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Perceptual organization of speech signals by children with and without dyslexia

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Abstract

Developmental dyslexia is a condition in which children encounter difficulty learning to read in spite of adequate instruction. Although considerable effort has been expended trying to identify the source of the problem, no single solution has been agreed upon. The current study explored a new hypothesis, that developmental dyslexia may be due to faulty perceptual organization of linguistically relevant sensory input. To test that idea, sentence-length speech signals were processed to create either sine-wave or noise-vocoded analogs. Seventy children between 8 and 11 years of age, with and without dyslexia participated. Children with dyslexia were selected to have phonological awareness deficits, although those without such deficits were retained in the study. The processed sentences were presented for recognition, and measures of reading, phonological awareness, and expressive vocabulary were collected. Results showed that children with dyslexia, regardless of phonological subtype, had poorer recognition scores than children without dyslexia for both kinds of degraded sentences. Older children with dyslexia recognized the sine-wave sentences better than younger children with dyslexia, but no such effect of age was found for the vocoded materials. Recognition scores were used as predictor variables in regression analyses with reading, phonological awareness, and vocabulary measures used as dependent variables. Scores for both sorts of sentence materials were strong predictors of performance on all three dependent measures when all children were included, but only performance for the sine-wave materials explained significant proportions of variance when only children with dyslexia were included. Finally, matching young, typical readers with older children with dyslexia on reading abilities did not mitigate the group difference in recognition of vocoded sentences. Conclusions were that children with dyslexia have difficulty organizing linguistically relevant sensory input, but learn to do so for the structure preserved by sine-wave signals before they do so for other sorts of signal structure. These perceptual organization deficits could account for difficulties acquiring refined linguistic representations, including those of a phonological nature, although ramifications are different across affected children.

1. Introduction

Developmental dyslexia is a relatively common disorder that can evoke a significant toll on affected individuals in terms of career, behavior, and social satisfaction (Chapman, Tunmer,

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& Allen, 2003; Snowling, Muter, & Carroll, 2007; Terras, Thompson, & Minnis, 2009). Nonetheless, the mechanism underlying this disorder has remained elusive to identification. At one time it was thought to arise from visual disturbances, specifically problems affiliated with the recognition of written symbols (e.g., Hinshelwood, 1900; Orton, 1937; Stephenson, 1907). In the 1970s, however, a major shift in paradigm occurred when I. Liberman, Shankweiler, and their colleagues at Haskins Laboratories revealed that children with dyslexia are poor at recovering and manipulating individual phonemic segments in the speech signal (e.g., Liberman, 1973; Shankweiler & Liberman, 1972; Shankweiler, Liberman, Mark, Fowler & Fischer, 1979). With that discovery, dyslexia changed from being within the purview of a visual disorder to being seen as a problem related to the processing of spoken language.

The work of I. Liberman and others actually grew out of basic research on the mechanisms that underlie speech perception that was being done by A. Liberman and colleagues at the Haskins Laboratories. Around the mid-twentieth century, the common wisdom was that speech signals are comprised of isolable units, known as phonemes. Because most speakers of a language are able to separate the speech they hear into strings of these units, it was natural to conclude that phonemes are present in the signal in transparent and serial fashion. In turn, these phonemes serve as the building blocks of all other linguistic structure, such as words and sentences – according to the common wisdom. In his book recounting the history of Haskins Laboratories, A. Liberman (1996) explains that one of the first goals of laboratory staff was to develop a reading machine for the blind. Based on the common view, scientists thought it would be a fairly straightforward task to uncover the acoustic correlates of phonemic segments, and invent a device that would translate letters on a page into series of acoustic elements, each designed with those correlates set to specify the intended phoneme. But it soon became evident that the task would not be so simple. The speech spectrograph was the technological device that revealed what would become the largely intractable problems facing speech perception researchers. This tool allowed scientists for the first time to display speech signals on time × frequency plots. The two major challenges to the common view (that phonemes are represented serially in the speech signal) became immediately apparent, and sometime later were described by Pisoni (1985) as the problems of segmentation and acoustic invariance. Both problems are illustrated in Figure 1, showing spectrograms of the word *bug* spoken by a man and a child. The problem of segmentation is exposed by the fact that it would be impossible to draw lines perpendicular to the time axis indicating where one phoneme ends and the next begins. Regarding the problem of acoustic invariance, these spectrograms illustrate how different the acoustic structure of this word is for the two speakers.

These problems led A. Liberman and colleagues to propose that speech is a code, rather than a cipher (Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967). In a cipher, there would be clear and unique acoustic correlates to each phoneme. The term *code*, on the other hand, specifies that there is considerable lack of correspondence between the units to be recovered (the phonemes in this case) and the way they are represented in the medium (the acoustic structure in this case). This lack of transparency means that listeners are required to perform some kind of perceptual feat to extricate the phonemes, a process that was termed *decoding*. That terminology was later extended to the process of reading, where the translation from orthographic symbols to phonemes is known as decoding, and the major chore facing children learning to read is described as *breaking the code* (e.g., Shaywitz, 2005).

1.1. Problems breaking the code define developmental dyslexia

Not long after the discovery by I. Liberman and colleagues, research was undertaken to try to identify the source of the problems facing individuals with dyslexia. One of the first findings from that work was that individuals with dyslexia have relatively unrefined phonemic representations, demonstrated by shallow category boundaries for synthetic speech stimuli that vary along some acoustic dimension (e.g., Bogliotti, Serniclaes, Messaoud-Galusi, & Sprenger-Charolles, 2008; Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Hazan & Barrett, 2000; Manis et al., 1997; Werker & Tees, 1987). At the same time, individuals with dyslexia in these studies demonstrated better than average discrimination of stimuli belonging to a single phonemic category (Serniclaes, Sprenger-Charolles, Carre, & Demonet, 2001), leading to the suggestion that individuals with dyslexia may actually recognize individual allophones (Serniclaes, Van Heghe, Mousty, & Carre, 2004). These studies shared the perspective that the source of difficulty for individuals with developmental dyslexia could be found in how they process the spectro-temporal details of the acoustic signal in order to judge phonemic categories.

An alternative explanation for the problems faced by individuals with dyslexia was offered by Tallal, who proposed that the difficulty rests with the rate of arrival of relevant sensory information (Tallal, 1980; Tallal & Piercy, 1973a; 1973b; 1974). This hypothesis was a shift in paradigm because the focus was not strictly on phonemic segments and the relatively stable acoustic correlates of those segments. Instead the locus of effect was placed on formant transitions, which are sections of spectral structure that arise when a speaker moves from a consonant target to a vowel target, or vice versa. When the frequencies of these formants change rapidly, the account proposed, children with dyslexia are unable to keep up. An important aspect of that explanation was that the problem is not specific to speech signals; rather it was proposed that children with dyslexia have a generalized problem processing any sensory information that arrives rapidly (Farmer & Klein, 1995; Merzenich et al., 1996; Miller & Tallal, 1996; Tallal, 1994).

This account was soon challenged by several investigators. Many of these scientists simply failed to replicate the finding of poorer discrimination of rapidly arriving acoustic signals for children with dyslexia than for those without dyslexia (e.g., Marshall, Snowling, & Bailey, 2001; Nittrouer, 1999; Ramus et al., 2003; Share, Jorm, MacLean, & Matthews, 2002; Waber et al., 2001). Neither was any benefit found to slowing down the signal (McAnally, Hansen, Cornelissen, & Stein, 1997), which should have been an automatic corollary to the temporal deficit account. Still others disagreed with the notion that a deficit in discrimination of nonspeech signals can explain anything about speech perception. Instead it was suggested that phonetic similarity is the source of the problem for children with dyslexia (Mody, Studdert-Kennedy, & Brady, 1997). In particular, several studies showed that when it comes to formant transitions, children with dyslexia are at least as sensitive as children without dyslexia to this property (Boada & Pennington, 2006; Goswami, Fosker, Huss, Mead, & Szücs, 2011; Mody et al., 1997; Nittrouer, 1999), thus refuting the argument that children with dyslexia have problems with this particular kind of signal structure.

But even though the exact nature of the perceptual deficit experienced by children with dyslexia might not have been captured by the temporal deficit account, the general idea that these children experience some kind of perceptual problem has been broadly embraced by scientists. As a consequence, others have continued the search for the precise problem. For example, Wright et al. (1997) reported that children with dyslexia experience greater backwards masking effects than children without dyslexia. As with Tallal’s work, however, the demonstration of that deficit was proffered using nonspeech signals, and a later study revealed that the problem with those stimuli could not explain speech perception deficits (Rosen & Manganari, 2001).

Another proposal offered is that children with dyslexia experience difficulty recognizing the relatively slow amplitude modulations in the range associated with vocal-tract opening and closing (e.g., Goswami et al., 2002; Lorenzi, Dumont & Füllgrabe, 2000). Typical listeners require consistent depth of amplitude modulation in the range of fluctuations affiliated with that opening and closing to detect the modulation. As rate increases above the typical limit (e.g., 16 Hz), the depth of fluctuation required for listeners to recognize modulation increases (Viemeister, 1979). Children with dyslexia, on the other hand, require greater depth of modulation than either typical children or adults in the low-rate modulations (Lorenzi et al., 2000). Supporters of the slow-modulation deficit account propose that this deficit would affect speech perception by making it difficult to recover linguistic structure, including prosodic, syllabic, and segmental structure (e.g., Corriveau, Goswami, & Thomson, 2010; Goswami, Gerson, & Astruc, 2010; Poelmans et al., 2011; Richardson, Thomson, Scott, & Goswami, 2004; Rocheron, Lorenzi, Füllgrabe, & Dumont, 2002).

Still other investigators have looked at sensitivity to frequency modulation in the signal for a potential explanation of developmental dyslexia. As with slow-rate amplitude modulations, some studies have shown that individuals with dyslexia require greater changes than individuals without dyslexia to detect changes in frequency. These group differences have been found to be statistically significant for adults (Witton et al., 1998; Witton, Stein, Stoodley, Rosner, & Talcott, 2002), but not for children (Vandewalle, Boets, Ghesquière, & Zink, 2012). Again, much of this work has involved nonspeech signals.

1.2. Recognizing degraded signals

In addition to evidence of the kinds of auditory deficits described above, children with dyslexia have been observed to have poor recognition of speech signals that are in any way degraded. In particular, they are worse than children without dyslexia at recognizing speech in noise. One of the first demonstrations of this difference was reported by Brady, Shankweiler, and Mann (1983), who examined recognition in noise of words and environmental sounds by children with and without dyslexia. Children in both groups were able to recognize the words and sounds presented in quiet with little error. With the addition of noise, recognition of environmental sounds declined by a similar amount for both groups, but recognition of words showed a greater decline for the children with dyslexia than for the children without dyslexia. That finding has been replicated for children (e.g., Ziegler, Pech-Georgel, George, & Lorenzi, 2009), but not for adults (Hazan, Messaoud-Galusi, Rosen, Nouwens, & Shakespeare, 2009). Furthermore, it has been observed that children with dyslexia are poorer at speech recognition than children without dyslexia when speech is degraded through signal processing strategies, such as noise vocoding (e.g., Johnson, Pennington, Lowenstein, & Nittrouer, 2011). In general, such findings are interpreted as consequences of the poor sensitivity these children demonstrate for various forms of structure in the acoustic signal.

1.3. Perceptual Organization

The studies reviewed above are just a sampling of the numerous investigations being conducted across laboratories on potential auditory processing deficits in children with dyslexia. Efforts continue, primarily investigating what may be called slowly changing structure in acoustic signals. Most of these efforts involve nonspeech stimuli, and show that children with dyslexia are generally less sensitive to slowly changing structure in both the amplitude and frequency domains. Several reviews of this work are available, including those by Hämäläinen, Salminen, and Leppänen (2012), Poelmans et al. (2011) and Vandewalle et al. (2012). The broad conclusion of these studies is that a lack of sensitivity to the kind of acoustic structure in the speech signal that specifies linguistic structure, including structure important to identifying phonemes, underlies dyslexia.

The current study tested an alternative hypothesis. The accounts described above all invoke, perhaps implicitly, what may be considered traditional views of speech perception in which the process is modeled largely as an input-output system: Acoustic structure in the speech signal serves as the input to the system, and discrete phonemes are the output. Accordingly, a lack of sensitivity to structure in the input can account for deficient representations at output. The model tested in the current study examined a different phenomenon, one having to do with how the sensory evidence recovered at input gets organized.

Two kinds of processed signals have primarily been used to study perceptual organization for speech: sine-wave and noise-vocoded replicas. Each of these kinds of signal processing recovers and represents a different sort of structure in the speech signal, as seen in Figure 2. Sine-wave replicas recover the spectral fluctuations created by the continuously changing pattern of vocal-tract size and shape. This kind of structure is exactly the same as formant transitions, which have been studied extensively as cues to phonemic categories. However, sine-wave replicas of speech, as they are implemented in most perceptual studies, typically capture that structure on longer time scales by representing structure across whole words or sentences.

Noise-vocoded signals preserve a different kind of structure found in the speech signal. Typically, it is described as being the same as that represented in the amplitude-modulated signals used to measure sensitivity to temporal envelopes by investigators such as Lorenzi et al. (2000). But that latter structure involves the whole waveform, and in terms of speech production, is affiliated with the slow modulations of vocal-tract opening and closing. In generating noise-vocoded replicas of speech, it is the case that the amplitude-modulated structure across a broad swath of frequencies is recovered, but not across the entire spectrum. Instead, the spectrum is divided into some small number of frequency channels, usually four or eight. Then, amplitude structure over time in each of those channels (i.e., temporal envelopes) is recovered and used to modulate noise limited to the same frequency bands. At the level of each band, these signals are appropriately described as strictly amplitude modulated signals. However, when the signal is summed across those bands, the structure that results is more appropriately described as representing the continuously changing, broad spectral shapes affiliated with vocal-tract filters, known as the gross spectral envelope. In one sense, it is similar to what is represented by sine-wave replicas. The difference between the two types of signals is that sine-wave replicas present clear time-varying, but spectrally narrow representations of the first three formant frequencies, whereas noise-vocoded signals provide broad and greatly smeared frequency structure. As these signals are typically generated, both retain the low-frequency amplitude modulations associated with vocal-tract opening and closing. Consequently, if that is the locus of the perceptual problem for children with dyslexia, they should perform similarly and poorly with both sorts of processed signals.

Where the hypothesis being tested by this study differs from those of experiments that have gone before is that it is being suggested that perceptual studies using these kinds of signals actually assess perceptual organization, rather than auditory sensitivity. It has been known for quite some time that listeners can be sensitive to a component of the speech signal, yet fail to integrate that component into their phonetic percepts. A good example of this phenomenon comes from studies of second language learners. As early as 1975, Miyawaki et al. demonstrated that native Japanese speakers are just as sensitive as native English speakers to glides in the region of the third formant, but fail to incorporate those glides into phonetic percepts for the purpose of making [r]-[l] labeling decisions. This finding is one piece of support for the claim that human speech perception does not function as a simple input-output device that recovers acoustic cues from the signal and automatically translates them into phonemic segments. Some additional processing of the sensory data occurs within that system. Perhaps it is at that level that children with dyslexia encounter difficulty.

Evidence that some kind of language-specific organizing of the sensory data occurs is gleaned from cross-linguistic studies, as well. Using sine-wave and noise-vocoded signals, Nittrouer, Lowenstein, and Packer (2009) demonstrated language-specific differences in perceptual organization for acoustic structure spanning several phonemes, similar to the effects demonstrated by Miyawaki et al. (1975) for how signal components get integrated in phonetic decisions. In the Nittrouer et al. study, sine-wave and noise-vocoded versions of four-word sentences were presented to native English-speaking adults, native Mandarin-speaking adults, and native English-speaking 7-year-olds. In principle, native speakers of any language other than English could have participated as listeners. However, native speakers of Mandarin Chinese were expressly recruited for that study because it had already been demonstrated that when listening to noise-vocoded versions of Mandarin sentences, Mandarin-speaking listeners show similar recognition scores to those of English-speaking listeners presented with vocoded English sentences (Fu, Zeng, Shannon, & Soli, 1998). Thus they must be just as sensitive to this kind of acoustic structure as are native English speakers, and able to organize it efficiently in their native language. Moreover, all native Mandarin speakers were high-functioning second-language users of English, so possessed adequate knowledge of English syntax. Nonetheless, these listeners' recognition scores for the sine-wave and noise-vocoded versions of English sentences were significantly poorer than those of the native English-speaking adults, leading to the conclusion that they were less skilled at organizing these kinds of signal structure for the purpose of speech recognition in a language that was not their first. The English-speaking 7-year-olds in that study performed similarly to the Mandarin-speaking adults with the vocoded sentences, but scored as well as the native English-speaking adults with the sine-wave speech. It was concluded that children learn to organize signal structure preserved by sine-wave analogs sooner than they learn to recognize the structure preserved by vocoded speech. That outcome was replicated by Nittrouer and Lowenstein (2010).

1.4. Current study

The current study was undertaken to test the hypothesis that the perceptual deficit underlying dyslexia might involve the organization of sensory information. Testing this hypothesis was accomplished by generating both sine-wave and noise-vocoded replicas of speech signals, and presenting them to children with and without dyslexia, who varied in age from 8 to 11 years. Although all participants in the dyslexia group were selected based on prior diagnoses, additional testing was done to see if they met the designation of *phonological* dyslexia. The primary way that a problem with perceptual organization would be expected to influence reading acquisition would be through its effect on children's abilities to recover highly refined phonological structure from the speech signal. As the work of Miyawaki et al. (1975) demonstrated, appropriate organizational strategies are required to recover phonological structure. The current study sought to examine that claim by looking at the relationship between perceptual organization and both reading ability and phonological awareness. Consequently it was considered important that the children with dyslexia in the current study had phonological awareness deficits.

At the same time, however, some children with developmental dyslexia exhibit typical or close to typical skills with phonological awareness (Castles & Coltheart, 1993), raising questions about whether problems with phonological awareness really form a causal link to dyslexia (Castles & Coltheart, 2004). Instead, some children with reading problems may encounter problems with word recognition because of non-phonological language problems (e.g., Ramus, Marshall, Rosen, & van der Lely, 2013). That suggestion sparked interest in examining the possibility that problems with perceptual organization might influence language functions other than just those associated with phonological representations. In the current study, the additional language ability of expressive vocabulary was examined for a potential relationship to perceptual organization of linguistically significant signals. Expressive vocabulary is known to influence word recognition in reading (e.g., Lindsey, Manis, & Bailey, 2003; Wise, Sevcik, Morris, Lovett, & Wolf, 2007). It may be that the development of the lexicon is influenced by a child’s ability to organize sensory signals into meaningful linguistic form, and a deficit in this ability could have an influence on reading through that pathway.

It has already been shown that children with dyslexia – specifically, phonological dyslexia – are poorer than their peers without dyslexia at recognizing noise-vocoded sentences (Johnson et al., 2011). Because vocoded stimuli were the only processed materials used in that experiment, however, it was impossible to assess whether the outcome could best be explained by a deficit in perceptual organization on the part of the children with dyslexia, or by poor skills at recognizing degraded signals more generally. In the current study it was reasoned that some evidence might be gathered to support a determination one way or the other. If children with dyslexia were found to be just as capable as children without dyslexia at recognizing one kind of processed signal, but not the other, it could be argued that they have circumscribed difficulty organizing that kind of signal structure, rather than a generalized deficit with degraded signals. Furthermore, it was considered possible that children with dyslexia might show developmental improvements in recognition of one kind of signal, but not the other. This finding would provide evidence that the ease and efficiency with which strategies for perceptual organization develop differs across signal types. In particular, it was predicted that children with dyslexia might perform more similarly to children without dyslexia for sine-wave signals than for vocoded signals, based on the fact that children with dyslexia have been found to show strong attention to formant transitions in phonetic decisions (Boada & Pennington, 2006; Mody et al., 1997; Nittrouer, 1999). That trend suggests that they are able at least to recover the time-varying spectral structure affiliated with changes in vocal-tract cavity shape and size that occurs over brief time periods.

1.5. Top-down linguistic effects

In conducting the experiment reported here, it was important to examine the extent to which recognition of words within sentences might be explained by children’s abilities to apply linguistic structure to the recognition process. Similarity in these effects for children with and without dyslexia would ensure that any differences between these groups that might be observed were not due to differences in their use of linguistic context. The focus of this study was on how the perceptual system organizes the sensory information it receives. Consequently, a metric that has been used previously was applied to these data, known as the *j* factor. This factor quantifies the number of effective channels of information needed to recognize smaller linguistic units within larger ones, such as words within sentences. The derivation of this factor is described elsewhere (e.g., Boothroyd & Nittrouer, 1988). In general, however, the smaller this factor is, the greater the influence of top-down linguistic structure.

Nittrouer and Boothroyd (1990) used the *j* factor to index the contributions of top-down linguistic structure on recognition for 4- to 6-year-old children and adults listening to sentences in background noise. Their results showed that top-down effects were similar for children and adults, even though recognition probabilities were lower for children. The conclusion reached was that children are capable of applying linguistic structure to their speech recognition, as long as they are knowledgeable about that structure. Because the sentences in Nittrouer and Boothroyd were simple, that was likely the case.

Johnson et al. (2011) applied *j* factors to recognition scores of words in sentences for children with and without dyslexia. The sentences were similar to those used by Nittrouer and Boothroyd (1990), but were vocoded rather than presented in noise. In Johnson et al., it was found that top-down linguistic structure contributed similarly to recognition scores across reading groups. Again, that outcome was observed in spite of the fact that one group (the children with dyslexia, in this case) had lower recognition scores than the other group (the children without dyslexia).

In the current work, *j* factors were again calculated to index the contribution of sentence context effects on recognition of the words within those sentences to assess whether or not context effects differed for children with and without dyslexia.

1.6. Summary

The experiment reported here was undertaken to test the hypothesis that the problems facing children with dyslexia might hinge on how they organize the sensory information reaching their perceptual systems. For decades these individuals have largely been characterized as having difficulty recognizing individual phonemes in the speech signal, a process termed decoding. Through the years, many accounts of these problems have proposed that children with dyslexia lack sensitivity to one sort or another of the signal structure required for decoding the signal so that those individual elements can be recovered. Testing these accounts has generated mixed results, appearing to explain the problems of children with dyslexia in some cases, but not in others. Here it is suggested that the difficulty for these children might rest not with sensitivity, but with being able to organize the sensory information transmitted by speech signals. The problems that are demonstrated by most children with dyslexia when it comes to recognizing and manipulating phonemic units might be just one instantiation of broader difficulties organizing signal structure in order to recover meaningful linguistic structure. Perhaps the variability across results from different groups of children with dyslexia reflects the fact that this problem with organizational strategies can present itself differently for different children.

2. Method

2.1. Participants

Seventy children between the ages of 8 years; 0 months and 12 years; 0 months (39 boys and 31 girls) participated in this study. Recruitment for the study targeted children between the ages of 8 and 11 years, but one 11-year-old's appointment could not be scheduled before the child's 12th birthday. The children were split into two groups by age, with 8- to 9-year-olds comprising one group and 10- to 11-year-olds (including the one 12-year-old) comprising the other group.

Children with dyslexia (DYS) were recruited through three venues: 1) a local school specializing in the education of children with dyslexia; 2) local reading clinics; and 3) parent support groups. To be included in the DYS group, children were required to have a diagnosis of dyslexia that was made by a school or (more often) an independent psychologist, and to be currently receiving reading services through their schools. In total, 41 children with dyslexia were recruited: 24 who fit in the younger age group, and 17 who fit into the older age group.

Children with typical reading development (TYP) were selected from the laboratory's pool of research participants to match as closely as possible the DYS participants on age, gender, and socio-economic status. To be included in the TYP group, parents needed to report that the child had no history of hearing, speech or language disorder, and children could not have ever received speech, language or reading services. A total of 29 children were recruited for this group: 16 children were in the 8- to 9-year-old TYP group (youngTYP) and 13 children were in the 10- to 11-year-old TYP group (oldTYP). This number is fewer than those recruited to the DYS group because not all children in the DYS group were retained in that group, once phonological awareness criteria were applied.

2.1.1. Phonological awareness criteria—In this study, questions regarding perceptual organization focused on children with phonological dyslexia. Therefore, children recruited into the study on the basis of having a diagnosis of dyslexia had to demonstrate deficits on specific phonological awareness tasks to remain in the DYS group. Three tasks were used to assess phonological awareness, as defined by Wagner and Torgesen (1987). Performance of children who participated in earlier studies using these three specific tasks (e.g., Nittrouer, 1999; Nittrouer & Lowenstein, 2012; Nittrouer & Miller, 1999; Nittrouer, Shune & Lowenstein, 2011) served as the source for descriptions of developmental level, or difficulty, and the basis for determining cut-off scores for retention in the DYS group. Children who had been diagnosed with dyslexia, but scored above the cut-off criteria on the phonological awareness tasks were considered to have non-phonological dyslexia (NON). These children were kept in the study, but formed separate groups. Inclusionary and exclusionary criteria for each phonological awareness task are described below, and specific details about administration are provided in section 2.4.2.

2.1.1.1. Initial Consonant Choice: This task served as a basic inclusionary criterion. It was considered to be the easiest (i.e., first skill to appear developmentally) of the three phonological awareness tasks, and was used mostly to ensure that all children in the study were capable of exhibiting metaphonological skills. Establishing this criterion diminished the probability that any poor performance observed on the other two phonological awareness tasks might actually be due to inability to perform tasks requiring meta-cognition, rather than to poor sensitivity to phonological structure.

The initial consonant choice (ICC) task assessed children’s sensitivity to word-initial consonants. The task, which requires deciding which of three words has the same initial sound as a target word, makes demands on short-term memory and on awareness of initial sounds, but does not require more advanced phonological skills such as elision or blending. A minimum score of 46% correct was required from each child in order for the child to remain in the study because this was the 95% upper confidence limit of chance responding. All children met this criterion.

2.1.1.2. Phoneme Deletion: The phoneme deletion (PD) task was considered to be intermediate in developmental difficulty for the three phonological awareness tasks used in this study. In this task, the listener is required to provide the real word that derives from removing a specified segment from a nonword. This task is more difficult than the ICC task because the listener not only has to recognize the phonemic structure of an item, but also has to remove one segment from that structure (elision), and blend the remaining parts. Scores on this task served as the inclusionary criterion for the 8- to 9-year-olds in the DYS group. In earlier studies (e.g., Nittrouer & Miller, 1999), children with typical language development obtained scores of roughly 75% correct, with standard deviations of close to 20%. A specific criterion of 59% correct was established as the upper limit for fitting into the DYS group in this study, which was roughly the twentieth percentile of scores for children with typical language development in earlier studies. Children in this age group who were recruited for the DYS group and scored better than 59% correct were placed in the NON group. By the same logic, children in the TYP group had to demonstrate age appropriate phonological awareness: In order to be retained in the TYP group, children had to score better than 65% correct on this task, which was roughly the thirtieth percentile for children with typical language development in earlier studies. Using these criteria, a total of

16 children (9 boys and 7 girls) were placed in the 8- to 9-year-old DYS group (youngDYS) and 8 children (6 boys and 2 girls) were placed in the 8- to 9-year-old NON group (youngNON). Three additional children (not reported in overall participant numbers) had originally been recruited for the TYP group of 8- to 9-year-olds (youngTYP), but failed to obtain a qualifying score on the PD task. Children in the youngTYP group matched children in the youngDYS group in gender distribution.

2.1.1.3. Pig Latin:

Pig Latin (PL) was considered to be the most difficult phonological awareness task used in this study. In this task, the listener is required to change real mono- and disyllabic words into pig Latin words. The specific task used imposed the restriction that only the first segment of any word-initial consonant cluster should be moved. This task was considered the most difficult of the three phonological awareness tasks in this study because the listener has to remove a segment (elision) from one part of the word and synthesize a new syllable with that segment, which is placed at the end of the word.

Scores on this task served as the inclusionary criterion for 10- to 11-year-olds in the DYS group. In Nittrouer and Miller (1999), 11-year-olds scored in roughly the same range on the PL task as younger children did on the PD task. Thus, the same cut-offs were applied: 10- to 11-year-olds in this study could score no more than 59% correct to be retained in the DYS group and needed to score better than 65% correct to be retained in the TYP group. Children who were originally in the DYS group, but who scored better than 59% correct were placed into the NON group. Using these criteria, a total of 13 children (7 boys and 6 girls) were placed in the 10- to 11-year-old DYS group (oldDYS) and 4 children (1 boy and 3 girls) were placed in the 10- to 11-year-old NON group (oldNON). One additional child (not reported in the previous section) had originally been recruited for the TYP group of 10- to 11-year-olds (oldTYP), but failed to obtain a qualifying score on the PL task. Children in the oldTYP group matched children in the oldDYS group in gender distribution.

2.1.2. Other demographic information—

All listeners needed to pass hearing screenings consisting of the pure tones .5, 1, 2, 4, and 6 kHz presented at 25 dB hearing level to each ear separately in order to participate in the study. In addition, parents were asked about their children's histories of middle ear infections before 3 years of age. The parents of children in the TYP group reported that their children were free from significant histories of otitis media, defined as six or more episodes during the first three years of life. Significant histories of otitis media for children in the DYS and NON groups were not considered to be a reason for exclusion from participation because chronic otitis media early in life can negatively affect phonological awareness (Nittrouer & Burton, 2005), precisely the phenomenon of interest in this study. Means and ranges for numbers of middle ear infections before 3 years of age for each participant group are listed in Table 1.

Socio-economic status (SES) was indexed for each child, and used in matching participants in the TYP group to those in the DYS group. To index SES, a two-factor scale considering both the highest educational level and the occupational status of the primary income earner in the home was used (Nittrouer & Burton, 2005; Nittrouer, Caldwell, Lowenstein, Tarr, & Holloman, 2012). Scores for each of these factors range from 1 (low) to 8 (high). Values for the two factors are multiplied together, resulting in a range of possible scores from one to 64. Means and ranges for SES for each participant group are listed in Table 1. Mean SES scores were between 30 and 40 for all groups, which indicates that most children in the study were in middle-class families with college-educated parents. However, there were a few children with SES in the range typically considered low (15 or less) in each participant group. In matching children in the TYP groups to children in the DYS groups, care was taken to match on SES. Mean SES was slightly higher for the children in the two NON groups, but a two-way analysis of variance (ANOVA) performed on these SES scores revealed no main effects of age or reading group, and the Age × Reading Group interaction was not significant.

Children were given the Goldman Fristoe 2 Test of Articulation (Goldman & Fristoe, 2000), and means and ranges for numbers of errors for each participant group are listed in Table 1. All children in the TYP group and the majority of children in the NON group were free from errors, but 11 out of 16 children in the youngDYS group and 2 out of 13 children in the oldDYS group made one or more errors. Poor performance on this test of articulation was not considered to be reason for exclusion from participation because speech sound disorder is known to co-occur with phonological impairment (Pennington & Bishop, 2009). Thus, it would have been difficult to recruit a group of children with phonological dyslexia, without some of those children having some evidence of speech sound disorder.

Children were given the reading subtest of the Wide Range Achievement Test 4 (WRAT; Wilkinson & Robertson, 2006), which is a word reading task that was used to index reading ability. Means and ranges for WRAT raw and standard scores for each participant group are listed in Table 1. There is little overlap in scores between the TYP and DYS groups, across either age group. The youngDYS group had a mean standard score of 82.6, which corresponds to the 11th percentile and is more than one standard deviation below the published normative mean for this test. The other three groups comprised of children with dyslexia (youngNON, oldDYS, and oldNON) all had mean standard scores slightly better than 90, which corresponds to roughly the 30th percentile. Both TYP groups had mean standard scores of 110, which corresponds to the 75th percentile. A two-way ANOVA performed on the WRAT standard scores showed a significant main effect of reading group, $F(2, 64) = 52.59$, $p < .001$, $\eta^2 = .62$. However, neither the main effect of age nor the Age × Reading Group interaction was significant.

2.2. Equipment

All testing took place in a soundproof booth, with the computer that controlled stimulus presentation in an adjacent room. Hearing was screened with a Welch Allyn TM262 audiometer using TDH-39 headphones. Stimuli for the phonological awareness and degraded sentences tasks were recorded with an AKG C535 EB microphone, a Shure M268 amplifier, and a Creative Laboratories Soundblaster analog-to-digital converter. After generation, stimuli were stored on a computer and presented through a Creative Labs Soundblaster card, a Samson C-que8 headphone amplifier, and AKG-K141 headphones. This system has a flat frequency response and low noise. Custom-written software controlled presentation of all stimuli.

2.3. General Procedures

All procedures were approved by the Institutional Review Board of the Ohio State University. All children and their parents gave informed consent prior to participating in the study. Testing took place in a single session of roughly 1 hour and 15 minutes to 1 hour and 30 minutes. The hearing screening was administered first, followed by the Goldman-Fristoe Test of Articulation and the reading subtest of the WRAT. Then the three phonological awareness tasks and two degraded sentences tasks were alternated such that listeners completed one phonological awareness task, one condition of the degraded sentences task, a second phonological awareness task, the remaining degraded sentences task, and then the last phonological awareness task. This resulted in 12 possible orders of presentation. Next listeners were presented with the complete list of sentences from the two degraded sentences tasks in their natural (unprocessed) form, and children were asked to repeat each sentence. This task was used to ensure that all children could recognize the sentences when they were not degraded. Children needed to have word recognition scores of at least 90% correct on these unprocessed sentences in order to be included in the analysis. No child failed to meet that criterion. Finally, a measure of vocabulary knowledge was administered.

The phonological awareness tasks and the degraded sentences tasks were presented via headphones at a peak intensity of 68 dB sound pressure level. Listeners removed their headphones between tasks to take a short break from testing. A game board and game piece were used to keep track of progress through each phonological awareness and degraded sentences task. In both cases, a game piece was moved to the next number on the game board after a specific number of items (e.g., 10 for the sentence tasks). This procedure provided some reinforcement, and served as a visible indicator of progress.

2.4. Materials and task-specific procedures

2.4.1. Expressive vocabulary task—A measure of expressive vocabulary was collected from children because it has been shown to be a non-phonological language skill that is related to reading ability (e.g., Ramus et al., 2013; Wise et al., 2007). In this case, the measure used was the Expressive One Word Picture Vocabulary Test-4th Edition (EOWPVT-4; Martin & Brownell, 2011). In this task, children are shown pictures on easels one at a time, and they must provide the word that labels the picture. The primary question explored with this measure was whether children's abilities to perceptually organize the sine-wave and vocoded speech signals would explain significant proportions of variance in this non-phonological contributor to reading ability.

2.4.2. Phonological awareness tasks—All stimuli were presented via computer so that all children heard exactly the same stimuli. During creation, stimuli for the phonological awareness tasks were recorded at a 44.1 kHz sampling rate with 16-bit digitization by an adult male speaker of American English. Words were separated into individual files, and root mean square amplitude was equalized across all items within each task. Software was written for each task to control presentation and record responses.

During testing, the examiner entered all responses directly into the computer. Each phonological awareness task was introduced by the experimenter with a standard verbal script, instructing the child on how to perform the task and providing three live-voice examples with feedback. Then the child put on headphones and was given practice on the same task with recorded stimuli. Feedback was given during practice. There were 6 practice items for each of the ICC and PD tasks, and 12 practice items for the PL task. After practice was completed, testing commenced and feedback was no longer given. The computer software automatically discontinued testing after six incorrect answers in a row. When this happened, children were told the computer said they could finish the task early. Percent correct scores were used as dependent measures for all three tasks.

ICC consisted of 48 items and began with the child hearing and repeating a target word. Children were given three chances to repeat each target word correctly, but rarely needed more than one chance. Following correct repetition of the target word, the child heard three more words and had to choose the one that had the same beginning sound as the target word. The examiner entered which word the child selected into the computer. Items for this task can be found in Appendix A.

PD consisted of 32 items and began with the child hearing and repeating a target nonword ("Say _________."). Children were given three chances to repeat each nonword correctly. After the child repeated that nonword correctly, the child heard instructions to repeat it without a specified segment ("Now say ________ without the ____ sound."). The experimenter either entered that the child said the correct real word, or typed the word that was said into the computer, and it was scored as incorrect. If the child failed to repeat the nonword correctly in three tries, that trial was skipped. This ensured that children were being asked to perform the task on only nonwords that they recognized correctly. However, it was a rare occurrence that a child could not repeat the target nonwords: Only one child in each of the young groups was unable to repeat one nonword each. Items for this task can be found in Appendix B.

PL consisted of 48 items and began with the child hearing and repeating a target word. Children were given up to three chances to repeat each target word correctly, but children generally repeated it correctly on the first try. Next the child was instructed to say the word in pig Latin. In this variant of the game, only the initial segment of the word was moved, even if it was part of a cluster. Children were instructed accordingly prior to testing. The experimenter either entered that the child said the pig Latin version of the word correctly, or typed what was said into the computer interface, and it was scored as incorrect. Items for this task can be found in Appendix C.

One concern with the pig Latin task could be that some children would have had experience with it, so would be advantaged in doing this experimental task. Consequently, each child was queried at the start of the task as to whether they had ever played with making pig Latin versions of words. None of the children reported any substantive experience doing so.

For a dependent measure, scores from these three separate phonological awareness tasks were used to compute a mean score, termed the *phonological awareness mean* (PA mean). This composite score was primarily used in analyses designed to investigate whether variability across children in abilities to perceptually organize the sine-wave and vocoded speech signals could explain significant proportions of variance in phonological awareness.

2.4.3. Degraded sentences task—The same 72 sentences (12 for practice and 60 for testing) used in Nittrouer and Lowenstein (2010) were used here. They originally came from the Hearing in Noise Test (Nilsson, Soli, & Sullivan, 1994). The sentences were all five words in length, were syntactically correct and semantically predictable, and followed a subject-predicate structure. To create the stimuli, sentences were recorded onto a computer at a 44.1-kHz sampling rate with 16-bit digitization by an adult male speaker of American English who is a trained phonetician. Each sentence was put into its own file. All sentences were used to create two types of degraded signals: four-channel vocoded (VOC) and sine-wave (SW) signals. To create the VOC stimuli, a Matlab routine was used. All signals were first low-pass filtered with an upper cut-off frequency of 8000 Hz. Cut-off frequencies between bands were 800, 1600, and 3200 Hz. Each channel was half-wave rectified, and the output used to modulate white noise, limited by the same band-pass filters as those used to divide the speech signal into channels. Resulting bands of white noise were low-pass filtered using a 160-Hz high-frequency cut-off, and combined.

To create the SW stimuli, a PRAAT routine written by Darwin (2003) was used to extract the center frequencies of the first three formants. Formant tracking in PRAAT (Boersma & Weenink, 2009) was adjusted on a sentence-by-sentence basis to ensure that the trajectories of the sine waves matched those of formants in the original speech file closely. Stimuli were generated from the extracted formant tracks. In each case, a spectrogram of the original sentence was compared to a spectrogram of the SW version to check the similarity between formant tracks in the original file and in the SW version. Formant extraction, with adjustments, was repeated if need be. Smoothing of tracks could also be done in Matlab.

All stimuli (natural, VOC, and SW) were equalized for root mean square amplitude across sentences after they were created. Samples of all three kinds of processed stimuli are shown for a single sentence in Figure 2. The presentation software randomly selected 30 sentences to present as VOC and 30 to present as SW prior to testing, and order of presentation of the sentences was randomized independently for each listener.

Training was the same for each condition. The child was instructed that they would hear a man saying a sentence, and they should repeat it. Then children were told that a robot voice (described as a squeaky robot voice for SW sentences, and a scratchy robot voice for VOC sentences) would say the same sentence, and they should repeat it. The child repeated a total of six training sentences for each condition. Then the child was instructed that only the robot would be heard saying the sentences. Children were asked to repeat those sentences as best as possible. Each sentence was played once, and children were instructed that sentences could not be replayed. The number of incorrect words for each sentence was entered into the computer interface during testing. The percentage of words correctly recognized across all sentences within any one condition served as the dependent measure for this task.

2.5. Analysis

The first analyses conducted were meant to examine potential group differences. Two-way ANOVAs were performed to see if scores for children differed as a function of age or reading group for each of the measures of interest: vocabulary, phonological awareness, and word recognition for sentences degraded by the use of sine wave synthesis or vocoding. For these analyses, children with dyslexia were treated as two separate groups, depending on whether they had phonological dyslexia or not. A central question with these analyses concerned whether or not children with dyslexia would be found to have poorer word recognition for either the sine-wave or vocoded sentences.

In order to examine whether any potential differences across groups in word recognition for the degraded sentences might be explained by variability across children in how they used top-down linguistic context, the j factors described by Boothroyd and Nittrouer (1988) were calculated, according to the equation $j = \log(p_w)/\log(p_p)$, where p_w is the probability of recognizing the whole sentence, and p_p is the probability of recognizing each part, or word in this case.

Next, a series of regression analyses were performed, examining how much variance in reading, phonological awareness, and vocabulary scores was explained by word recognition for the two kinds of degraded sentences. These analyses addressed the question of whether the skills of children with dyslexia to organize the sine-wave or vocoded signals might explain any of the variance in their reading abilities, or their abilities on phonological and non-phonological skills thought to underlie reading abilities.

Finally, children in the 8- to 9-year-old TYP group were selected to match children in the 10- to 11-year-old DYS group on raw WRAT scores. Then t tests were conducted on scores for word recognition of the sine-wave and vocoded sentences as a way to see if word recognition for the degraded sentences were simply related to reading abilities.

3. Results

All data were screened to check for normal distributions and homogeneity of variance across groups. Where percent correct scores are reported (i.e., phonological awareness and degraded sentences), arcsine transformations were used in statistical analyses. For the WRAT reading and EOWPVT vocabulary scores, raw rather than standard scores were used in regression analyses because they index performance independent of age. However, standard scores are also reported so that relative abilities at each age level can be compared. Precise outcomes are reported, unless $p > .10$ when outcomes are described simply as *not* *significant* (NS). Bonferroni adjustments for multiple comparisons were applied to post hoc *t* tests.

3.1 Expressive vocabulary

Means and ranges for EOWPVT raw and standard scores for each participant group are shown in Table 2. Looking first at standard scores for the 8- to 9-year-olds, there was little overlap between scores of children in the youngTYP group and children in either the youngDYS or youngNON groups. Children in the youngDYS group had a mean standard score of 96, which corresponds to the 39th percentile, and is only about a quarter of a standard deviation below the published normative mean of Martin and Brownell (2011). However, this score was more than two standard deviations below the mean of children in the youngTYP group, who had a mean standard score of 119, which corresponds to the 90th percentile according to the published normative data. It is common to find high vocabulary scores for children from middle-class families because vocabulary strongly correlates with SES (e.g., Hart & Risley, 1995). Consequently, similar mean vocabulary scores would have been predicted for the children with dyslexia in this study, given that their mean SES was similar to that of the children without dyslexia. Children in the youngNON group had a mean standard score precisely at the published normative mean of 100, but this was still more than a standard deviation below the performance of children in the youngTYP group.

Older children showed more overlap in their standard vocabulary scores across reading groups. Children in the oldDYS group had a mean standard score of 102, which corresponds to the 55th percentile, just above the published normative mean. Children in the oldTYP and oldNON groups had mean standard scores similar to each other, 114 and 118, corresponding to the 82nd and 88th percentiles, respectively, which is about one standard deviation above the published normative mean.

A two-way ANOVA performed on these standard vocabulary scores, with age and reading group as factors, showed significant effects of both: age, $F(1, 64) = 5.70$, $p = .020$, $\eta^2 = .08$, and reading group, $F(2, 64) = 21.65$, $p < .001$, $\eta^2 = .40$. In addition, the Age × Reading Group interaction was significant, $F(2, 64) = 5.36$, $p = .007$, $\eta^2 = .14$. Because of that interaction, separate one-way ANOVAs were run on scores for children in each age group separately. For the 8- to 9-year-olds, a significant main effect of reading group was found, $F(2, 37) = 31.72$, $p < .001$, $\eta^2 = .63$. Post hoc *t* tests showed significant differences between the youngTYP group and both the youngDYS and youngNON groups ($p < .01$ in both cases). However, the difference between the youngDYS and youngNON groups was not significant. For the 10- to 11-year-olds, the main effect of reading group was significant, $F(2, 27) = 4.53$, $p = .020$, $\eta^2 = .25$, but only the difference between the oldTYP and oldDYS groups was significant ($p = .047$); the difference between the oldDYS and the oldNON groups was only close to significant ($p = .079$) in this case. Thus, there were differences in expressive vocabularies across reading groups at both age levels, even though SES was similar across groups.

3.2 Phonological awareness

3.2.1 Comparison with previous studies—To assess the reliability of results from the phonological awareness tasks used in this study, mean scores were compared to those of children in earlier studies using the same tasks. For the ICC task, results from the youngTYP group were compared to results from typical 8- to 10-year-olds in Nittrouer (1999), who obtained a mean score of 95% correct on the ICC task. That is very close to the mean score of children in the youngTYP group of 96.0% correct (SD = 4.7%). For the PD task, the performance of typical 8-year-olds in a study by Nittrouer and Lowenstein (2012) served as the comparison. Those children had a mean score of 83% correct, which is within one standard deviation of the mean score of the youngTYP group of 88.9% (SD = 9.5%). To assess the reliability of the PL task, results from typical 11-year-olds in Nittrouer and Miller (1999) were compared to those of children in the oldTYP group. The children in that earlier study obtained a mean score of 79% correct, which is within one standard deviation of the mean score of children in the oldTYP group of 87.2% (SD = 9.8%). For both the PD and PL tasks, the slightly higher scores obtained for children in the TYP groups in the current study compared to earlier studies may be explained by the requirement of the current study that children needed to score at specified levels in order to be included in the TYP groups.

3.2.2 Group comparisons—Table 3 shows means and standard deviations for the three separate phonological awareness tasks and for PAmean. Table 4 shows the outcomes of two-way ANOVAs performed on data from each of the tasks, and on scores for PAmean. Although precise outcomes vary somewhat across tasks, the overall trends are similar in that the strongest effect is always reading group: Children with dyslexia performed more poorly on these phonological awareness tasks than children without dyslexia.

In further analyses, only the PAmean score was used. Therefore, only these scores were examined for reading-group effects at each age level separately. In those analyses, significant effects of reading group were observed at both age levels: 8- to 9-year-olds, $F(2, 37) = 96.74$, $p < .001$, $\eta^2 = .84$, and 10- to 11-year-olds, $F(2, 27) = 29.23$, $p < .001$, $\eta^2 = .68$. The post hoc comparisons revealed that all reading groups differed from each other at the younger age level ($p < .01$ for TYP *vs.* DYS and NON *vs.* DYS, and $p = .048$ for NON *vs.* TYP). For the older age level, the DYS group differed from each of the other groups ($p < .01$ for both comparisons), but the NON and the TYP groups did not differ from each other.

3.3 Degraded sentences

3.3.1 Top-down linguistic effects—The first question addressed was whether there were differences across groups in the extent to which top-down linguistic effects were used to recognize words within the degraded sentences. To answer that question, j factors were computed for individual listeners using word and sentence recognition scores. Because most of the children in the older group scored 95% or more correct on the SW stimuli, j factors were only calculated for the VOC condition. Those j factors could be calculated for all participants, with the exception of three children in the youngDYS group who had less than 5% correct recognition for VOC sentences. Mean scores for all groups are shown in Table 5. These scores have a possible range of 1 to 5. A two-way ANOVA performed on these scores revealed no statistically significant main effects, and no significant Age × Reading Group interaction. Thus, children across groups were generally able to use linguistic context, which in this case was fairly simple, to a similar extent.

3.3.2 Recognition of words in sentences—Table 6 displays word recognition scores for the two degraded sentences tasks. Looking first at the SW condition, mean scores for children in the youngTYP group and all older groups were between 93% to 96% correct, while mean scores for the youngDYS and youngNON groups were 89% and 91% correct, respectively. A two-way ANOVA with age and reading group as factors was performed on these scores. Both main effects were significant: age, $F(1, 64) = 16.23$, $p < .001$, $\eta^2 = .20$, and reading group, $F(2, 64) = 3.43$, $p = .039$, $\eta^2 = .10$ The interaction of Age × Reading group was not significant. Nonetheless, given the significant main effect of age, one-way ANOVAs with reading group as the factor were performed on these recognition scores for the SW condition for each age level separately. For the 8- to 9-year-olds, a significant main effect of reading group was found, $F(2, 37) = 4.37$, $p = .020$, $\eta^2 = .19$. *Post hoc* comparisons were only significant for the TYP *vs.* DYS groups ($p < .05$). For the 10- to 11-year-olds, no significant effect of reading group was found.

Turning to the VOC condition, it is striking that the difference in accuracy between the TYP groups and the two groups with dyslexia appears consistent across age level: the TYP groups recognized 63% to 66% of words correctly, while scores for the NON and DYS groups ranged between 49% and 53%. An ANOVA with age and reading group as factors was performed on these scores. The main effect of age was not significant. The main effect of reading group was significant, $F(2, 64) = 11.15$, $p < .001$, $\eta^2 = .26$, but the Age × Reading Group was not. Given the lack of significant effects for either age or the interaction term, *post hoc* comparisons were performed on scores for reading groups, across age levels. Comparisons of the TYP group with each of the groups comprised of children with dyslexia were significant ($p < .01$), but the comparison of the DYS and NON groups was not significant. These results indicate that children in both dyslexic groups performed more poorly than children in the typical group, and there was no difference between the phonological and non-phonological dyslexic groups.

Cohen's *d*s (Cohen, 1988) were computed as effect sizes, and are shown in Table 7. These values reveal that for the SW condition, the only large effects of reading group are seen for the younger children: children in the youngDYS group performed much more poorly than children in the youngTYP group, and children in the youngNON group performed moderately more poorly. No large effects are seen across groups for the 10- to 11-year-olds.

For the VOC condition, on the other hand, large effects of reading group are observed at both age levels, with children in both dyslexia groups showing effects of roughly 1.00 compared to children in the typical reading groups. Thus, children with dyslexia, regardless of whether it was categorized as phonological dyslexia or not, had difficulty perceptually organizing the vocoded signals in order to recognize them. That was true for both age groups.

3.4 Regression Analyses

A series of regression analyses were done to examine whether abilities to organize the degraded sentences might underlie each of the three dependent measures: reading ability, and two measures that might underlie reading ability, one phonological (PAmean) and one non-phonological (expressive vocabulary). Outcomes are shown in Table 8. Mean standardized β coefficients for all children are shown in the top rows, and those just for children with dyslexia (DYS and NON) are shown in the bottom rows. Although the mean β coefficients computed across all children suggest that the ability to recognize words in either kind of degraded sentence explains variance in the dependent measures to equal extents, the β coefficients for just the children with dyslexia suggest that performance within this group is largely explained only by their abilities to recognize words in sine-wave sentences.

3.5. Comparison of reading-level match

Finally, analyses were conducted to examine whether word recognition for the degraded sentences was explained just by reading level. To accomplish this goal, children in the oldDYS group were matched to children in the youngTYP group as closely as possible on raw WRAT reading scores. Thus, a subset of the 13 children from the original youngTYP group was assembled. Table 9 shows mean scores for each group, for reading scores, and word recognition for each of the SW and VOC conditions. When t tests were computed on these scores, only recognition scores for the VOC condition were significant, $t(24) = 2.47$, $p = .021$. Thus, even when children were matched as closely as possible on reading level, there was still a significant difference in their abilities to organize signal structure in the VOC condition.

4. Discussion

Developmental dyslexia is a relatively common disorder of childhood, with estimates of its prevalence ranging from five to 20 percent of school-age children (e.g., Mogasale, Patil, Patil, & Mogasale, 2012; Shaywitz, Fletcher, Holahan, & Shaywitz, 1992; Snowling, 2000). For roughly the past four decades, it has been generally accepted that phonological awareness deficits are largely to blame for problems learning to read: If children lack the ability to recognize constituent phonemes within words, they will not be able to translate orthographic symbols into phonemes, which is presumed necessary to the reading process. Ramus et al. (2013) provides a comprehensive review of the history of this work.

As a result of that pervasive view, substantive effort has concentrated on trying to identify the underlying source of reading and related phonological awareness deficits, with great attention paid to the idea that there may be something amiss in the auditory perception of children with developmental dyslexia. In turn, those perceptual problems could explain why children experiencing difficulty learning to read exhibit phonological deficits. Specific accounts have suggested that children with dyslexia have problems processing the relatively slow changes in gross amplitude structure across speech signals (e.g., Goswami et al., 2002; Lorenzi et al., 2000) or problems with the rapidly changing spectral structure arising from continuously moving vocal tracts (e.g., Tallal, 1980; Merzenich et al., 1996; Miller & Tallal, 1996). However, these suggested accounts have met with equivocal success in how completely they explain the problems exhibited by children with dyslexia.

The current study adopted a somewhat different view from which to generate hypotheses about the challenges facing children with dyslexia. The view taken in this work was that perhaps the difficulty these children face does not rest with how sensitive they are to any specific aspect of acoustic speech signals. Rather, perhaps their problems involve being able to organize these signals appropriately over the course of perception in order to extricate linguistically relevant form. Testing this hypothesis required that the acoustic signals themselves be processed in some way: If unprocessed signals are used it becomes impossible to determine whether any differences observed among groups involve sensitivity to specific sorts of structure, or the kind of organization of sensory information being suggested here. In the current study, sine-wave resynthesis and noise-vocoding of simple sentences were the two methods of signal processing implemented. With sine-wave resynthesis, much of the naturalness of typical speech is sacrificed, but the time-varying structure that arises as the vocal tract changes shape and size is reliably retained. It was deemed important to preserve that kind of structure in one of the processing algorithms used in this study because children with dyslexia seem to rely on these long-term spectral patterns in making phonemic judgments at least as well as children without dyslexia (Goswami et al, 2011; Johnson et al., 2011; Nittrouer, 1999), although perhaps at older ages than typically developing children (Boada & Pennington, 2006). The other kind of signal processing applied to natural sentences in the current study (i.e., noise vocoding) created signals with broad spectral structure that was generally blurred in how well it represented the time-varying consequences of vocal-tract movements. These signals require substantial perceptual organization in order for listeners to recognize linguistic form.

Results of this study showed that children with dyslexia performed more poorly than children without dyslexia with both kinds of signals, but group differences were larger for the vocoded signals. That suggests that they had difficulty with perceptual organization. If they had exhibited difficulty of similar magnitude for both kinds of signals, it could have been suggested that children with dyslexia have difficulty using linguistic knowledge and/or language-specific strategies to process degraded speech signals, the kind of effect indexed by the *j* factors used here. In that case, the direction of effect could be what is traditionally classified as “top-down.” However, the finding that children performed better with one kind of signal – and that there was a developmental improvement with that kind of signal – gives some indication that the direction of effect may be such that difficulty organizing signal structure in order to recover linguistic form could explain the impoverished language abilities of these children, including phonological and lexical abilities. That is, their difficulties in appropriately organizing acoustic signals may account for their language deficits, of which three kinds were measured: reading, phonological awareness, and vocabulary.

This study offers somewhat of a challenge to the hypothesis that poor sensitivity to the slow amplitude modulations in the speech signal accounts for dyslexia. If that were strictly the explanation, children with dyslexia in the current study should have performed similarly for both kinds of degraded sentences, and poorly across both age levels because both kinds of signals preserved that structure, while degrading other kinds. The finding that older children with dyslexia were able to recognize the sine-wave materials as well as children without dyslexia suggests that they were not hindered by a lack of sensitivity to the slow modulations of the signal. In fact, that similarity in scores across reading groups for the older children is a very important result of the current study. Although this study used a cross-sectional design rather than a longitudinal one, that outcome suggests that children with dyslexia do indeed learn to organize and use this kind of signal structure, just at older ages than children without dyslexia. That finding matches results of others, such as Boada and Pennington (2006), showing that children with dyslexia weight formant transitions more than age-matched peers without dyslexia in phonemic judgments, and similarly to younger children without dyslexia.

The suggestion being made here – that the source of the challenges faced by children with dyslexia might rest with how they *organize* sensory input, rather than with *sensitivity* to sensory input – offers a potential explanation for findings of other studies that investigated auditory processing of non-speech signals by children with dyslexia. Although the current outcomes were obtained with linguistically meaningful signals, speech and non-speech stimuli alike generally require some kind of perceptual organization beyond simple sensory input in order for listeners to perform the tasks demanded of laboratory experiments. For example, Remez, Pardo, Piorkowski, and Rubin (2001) asked listeners to make different decisions with a single set of sine-wave stimuli: one task required that signals be organized as speech and the other required that signals be organized as non-speech signals. Outcomes showed that the signals were organized into different auditory forms, depending on the task at hand. That finding was complementary to outcomes of a still earlier study by Best, Studdert-Kennedy, Manuel, and Rubin-Spitz (1989) showing that listeners organize auditory input differently depending on whether they are biased to hear the signals as speech or non-speech, and it is only when listeners organize those signals as speech that they are able to make phonemic judgments. The outcomes of the current experiment might indicate generalized difficulty on the part of children with dyslexia in being able to organize sensory inputs. These difficulties could extend to experimental tasks involving non-speech signals, as well as the task used here involving speech-like stimuli.

Finally, the outcomes reported here provide information about what children with dyslexia can do, which is to use structure deriving from the relatively slow changes in vocal-tract configurations to perform language functions. It has been suggested that this kind of structure serves an important role in language learning for younger children developing typically, helping them discover the global articulatory patterns of their native language (e.g., Nittrouer, 2006). That is really the only level of linguistic structure that is available when the slowly changing, global patterns of articulatory movements are the focus of attention. However, the strong attention to formant transitions found in the speech perception of young children gives way to stronger attention to brief, spectrally isolated pieces of the acoustic signal by seven years of age or so (e.g., Nittrouer, 1992; Nittrouer & Studdert-Kennedy, 1987). That change in attentional focus coincides with when children are honing their phonological representations and expanding their lexicons. It may be that children with dyslexia are delayed in applying this kind of structure to acquisition, and those delays inhibit phonological and lexical development.

4.1. Implications for intervention

If future research supports the primary outcomes of the current study, the collective results could influence how intervention is provided to children with dyslexia. Following from the common view that this disorder arises from phonological awareness deficits, most interventions currently emphasize efforts to focus children's attention on sublexical units, especially phonemes. The idea that children with dyslexia might have difficulty organizing the sensory information reaching them in an effective manner suggests that they might benefit from intervention strategies that are broader in focus. To appreciate this suggestion, it is worth considering a visual model of perceptual organization. Figure 3 shows a field of squares of various shades of gray. At least for viewers from the United States, these squares can be organized perceptually so that an image of Abraham Lincoln's profile is recovered. The suggestion made here is that children with dyslexia may need to learn how to accomplish a similar perceptual feat for the complex signals that are speech. Facilitating this kind of perceptual strategy could not be done by focusing on isolated segments of the acoustic speech signal any more than a viewer would be able to organize the optic signal in Figure 3 in order to recover an image of Abraham Lincoln by focusing on isolated areas of the figure.

The finding that children with dyslexia showed improved skill at recognizing the sine-wave speech signals across the two age levels tested suggests other possible approaches to intervention. In particular, it might be that children with dyslexia would benefit from training with formant tracks that have been artificially narrowed. A similar approach has been considered for listeners with hearing loss as a possible way to deal with their broadened auditory filters (Turner & Van Tasell, 1984). That work used brief sections of speech signals, and eventually concluded that the approach did not enhance recognition. But again, a general suggestion arising from the current work is that an important aspect of training would involve using long signal sections. Perhaps training with spectrally narrow, long segments of speech would help children with dyslexia discover how these signals should be organized.

4.2. Conclusions

The current study was undertaken to explore the hypothesis that developmental dyslexia may be due to faulty perceptual organization of linguistically relevant signals. Results supported the general idea, but suggested that children with dyslexia may eventually learn to organize signal structure affiliated with the relatively slow, global changes in vocal-tract shape and size. The proposed perceptual organization deficit could explain problems often exhibited by children with dyslexia in areas other than reading, including phonological awareness and vocabulary development, and could explain their poor performance on experimental tasks involving nonspeech stimuli. Thus, if supported by future investigations, this explanation could serve as a unifying principle, accounting for the disparate findings observed with children with dyslexia.

Acknowledgments

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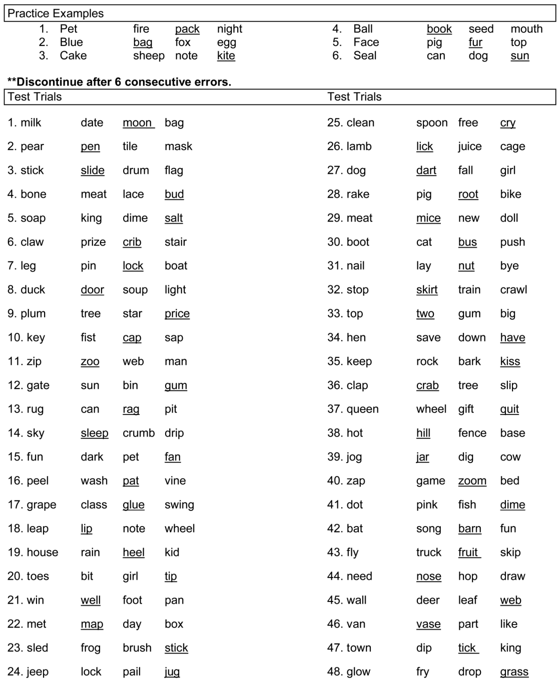
Appendix A. Initial consonant choice

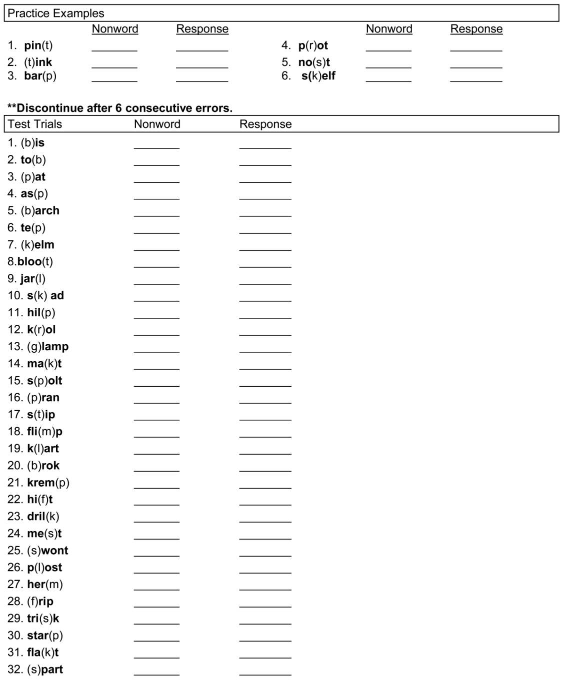


Practice Examples							
1. Pet	fire	pack	night	4. Ball	book	seed	mouth
2. Blue	bag	fox	egg	5. Face	pig	fur	top
3. Cake	sheep	note	kite	6. Seal	can	dog	sun

****Discontinue after 6 consecutive errors.**

Test Trials				Test Trials			
1. milk	date	moon	bag	25. clean	spoon	free	cry
2. pear	pen	tile	mask	26. lamb	lick	juice	cage
3. stick	slide	drum	flag	27. dog	dart	fall	girl
4. bone	meat	lace	bud	28. rake	pig	root	bike
5. soap	king	dime	salt	29. meat	mice	new	doll
6. claw	prize	crib	stair	30. boot	cat	bus	push
7. leg	pin	lock	boat	31. nail	lay	nut	bye
8. duck	door	soup	light	32. stop	skirt	train	crawl
9. plum	tree	star	price	33. top	two	gum	big
10. key	fist	cap	sap	34. hen	save	down	have
11. zip	zoo	web	man	35. keep	rock	bark	kiss
12. gate	sun	bin	gum	36. clap	crab	tree	slip
13. rug	can	rag	pit	37. queen	wheel	gift	quit
14. sky	sleep	crumb	drip	38. hot	hill	fence	base
15. fun	dark	pet	fan	39. jog	jar	dig	cow
16. peel	wash	pat	vine	40. zap	game	zoom	bed
17. grape	class	glue	swing	41. dot	pink	fish	dime
18. leap	lip	note	wheel	42. bat	song	barn	fun
19. house	rain	heel	kid	43. fly	truck	fruit	skip
20. toes	bit	girl	tip	44. need	nose	hop	draw
21. win	well	foot	pan	45. wall	deer	leaf	web
22. met	map	day	box	46. van	vase	part	like
23. sled	frog	brush	stick	47. town	dip	tick	king
24. jeep	lock	pail	jug	48. glow	fry	drop	grass

Appendix B. Phoneme deletion



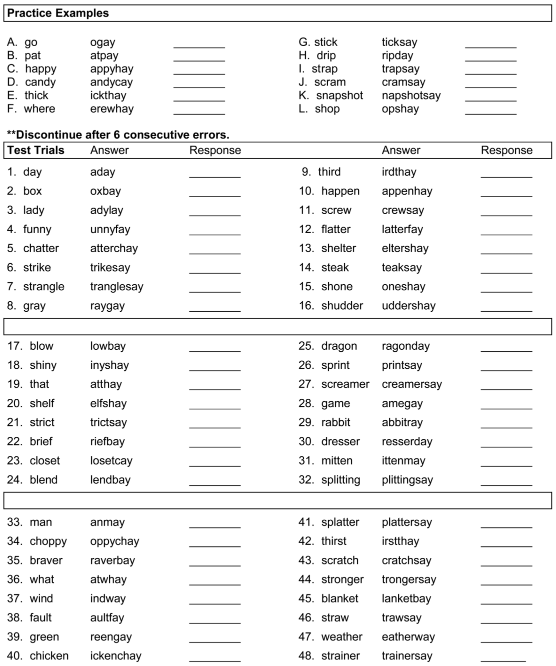
Practice Examples

	Nonword	Response		Nonword	Response
1. **pin**(t)			4. **p**(r)**ot**		
2. (t)**ink**			5. **no**(s)**t**		
3. **bar**(p)			6. **s**(k)**elf**		

****Discontinue after 6 consecutive errors.**

Test Trials	Nonword	Response
1. (b)**is**		
2. **to**(b)		
3. (p)**at**		
4. **as**(p)		
5. (b)**arch**		
6. **te**(p)		
7. (k)**elm**		
8.**bloo**(t)		
9. **jar**(l)		
10. **s**(k) **ad**		
11. **hil**(p)		
12. **k**(r)**ol**		
13. (g)**lamp**		
14. **ma**(k)**t**		
15. **s**(p)**olt**		
16. (p)**ran**		
17. **s**(t)**ip**		
18. **fli**(m)**p**		
19. **k**(l)**art**		
20. (b)**rok**		
21. **krem**(p)		
22. **hi**(f)**t**		
23. **dril**(k)		
24. **me**(s)**t**		
25. (s)**wont**		
26. **p**(l)**ost**		
27. **her**(m)		
28. (f)**rip**		
29. **tri**(s)**k**		
30. **star**(p)		
31. **fla**(k)**t**		
32. (s)**part**		

Appendix C. Pig Latin



Practice Examples

A. go	ogay		G. stick	ticksay	
B. pat	atpay		H. drip	ripday	
C. happy	appyhay		I. strap	trapsay	
D. candy	andycay		J. scram	cramsay	
E. thick	ickthay		K. snapshot	napshotsay	
F. where	erewhay		L. shop	opshay	

****Discontinue after 6 consecutive errors.**

Test Trials	Answer	Response		Answer	Response
1. day	aday		9. third	irdthay	
2. box	oxbay		10. happen	appenhay	
3. lady	adylay		11. screw	crewsay	
4. funny	unnyfay		12. flatter	latterfay	
5. chatter	atterchay		13. shelter	eltershay	
6. strike	trikesay		14. steak	teaksay	
7. strangle	tranglesay		15. shone	oneshay	
8. gray	raygay		16. shudder	uddershay	
17. blow	lowbay		25. dragon	ragonday	
18. shiny	inyshay		26. sprint	printsay	
19. that	atthay		27. screamer	creamersay	
20. shelf	elfshay		28. game	amegay	
21. strict	trictsay		29. rabbit	abbitray	
22. brief	riefbay		30. dresser	resserday	
23. closet	losetcay		31. mitten	ittenmay	
24. blend	lendbay		32. splitting	plittingsay	
33. man	anmay		41. splatter	plattersay	
34. choppy	oppychay		42. thirst	irstthay	
35. braver	raverbay		43. scratch	cratchsay	
36. what	atwhay		44. stronger	trongersay	
37. wind	indway		45. blanket	lanketbay	
38. fault	aultfay		46. straw	trawsay	
39. green	reengay		47. weather	eatherway	
40. chicken	ickenchay		48. strainer	trainersay	

References

Best CT, Studdert-Kennedy M, Manuel S, Rubin-Spitz J. Discovering phonetic coherence in acoustic patterns. Perception & Psychophysics. 1989; 45:237–250. [PubMed: 2710622]

Boada R, Pennington BF. Deficient implicit phonological representations in children with dyslexia. Journal of Experimental Child Psychology. 2006; 95:153–193. [PubMed: 16887140]

Boersma, P.; Weenink, D. Praat: doing phonetics by computer (Version 5.1.1). 2009. http://www.praat.org. (Downloaded July 19, 2009)

Bogliotti C, Serniclaes W, Messaoud-Galusi S, Sprenger-Charolles L. Discrimination of speech sounds by children with dyslexia: comparisons with chronological age and reading level controls. Journal of Experimental Child Psychology. 2008; 101:137–155. [PubMed: 18462745]

Boothroyd A, Nittrouer S. Mathematical treatment of context effects in phoneme and word recognition. Journal of the Acoustical Society of America. 1988; 84:101–114. [PubMed: 3411038]

Brady S, Shankweiler D, Mann V. Speech perception and memory coding in relation to reading ability. Journal of Experimental Child Psychology. 1983; 35:345–367. [PubMed: 6842131]

Castles A, Coltheart M. Varieties of developmental dyslexia. Cognition. 1993; 47:149–180. [PubMed: 8324999]

Castles A, Coltheart M. Is there a causal link from phonological awareness to success in learning to read? Cognition. 2004; 91:77–111. [PubMed: 14711492]

Chapman JW, Tunmer WE, Allen R. Findings from the International Adult Literacy Survey on the incidence and correlates of learning disabilities in New Zealand: is something rotten in the state of New Zealand? Dyslexia. 2003; 9:75–98. [PubMed: 12775082]

Cohen, J. Statistical Power Analysis for the Behavioral Sciences. 2nd ed.. Erlbaum; Hillsdale, NJ: 1988.

Corriveau KH, Goswami U, Thomson JM. Auditory processing and early literacy skills in a preschool and kindergarten population. Journal of Learning Disabilities. 2010; 43:369–382. [PubMed: 20457882]

Darwin, C. Sine-wave speech produced automatically using a script for the PRAAT program. http://www.lifesci.sussex.ac.uk/home/Chris_Darwin/SWS/ (Last viewed February 26, 2013)

Farmer ME, Klein RM. The evidence for a temporal processing deficit linked to dyslexia: A review. Psychonomic Bulletin & Review. 1995; 2:460–493.

Fu Q, Zeng FG, Shannon RV, Soli SD. Importance of tonal envelope cues in Chinese speech recognition. Journal of the Acoustical Society of America. 1998; 104:505–510. [PubMed: 9670541]

Godfrey JJ, Syrdal-Lasky AK, Millay KK, Knox CM. Performance of dyslexic children on speech perception tests. Journal of Experimental Child Psychology. 1981; 32:401–424. [PubMed: 7320677]

Goldman, R.; Fristoe, M. Goldman Fristoe 2: Test of Articulation. American Guidance Service, Inc.; Circle Pines, MN: 2000.

Goswami U, Fosker T, Huss M, Mead N, Szücs D. Rise time and formant transition duration in the discrimination of speech sounds: the Ba-Wa distinction in developmental dyslexia. Developmental Science. 2011; 14:34–43. [PubMed: 21159086]

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

Goswami U, Thomson J, Richardson U, Stainthorp R, Hughes D, Rosen S, et al. Amplitude envelope onsets and developmental dyslexia: A new hypothesis. Proceedings of the National Academy of Sciences of the United States of America. 2002; 99:10911–10916. [PubMed: 12142463]

Hämäläinen JA, Salminen HK, Leppänen PH. Basic Auditory Processing Deficits in Dyslexia: Systematic Review of the Behavioral and Event-Related Potential/Field Evidence. Journal of Learning Disabilities. 2012 Published online February 8, 2012. http://dx.doi.org/10.1177/0022219411436213.

Harmon L. The Recognition of Faces. Scientific American. 1973; 229:71–82. [PubMed: 4748120]

Hart, B.; Risley, TR. Meaningful differences in the everyday experience of young American children. Paul H. Brookes Publishing Co.; Baltimore, MD: 1995.

Hazan V, Barrett S. The development of phonemic categorization in children aged 6-12. Journal of Phonetics. 2000; 28:377–396.

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

Hinshelwood J. Congenital word-blindness. Lancet. 1900; 1:1506–1508.

Johnson EP, Pennington BF, Lowenstein JH, Nittrouer S. Sensitivity to structure in the speech signal by children with speech sound disorder and reading disability. Journal of Communication Disorders. 2011; 44:294–314. [PubMed: 21329941]

Liberman, AM. Speech: A special code. MIT Press; Cambridge, MA: 1996.

Liberman AM, Cooper FS, Shankweiler DP, Studdert-Kennedy M. Perception of the speech code. Psychological Review. 1967; 74:431–461. [PubMed: 4170865]

Liberman IY. Segmentation of the spoken word and reading acquisition. Bulletin of the Orton Society. 1973; 23:65–77.

Lindsey KA, Manis FR, Bailey CE. Prediction of first-grade reading in Spanish-speaking English-language learners. Journal of Educational Psychology. 2003; 95:482–494.

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

Manis FR, McBride-Chang C, Seidenberg MS, Keating P, Doi LM, Munson B, et al. Are speech perception deficits associated with developmental dyslexia? Journal of Experimental Child Psychology. 1997; 66:211–235. [PubMed: 9245476]

Marshall CM, Snowling MJ, Bailey PJ. Rapid auditory processing and phonological ability in normal readers and readers with dyslexia. Journal of Speech Language and Hearing Research. 2001; 44:925–940.

Martin, N.; Brownell, R. Expressive One-Word Picture Vocabulary Test (EOWPVT). 4th ed.. Academic Therapy Publications, Inc.; Novato, CA: 2011.

McAnally KI, Hansen PC, Cornelissen PL, Stein JF. Effect of time and frequency manipulation on syllable perception in developmental dyslexics. Journal of Speech Language and Hearing Research. 1997; 40:912–924.

Merzenich MM, Jenkins WM, Johnston P, Schreiner C, Miller SL, Tallal P. Temporal processing deficits of language-learning impaired children ameliorated by training. Science. 1996; 271:77–81. [PubMed: 8539603]

Miller S, Tallal P. Acoustically modified speech training studies: Implications for dyslexia. Perspectives: Proceedings of the Orton Dyslexia Society. 1996:8–9.

Miyawaki K, Strange W, Verbrugge R, Liberman AM, Jenkins JJ, Fujimura O. An effect of linguistic experience: The discrimination of [r] and [l] by native speakers of Japanese and English. Perception & Psychophysics. 1975; 18:331–340.

Mody M, Studdert-Kennedy M, Brady S. Speech perception deficits in poor readers: Auditory processing or phonological coding? Journal of Experimental Child Psychology. 1997; 64:199–231. [PubMed: 9120381]

Mogasale VV, Patil VD, Patil NM, Mogasale V. Prevalence of specific learning disabilities among primary school children in a South Indian city. Indian Journal of Pediatrics. 2012; 79:342–347. [PubMed: 21887581]

Nilsson M, Soli S, Sullivan JA. Development of the Hearing in Noise Test for the measurement of speech reception thresholds in quiet and in noise. Journal of the Acoustical Society of America. 1994; 95:1085–1099. [PubMed: 8132902]

Nittrouer S. Age-related differences in perceptual effects of formant transitions within syllables and across syllable boundaries. Journal of Phonetics. 1992; 20:351–382.

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

Nittrouer S. Children hear the forest. Journal of the Acoustical Society of America. 2006; 120:1799–1802. [PubMed: 17069277]

Nittrouer S, Boothroyd A. Context effects in phoneme and word recognition by young children and older adults. Journal of the Acoustical Society of America. 1990; 87:2705–2715. [PubMed: 2373804]

Nittrouer S, Burton LT. The role of early language experience in the development of speech perception and phonological processing abilities: Evidence from 5-year-olds with histories of otitis media with effusion and low socioeconomic status. Journal of Communication Disorders. 2005; 38:29–63. [PubMed: 15475013]

Nittrouer S, Caldwell A, Lowenstein JH, Tarr E, Holloman C. Emergent literacy in kindergartners with cochlear implants. Ear and Hearing. 2012; 33:683–697. [PubMed: 22572795]

Nittrouer S, Lowenstein JH. Learning to perceptually organize speech signals in native fashion. Journal of the Acoustical Society of America. 2010; 127:1624–1635. [PubMed: 20329861]

Nittrouer S, Lowenstein JH. Separating the effects of acoustic and phonetic factors in linguistic processing with impoverished signals by adults and children. Applied Psycholinguistics. 2012 Published online October 22, 2012. http://dx.doi.org/10.1017/S0142716412000410.

Nittrouer S, Lowenstein JH, Packer R. Children discover the spectral skeletons in their native language before the amplitude envelopes. Journal of Experimental Psychology: Human Perception and Performance. 2009; 35:1245–1253. [PubMed: 19653762]

Nittrouer S, Miller ME. The development of phonemic coding strategies for serial recall. Applied Psycholinguistics. 1999; 20:563–588.

Nittrouer S, Shune S, Lowenstein JH. What is the deficit in phonological processing deficits: Auditory sensitivity, masking, or category formation? Journal of Experimental Child Psychology. 2011; 108:762–785. [PubMed: 21109251]

Nittrouer S, Studdert-Kennedy M. The role of coarticulatory effects in the perception of fricatives by children and adults. Journal of Speech and Hearing Research. 1987; 30:319–329. [PubMed: 3669639]

Orton, S. Reading, writing and speech problems in children: A presentation of certain types of disorders in the development of the language faculty. W. W. Norton; New York: 1937.

Pennington BF, Bishop DVM. Relations among speech, language, and reading disorders. Annual Review of Psychology. 2009; 60:283–306.

Pisoni DB. Speech perception: Some new directions in research and theory. Journal of the Acoustical Society of America. 1985; 78:381–388. [PubMed: 4031245]

Poelmans H, Luts H, Vandermosten M, Boets B, Ghesquière P, Wouters J. Reduced sensitivity to slow-rate dynamic auditory information in children with dyslexia. Research in Developmental Disabilities. 2011; 32:2810–2819. [PubMed: 21645986]

Ramus F, Marshall CR, Rosen S, van der Lely HK. Phonological deficits in specific language impairment and developmental dyslexia: towards a multidimensional model. Brain. 2013; 136:630–645. [PubMed: 23413264]

Ramus F, Rosen S, Dakin SC, Day BL, Castellote JM, White S, et al. Theories of developmental dyslexia: insights from a multiple case study of dyslexic adults. Brain. 2003; 126:841–865. [PubMed: 12615643]

Remez RE, Pardo JS, Piorkowski RL, Rubin PE. On the bistability of sine wave analogues of speech. Psychological Science. 2001; 12:24–29. [PubMed: 11294224]

Richardson U, Thomson JM, Scott SK, Goswami U. Auditory processing skills and phonological representation in dyslexic children. Dyslexia. 2004; 10:215–233. [PubMed: 15341199]

Rocheron I, Lorenzi C, Füllgrabe C, Dumont A. Temporal envelope perception in dyslexic children. Neuroreport. 2002; 13:1683–1687. [PubMed: 12352627]

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

Serniclaes W, Sprenger-Charolles L, Carre R, Demonet JF. Perceptual discrimination of speech sounds in developmental dyslexia. Journal of Speech, Language, and Hearing Research. 2001; 44:384–399.

Serniclaes W, Van Heghe S, Mousty P, Carre R, Sprenger-Charolles L. Allophonic mode of speech perception in dyslexia. Journal of Experimental Child Psychology. 2004; 87:336–361. [PubMed: 15050458]

Shankweiler, D.; Liberman, IY. Misreading: A search for causes. In: Kavanagh, JF.; Mattingly, IG., editors. Language by ear and by eye. MIT Press; Cambridge: 1972. p. 293-317.

Shankweiler D, Liberman IY, Mark LS, Fowler CA, Fischer FW. The speech code and learning to read. Journal of Experimental Psychology. 1979; 5:531–545.

Shannon, RV.; Fu, QJ.; Galvin, J.; Friesen, L. Speech perception with cochlear implants. In: Zeng, FG.; Popper, AN.; Fay, RR., editors. Cochlear implants: Auditory prostheses and electric hearing. Springer-Verlag; New York: 2004. p. 334-376.

Share DL, Jorm AF, Maclean R, Matthews R. Temporal processing and reading disability. Reading and Writing. 2002; 15:178.

Shaywitz BA, Fletcher JM, Holahan JM, Shaywitz SE. Discrepancy compared to low achievement definitions of reading disability: results from the Connecticut Longitudinal Study. Journal of Learning Disabilities. 1992; 25:639–648. [PubMed: 1460385]

Shaywitz, SE. Overcoming Dyslexia: A new and complete science-based program for reading problems at any level. Vintage Books; New York: 2005.

Snowling, MJ. Dyslexia. Blackwell; Oxford: 2000.

Snowling MJ, Muter V, Carroll J. Children at family risk of dyslexia: a follow-up in early adolescence. Journal of Child Psychology and Psychiatry and Allied Disciplines. 2007; 48:609–618.

Stephenson S. Six cases of congenital word-blindness affecting three generations of one family. Opthalmoscope. 1907; 5:482–484.

Tallal P. Auditory temporal perception, phonics, and reading disabilities in children. Brain and Language. 1980; 9:182–198. [PubMed: 7363063]

Tallal, P. In the perception of speech time is of the essence. In: Buzsaki, G.; Llinas, R.; Singer, W.; Berthoz, A.; Christen, Y., editors. Temporal coding in the brain. Springer-Verlag; Berlin: 1994. p. 291-299.

Tallal P, Piercy M. Defects of non-verbal auditory perception in children with developmental aphasia. Nature. 1973a; 241:468–469. [PubMed: 4705758]

Tallal P, Piercy M. Developmental aphasia: Impaired rate of non-verbal processing as a function of sensory modality. Neuropsychologia. 1973b; 11:389–398. [PubMed: 4758181]

Tallal P, Piercy M. Developmental aphasia: Rate of auditory processing and selective impairment of consonant perception. Neuropsychologia. 1974; 12:83–93. [PubMed: 4821193]

Terras MM, Thompson LC, Minnis H. Dyslexia and psycho-social functioning: an exploratory study of the role of self-esteem and understanding. Dyslexia. 2009; 15:304–327. [PubMed: 19384920]

Turner CW, Van Tasell DJ. Sensorineural hearing loss and the discrimination of vowel-like stimuli. Journal of the Acoustical Society of America. 1984; 75:562–565. [PubMed: 6699294]

Vandewalle E, Boets B, Ghesquière P, Zink I. Auditory processing and speech perception in children with specific language impairment: relations with oral language and literacy skills. Research in Developmental Disabilities. 2012; 33:635–644. [PubMed: 22155538]

Viemeister NF. Temporal modulation transfer functions based upon modulation thresholds. Journal of the Acoustical Society of America. 1979; 66:1364–1380. [PubMed: 500975]

Waber DP, Weiler MD, Wolff PH, Bellinger D, Marcus DJ, Ariel R, et al. Processing of rapid auditory stimuli in school-age children referred for evaluation of learning disorders. Child Development. 2001; 72:37–49. [PubMed: 11280488]

Wagner RK, Torgesen JK. The nature of phonological processing and its causal role in the acquisition of reading skills. Psychological Bulletin. 1987; 101:192–212.

Werker JF, Tees RC. Speech perception in severely disabled and average reading children. Canadian Journal of Psychology. 1987; 41:48–61. [PubMed: 3502888]

Wilkinson, GS.; Robertson, GJ. The Wide Range Achievement Test (WRAT). 4th ed.. Psychological Assessment Resources; Lutz, FL: 2006.

Wise JC, Sevcik RA, Morris RD, Lovett MW, Wolf M. The relationship among receptive and expressive vocabulary, listening comprehension, pre-reading skills, word identification skills, and reading comprehension by children with reading disabilities. Journal of Speech, Language, and Hearing Research. 2007; 50:1093–1109.

Witton C, Stein JF, Stoodley CJ, Rosner BS, Talcott JB. Separate influences of acoustic AM and FM sensitivity on the phonological decoding skills of impaired and normal readers. Journal of Cognitive Neuroscience. 2002; 14:866–874. [PubMed: 12191454]

Witton C, Talcott JB, Hansen PC, Richardson AJ, Griffiths TD, Rees A, et al. Sensitivity to dynamic auditory and visual stimuli predicts nonword reading ability in both dyslexic and normal readers. Current Biology. 1998; 8:791–797. [PubMed: 9663387]

Wright BA, Lombardino LJ, King WM, Puranik CS, Leonard CM, Merzenich MM. Deficits in auditory temporal and spectral resolution in language-impaired children. Nature. 1997; 387:176–178. [PubMed: 9144287]

Ziegler JC, Pech-Georgel C, George F, Lorenzi C. Speech-perception-in-noise deficits in dyslexia. Developmental Science. 2009; 12:732–745. [PubMed: 19702766]

Highlights

- Dyslexia may result from poor perceptual organization of speech signals
- Sentences (vocoded and sine-wave) were played to children with and without dyslexia
- Children with dyslexia had greater difficulty organizing vocoded signals
- Sine waves preserve the kind of structure learned first by children with dyslexia

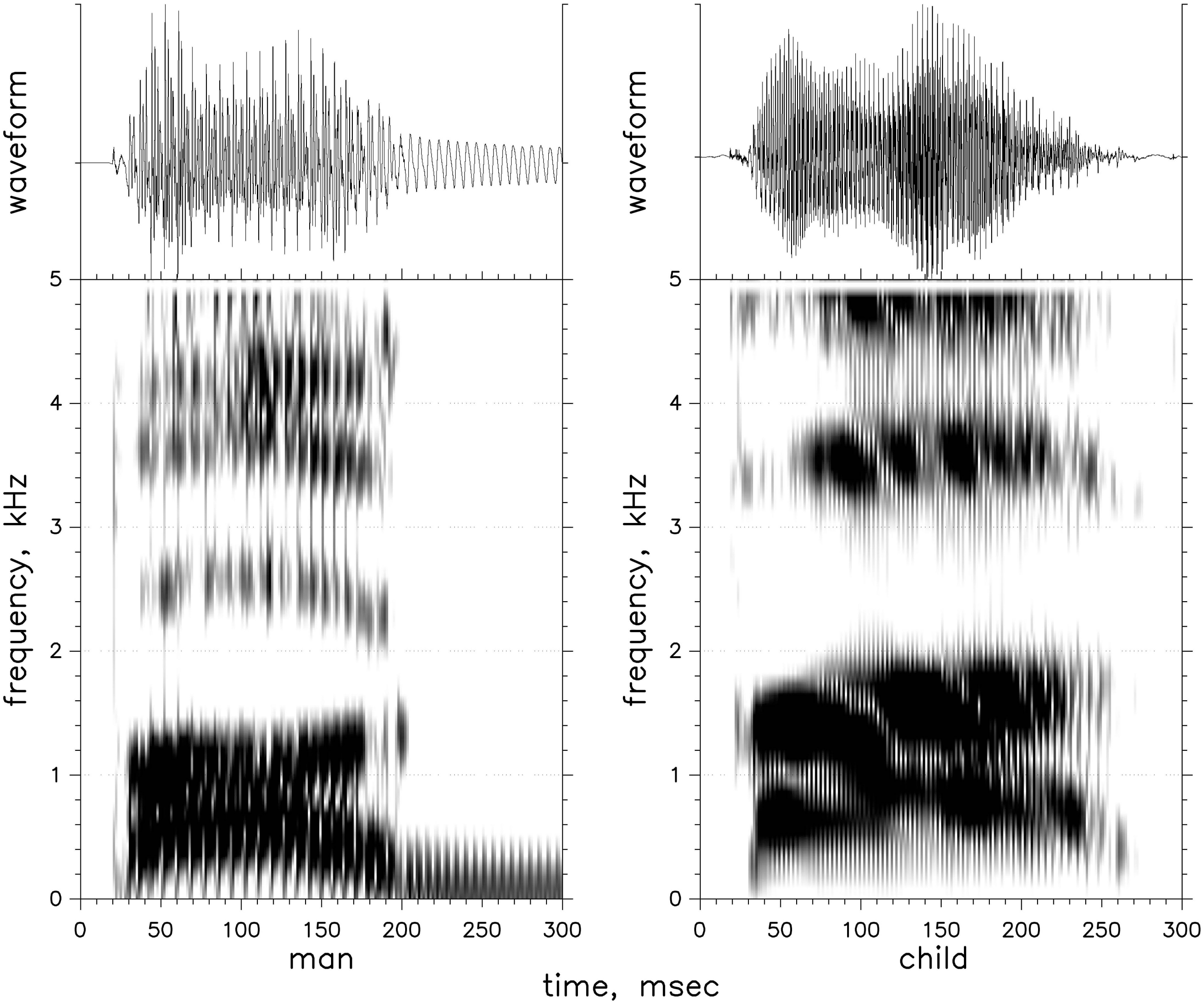


Figure 1.

Spectrograms of *bug* spoken by a man (left) and child (right).

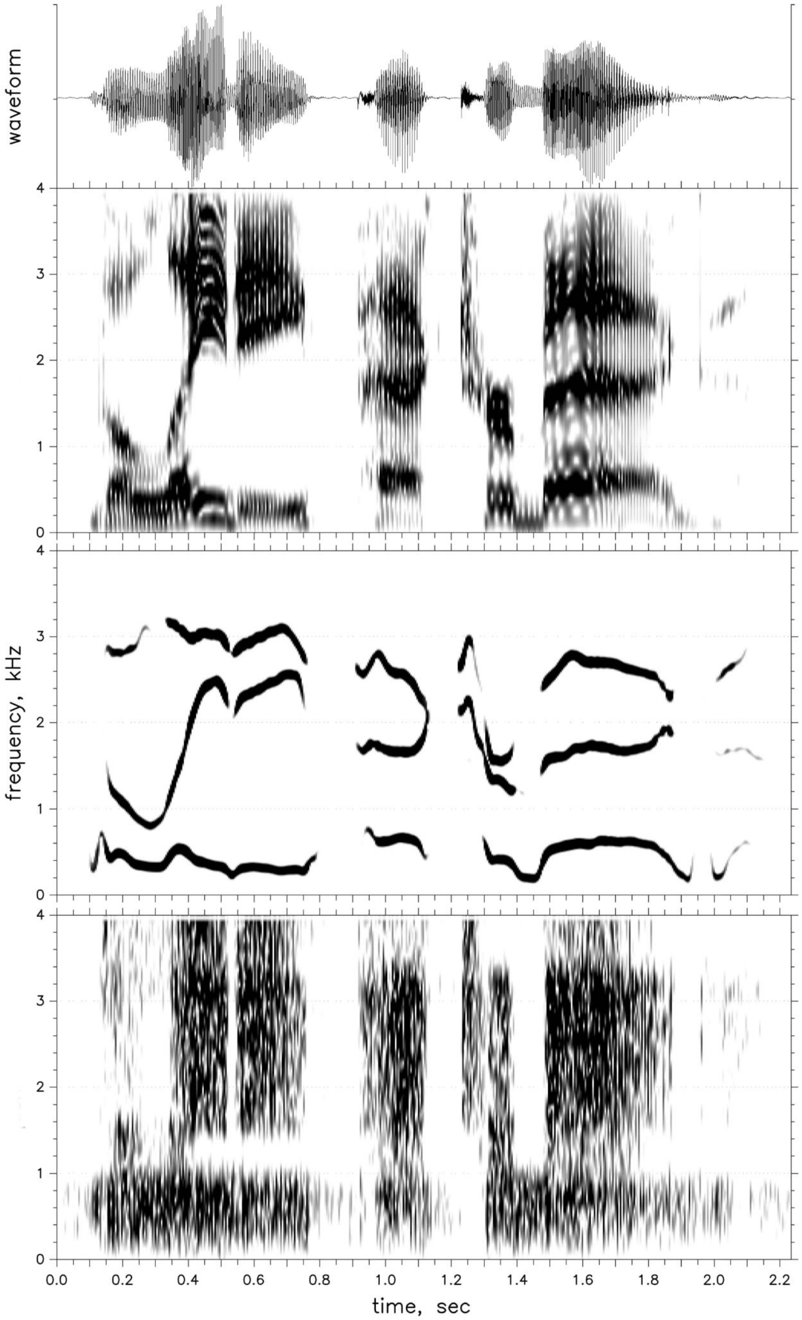


Figure 2.

Waveform and three spectrograms of the sentence *The lady packed her bag*: Unprocessed sample (top); sine-wave (SW) sample (middle); and vocoded (VOC) sample (bottom).

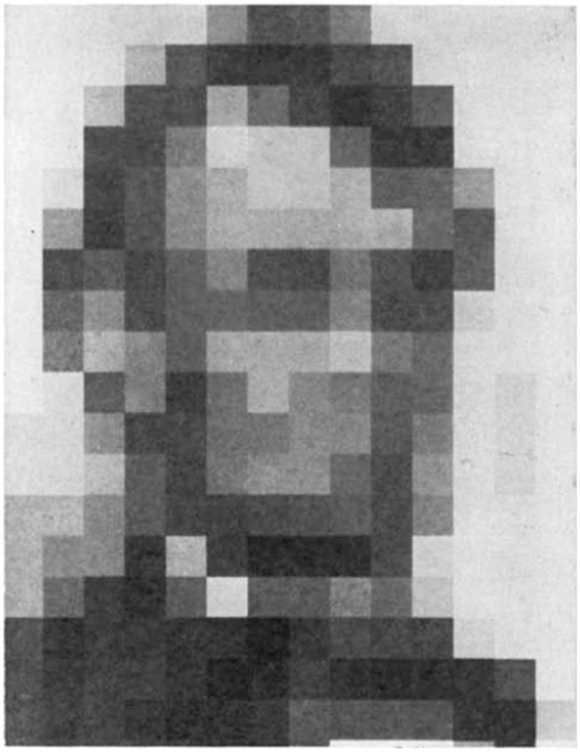


Figure 3.
Block portrait of Abraham Lincoln (Harmon, 1973; Shannon, Fu, Galvin, & Friesen, 2004).

Table 1

Demographic data for each participant group. Standard deviations are in parentheses. Ranges are below, in brackets. Age is in years; months. Ear infections: number before 3 years. SES: Socio-economic status. G-F errors: number of errors on the Goldman Fristoe 2 Test of Articulation. WRAT raw: Raw score on the Word Reading subtest of the Wide Range Achievement Test-4. WRAT std: Standard score on the Word Reading subtest of the WRAT.

	8- to 9-year-olds			**10- to 11-year-olds**		
	TYP	**DYS**	**NON**	**TYP**	**DYS**	**NON**
N	**16**	**16**	**8**	**13**	**13**	**4**
Age	9;0 (0;7) [8;1–9;10]	8;9 (0;8) [8;0–9;10]	9;4 (0;5) [8;5–9;9]	10;11 (0;6) [10;4–11;10]	11;1 (0;7) [10;2–11;10]	10;11 (0;9) [10;3–12;0]
Ear infections	1.5 (2.0) [0–5]	3.3 (3.9) [0–10]	3.6 (3.7) [0–10]	1.5 (2.2) [0–5]	5.5 (5.1) [0–15]	2.8 (3.4) [0–7]
SES	32.3 (11.8) [9–56]	31.9 (10.9) [8–49]	34.3 (11.4) [15–49]	30.4 (11.6) [12–56]	32.4 (13.1) [8–64]	37.8 (9.4) [30–49]
G-F errors	0	3.8 (8.3) [0–34]	.4 (.5) [0–1]	0	1.1 (3.3) [0–12]	0
WRAT raw	40.6 (5.5) [31–49]	24.2 (4.3) [18–32]	32.6 (6.1) [26–40]	47.9 (5.7) [39–60]	36.7 (4.7) [30–43]	39.3 (3.2) [37–44]
WRAT std	110.6 (7.9) [100–124]	82.6 (8.9) [69–100]	92.8 (8.3) [81–102]	109.5 (12.6) [97–145]	90.5 (5.8) [82–100]	94.8 (1.7) [93–97]

Table 2

Mean raw and standard scores on the Expressive One-Word Picture Vocabulary Test-4th Edition (EOWPVT).

	8- to 9-year-olds			10- to 11-year-olds		
	TYP	**DYS**	**NON**	**TYP**	**DYS**	**NON**
EOWPVT raw	119.3 (9.1) [107–138]	94.8 (11.1) [79–112]	104.0 (7.8) [91–114]	126.9 (11.8) [107–146]	116.4 (13.2) [92–138]	131.0 (5.3) [126–138]
EOWPVT std	118.9 (8.8) [106–138]	96.3 (8.7) [82–108]	100.4 (6.8) [87–107]	114.3 (13.5) [91–135]	102.3 (11.5) [82–122]	118.3 (4.1) [113–123]

Table 3

Mean percent correct scores on the phonological awareness tasks for each participant group. Standard deviations are in parentheses. Ranges are below, in brackets. ICC: Initial consonant choice. PD: Phoneme deletion. PL: Pig Latin. PAmean: Computed for individuals across the three measures.

	8- to 9-year-olds			**10- to 11-year-olds**		
	TYP	**DYS**	**NON**	**TYP**	**DYS**	**NON**
ICC	96.0 (4.7) [83–100]	69.4 (11.0) [46–88]	88.3 (7.4) [75–96]	94.4 (4.5) [88–100]	88.3 (14.4) [54–100]	93.2 (6.7) [88–100]
PD	88.9 (9.5) [66–100]	34.2 (17.2) [0–59]	80.1 (14.5) [63–100]	92.8 (8.2) [72–100]	56.0 (25.8) [9–97]	73.4 (1.8) [72–75]
PL	72.1 (22.7) [27–96]	3.3 (6.4) [0–23]	57.0 (27.8) [23–96]	87.2 (9.8) [71–100]	23.6 (25.0) [0–58]	81.2 (11.9) [71–98]
PA mean	85.7 (10.2) [65–98]	35.6 (7.9) [19–48]	75.1 (12.1) [61–97]	91.5 (4.4) [81–97]	56.0 (16.2) [23–73]	82.6 (4.1) [78–87]

Table 4

Results for percent correct scores on the three separate phonological awareness tasks and for PAmean, using arcsine transforms. Precise *p* values are shown if they are less than .10; NS (not significant) is shown for values greater than .10. Degrees of freedom are 1, 64 for age level, and 2, 64 for reading group and the Age x Reading Group interaction.

Task	***F***	***p***	**Partial η^2**
Initial Consonant Choice			
Age Level	8.42	.005	.12
Reading Group	22.15	<.001	.41
Age × Reading Group	9.71	<.001	.23
Phoneme Deletion			
Age Level	1.32	NS	
Reading Group	52.13	<.001	.62
Age × Reading Group	3.07	.053	.09
Pig Latin			
Age Level	15.00	<.001	.19
Reading Group	94.32	<.001	.75
Age × Reading Group	.44	NS	
PAmean			
Age Level	13.63	<.001	.18
Reading Group	110.45	<.001	.78
Age × Reading Group	4.09	.021	.11

Table 5

j factors for the VOC condition for each participant group. Standard deviations are in parentheses.

	8- to 9-year-olds			10- to 11-year-olds		
	TYP	**DYS**	**NON**	**TYP**	**DYS**	**NON**
j factors	2.61 (.48)	2.42 (.50)	2.67 (1.10)	2.40 (.29)	2.35 (.63)	2.71 (.39)

Table 6

Mean percent correct word recognition scores on the vocoded (VOC) and sine-wave speech (SW) degraded sentences task. Standard deviations are in parentheses.

	8- to 9-year-olds			**10- to 11-year-olds**		
Condition	**TYP**	**DYS**	**NON**	**TYP**	**DYS**	**NON**
SW	93.6 (2.5)	89.0 (4.8)	90.9 (5.9)	95.5 (2.6)	94.9 (2.7)	95.0 (2.6)
VOC	62.5 (6.2)	50.9 (8.9)	49.0 (18.7)	65.6 (6.8)	50.1 (15.3)	53.0 (14.9)

Table 7

Cohen’s ds (effect sizes) for recognition scores of the degraded sentences.

	8- to 9-year-olds			**10- to 11-year-olds**		
	TYP/DYS	**TYP/NON**	**NON/DYS**	**TYP/DYS**	**TYP/NON**	**NON/DYS**
SW	1.20	0.59	0.35	0.23	0.19	0.04
VOC	1.51	0.97	−0.13	1.31	1.09	0.19

Table 8

Standardized β coefficients from regression analyses. Dependent variables are shown at the top of each column. Predictor variables were percent correct recognition scores for the SW and VOC sentences. Separate analyses were performed for all children, and for children with dyslexia (DYS and NON) only.

	WRAT raw	**PAmean**	**EOWPVT raw**
SW			
All children	.47**	.41**	.59**
Only children with dyslexia	.46**	.35*	.62**
VOC			
All children	.48**	.41**	.40**
Only children with dyslexia	.16	.06	.21

** significant at .01 level

* significant at .05 level

Table 9

Mean raw WRAT scores and percent correct recognition scores for the oldDYS group and reading-level matched youngTYP group. Standard deviations are in parentheses.

	oldDYS	**youngTYP**
WRAT raw	36.7 (4.7)	39.1 (4.9)
SW	94.9 (2.7)	94.0 (2.1)
VOC	50.1 (15.3)	61.8 (6.6)