support (Mody, Studdert-Kennedy, & Brady, 1997; Nittrouer, 1999; Rosen, 2003). And although it has been proposed that this kind of perceptual problem could account for the phonological deficit demonstrated by children with dyslexia by making it difficult for them to recover the cues to phonemic sequences rapidly enough, it is not clear how it could account for the speech-in-noise recognition deficit. However, temporal processing is not the only function that has been examined for potential, causative deficits in dyslexia. Other auditory dysfunctions proposed as being the source of the problems faced by individuals with dyslexia include exacerbated backwards masking (Wright et al., 1997), poor frequency discrimination (McAnally & Stein, 1996), and impaired processing of slower temporal structures than those examined by Merzenich and Tallal (Goswami, Fosker, Huss, Mead, & Szucs, 2011). In the current study, we chose to focus on potential deficits in spectral processing, in the belief that problems with these processes could provide a unifying account of the phonological and speech recognition in noise deficits exhibited by children with dyslexia.

1.2. Spectral processing deficit hypothesis

The specific hypothesis examined in this study was that poor spectral processing might explain both the poor phonological sensitivity and poor speech-in-noise recognition of children with dyslexia. This term, spectral processing, incorporates both spectral resolution and spectral integration (Davies-Venn, Nelson, & Souza, 2015). Spectral resolution refers to a listener's ability to resolve the frequency structure of a complex signal, such as speech. Spectral integration refers to a listener's ability to combine signal structure across a range of frequencies to recover spectral shape. Overall, the term refers to the ability of the auditory system to recover and retain a detailed, but complete spectral representation.

Efforts to examine the relationship between speech perception and spectral processing have varied widely, both in terms of the spectral processing task used and in the speech materials used. A typical application of this approach, however, has involved examining spectral resolution and recognition of simple syllables in noise by listeners with hearing loss. The reason for the application of these methods is that listeners with even mild hearing loss generally have broader-than-normal auditory filters, suggestive of poor spectral resolution. This poor spectral resolution has been found to be associated with poor speech recognition in noise (e.g., Leek & Summers, 1996; Thibodeau & Van Tasell, 1987).

In the current study, the examination of spectral processing was not limited to auditory filter bandwidth, in light of the fact that poor spectral processing of any sort would result in effectively smeared representations of the sensory inputs. Such spectral smearing has been shown to diminish speech recognition and exacerbate the effects of noise (Baer & Moore, 1993; Boothroyd, Mulnearn, Gong, & Ostroff, 1996; ter Keurs, Festen, & Plomp, 1992). Of particular importance to the hypothesis under examination here was the fact that several of these investigations have explicitly examined listeners' abilities to recognize phonemes under conditions of spectral smearing. For example, Boothroyd et al. (1996) observed that phoneme recognition for adults with normal auditory thresholds diminished as the degree of spectral smearing increased. This finding for adults supports the suggestion that children who are in the course of developing phonological representations would be hindered in their progress if they are operating with any sort of spectral smearing.

Specific support for the hypothesis tested in this study was provided by the results of an earlier study. Nittrouer and Lowenstein (2013) observed that children with dyslexia were significantly impaired, compared to children without dyslexia, in their recognition of sentences that had been vocoded. In this signal processing method the speech spectrum was divided into four bands, the temporal envelope of each band was recovered, and those envelopes were used to shape noise in the same four bands. This technique results in spectral smearing more severe than anything most listeners would encounter in their daily lives. In the current study, the extent of spectral smearing was not so severe, and the processed sentences were presented in a noisy background, thus representing the naturalistic settings where children with dyslexia have been observed to have difficulty recognizing speech (Purdy, Smart, Baily, & Sharma, 2009). Consequently, the results of the current study should address the question at stake more directly: Can spectral processing deficits explain the problems of children with dyslexia?

The experimental method employed in this study was similar in approach to that of other studies investigating potential roles of perceptual processing deficits in speech recognition impairments. For example, Gordon-Salant and Fitzgibbons (1993) tested the hypothesis that *temporal* processing deficits in elderly listeners account for many of their speech-recognition problems by presenting them with speech signals that were distorted in the temporal domain in some way, such as through time compression. The elderly listeners indeed were found to be disproportionately more affected by this temporal distortion than young listeners. The authors' interpretation was that the elderly listeners' temporal processing deficits left them at a disadvantage for processing temporally distorted signals. McAnally, Hansen, Cornelissen, and Stein (1997) took the same approach, with the same reasoning in a study involving children with dyslexia, but failed to find any effects. In the current study, a similar approach was applied, but to test the effects of signals degraded in the spectral, rather than the temporal domain.

1.3. Current study

The purpose of the current study was to measure speech recognition in noise for children, examine whether this skill is related to reading ability, and determine if a spectral processing deficit might underlie performance on both tasks. Although past results have been mixed, it has been reported that children with dyslexia display poorer than typical abilities to recognize speech that is degraded in some way, such as by background noise. In the current experiment, speech recognition in noise for children with and without dyslexia was compared. In order to assess the hypothesis that this recognition for children with dyslexia is impaired due to the presence of poor spectral processing, the speech spectrum was also smeared, and those stimuli presented in noise. Earlier work (Nittrouer, Tarr, Wucinich, Moberly, & Lowenstein, 2015) showed that the masking effects of noise were exacerbated with these smeared speech signals for listeners with normal auditory thresholds and typical language abilities, in spite of the fact that recognition in quiet for the smeared signals was near perfect. Applying the principles of experiments such as those of Gordon-Salant and Fitzgibbons (1993) and McAnally et al. (1997), speech recognition in noise should be even further diminished for children with dyslexia when these smeared spectral signals are presented, if they have spectral processing disorders.

In addition to investigating potential effects of spectral smearing, several other variables were examined as possibly predictive of reading ability and of speech recognition in noise. These analyses were included in the study to see if there are any underlying functions that explain both reading and speech recognition in noise, or if these two abilities are dependent on different functions. Of most relevance, phonological awareness was examined, with special attention to *phonemic* structure. Sensitivity to phonemic structure should be most pertinent to reading with an alphabetic orthography, rather than sensitivity to syllabic structure, for example. Furthermore, poor spectral processing would be expected to affect the integrity of the kinds of detailed signal properties generally considered to underlie phonemic representations, whereas other levels of phonological structure, such as syllabic structure, might be more discernible with less detailed spectral representations. Thus, abilities to recognize speech in noise should be well correlated with our measures of phonological awareness for children with dyslexia, if spectral processing deficits underlie their difficulties.

However, two linguistic skills and one cognitive skill were measured in addition to phonological awareness, to see if these non-auditory factors accounted for variability in either reading or speech recognition. Vocabulary abilities were examined, because some models of reading suggest that phonological codes do not need to be accessed in the reading process, that readers are able to use visual word structure to recover items directly from the lexicon (Ehri, 1992; Van Orden, Pennington, & Stone, 1990). That would suggest that the size of a reader's lexicon should be related to reading ability. Where speech recognition in noise is concerned, larger vocabularies should facilitate word recognition with degraded signals. This would be a linguistic-context effect, rather than an auditory effect. Thus, vocabulary skills could explain both reading and speech recognition in noise, without appealing to perceptual processing.

Knowledge of grammatical structure was also examined, as this knowledge should be pertinent to both reading and speech recognition in noise. To assess this knowledge, children were asked to judge the grammatical correctness of sentences. These judgments depended on children's knowledge of both syntax, or word order, and morphology, including bound morphemes that serve to inflect words. Although not completely redundant with phonological awareness, scores on tests of grammaticality judgments can be related to phonological abilities because items involving bound morphemes are at least partially testing sensitivity to phonological structure.

Finally, short-term memory was assessed using a digit span task. This capacity refers to the ability to hold recently presented material in a memory buffer long enough for it to be made available to other cognitive operations. Adults with dyslexia self-report that it is a significant problem in their daily lives (Smith-Spark, Henry, Messer, Edvardsdottir, & Zięcik, 2016), and children with dyslexia show significant deficits in short-term memory (Brady et al., 1983; Katz, Shankweiler, & Liberman, 1981; Wang & Yang, 2015). Verbal working memory, which is strongly related to short-term memory, has been found to be dependent on sensitivity to phonological structure (Nittrouer & Miller, 1999; Pennington, Van Orden, Smith, Green, & Haith, 1990; Salame & Baddeley, 1986), although working memory makes contributions to reading ability independently of phonological awareness (Mann & Liberman, 1984). Short-term memory has also been found to contribute to speech recognition performance, especially in noise (Akeroyd, 2008; Foo, Rudner, Rönnberg, & Lunner, 2007; Gatehouse, Naylor, & Elberling, 2003), although evidence contradicting that finding has also been reported (Füllgrabe & Rosen, 2016; Moberly, Harris, Boyce, & Nittrouer, 2017).

In summary, the current study was undertaken to examine two hypotheses. First, it was asked if evidence could be found for the hypothesis that a spectral processing disorder might explain the difficulties exhibited by children with dyslexia in reading and speech-in-noise recognition. Second, the independence of these skills was examined to see if dyslexia represents an assortment of disorders arising from a common deficit, or if it is better modeled as a set of broad-based language disorders that are largely independent of one another.

2. Method

2.1. Participants

Data are presented for 97 children between the ages of 7 years; 10 months and 12 years; 9 months: 46 with diagnoses of dyslexia (DYS) and 51 with typical language and literacy (TYP). We selected this broad age range because we wished to examine whether the nature of deficit was different for younger children, largely in the process of learning to read, and slightly older children, who have typically mastered the skill to a great extent.

Table 1
Means and standard deviations (*SDs*) for demographic indicators, standard test scores, and four-frequency PTA thresholds for children with typical reading abilities and dyslexia.

	8–9 year olds				*10–12 year olds*			
	Typical (21)		*Dyslexic (21)*		*Typical (30)*		*Dyslexic (25)*	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Age (years; months)	8;9	*0;8*	8;9	*0;7*	11;0	*0;8*	11;1	*0;10*
Socio-economic status (out of 64)	37	*10*	31	*14*	33	*13*	30	*15*
Reading Standard Score	108	*12*	91	*6*	107	*9*	89	*8*
Vocabulary Standard Score	113	*13*	103	*14*	112	*14*	100	*17*
Grammaticality Standard Score	110	*9*	100	*7*	105	*11*	88	*12*
Forward Digit Span (number)	4.9	*1.0*	4.4	*0.7*	5.8	*0.9*	4.8	*0.8*
4-freq. PTA Threshold (dB HL))	4.2	*4.3*	2.6	*5.3*	2.1	*5.6*	2.9	*4.0*

Note: Numbers of children in each group are shown in parentheses.

Diagnoses of dyslexia were made at either the child's school or an independent clinical facility by psychologists or speech-language pathologists who specialize in dyslexia diagnoses. Although exact testing done to reach the diagnoses varied, it always included tests of word reading, reading fluency, and reading comprehension. All children with diagnoses of dyslexia were receiving intervention services through their home schools, and in some cases, through private clinics. None of the children with dyslexia had any other diagnosis that would be suspected of causing language delays, such as autism or specific language impairment. Typical children were recruited to participate from the public schools, and were chosen to match as closely as possible the participants with dyslexia on age, gender, and socio-economic status.

For children in both groups, auditory thresholds were measured for octave frequencies from 250 Hz to 8000 Hz, and all children had to have pure-tone average (PTA) thresholds for the four frequencies of 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz of better than 20 dB hearing level in each ear, and no poorer than 25 dB hearing level for each of the other two frequencies. There are five fewer children in the DYS than in the TYP group, for the following reasons: one of these children had a PTA threshold poorer than 20 dB and four children displayed evidence of having a secondary impairment that could affect language development. These four children were generally unable to attend well to the tasks presented. Further questioning of parents revealed that each had been suspected of having additional deficits, but diagnoses were equivocal. Out of an abundance of caution, it was decided these four children may have additional deficits, so would be best dismissed.

Children were further divided into two age groups. Usually children are 9 years old when they finish third grade, and many states in the United States mandate that children must demonstrate a specified level of reading proficiency by the end of third grade in order to be promoted to fourth grade. Based on that common benchmark, children in this study were divided into the age groups of 7 to 9 year olds and 10 to 12 year olds. That age break also coincides with the developmental time when many educational programs end explicit reading instruction on the assumption that by fourth grade typical children have acquired fundamental reading abilities. Table 1 displays mean scores and standard deviations (SDs) for demographic indicators, standard test scores, and PTA thresholds for children in each group, at each age.

The metric of socioeconomic status is one in which parental occupational status and highest educational level are ranked on scales from 1 to 8, from lowest to highest, for each parent in the home. These scores are multiplied together, for each parent, and the highest value obtained for either parent is used as the socioeconomic metric for the family (Nittrouer & Burton, 2005). A score of roughly 30 indicates that at least one parent received a Bachelor's degree, and has a job as a middle manager, teacher, nurse, or equivalent position.

The four standard tests administered were: (1) the word reading subtest of the Wide Range Achievement Test – 4 (WRAT-4; Wilkinson & Robertson, 2006); (2) the Expressive One-Word Picture Vocabulary Test – 4 (EOWPVT-4; Martin & Brownell, 2011); (3) the Grammaticality Judgment subtest of the Comprehensive Assessment of Spoken Language (CASL; Carrow-Woolfolk, 1999); and (4) the Forward Digit Span test of the Wechsler Intelligence Scale for Children – IV (WISC-IV; Wechsler, 2003). The first three of these have standardized mean scores of 100, with standard deviations of 15. Digit span scores are the number of digits for which the child can accurately recall order. Procedures for these tests are described in detail below under the section titled Stimuli and Task-Specific Procedures.

Table 2 shows outcomes of *t* tests performed on all measures displayed in Table 1. Precise significance levels are shown for $p < .10$; when $p > .10$, it is described simply as *not significant* (*NS*). Children in the TYP and DYS groups did not differ from each other on age, socioeconomic status, or PTA thresholds. As expected, children in the TYP and DYS groups did differ significantly on the reading measure, at both ages. And as indicated by the finding that means for the DYS groups were greater than 85, some children in the DYS groups had reading standard scores within the normal range (> 85). Nonetheless, concern that they might not meet criteria for diagnoses of dyslexia did not arise, because they had all reached criteria for dyslexia diagnoses in the past, and were currently receiving intervention. The TYP and DYS groups also differed on the vocabulary and grammaticality measures. Although mean digit spans were lower for the DYS than the TYP groups, this difference was only significant for the older children.

Table 2
Outcomes for *t* tests performed on demographic indicators, standard test scores, and PTA thresholds between children in the typical reading and dyslexic groups at each age.

	8–9 year olds		*10–12 year olds*	
	t	*p*	*t*	*p*
Age (years; months)	0.06	*NS*	0.69	*NS*
Socio-economic status (out of 64)	1.65	*NS*	0.82	*NS*
Reading Standard Score	5.87	< *.001*	7.63	< *.001*
Vocabulary Standard Score	2.17	*.036*	3.01	*.004*
Grammatical Standard Score	4.26	< *.001*	5.68	< *.001*
Forward Digit Span	2.00	*.052*	4.00	< *.001*
PTA Threshold	1.08	*NS*	−0.58	*NS*

Note: Degrees of freedom are 40 for 8–9 year olds and 53 for 10–12 year olds. *NS = not significant*, meaning $p > .10$.

2.2. Equipment

For creation of the sentence materials, recordings were made in a sound booth, directly onto the computer hard drive, via an AKG C535 EB microphone, a Shure M268 amplifier, and a Creative Laboratories Soundblaster soundcard. Testing took place in a sound booth, with the computer that controlled stimulus presentation in an adjacent room. Stimuli were stored on a computer and presented through a Samson headphone amplifier and AKG-K141 headphones. The hearing screening was done with a Welch Allyn TM262 audiometer and TDH-39 headphones. All test sessions were video-recorded using a Sony HDR-XR550V video recorder so that scoring could be done later. Participants wore Sony FM microphones that transmitted speech signals directly to the camera, ensuring good sound quality for all recordings. For digit span, an HP Compaq L2105TM touch-screen monitor was used for responding.

2.3. Materials and task-specific procedures

2.3.1. Speech-in-noise sentence materials

Stimuli for the sentence recognition task consisted of 54 four-word sentences that have been used previously (Nittrouer et al., 2015). All words in these sentences are monosyllabic, and were selected to be within the vocabularies of school-aged children. Sentences are syntactically correct, but lack strong semantic or real-world contextual cues. Fifty of these sentences were used for testing, and another four for training. Examples of these sentences are *Great shelf needs tape* and *Green hands don't sink*. Sentences of this type were selected for presentation because they appropriately utilize word class and morphological markers, and retain syntactic structure. However, they do not provide extensive semantic information, and real-world knowledge does not constrain recognition. Thus, knowledge of simple morphosyntactic structures is the only linguistic or contextual influence on recognition beyond sensory information.

All sentences were recorded by a male talker with a 44.1-kHz sampling rate and 16-bit digitization. The sentences were down sampled to a 20-kHz sampling rate before further processing. The spectra of the voiced portions of all sentences were smeared so that the peaks and valleys of all spectra were only half as distant from the source spectrum as in the original signals. This goal was accomplished using procedures developed earlier (Nittrouer et al., 2015), which involved manipulating the amplitude of individual harmonics. That meant that only voiced portions of the sentences could be manipulated. Voiced signal portions were located by counting zero-crossings in 30-ms time frames, with 10-ms overlap. Stretches in which there were regular zero crossings close to the value estimated based on the talker's fundamental frequency were marked as voiced. All boundaries were subsequently checked by eye. Next, individual pitch periods were located. The fundamental frequency of each pitch period was derived by taking the inverse of that period. The amplitude of each pitch period was recorded, and retained for post-processing reassembly of the signal. Individual harmonics were then divided into separate bins, and the amplitude of each bin computed. Those amplitude values were used to generate the source spectrum by fitting a logarithmic least-squares fit line, as shown in Fig. 1. Next, differences were computed between the amplitude of each harmonic and the value of the source spectrum at that particular point. This difference was decreased by half for each harmonic, such that the amplitude of harmonics greater than the value of the source spectrum at that location was decreased and the amplitude of harmonics less than the value of the source spectrum at that location was increased. Once each pitch period in a sentence was modified in this way, the amplitude of each pitch period was adjusted to match its preprocessing value.

The RMS amplitude of sentences in both the unprocessed and the smeared conditions were equalized, and sentences were embedded in noise shaped to match the long-term average spectrum of the sentence materials, at a signal-to-noise ratio of 0 dB. Twenty five sentences of each kind (unprocessed, or UP, and smeared, or SM) were randomly selected by the software for presentation in noise, creating the UPnoise and SMnoise conditions. After presentation in noise, all 50 sentences were presented in quiet, in the unprocessed form (UPquiet).

Sentences in both the UPnoise and SMnoise conditions were presented together in one block of trials that included sentences of both types. The four practice sentences were presented before testing. Each practice sentence was first presented in quiet and the child was asked to repeat it, and then presented unprocessed in noise, and the child was asked to repeat it. The software randomized the order of presentation of sentences in the UPnoise and SMnoise conditions, such that no more than two sentences in one or the

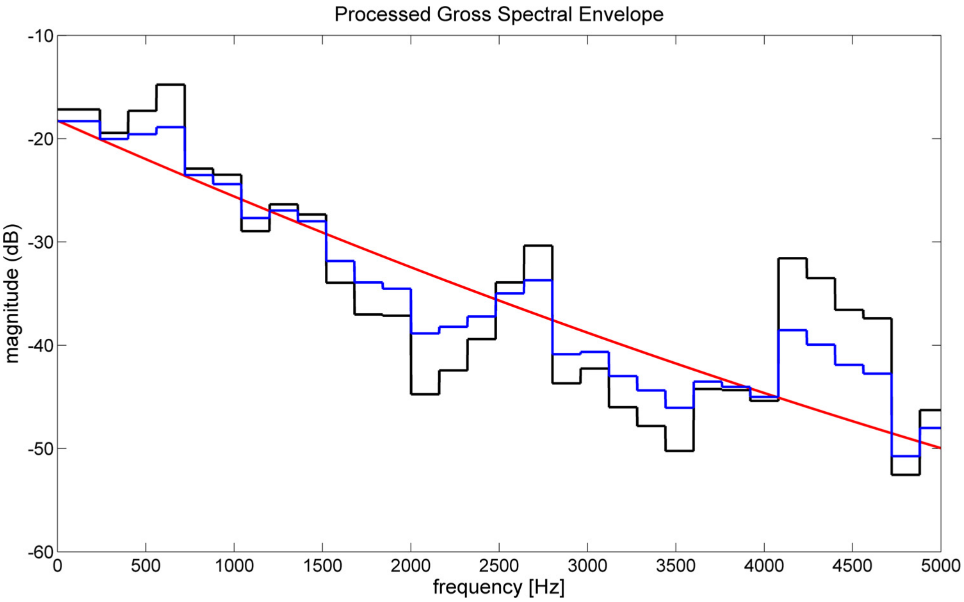

Fig. 1. Spectral envelope showing individual harmonics in one pitch period, before processing (black line) and after processing (blue line). The red line shows the mean spectral slope. (Reprinted from Nittrouer et al., 2015). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

other condition were presented in a row. Participants' responses in both noise and quiet were video recorded, and scored later by the second author. Another member of the staff scored 25% of listeners' responses in each group. Inter-rater reliability was obtained on a word-by-word basis by dividing the number of words on which the two raters agreed by 200, the total number of words in 50 four-word sentences.

2.3.2. *Phonological awareness*

Phonological awareness was assessed with two tasks that have been used previously (e.g., Nittrouer, 1999; Nittrouer & Lowenstein, 2013; Nittrouer et al., 2011). Final consonant choice examined sensitivities to phonological structure, and pig Latin examined facility with manipulating phonological structure. Each task consisted of 48 items that were recorded by a male talker using a 44.1-kHz sampling rate and 16-bit digitization. In the final consonant choice task, a target word is presented auditorily and the child must repeat it correctly. If the child does not repeat it correctly, the target word is repeated. The child is given up to three trials to repeat the target correctly. In this experiment, it never happened that a child was unable to repeat any of the target words correctly. Next, three choice words are presented, and the child must say which of the three words ends with the same sound as the target word. Trials are organized according to increasing difficulty. If the child responds incorrectly on six consecutive trials, ceiling is reached, meaning that it is the presumed limit of the child's abilities. At that point testing is discontinued.

In the pig Latin task, a word is presented auditorily and the child must repeat it correctly. Then the child must generate the pig Latin version of the word. As in the final consonant choice task, three opportunities were provided, if needed, to repeat the target word, but again, no child was unable to repeat even a single target word for this task. Items were organized according to increasing difficulty, and ceiling was reached with six consecutive errors.

Scoring for both phonological awareness tasks was done during testing so that the experimenter could determine when ceiling had been reached, but this testing was also video recorded. Later a laboratory staff member checked all responses.

2.3.3. *Standardized measures*

Four standardized tests were administered. The reading subtest of the WRAT-4 consists of having the child read a list of letters and words from a chart. This task is stopped when the child misses ten consecutive words. Scoring was done at the time of testing, but was also video recorded so that scoring could be checked later by another member of the laboratory staff.

For the vocabulary measure, the EOWPVT-4, children are shown pictures one at a time and must produce the word that labels each picture. Ceiling is reached when the child misses six consecutive items. Scoring was done at the time of testing, but testing was also video recorded so that scoring could be checked later by another member of the laboratory staff.

For the Grammaticality Judgment subtest of the CASL, test items were video recorded for presentation. The child watches the video-recorded materials, consisting of a woman reading sentences. After each sentence the child must state whether it is correct or not. If the child judges the sentence to be incorrect, the child must state what change needs to be implemented to make it correct. Scoring is dependent on whether the sentence is correct or not: if it is correct, one point is given if the child identifies it as correct; if it is incorrect, one point is given if the child identifies the sentence as wrong and another point if the child correctly explains how it can be fixed. Testing is discontinued after five responses on which the child fails to obtain the maximum number of points possible.

Scoring was done at the time of testing, but testing was video recorded so that scoring could be checked later by another member of the laboratory staff.

For the Forward Digit Span test of the WISC-IV, test materials were audio recorded. The child listened to the string of digits, and then all digits from 1 to 9 appeared at the top of the monitor. The child touched the digits in the order recalled. Two strings were presented at each length, starting with two-digit strings. Digit span was defined as the length at which the child could recall at least one string correctly. The software kept track of scoring.

2.4. General procedures

Half of the children in this study were tested at the Ohio State University and half were tested at the University of Florida. All procedures were approved by the Institutional Review Boards of both universities. Equipment was moved from the Ohio State University to the University of Florida, so all testing took place with exactly the same equipment in sound booths.

Testing was completed over two test sessions of roughly one-hour each. After obtaining parental consent and child assent at the first session, the hearing screening was administered, followed by the reading subtest of the WRAT. Next the UPnoise and SMnoise stimuli were presented. Finally, either the phonological awareness or the digit span task was presented, with half of the children being presented with each. In the second session, either the digit span task or the phonological awareness tasks were presented first, depending on which the child had not done at the first session. Next, children heard the sentences in quiet. Finally, the expressive vocabulary and grammaticality judgment tasks were administered.

3. Results

3.1. Explaining variability in reading performance

The first objective of the statistical analyses was to assess whether phonological deficits explained reading performance for these children. Two measures of phonological awareness had been obtained: final consonant choice and pig Latin. In addition, individual means across these two measures for each child were computed (PAmean). Fig. 2 shows performance for each group on these three separate measures. Mean scores were higher for the older than for the younger children in each reading group (TYP and DYS), but the age effect does not appear as strong as the effect of reading group. Clear differences can be observed between children in the TYP and DYS groups at each age, for all three measures, with the strongest differences apparent for PAmean. Consequently, this composite measure was used as the index of phonological awareness in further analyses. Screening of these scores revealed adequate homogeneity of variances and a normal distribution. Thus, no transformation was required.

In order to assess the basis of reading skill across age and reading groups, raw scores were used for all measures being evaluated as potential predictor measures. Fig. 3 displays these raw scores for vocabulary, grammaticality, and digit span. Table 3 shows outcomes of two-way Analyses of Variance (ANOVAs) performed on PAmean and each of these measures, with age group and reading group as between-subjects factors. None of these analyses resulted in a significant interaction, so only outcomes for main effects are shown. All measures show significant age and reading group effects. Table 4 shows effect sizes, given as Cohen's *ds* for differences between children in the TYP and DYS groups, for each age group separately. PAmean shows the largest effects, while vocabulary shows the smallest effects. Grammaticality shows the second largest effects, perhaps reflecting the relationship between sensitivity to phonological structure and knowledge of bound morphemes.

The contribution of each of these four measures to reading ability was assessed by computing Pearson product-moment

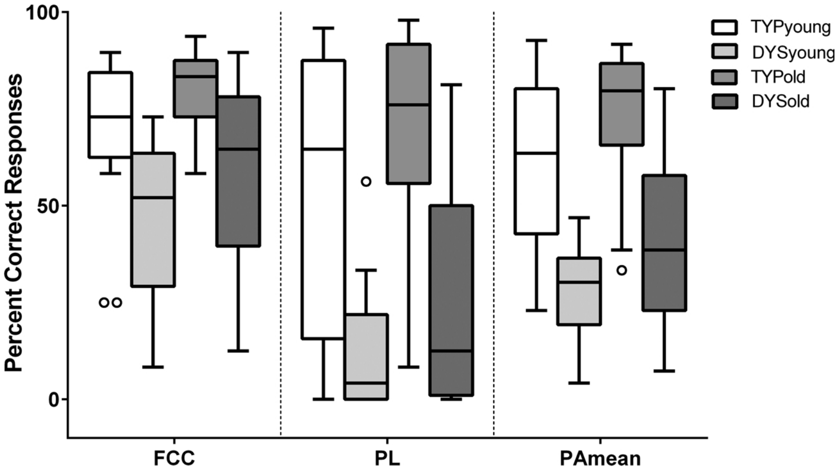

Fig. 2. Median and interquartile ranges of scores on three measures of phonological awareness: final consonant choice (FCC); pig Latin (PL); and individual means of those two measures (PAmean).

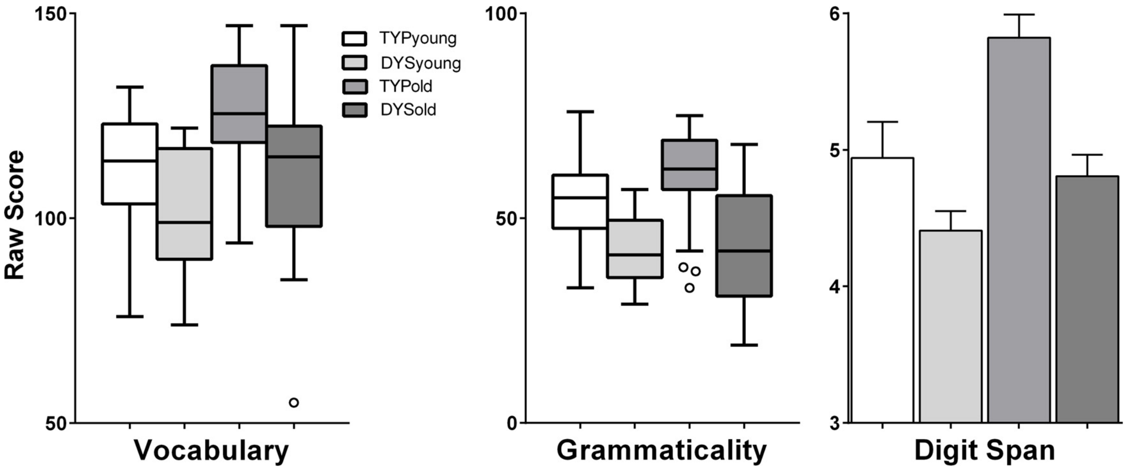

Fig. 3. Median and interquartile ranges of two potential predictor measures of reading ability (vocabulary and grammaticality), as well as means and standard errors for one other potential predictor (forward digit span).

Table 3
Outcomes for Analysis of Variance performed on potential predictor variables, using raw scores.

	Age Group		*Reading Group*	
	F	*p*	*F*	*p*
PAmean	12.38	*.001*	79.02	< *.001*
Vocabulary	13.05	< *.001*	11.05	*.001*
Grammaticality	3.86	*.053*	37.91	< *.001*
Digit Span	14.26	< *.001*	17.20	< *.001*

Note: Degrees of freedom are 1,93 for all effects.

Table 4
Effect sizes, given as Cohen's *d*, for differences between TYP and DYS groups.

	Young	Old
PAmean	1.90	1.74
Vocabulary	0.58	0.75
Grammaticality	1.23	1.34
Digit Span	0.62	1.09

correlation coefficients between reading raw scores and these measures across all children. The use of raw scores meant that any developmental effects would be handled, because unlike standard scores, raw scores typically increase with age. Each of the four predictor variables was significantly related to the reading raw scores, with $p < .001$: PAmean, $r = .767$; vocabulary, $r = .652$; grammaticality, $r = .708$, and digit span, $r = .529$. Next, a stepwise multiple regression was performed with reading raw scores as the dependent measure and the other four scores as predictor variables. In this analysis, two predictor variables were found to explain significant amounts of unique variance: PAmean, $\beta = .588$, $p < .001$, and vocabulary, $\beta = .354$, $p < .001$. This solution was obtained with both forward selection and backward elimination.

Because phonological awareness had been expected to be the strongest predictor of reading, and it showed the largest effect of reading group, its relationship to reading was explored further. Fig. 4 shows this relationship between reading skill and sensitivity to phonological structure, across all groups. Clearly, children with the best reading scores had the strongest phonological awareness, while children with the lowest reading scores had the poorest phonological awareness. In fact, Fig. 4 reveals that there was little overlap between children in the TYP and DYS groups regardless of age, and none whatsoever between children in the TYPold and DYSyoung groups. Thus, all evidence supports the conclusions that phonological awareness explained reading ability across groups, and groups were well separated on these two measures.

Nonetheless, patterns of relationship observed across groups may not be the same patterns observed within each group. Here we see that variability in phonological awareness strongly accounts for differences in reading ability across groups, but other factors could account for within-group variability for each of those subgroups. To assess that possibility, separate stepwise regressions were performed for each of the four groups, with reading raw scores as the dependent measure and the other four measures as predictor variables. For the young groups, PAmean alone explained the largest proportion of within-group variability: for TYPyoung, $\beta = .670$,

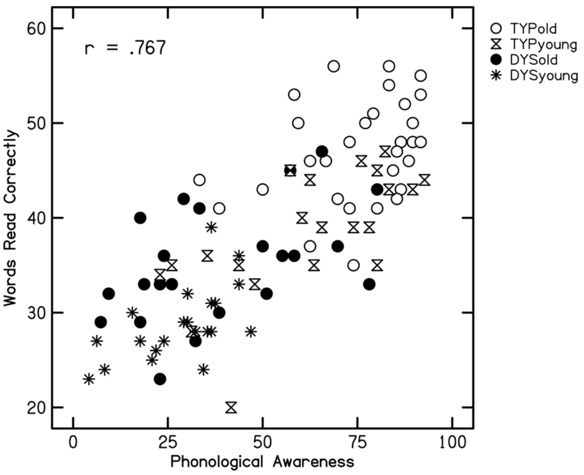

Fig. 4. Scatter plot depicting relationship between phonological awareness and word reading.

p = .001; for DYSyoung, β = .593, *p* = .005. These solutions were obtained with both forward selection and backward elimination. Thus, for these young children still in the throes of learning to read, sensitivity to phonemic structure explained the largest amount of variability across individual children. However, other factors were found to be associated with the largest proportion of within-group variability for the older groups: For TYPold, vocabulary alone was associated with the most variability, β = .548, *p* = .002, and this solution was obtained with forward selection and backward elimination. For DYSold, grammaticality alone was associated with the most variability when forward selection was used, β = .716, $p < .001$; when backward elimination was employed, grammaticality still explained the largest amount of unique variance, β = .463, *p* = .029, but vocabulary was also a component of the final model, β = .356, *p* = .087. Thus, for older children language functions other than phonological awareness were associated with word reading abilities. However, these results do not necessarily indicate causality. In particular, for these older children who had reached the age where they were "reading to learn" – even if at lower than age-appropriate levels – these regression outcomes may indicate how reading has affected their vocabulary or grammatical knowledge.

In summary, phonological awareness was found to be the strongest predictor of overall reading ability. For younger children, this relationship was found to explain within-group variability, as well; for older children, other language factors were associated with within-group variability.

3.2. *Explaining variability in speech-in-noise sentence recognition*

Average agreement in scores for sentence recognition across the first and second scorers was .969 (SD = .012), which was considered good reliability. The scores of the first scorer were used in all subsequent analyses.

Examination of the scores for sentence recognition revealed normal distributions and homogeneity of variance for scores in the two noise conditions, but a negatively skewed distribution for scores in the UPquiet condition, reflecting the fact that many scores were near 100% accuracy. As a result, arcsine transformations were applied to sentence recognition scores in all three conditions. Although scores for the SMnoise and the UPnoise conditions were not near 100% accuracy, so did not necessarily require transformations, these transformed scores were used across conditions for consistency. Examination of these transformed scores revealed homogeneity of variances and normal distributions, in all conditions.

First, recognition in quiet was examined. Fig. 5 displays mean untransformed recognition scores in quiet, and shows that children in the DYS groups were not as close to 100% accuracy as children in the TYP groups. A two-way ANOVA was performed on these scores, with age and reading group as between-subjects factors. Outcomes revealed a significant effect of reading group only, *F*(1,93) = 23.25, $p < .001$, $\eta^2 = .200$. Thus, children in the DYS groups were somewhat poorer at speech recognition in quiet than children in the TYP groups. Nonetheless, mean scores were all better than 90% correct, which should be sufficiently high to allay any concerns that outcomes for speech recognition in noise would be due to children being unable to recognize the sentences in quiet.

Turning attention to scores for speech recognition in noise, Fig. 6 displays mean untransformed scores. From this figure it is clear that children in the DYS groups performed more poorly than children in the TYP groups. A three-way, repeated-measures ANOVA was performed on these scores, with condition as the repeated measure (SMnoise or UPnoise), and age and reading group as the between-group factors. Results showed significant main effects of condition, *F*(1,93) = 45.05, $p < .001$, $\eta^2 = .326$, and reading group, *F*(1,93) = 15.00, $p < .001$, $\eta^2 = .139$. No significant effect of age group was found, and there were no significant interactions. Consequently, it must be concluded that the effect of spectral smearing was similar across reading groups. Even though children in the DYS groups had lower overall recognition scores, they were not disproportionately affected by the spectral distortion of the smeared signals. Furthermore, it is apparent that the magnitude of the effect of reading group for speech recognition in noise is similar to the magnitude of that effect for speech recognition in quiet.

The next question asked was whether any of the language or cognitive measures could explain the poorer speech recognition in

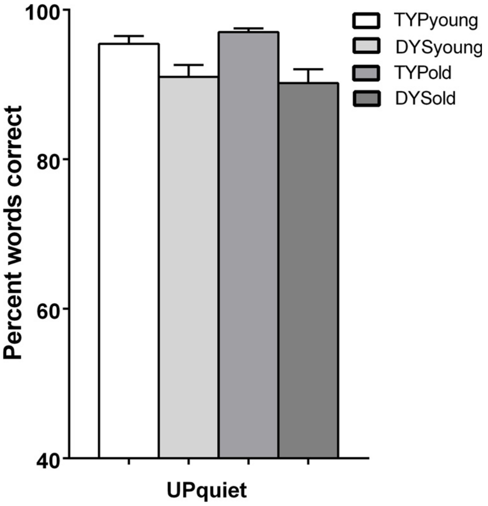

Fig. 5. Mean percent correct speech recognition in quiet, and standard errors.

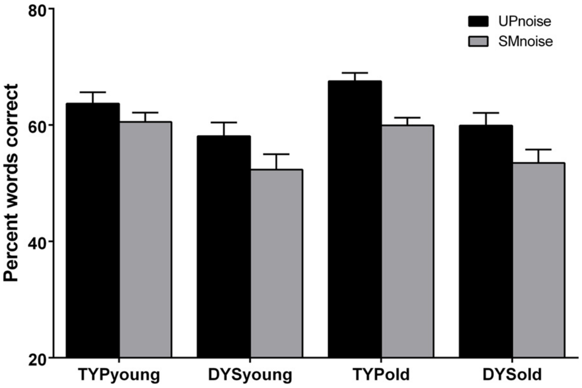

Fig. 6. Mean percent correct speech recognition in noise for unprocessed signals and signals with spectral smearing, with standard errors.

noise by children with dyslexia. Is the source of this effect the same as the source of their poor reading abilities, which were traced back largely to poor phonological awareness? To address these questions, Pearson product-moment correlation coefficients were computed between speech recognition scores, and the four measures incorporated into the study as potential predictors of reading ability. Scores for the UPnoise condition were used in these analyses, which seemed most appropriate given that the original goal of the study was to examine factors accounting for poor speech recognition in noise by children with dyslexia.

Each of the four predictor variables was significantly related to the UPnoise scores, with $p < .001$: PAmean, $r = .421$; vocabulary, $r = .657$; grammaticality, $r = .656$, and digit span, $r = .475$. Thus, it appeared that general language functions, and even short-term memory, help to explain children's abilities to recognize speech in noise. Unlike reading ability, however, phonological awareness did not explain the largest proportion of variability in speech recognition in noise. Instead, vocabulary skill and grammaticality appear to explain the most and roughly equal amounts of variability. This observation was confirmed when a stepwise multiple regression was performed with UPnoise scores as the dependent measure and the other four scores as predictor variables. Both vocabulary and grammaticality were found to explain significant amounts of unique variance in the UPnoise scores: vocabulary $\beta = .378$, $p = .001$, and grammaticality $\beta = .374$, $p = .001$. Phonological awareness and digit span did not. This solution was obtained with both forward selection and backward elimination. Figs. 7 and 8 show the relationships between UPnoise scores and vocabulary and grammaticality, respectively. Unlike the relationship between reading and phonological awareness shown in Fig. 4, however, there is considerable overlap among scores for children in the four groups.

In spite of the overlap among groups in scores, it was again possible that relationships among measures could be different for separate groups of children than for the entire sample. To examine this possibility, separate stepwise regression analyses were performed. In this case, however, participants were grouped according to reading abilities only, because significant effects of age on speech recognition in noise were not observed. Once again, UPnoise scores were the dependent measure and the other four measures were predictor variables. Outcomes for both reading groups conformed to what had been observed across groups, and what is shown in Figs. 7 and 8. For the TYP group, vocabulary alone explained the most variability using forward selection, $\beta = .579$, $p < .001$; with backward elimination, the solution included both vocabulary, $\beta = .335$, $p = .054$, and grammaticality, $\beta = .328$, $p = .059$. For

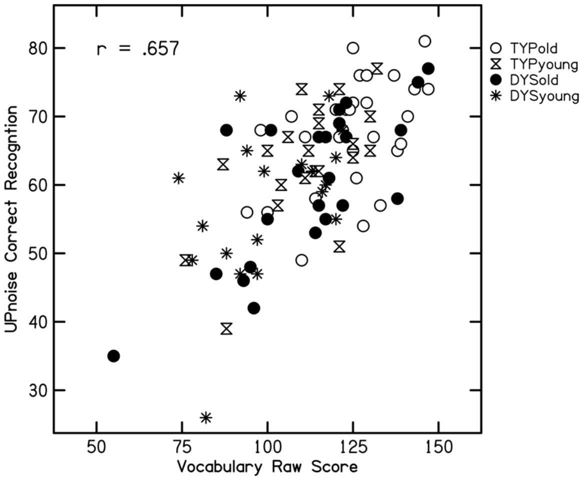

Fig. 7. Scatter plot depicting relationship between vocabulary and speech recognition in noise for unprocessed signals.

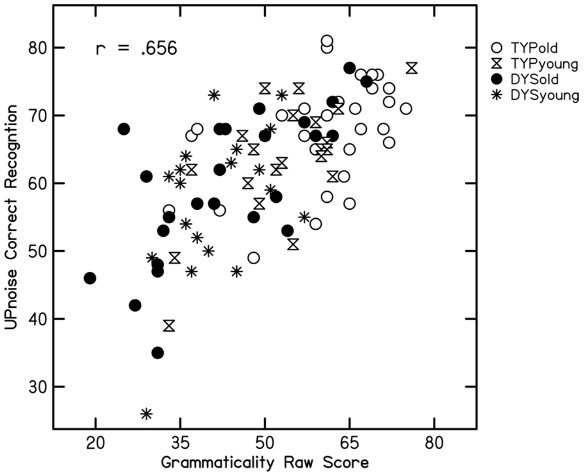

Fig. 8. Scatter plot depicting relationship between grammaticality and speech recognition in noise for unprocessed signals.

the DYS group, both vocabulary, β = .402, *p* = .013, and grammaticality, β = .344, *p* = .032, explained significant amounts of unique variability in the UPnoise scores, regardless of whether forward selection or backward elimination was employed.

Although speech recognition in noise was the central interest in this study, the finding that vocabulary and grammaticality were the strongest predictors for that recognition raised the question of what accounted for speech recognition in quiet. Was it possible that phonological awareness was not found to be a significant predictor precisely because of the noise masking, which might make it difficult for the children to recover phonological structure, or are these relationships the same as what is found for speech recognition in quiet? In order to answer that question, a stepwise regression was performed, using speech recognition scores in quiet as the dependent measure and the same four predictor variables as have been used in all these analyses. As was found for speech recognition in noise, only vocabulary and grammaticality were found to explain significant portions of unique variance: vocabulary, β = .458, *p* = .013, and grammaticality, β = .398, *p* = .032. This solution was obtained with both forward selection and backward elimination.

3.3. One factor or two

Overall, reading and speech recognition in noise appear to be based on different underlying skills, with reading ability largely explained by a child's sensitivity to phonological structure and speech recognition in noise explained by the size of a child's vocabulary and knowledge of grammar. However, a question of interest in this study was whether the deficits exhibited by the children with dyslexia for reading and speech recognition in noise were strongly related. To examine that question, a Pearson product-moment correlation analysis was performed on raw reading scores and recognition scores for the UPnoise condition, from the children with dyslexia. This correlation coefficient was found to be only .307, *p* = .038. That means that these two measures had only 9% of their variance in common.

It is perhaps relevant that the magnitude of the differences in abilities between children in the TYP groups and children in the DYS groups differed for phonological and lexical skills. Across age groups, Cohen's *d* for PAmean was 1.83, indicating that children in the DYS group had a mean score almost two standard deviations below the mean score of children in the TYP group. However, Cohen's *d* for vocabulary was only 0.67, indicating that although children in the DYS group had poorer vocabularies, this deficit was not nearly as severe as that observed for phonological skills. Furthermore, these effect sizes are proportional to those found for reading and speech recognition in noise: Across age groups, Cohen's *d* for the difference in reading for the TYP and DYS groups was 1.89, while the Cohen's *d* for the difference in UPnoise recognition scores was 0.67. In both cases, the effect size of the group difference for the dependent measure matched that of its most significant predictor variable. This finding provides further evidence for the suggestion that keen sensitivity to phonological structure is required in order to develop reading skill, but vocabulary abilities strongly impact an individual's ability to recognize speech in noise. Thus, reading and speech recognition in noise are based on sensitivity to different levels of linguistic structure.

4. Discussion

The study described here was undertaken to examine potential sources of variability in two problems faced by children with dyslexia, and two hypotheses were examined. First, the possibility was considered that children with dyslexia have spectral processing deficits. If support was obtained for this hypothesis, these deficits could provide a unifying basis for two problems facing children with dyslexia: (1) poor sensitivity to phonological structure, because many acoustic cues to phoneme identity are spectral in nature and spectral processing deficits would result in smeared signals; and (2) greater susceptibility to noise masking in speech recognition, because poor spectral processing would exacerbate the effects of noise. Because poor phonological awareness is often the source of reading disability, as it was found to be here, a finding of poor spectral processing could explain why reading and speech-recognition-in-noise problems co-occur for children with dyslexia.

The second hypothesis considered was that reading and speech recognition in noise are separable phenomena, both of which can be impaired in this population, but are not necessarily related. The reading deficit of children with dyslexia is what defines this population. However, it may be that these individuals have more generalized deficits, and various communication functions are affected by those deficits to varying extents across those individuals.

4.1. Spectral processing deficit

Regarding the first hypothesis, no strong evidence was obtained to support the claim that poor spectral processing might explain the reading deficits of children with dyslexia. Children with dyslexia were poorer at recognizing speech in noise than were children without dyslexia, but they were also poorer at recognizing speech in quiet. Furthermore, children with dyslexia were not disproportionately affected by the spectral distortion introduced by the smeared signal, as would have been expected if they had spectral processing deficits. Thus, the only evidence suggesting that children with dyslexia might have any sort of suprathreshold auditory processing disorder – whether specifically with spectral structure or otherwise – is that their overall recognition was poorer than that of children without dyslexia.

Over the years, several different auditory problems have been investigated as potential sources of the deficits faced by individuals with dyslexia, including temporal processing disorders (Merzenich et al., 1996; Tallal, 1980, 1984), backwards masking difficulties (Wright et al., 1997), and poor sensitivity to relatively slow amplitude change over time (Goswami et al., 2011). None of these problems would necessarily be expected to originate in the periphery, and that may be one lesson from the current study: The deficits of children with dyslexia may be perceptual in origin, but not necessarily related to peripheral auditory processes. Further investigation will need to examine other candidate perceptual problems.

One potential explanation has been offered by Nittrouer and Lowenstein (2013), who proposed that the difficulties in speech recognition exhibited by children with dyslexia are not the result of faulty auditory processing, but rather with a perceptual disorder more cognitive in nature. Accurate perception requires that sensory signals be organized in some way. With clear sensory signals, there is little uncertainty regarding how these signals should be organized. As signals become more ambiguous, more uncertainty can arise concerning how those signals should be organized. Nittrouer and Lowenstein found that children with dyslexia were significantly impaired in their abilities to recognize speech signals degraded by noise vocoding, leading these authors to conclude that children with dyslexia have deficits in perceptual organization, meaning that they appear not to organize signals appropriately. The current results are commensurate with that suggestion, and if accurate, it could explain the lack of agreement across studies. It could be that speech perception deficits are most clearly observed when the signal degradation is of a nature and severity that increases the need for appropriate perceptual organization strategies.

4.2. Independence of reading and speech perception deficits

Children with dyslexia were found to have deficits on all language and cognitive measures obtained. Nonetheless, reading and speech recognition in noise were not strongly correlated, nor did these skills seem to depend on a singular underlying language function. Reading appeared to depend strongly on phonological sensitivity, whereas speech recognition in noise was strongly related to lexical and grammatical abilities. These findings suggest that reading and speech recognition make use of different levels of linguistic structure, with speech recognition in noise dependent on lexical structure – or whole words – and reading more dependent on word-internal structure. This suggestion matches proposals of some linguists, including Port (2007), who contends that phonological structure is not utilized for most language functions, including long-term lexical representations. Although speech recognition in noise was the focus of this experiment, the analysis performed using speech recognition in quiet as the dependent measure supports the general suggestion being offered here.

One prominent model of language development proposes that children's earliest entries in the lexicon are not structured phonologically, but rather are based on more “global” structure (e.g., Charles-Luce & Luce, 1990; Menn, 1978; Menyuk & Menn, 1979; Vihman, 1996; Waterson, 1971, 1987). The nature of this structure is not well specified in these accounts, but should be described in both acoustic and linguistic terms. In acoustic terms, global structure would likely refer to relatively slow patterns of broad spectral change that arise as a consequence of changes in vocal-tract shape (Nittrouer, 2006). In linguistic terms, early lexical entries are likely based on something larger than the phoneme, such as the whole word. It is not until later – during the preschool years – that sensitivity to acoustic details affiliated with specific phonemic segments begins to emerge. Several models of lexical development suggest that at this time the lexicon is restructured according to phonological units, and new items to the lexicon are entered with a phonological code (Charles-Luce & Luce, 1990; Storkel, 2002; Walley, 1993). Based on this proposed model, children with dyslexia could be viewed as severely delayed in this process of discovering word-internal phonological units. This suggestion would explain why children with dyslexia were found to be closer in abilities to children with typical reading skills on lexical than on phonological abilities: they were able to acquire lexical items with the coarse code used by younger children, but were impaired in restructuring these lexical items or acquiring new items with the presumably more efficient phonological code.

4.3. Summary

In summary, the current study was undertaken to examine whether evidence could be found for the hypothesis that a spectral processing disorder might account for the reading and speech-in-noise recognition problems exhibited by children with dyslexia, or if these two problems are largely independent, although co-occurring. In the end, no evidence beyond the finding of poorer speech recognition in children with dyslexia than in those without dyslexia was obtained to support the hypothesis that children with dyslexia have a spectral processing disorder that could be the source of their problems. And although both reading and speech recognition in noise were impaired for the children with diagnoses of dyslexia, performance on these skills was not correlated, and ability for each skill was related to different underlying factors for children in the two groups. These findings suggest that dyslexia may represent a broader based deficit than one solely associated with reading.

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