Developmental Science

Developmental Science 12:5 (2009), pp 753–767 DOI: 10.1111/j.1467-7687.2009.00806x

PAPER

Categorical speech perception deficits distinguish language and reading impairments in children

Erin K. Robertson, Marc F. Joanisse, Amy S. Desroches and Stella Ng

Department of Psychology, The University of Western Ontario, Canada

Abstract

We examined categorical speech perception in school-age children with developmental dyslexia or Specific Language Impairment (SLI), compared to age-matched and younger controls. Stimuli consisted of synthetic speech tokens in which place of articulation varied from 'b' to 'd'. Children were tested on categorization, categorization in noise, and discrimination. Phonological awareness skills were also assessed to examine whether these correlated with speech perception measures. We observed similarly good baseline categorization rates across all groups; however, when noise was added, the SLI group showed impaired categorization relative to controls, whereas dyslexic children showed an intact profile. The SLI group showed poorer than expected between-category discrimination rates, whereas this pattern was only marginal in the dyslexic group. Impaired phonological awareness profiles were observed in both the SLI and dyslexic groups; however, correlations between phonological awareness and speech perception scores were not significant. The results of the study suggest that in children with language and reading impairments, there is a significant relationship between receptive language and speech perception, there is at best a weak relationship between reading and speech perception, and indeed the relationship between phonological and speech perception deficits is highly complex.

Introduction

Children with developmental dyslexia fail to develop age-appropriate reading skills despite normal-range nonverbal intelligence, adequate learning opportunities, and the absence of a frank neurological disorder (Snowling, 2000). While dyslexia is by definition a reading disorder, there is a strong consensus that spoken language deficits also play a role in reading failure. Specifically, theories suggest that difficulties with phonological processing impair the ability to learn consistencies in the mapping between letters and sounds, which in turn impacts the ability to efficiently read familiar and novel words (Bradley & Bryant, 1983; Stanovich & Siegel, 1994; Wagner, Torgesen & Rashotte, 1994). These phonological impairments are typically identified via phonological awareness measures in which children are asked to identify and manipulate phonological aspects of spoken words, such as rhyme identification, or phoneme elision, blending and counting. On the other hand, there is also some evidence that children with dyslexia have a more basic form of phonological deficit, having to do with how they categorize or discriminate phonemes presented auditorily (Godfrey, Syrdal-Lasky, Millay & Knox, 1981; Mody, Studdert-Kennedy & Brady, 1997; Werker & Tees, 1987). The present study examines the nature and extent of such speech perception problems in dyslexia, and how they are related to broader deficits in phonological processing, reading and oral language.

Speech perception involves mapping an acoustic signal onto basic features of individual phonemes, such as voicing, place, and manner of articulation. These cues are used to make precise category judgments and to discriminate meaningful differences between sounds with minimal phonetic contrasts (e.g. discriminating the initial consonant in the syllables *ba* and *da*). A key finding in speech research is the observation that listeners perceive many speech sounds *categorically*. That is, children and adults selectively attend to acoustic changes that signal a speech contrast while ignoring other differences that are phonetically irrelevant (Liberman, Harris, Hoffman & Griffith, 1957). For example, the initial consonants in the syllables /ba/ and /da/ differ in their place of articulation (POA), or the point in the oral tract at which stop consonants are articulated. Acoustically, POA translates to the onset frequencies of formant transitions. While this is a continuous parameter acoustically, listeners typically respond to changes in this parameter categorically; that is, they tend to ignore acoustic changes that are phonetically irrelevant, but are much more sensitive to changes of a similar magnitude that signal a phonetic distinction. Consequently, listeners show non-monotonic categorization and discrimination functions even though the acoustic parameter is itself continuous. In categorization tasks,

Address for correspondence: Erin K. Robertson, Université du Québec à Montréal, Départment de Psychologie, Montréal, Québec, Canada, H3C 3P8; e-mail: robertson.erin.k@gmail.com or Marc F. Joanisse, The University of Western Ontario, Department of Psychology, London, Ontario, Canada N6A 5C2; e-mail: marcj@uwo.ca

listeners consistently categorize both endpoint and midpoint items as belonging to one category or the other. In discrimination tasks, listeners show stronger sensitivity to between-category acoustic changes compared to within-category changes of the same magnitude.

Some studies have suggested that children with dyslexia process speech differently, however. First, they tend to show categorization curves that are shallower than what is observed in control children, leading to more random categorization rates for endpoint and/or midpoint items (Blomert & Mitterer, 2004; Chiappe, Chiappe & Siegel, 2001; Godfrey *et al.*, 1981; Mody *et al.*, 1997; Werker & Tees, 1987). Such a pattern is typically interpreted as indicative of imprecise phoneme categories. Second, with respect to discrimination tests, there is evidence that dyslexic children have poorer between-category discrimination rates than control children (Breier, Fletcher, Denton & Gray, 2004; Breier, Gray, Fletcher, Foorman & Klass, 2002; Godfrey *et al.*, 1981; Mody *et al.*, 1997; Serniclaes, Sprenger-Charolles, Carre & Demonet, 2001; Werker and Tees, 1987). This suggests that children with dyslexia have trouble discriminating acoustically similar speech sounds when they belong to different phonetic categories. There is also some evidence that dyslexic children have higher rates of within-category discriminations compared to control children (Serniclaes *et al.*, 2001; Werker & Tees, 1987); the implication of this pattern could be that these children are actually more likely to attend to phonetically irrelevant acoustic cues than control children. Note, however, that not all studies have found stronger within-category discrimination (e.g. Manis & Keating, 2005). Indeed, an alternative explanation is that dyslexic children's response rates are more random than those of control children, such that higher within-category discrimination rates represent a regression to the mean (i.e. a chance response rate of 50% or 33% accuracy in AX and ABX tasks, respectively).

It has been proposed that speech perception deficits lead to reading failure by impairing the development of more complex phonological representations, which in turn impede reading development (Harm & Seidenberg, 1999; Serniclaes, 2006). This theory suggests that reading failure begins with a basic weakness in speech perception that has downstream implications for the development of phoneme awareness and other types of phonological representations important to reading development. Consistent with this, McBride-Chang (1996) used structural equation modelling to show that, in a large sample of typically developing third and fourth grade children, the relationship between speech perception and reading skills was moderated by phonological processing. Manis, McBride-Chang, Seidenberg, Keating, Doi, Munson and Petersen (1997) similarly examined the relation between phonological awareness and speech perception deficits in dyslexic children, and found that speech perception deficits were more likely to occur in dyslexic individuals with concomitant phonological impairments compared to those non-phonological dyslexic profiles. Overall then, there is some evidence that speech perception is related to phonological awareness difficulties that are typically thought to play a causal role in dyslexia.

On the other hand, there is also evidence that the relationship among deficits in phonology, speech perception and reading is more complex than this. Specifically, speech perception deficits might only occur in a subset of dyslexic children. For instance, Joanisse, Manis, Keating and Seidenberg (2000) only observed impaired speech perception in dyslexic children who also had concomitant impairments in oral language. Children with dyslexia who had equally severe phonological deficits but normal oral language development performed no differently than control groups on two speech categorization tests. This pattern questions the sequential relation proposed among impaired speech perception, phonological deficits, and reading impairments.

As discussed above, there remains considerable debate about the preponderance of speech perception deficits in dyslexia, and also the relationship between perceptual and phonological impairments. Thus, the first goal of the present study was to more closely examine the occurrence of speech perception deficits in dyslexia, and the second was to examine how these deficits relate to phonological processing difficulties also observed in these children.

Phonology and speech perception in Specific Language Impairment

Much of what is known about categorical speech perception deficits in children also comes from studies of Specific Language Impairment (SLI), a spoken language disorder that has some interesting similarities to dyslexia. Children with SLI fail to develop age-appropriate receptive and/or expressive language skills despite normal-range nonverbal intelligence, and an absence of motor difficulties, a basic sensory impairment or a frank neurological disorder (Bishop, 1997). Particular attention has been directed at the extensive grammatical deficits in SLI (Marshall & van der Lely, 2006; van der Lely & Ullman, 2001; Rice & Wexler, 1996). However, there is also evidence that these children have deficits in phonological awareness (Bird, Bishop & Freeman, 1995; Goulandris, Snowling & Walker, 2000; Kamhi & Catts, 1986; Norbury, Bishop & Briscoe, 2001).

Of particular interest in the present study is the finding that children with SLI have categorical speech perception deficits, for instance shallow categorization curves and weak between-category discrimination (Stark & Heinz, 1996; Gerrits, 2003; Sussman, 1993). It has been proposed that weak speech perception in SLI can lead to problems in other aspects of phonological processing, such as phonological awareness (Joanisse & Seidenberg, 1998; Joanisse, 2004). Subsequently, these phonological processing deficits influence the development of complex linguistic processing, such as grammatical morphology and oral sentence comprehension.

The similarity in the types of phonological and speech perception profiles observed in dyslexia and SLI suggests that there is some value in examining both groups in parallel. That is, while SLI and dyslexia are clearly etiologically distinct (Bishop & Snowling, 2004), the comorbidity of the two disorders extends beyond what would be predicted by base rate alone (Catts, Adolf, Hogan & Ellis Weismer, 2005; McArthur, Hogben, Edwards, Heath & Mengler, 2000). Consequently, previous studies of either group have potentially included children with either impairment. Indeed, very few studies have precluded one disorder when studying speech perception in the other group. (The notable exception is a study by Mody *et al.*, 1997, which precluded language difficulties when examining speech deficits in dyslexia. To our knowledge, no studies of speech perception in SLI have similarly precluded dyslexia from their sample, however.)

It seems important, then, to assess speech perception in both populations in parallel, to determine whether differences exist in either the nature or preponderance of speech deficits in both populations. The data so far have been equivocal. Gerrits (2003) found that 3-year-old children diagnosed with SLI and 3-year-old children at familial risk for developing dyslexia showed similar levels of speech perception deficits; both groups had weaker categorization and discrimination compared to controls, and no group differences were observed between the SLI and at-risk for dyslexia group. One concern is whether these at-risk children are in fact representative of children who will develop reading problems but not language problems. For instance, the Joanisse *et al.* (2000) study discussed above found that only school-age dyslexic children with concomitant SLI-like language impairments showed speech perception deficits on a categorization test; other dyslexic children who had no concomitant oral language impairment beyond phonology performed similarly to control children. A similar effect was found in a follow-up study that tested a subset of these children on discrimination of the same speech stimuli (Manis & Keating, 2005).

One interpretation of these findings is that language impaired children are at greater risk of speech perception deficits compared to dyslexic children. This raises the possibility that prior findings of speech perception deficits in dyslexia were influenced by the inclusion of children with concomitant language impairments. An alternative explanation is that perceptual deficits are more subtle in dyslexia, and thus require more sensitive measures to detect them. It is also possible that the results reported in the Joanisse *et al.* study (and the Manis & Keating follow-up) were influenced by small sample size and permissive classification measures (i.e. the criterion for dyslexia was word recognition performance below the 25th percentile, raising the possibility that children with more severe reading delays might be more likely to show problems with speech perception).

Overview of the present study

While previous studies have identified speech perception deficits in dyslexia, there remains some controversy over the extent of these deficits, and in particular whether they are instead restricted to children with language impairments. The goal of the current study was to examine this issue by testing speech perception abilities both in language and reading impaired groups of children. We also sought to increase sensitivity to speech problems by using a broader set of speech perception measures. Specifically, both categorization and discrimination tests were used, on the assumption that their differing task demands might influence the likelihood of observing impaired performance. In categorization trials, one stimulus needs to be identified. In discrimination trials, two stimuli are perceived (and perhaps categorized) and are then rated as the same or different. The increased load introduced by the discrimination task could reveal deficits not apparent in categorization.

We also sought to increase the sensitivity of the categorization task by manipulating the quality of the auditory signal that participants heard. Standard speech perception tests are typically conducted in ideal acoustic environments, where participants listen to sounds over headphones and often in a sound attenuated booth. Paradoxically, this approach may actually decrease the sensitivity of the test by minimizing the load on the auditory system, leading to ceiling effects in performance. Thus, some studies have observed speech or auditory perception deficits in children only when presenting speech that is embedded noise (Brady, Shankweiler & Mann, 1983; Ziegler, Pech-Georgel, George, Alario & Lorenzi, 2005). The inclusion of noise increases the load in the perceptual stream by reducing the strength of the signal that is being detected, relative to attendant noise. Consequently, it might draw out subtle deficits in perception not evident when noise is not present.

We have included two control groups in this study, age-matched and younger children, to examine whether observed deficits in dyslexic or language impaired groups reflect age-related changes in typical speech perception abilities. For instance, speech perception studies have typically compared reading or language impaired children to chronological-age-matched controls (Coady, Evans, Mainela-Arnold & Kluender, 2007; Mody *et al.*, 1997; Serniclaes *et al.*, 2001; Werker & Tees, 1987). However, recent electrophysiological evidence showed that auditory processing in SLI is qualitatively similar to younger control children, suggesting that these children's problems stem from an immature auditory system (Bishop & McArthur, 2004). It is unclear whether the same can be said for speech perception, however.

Also of interest in the present study was the relationship between speech perception and higher-level phonological processing abilities. As discussed above, there is evidence that phonological deficits are implicated in both reading and language impairment. However, it is unclear how these are related to children's speech perception abilities. For example, prior studies suggest that the relationship between phonological processing and speech perception is not direct (Joanisse *et al.*, 2000; Manis & Keating, 2005), such that dyslexic children who show significant phonological awareness difficulties do not differ from controls with respect to speech perception. In the present study we examined this by measuring children's phonological awareness and correlating it with the above measures of speech perception, which might better reveal how performance in these two measures is related.

To summarize, the primary goal of this study was to investigate the occurrence of speech perception deficits in groups of children with SLI or dyslexia. This can in turn provide a better understanding of the relationship between the two disorders. Multiple measures were used to better identify potential differences in either the severity or types of deficits present in either group. We also examined whether there is a significant relationship between speech perception deficits and phonological processing.

Method

Procedures were approved by the University of Western Ontario Non-Medical Research Ethics Board. Measures were administered in two separate sessions, with a fixed order across all participants. Testing was divided across two sessions lasting 30–45 minutes. The first session was completed in local schools, and consisted of the standardized tests of reading, receptive grammar, vocabulary and nonverbal IQ, described below. The second session took place in our laboratory at the University of Western Ontario and included the three speech perception tasks followed by the phonological awareness task. A short break was given halfway through the laboratory session, as testing in this session took approximately one hour and included additional measures not reported here. Children received a small gift (books, colored pencils) to thank them for participating.

Participants

A total of 56 children were recruited from London, Ontario area schools. Children were excluded if they did not speak English as a first language, if they had a frank neurological disorder, pervasive developmental deficits or significant hearing impairment (based on parental report), or if they had an average scaled score lower than 7 or higher than 13 on two measures of nonverbal IQ (Performance subtests from WISC, described below). Participant groups are described in Table 1.

The dyslexic group consisted of 14 children who scored below the 15th percentile rank on the Word Identification subtest of the Woodcock Reading Mastery Tests-Revised (WRMT-R; Woodcock, 1989) but with standard scores above 87 on a standardized measure of receptive language (Test for the Reception of Grammar, or TROG; Bishop, 1989) and normal-range nonverbal IQ (standard score between 7 and 13 averaged across the two subtests). This scheme is consistent with how previous studies have classified dyslexia, as a severe delay in word reading ability that precludes a more general language impairment and/

Table 1 *Group performance on language, reading and cognitive measures. Mean (SD) raw scores are reported for standardized tests to permit comparisons across age groups*

	Group			
	CA control	Dyslexic	SLI	RL control
Age	9;8	10;6	10;4	8;0
(Range)	(8;0–11;4)	(9;1–12;1)	(8;11–11;9)	(6;0–9;11)
Word Identification[a]				
Raw score	60.5 (13.89)	37.0 (12.36)[1]	46.6 (15.81)[1]	33.9 (18.01)
Percentile	50.5 (6.08)	11.0 (5.64)	26.7 (19.68)	53.4 (6.84)
Word Attack[a]				
Raw score	24.5 (8.64)	10.9 (4.97)[2]	16.5 (8.62)[1]	11.1 (8.33)
Percentile	64.9 (14.89)	22.1 (12.64)	36.1 (20.45)	50.8 (20.27)
Phoneme Elision[b]				
Raw score	16.7 (1.81)	9.4 (2.85)[1]	10.4 (4.70)[1]	10.6 (4.50)
Percentile	63.8 (24.18)	16.5 (8.62)	31.9 (27.27)	53.0 (37.07)
Receptive Vocab[c]				
Raw score	119.8 (22.63)	112.1 (21.70)	111.4 (18.82)	114.9 (17.95)
Percentile	58.71 (32.96)	55.14 (24.68)	46.86 (22.81)	56.00 (24.67)
Receptive Language[d]				
Raw score	17.9 (1.68)	16.2 (2.04)[3]	11.9 (1.77)[4]	14.4 (2.24)
Std. score	111.1 (14.20)	98.9 (11.51)	77.21 (5.06)	99.4 (10.73)
Performance IQ[e]				
Scaled score	10.3 (1.45)	10.8 (1.78)	10.1 (1.16)	11.5 (1.76)

Note: [a] Woodcock Reading Mastery Test, Revised, [b] Comprehensive Test of Phonological Processing, [c] Peabody Picture Vocabulary Test-III, [d] Test for the Reception of Grammar (Std = standard), [e] Mean scaled score on two 'Performance' subtests of the WISC-III or WISC-IV. [1] Lower than CA control group ($p < .05$), [2] Lower than CA control and SLI group ($p < .05$), [3] Lower than CA control group and higher than RL control group ($p < .05$ for both), [4] Lower than CA control, RL control, and dyslexic group ($p < .05$).

or general cognitive delay (Joanisse *et al.*, 2000; Kamhi & Catts, 1986; Shankweiler, Crain, Katz, Fowler, Liberman, Brady, Thornton, Lundquist, Dreyer, Fletcher, Stuebing, Shaywitz & Shaywitz, 1995; Werker & Tees, 1987). The Word Attack subtest of the WRMT-R was also administered, and performance was generally low on this test, with six of the 14 children in the dyslexic group scoring below the 15th percentile.

The Specific Language Impairment (SLI) group consisted of 14 children who had a standard score of 83 or less on TROG (i.e. at least 1 *SD* below the mean), but whose average standard score on the nonverbal IQ measures was between 7 and 13. These classification criteria are similar to what is used in other studies to identify children with language delays, though our criteria were not based on clinical diagnoses (Bishop, Bishop, Bright, James, Delaney & Tallal, 1999; Gathercole & Baddeley, 1990; Montgomery, 1995; Norbury *et al.*, 2001). Our sample of children with SLI differed from more conservative definitions of SLI used elsewhere, as they were only required to show marked deficits on a specific grammatical comprehension test. Just as notably, we did not preclude children from the SLI group based on concomitant reading impairments, given that doing so would have significantly limited the sample size and likely make the sample less comparable to previous studies (Catts *et al.*, 2005; Goulandris *et al.*, 2000; Joanisse *et al.*, 2000; McArthur *et al.*, 2000; Snowling, Bishop & Stothard, 2000). Notably, four of the 14 children in the SLI group met the classification criteria for dyslexia, marked by a percentile rank below 15 on the Word Identification subtest of the WRMT-R.

Both control groups consisted of children who scored in normal ranges on reading and receptive language tests (40th–60th percentile on WRMT Word Identification and a standard score above 90 on TROG), and with normal-range nonverbal IQ. The chronological age (CA) group consisted of 14 children matched for age with the SLI and dyslexic groups, $t(26) = .817$, *ns*; $t(26) = 1.42$, *ns*, respectively. The Reading and Language Level (RL) control group consisted of 14 children who were on average 2 years younger than the SLI, dyslexic, and CA control. The RL control group was matched to the dyslexic group with respect to WRMT Word Identification and Word Attack scores, $t(26) = .526$, $p = .603$; $t(26) = .055$, $p = .956$. The RL control group was also matched to the SLI group with respect to PPVT receptive vocabulary raw scores, $t(26) = .503$, $p = .619$. The key purpose of the RL group was to examine the extent to which observed deficits in the dyslexic and SLI groups reflect a maturational trend, rather than a pattern that deviates from a typical developmental trajectory.

Classification and additional measures

Reading ability

Form G of the Word Identification and Word Attack subtests of the Woodcock Reading Mastery Tests-Revised (WRMT-R) were used to assess children's reading ability. The Word Identification test involves reading aloud common words that vary in complexity and familiarity. The Word Attack subtest is similar, but tests nonword reading ability, which was important in the present study since it is known to have a close relationship with phonological ability, especially in dyslexia (Griffiths & Snowling, 2002; Rack, Snowling & Olson, 1992).

Receptive grammar

The Test for the Reception of Grammar (TROG; Bishop, 1989) was used to classify a language delay. It is a broad measure of receptive language abilities including morphological and syntactic relationships. The test involves listening to sentences and pointing to one of four pictures that corresponds to that sentence.

Performance IQ

Nonverbal achievement was assessed using the Block Design and Picture Completion subtests of the Wechsler Intelligence Scale for Children, third edition (WISC-III; Wechsler, 1992) ($n = 46$) or the Block Design and Matrix Reasoning subtests from WISC-IV (WISC-IV; Wechsler, 2003) ($n = 10$). These measures are part of this test's Performance IQ component, and represent an estimate of cognitive development that depends minimally on language and reading ability.

Receptive vocabulary

The Peabody Picture Vocabulary Test-Third Edition (PPVT-III; Dunn & Dunn, 1997) was also administered. This test measures receptive vocabulary and involves listening to words and pointing to one of four pictures corresponding to that word. It was used only to identify children suitable for the RL control group, which was matched in vocabulary to the SLI group; it was not used to classify SLI.

Experimental materials

Phonological awareness

Phonological awareness was tested using the Phoneme Elision subtest of the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen & Rashotte, 1999), which consisted of deleting a specific sound from a word (e.g. saying *split* without the *p* sound).

Speech perception stimuli

Auditory stimuli consisted of the words 'ball' and 'doll', created using a digital implementation of the Klatt (1980) cascade parallel speech synthesizer. A continuum of eight sounds was produced in which a POA alteration was manipulated by varying a single acoustic parameter. The onset frequency of the second formant (F2) transition of the first consonant was manipulated in eight evenly spaced 100 Hz increments ranging from 900 Hz to 1600 Hz, yielding eight stimulus items labelled 1 through 8. The b/d contrast we used here is known to be categorical in nature such that individuals show a non-monotonic categorization curve in identifying items along the continuum, and are stronger at discriminating across the category boundary than within it (Liberman, 1996).[1]

Aside from the F2 onset frequency manipulation, all other parameters were held constant across the eight stimuli. Stimuli were 360 ms in duration. The duration of the formant transition of the onset consonant was 40 ms, with F1 and F3 frequencies set to 200 and 2600 Hz, respectively; this was followed by a 140 ms vowel /a/ (F1: 600, F2: 990, F3: 2600), which then changed to the /l/ liquid over the next 150 ms (F1: 310, F2: 900, F3: 2880). The voicing amplitude parameter (AV) was set to 76 for the onset, lowered to 72 for the vowel and 66 for the liquid, then fell to zero for the final 30 ms. To produce a stimulus that was as natural sounding as possible, the F0 frequency was modulated from 130 Hz at 0 ms, to 100 Hz at 180 ms, falling to 90 Hz at 330 ms. Stimuli were digitized at 11025 Hz, 16-bit quantization. Stimuli were then resampled to 44100 Hz for the purpose of computer playback. Stimulus intensity was normalized to −12 dB RMS intensity (where 0 dB represents the maximum possible output power level of the audio system). Items in the noise manipulation were created by adding white noise, at an intensity of −24 dB RMS.

Speech perception

Children were tested on three measures of speech perception: baseline categorization, categorization with noise, and discrimination, presented in fixed order. In each task, auditory stimuli were presented binaurally via headphones in a sound-attenuated booth using a desktop computer. Children were asked to set the volume to a comfortable level during the practice trials administered prior to each task. Feedback was provided for the practice trials, but not the experimental trials.

In the categorization task, children were presented with an item from the *doll-ball* continuum, and saw pictures of a doll and ball on screen. They were asked to identify the word by pointing to the corresponding picture. The experimenter recorded each response via a keyboard press. The task started with four practice trials, which consisted of endpoint items (items 1, 2, 7, and 8, presented in random order). This was followed by 40 test stimuli, representing five repetitions of each item, in random order. Note that one CA control participant elected not to perform this task and is not included in these analyses.

Categorization with noise was tested in a separate block of trials. Children were given the same instructions as above, and were told that there would be some noise in the background during these trials. Four practice trials were given, followed by 40 test trials (five repetitions of each stimulus item, presented at random). One RL control participant was not included in the analysis because of invalid responses (i.e. identifying all 40 stimuli as ‘doll’).

In the discrimination task, participants heard pairs of items in the continuum (ISI: 300 ms) and indicated verbally whether they sounded the same or different. The words ‘same’ and ‘different’ were displayed on the computer monitor to remind them of the two possible choices. The experimenter recorded responses via keyboard press. Practice trials consisted of two trials in which opposite endpoints were played (items 1 and 8, with order randomized) and two in which the same sound was repeated (items 1 or 8, repeated), in random order. These pairs were chosen as they represented the clearest possible cases of ‘same’ and ‘different’ trials. This was followed by 64 experimental trials, consisting of 42 different-by-1 pairs (the pairs 1–2, 2–3, 3–4, 4–5, 5–6, 6–7 and 7–8, each played six times); eight ‘same’ pairs (each stimulus item, repeated); and 14 different-by-7 trials (the 1–8 pair). The key trials were the ‘different-by-1’ pairs since these allowed us to test categorical perception by comparing between- and within-category discrimination. The ‘same’ and ‘different-by-7’ trials were included in order to provide the clearest cases of either response type, and would therefore help maintain motivation and focus across the task.

Discrimination trials were presented in random order, and for all pairs the order of item presentation was randomized and counterbalanced (e.g. the 1–2 pair was also presented as 2–1 in half the trials). Two RL control participants and one CA control participant chose not to perform the discrimination task.

Experimental design

A series of one-way ANOVAs was first conducted to examine groupwise differences on the Word Identification, Word Attack, TROG, PPVT, and Phoneme Elision tasks. Group means are reported in Table 1 in percentile ranks. However, analyses were performed on raw scores. Since the dyslexic, SLI, and CA control groups were matched on age, conversion to percentile ranks, which control for age, was not needed. Also, raw scores helped in comparing the younger control group to dyslexic and SLI groups. A one-way ANOVA was also conducted to assure that there were no group differences in performance IQ (scaled scores were used in this case, to assure that children had age-appropriate performance IQ skills). Significant effects were followed up with planned comparisons (independent

---

[1] Stimuli were piloted on a group of adult listeners, and as expected we observed typical S-shaped categorization curves for these stimuli. Similarly, typical categorical perception was observed in the discrimination tests, such that discrimination was better near the midpoint and poorer near the endpoints. Adult participants showed a category boundary between pairs 3 and 4, as indicated by their categorization and discrimination-by-1 stimulus step profiles.

samples *t*-tests, two-tailed) that examined differences between the CA control vs. dyslexic, CA control vs. SLI, SLI vs. dyslexic, RL control vs. dyslexic, and RL control vs. SLI groups.

Analyses of the speech perception and phonology tasks proceeded as follows: categorization curves were created for each participant by computing the proportion of 'doll' responses for each item in the continuum, separately for the baseline and noise measures. The slope of each curve was quantified by fitting it to a logistic function using the SPSS 14 analysis package. The logistic function is appropriate for stimuli presented on a continuous dimension that yields a two-alternative forced choice, on the assumption that the resulting response function can be characterized by an S-shaped curve. Shallower slopes (indicated by a higher ß parameter in the logistic function equation) are interpreted as indicative of weak categorization, marked by inconsistent responses along the continuum. Since the slope values are not normally distributed, they were square-root transformed for subsequent statistical analyses.

A 4 × 2 mixed ANOVA was conducted to examine the effects of Group and Categorization Measure (baseline vs. noise). Subsequently, planned group comparisons (independent *t*-tests, two-tailed) were conducted at each level of the Categorization Measure to compare the CA control vs. dyslexic, CA control vs. SLI, SLI vs. dyslexic, RL control vs. dyslexic, and RL control vs. SLI groups under the baseline and noise tests.

On the discrimination measure, groups were first compared on the proportion of discriminations made for the different-by-7 pairs using a one-way ANOVA. This examined whether participants were generally able to attend to the task and hear the broad difference between the endpoint stimuli. Categorical perception effects were examined by comparing groups on pairs across the category boundary (the between-category pair) and on pairs on either side of the boundary (the within-category pairs). A visual inspection of the data indicated all groups showed peak discrimination for the pair 3–4, which we interpreted as the boundary between phoneme categories. (Note that this was not the exact midpoint of the acoustic continuum; however, it reflects the crossover point for all groups' baseline categorization curves, and also corresponds to the category boundary observed for adult listeners in both categorization and discrimination pilot tests; see Footnote 1.) Two within-category variables were computed by taking the average proportion of discriminations made for pairs 1–2 and 2–3 (ball within-category) and the average proportion of discriminations made for pairs 4–5, 5–6, 6–7, and 7–8 (doll within-category). Accordingly, we compared groupwise discrimination rates for three groupings of pairs along the continuum (between-category, within-category 'ball', and within-category 'doll') using a two-way mixed ANOVA for Group and Stimulus Pair. Subsequently, planned comparisons (independent *t*-tests, two-tailed) were conducted at each grouping level to compare the CA control vs. dyslexic, CA control vs. SLI, SLI vs. dyslexic, RL control vs. SLI, and RL control vs. dyslexic groups.

A *d′* measure was also employed to examine discrimination with a bias-free test. *D′* scores were computed for each subject, at each different-by-1 pair along the continuum, and subsequently examined using a 4 (Group) × 3 (Pair) mixed ANOVA. The same groupings that were used in the main discrimination analyses were also used here, and the same group planned comparisons were also conducted with *d′* values.

Results

Standardized tests

Group profiles on the standardized tests are indicated in Table 1. There was a significant Group effect on the Word Identification test, $F(3, 55) = 8.69$, $p < .001$. The CA control group had higher raw scores than both the dyslexic and SLI groups, $t(26) = 4.73$, $p < .001$; $t(26) = 2.48$, $p < .05$, respectively, but there were no significant differences between the dyslexic and SLI groups, $t(26) = 1.79$, *ns*. As reported above, the RL control group was matched to the dyslexic group with respect to Word Identification and thus the two groups did not differ in this respect. We also did not observe a significant difference between the RL control and SLI group in this respect, $t(26) = 1.97$, *ns*. There was also a significant Group effect on the Word Attack test, $F(3, 55) = 9.39$, $p < .001$, such that the CA control group scored higher than the dyslexic and SLI groups, $t(26) = 5.09$, $p < .001$; $t(26) = 2.45$, $p < .05$; the SLI group also scored significantly higher than the dyslexic group, $t(26) = 2.10$, $p < .05$. As reported earlier, the RL control and dyslexic groups did not differ on Word Attack scores; we also did not observe a significant difference between the RL control and SLI group on this test, $t(26) = 1.69$. A significant Group effect was also observed on the TROG, $F(3, 55) = 24.40$, $p < .001$. The CA control group scored significantly higher than both the SLI and dyslexic groups, $t(26) = 9.17$, $p < .001$; $t(26) = 2.42$, $p < .05$, and the dyslexic group had significantly higher scores than the SLI group, $t(26) = 5.92$, $p < .001$. The RL control group had higher TROG scores than the SLI group, but lower scores than the dyslexic group, $t(26) = 3.18$, $p < .01$; $t(26) = 2.29$, $p < .05$, respectively. There was no significant Group effect on the raw PPVT scores, $F(3, 52) = 0.49$, *ns*, nor on the WISC Performance IQ measures, $F(3, 51) = 2.42$, *ns*.

With respect to the Phoneme Elision test, there was a significant Group effect, $F(3, 55) = 11.53$, $p < .001$, which was due to higher scores for the CA control group compared to the dyslexic and the SLI groups, $t(26) = 8.07$, $p < .001$; $t(26) = 4.72$, $p < .001$, respectively. The SLI and dyslexic groups did not differ from each other, $t(26) = .63$, *ns*. The RL control group scores did not differ from those of the dyslexic and SLI groups, $t(26) = .164$, *ns*; $t(26) = .85$, *ns*, respectively.

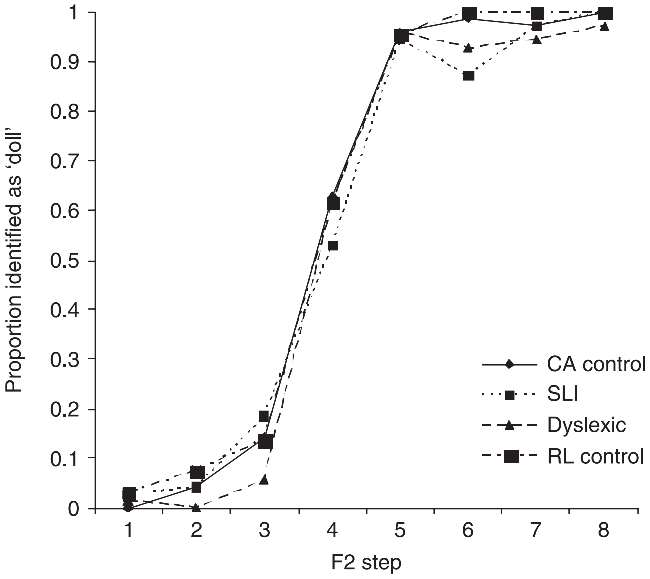

Figure 1 *Group baseline categorization curves.*

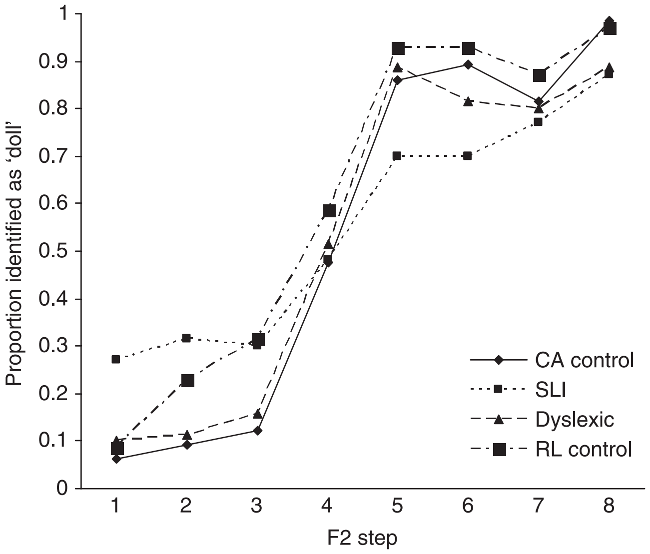

Figure 2 *Group categorization with noise curves.*

Speech perception: categorization

Categorization curves for the baseline and noise measures are presented in Figures 1 and 2, respectively. The square root-transformed slopes for these curves are presented in Table 2. As mentioned earlier, larger slope values are indicative of shallower curves. Analyses revealed significant main effects of Categorization Measure, $F(1, 50) = 51.32$, $p < .001$, and Group, $F(3, 50) = 3.79$, $p < .05$, and a significant Categorization Measure by Group interaction, $F(3, 50) = 3.80$, $p < .05$ (Figures 1 and 2, Table 2). The interaction was followed up by comparing groups' slopes on both Categorization measures using planned comparisons.

The dyslexic group did not differ from the CA control group in the baseline categorization condition, or in the noise condition, $t(26) = .309$, *ns*; $t(25) = .290$, *ns*, respectively (Figure 2). The SLI group did not differ from the CA control group in the baseline categorization condition; however, the SLI group showed significantly larger slopes than the CA control group in the categorization with noise condition, $t(26) = 1.05$, *ns*; $t(25) = 2.51$, $p < .01$. A direct comparison of the dyslexic and SLI groups showed no difference on baseline categorization, but a marginally significant difference on the noise condition, $t(26) = .53$, *ns*; $t(26) = 1.86$, $p = .07$. The dyslexic group did not differ from the RL control group on either the baseline or noise condition, $t(25) = 1.35$, *ns*; $t(26) = .950$. The SLI group did not differ from the RL control group on the baseline condition, but the SLI group showed significantly larger slopes than the RL control group on the noise condition, $t(26) = .97$, *ns*; $t(26) = 2.67$, $p < .05$. Overall, then, it appears that the SLI group showed poorer categorization curves, though only for categorization in noise. In contrast, the dyslexic children did not differ from controls on either categorization condition.

Additional analyses were conducted to examine if the same pattern was observed when the proportion of 'doll' responses at each step was used as the dependent variable. As predicted, a mixed ANOVA revealed a significant three-way interaction (group × noise × item), $F(21, 130) = 1.80$, $p < .05$. We interpret this to mean that the SLI group differed from the other groups in terms of their categorization profile, and that this difference was greatest on the categorization with noise test. This was verified using series of 2 (Group) × 8 (Step) mixed ANOVAs that compared the SLI and dyslexic groups to the control groups and each other, on both the baseline and noise measures. There was no significant interaction between group and step when the dyslexic group was compared to the CA control group on the baseline categorization test, $F(7, 182) = .41$, *ns*; and similarly there was no significant interaction on the noise test, $F(7, 182) = 1.17$, *ns*. There was no significant interaction between group and step when the SLI group was compared to the CA

Table 2 *Transformed slope values (and standard deviations) for baseline categorization and categorization with noise tests*

	Group			
Test	CA control	Dyslexic	SLI	RL control
Categorization baseline transformed slope	0.46 (0.04)	0.47 (0.07)	0.48 (0.06)	0.48 (.06)
Categorization with noise transformed slope	0.54 (0.09)	0.59 (0.13)	0.71 (0.19)[1]	0.56 (0.10)

Note: [1] Higher (poorer) than CA control and RL control group ($p < .05$).

control group on the baseline categorization test, $F(7, 182) = 1.47$, *ns*. However, the comparison on the categorization with noise test did yield a significant interaction, $F(7, 182) = 6.51$, $p < .001$. When the SLI group was compared to the dyslexic group, an interaction was found for categorization with noise, $F(7, 182) = 2.62$, $p < .05$, but not for the baseline test, $F(7, 182) = 1.89$, *ns*. When the RL control group was compared to the dyslexic group, there were no significant interactions in either the baseline or noise conditions, $F(7, 175) = .45$, *ns*; $F(7, 182) = .50$, *ns*. When the RL control group was compared to the SLI group, there was no significant interaction in the baseline categorization test, $F(7, 175) = 1.39$, *ns*. However, there was a significant interaction when these two groups were compared on the categorization with noise test, $F(7, 182) = 3.05$, $p < .05$. Overall, this analysis revealed the same pattern as in the slope analyses, marked by poorer speech categorization in the SLI group, though only when noise was added to the stimuli. The dyslexic group performed similarly to the control groups across both tests.

Speech perception: discrimination

Discrimination curves for each group are plotted in Figure 3. We first examined whether groups differed on the different-by-7 pairs using a one-way ANOVA. The results revealed no effect of group, $F(3, 52) = 2.09$, *ns* (Table 3), suggesting that children in all groups were generally good at differentiating endpoint stimuli.

The key analyses are concerned with performance on the different-by-1 pairs along the continuum. Discrimination curves for each group are plotted in Figure 3. Analyses revealed a significant main effect of Stimulus Pair, $F(2, 98) = 69.92$, $p < .001$, but not Group, $F(3, 49) = 1.11$, *ns*, and a significant Group by Stimulus Pair interaction, $F(6, 98) = 2.38$, $p < .05$. Planned comparisons were conducted to test differences between groups for the three different-by-1 pairs. On the between-category pair (items 3–4; Figure 3), the CA control group made a significantly higher proportion of discriminations than the SLI group, $t(25) = 2.60$, $p < .05$; however, the CA vs. dyslexic difference was not significant, $t(25) = 1.59$, *ns*. There was no difference between the SLI and dyslexic group, $t(26) = 1.14$, *ns*. The RL control group did not differ from the dyslexic or SLI group, $t(24) = .24$, *ns*; $t(24) = 1.30$, *ns*.

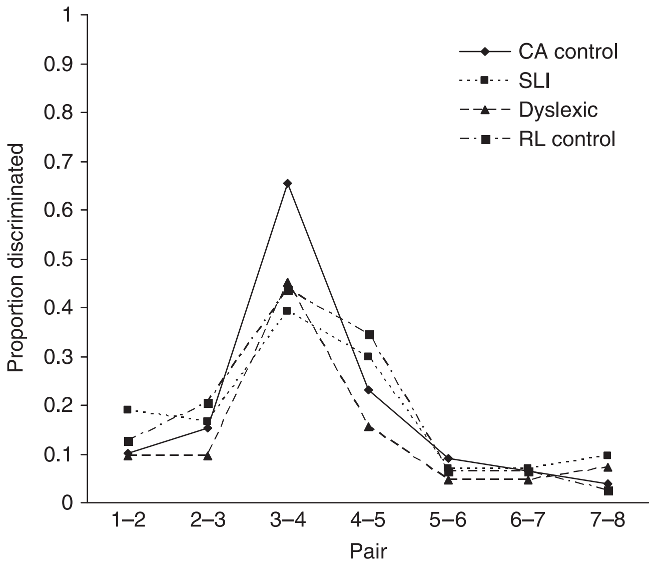

Figure 3 *Group discrimination curves for different-by-1 pairs.*

We next examined performance on within-category pairs (*ball* within-category and *doll* within-category; Table 3). There were no significant differences between the dyslexic and CA control group on either pair, $t(25) = 1.75$, *ns*; $t(25) = 1.04$, *ns*. No significant differences were found for either pair for the SLI and CA control groups, $t(25) = .12$, *ns*; $t(25) = 1.06$, *ns*, the SLI vs. dyslexic group, $t(26) = 1.78$, *ns*; $t(26) = .03$, *ns*, or the SLI vs. RL control group, $t(24) = .59$, *ns*; $t(24) = .08$, *ns*, on these items. The dyslexic group made fewer discriminations than the RL control group on the *ball* within-category pair, $t(24) = 2.13$, $p < .05$, but not on the *doll* within-category pair, $t(24) = .11$, *ns*.

Table 3 *Group means (and standard deviations) for discrimination scores*

	Group			
Test	CA control	Dyslexic	SLI	RL control
Discriminations for different-by-700 Hz pairs	0.98 (0.06)	0.84 (0.20)	0.84 (0.18)	0.86 (0.18)
Between-category: proportion discriminated (obtained)	0.65 (0.28)	0.45 (0.23)	0.39 (0.30)[1]	0.44 (0.30)
Between-category: proportion discriminated (predicted)	0.54 (0.30)	0.57 (0.30)	0.48 (0.27)	0.58 (0.22)
Between-category: *d′*	0.79 (1.14)	−0.14 (1.21)	−0.48 (1.63)[1]	−0.15 (1.56)
Ball within-category: proportion discriminated (obtained)	0.13 (0.15)	0.10 (0.09)[2]	0.18 (0.19)	0.18 (0.18)
Ball within-category: proportion discriminated (predicted)	0.11 (0.14)	0.04 (0.06)	0.11 (0.15)	0.16 (0.20)
Ball within-category: *d′*	0.13 (0.82)	−0.08 (0.51)	−0.23 (1.03)	0.21 (1.18)
Doll within-category: proportion discriminated (obtained)	0.11 (0.09)	0.08 (0.09)	0.13 (0.13)	0.13 (0.09)
Doll within-category: proportion discriminated (predicted)	0.12 (0.11)	0.18 (0.18)	0.18 (0.17)	0.17 (0.21)
Doll within-category *d′*	−0.19 (0.82)	−0.26 (0.54)[3]	0.34 (0.86)	0.17 (1.09)

Note: [1] Lower than the CA control group, $p < .05$.
[2] Lower than the RL control group, $p < .05$.
[3] Lower than the SLI group, $p < .05$.

One possibility is that group effects on this task were due to a bias toward 'same' responses in one of the groups. This was addressed by computing d' values for different-by-1 groupings (Table 3). A 4 (Group) × 3 (Pair) mixed ANOVA revealed no significant main effects of Group or Pair, $F(3, 49) = .81$, *ns*; $F(2, 98) = .01$, *ns*; however, the interaction was significant, $F(6, 98) = 2.32$, $p < .05$. Planned comparisons revealed that the SLI group had a smaller d' value than the CA control group for the between-category pair, $t(25) = 2.32$, $p < .05$. The dyslexic group also showed marginally lower between-category d' values than the CA control group, $t(25) = 2.05$; $p = .051$. There were no between-category d' differences between the dyslexic and SLI groups, the dyslexic and RL control groups, or the SLI and RL control groups, $t(26) = .63$, *ns*; $t(24) = .01$, *ns*; $t(24) = .53$, *ns*, respectively. For both within-category pairs, no differences were observed for the dyslexic vs. CA control group, $t(25) = .79$, *ns*; $t(25) = .27$, *ns*, or the SLI vs. CA control group, $t(25) = 1.00$, *ns*; $t(25) = 1.63$, *ns*. The dyslexic group showed significantly lower d' scores than the SLI group on the *doll* within-category pairs, $t(26) = 2.22$, $p < .05$, but not on the *ball* within-category pairs, $t(26) = .50$, *ns*. There were no differences on either within-category pair between the dyslexic vs. RL control group, $t(24) = .83$, *ns*; $t(24) = 1.16$, *ns*, nor the SLI vs. RL control group, $t(24) = 1.02$, *ns*; $t(24) = .58$, *ns*. Overall, the d' analyses suggest that the discrimination effects observed here are not strictly due to biases toward a greater number of 'same' responses in any of the groups.

An added benefit of obtaining both categorization and discrimination scores is the ability to derive predicted discrimination performance from categorization curves, and then compare them to obtained discrimination rates (Pollack & Pisoni, 1971). Individuals' predicted discrimination profiles were computed from their categorization performance using the procedure described by Pollack and Pisoni (1971). We used the formula $(P_{1a} \times P_{2b}) + (P_{1b} \times P_{2a})$, where subscripts '1' and '2' represent the adjacent pairs along the continuum and 'a' and 'b' refer to the proportion of times the individual categorizes this stimulus as belonging to category A or B (here, 'ball' and 'doll). We conducted a 2 (Predicted vs. Obtained) × 3 (Stimulus Pair) × 4 (Group) mixed ANOVA, again using the between-category pair, the *ball* within-category pair, and the *doll* within-category pair described in the earlier analyses. There was a significant main effect of Pair, but the main effects of Predicted vs. Obtained and Group were not significant, $F(2, 48) = 76.61$, $p < .001$; $F(1, 49) = 1.07$, *ns*; $F(3, 49) = .81$, *ns*, respectively. There was a significant interaction between Pair and Obtained vs. Predicted, but there were no significant interactions between Pair and Group, or Obtained vs. Predicted and Group, $F(2, 48) = 5.13$, $p < .05$; $F(6, 98) = 1.28$, *ns*; $F(3, 49) = 1.06$, *ns*. Finally, there was no significant three-way interaction between Pair, Obtained vs. Predicted, and Group, $F(6, 98) = .96$, *ns*. The results of these analyses suggest that while groups differed in discrimination rates, this was not reflected in differences in obtained vs. predicted discrimination scores.

Correlating speech perception with phonological awareness

Pearson correlations were conducted across all children to examine whether a significant relationship exists between phoneme elision raw scores and speech perception measures (between-category discrimination rates, baseline categorization transformed slopes and categorization with noise transformed slopes). No significant correlations were observed between phoneme elision and any of the speech perception measures (the baseline categorization: $r = .19$, *ns*, categorization with noise: $r = -.22$, *ns*, and between-category discrimination: $r = .02$, *ns*).

Non-reading-disabled SLI group

Four of the 14 children in the SLI group also had reading scores that would classify them as dyslexic (below the 15th percentile rank on WRMT-R Word Identification). Of interest is whether these participants influenced the pattern of results observed such that the SLI group showed stronger evidence of speech perception deficits. For instance, it is possible that children with both language and reading impairments have more severe problems with speech perception or phonological processing. This was examined by considering only the 10 non-reading-disabled participants in the SLI group (which we refer to as the Non-RD SLI group), who all had reading scores that fell above the threshold for dyslexia. Of particular interest was whether the significant speech perception and phonological awareness deficits observed in the entire SLI group remained when the reading disabled children were removed.

Speech perception and phonological awareness scores for this group are listed in Table 4. Similar to the analyses of the entire SLI group above, we observed larger (i.e. poorer) categorization with noise slopes in the Non-RD SLI group compared to the CA and RL control groups, $t(21) = 2.97$, $p < .01$; $t(22) = 2.68$, $p < .05$. Also, here again, the Non-RD SLI group's slopes were not significantly larger than those in the dyslexic group, $t(22) = 1.71$, *ns*. Similarly, this group showed a smaller proportion of between-category discriminations compared to the CA control group but did not differ from the dyslexic or RL control

Table 4 *Speech perception and phonological awareness in the Non-RD SLI group*

Test measure	Mean (*SD*)
Categorization with noise (slope)	.66 (.14)
Discrimination (proportion 'different' responses)	
between-category	.28 (.26)
within-category 'ball'	.17 (.19)
within-category 'doll'	.11 (.105)
Phoneme elision (raw score)	11.80 (4.80)

group, $t(21) = 2.50$, $p < .05$; $t(22) = 1.20$, *ns*; $t(20) = 1.33$, *ns*. They also did not differ from the CA control, dyslexic, or RL control groups on either of the ball or doll within-category discrimination pairs, $t(21) = 0.66$, *ns*; $t(22) = 1.37$, *ns*; $t(20) = .21$, *ns*; $t(21) = .06$, *ns*; $t(22) = .070$, *ns*; $t(20) = .57$, *ns*, respectively. The Non-RD SLI subgroup also showed lower Phoneme Elision scores than the CA control group, $t(22) = 3.52$, $p < .01$, but not the dyslexic group, $t(22) = 1.52$, *ns*, or the RL control group, $t(20) = .66$, *ns*. Overall, the results suggest that the presence of reading disabled children in the SLI group did not strongly influence this group's performance on phonology and speech measures.

Discussion

Developmental dyslexia is typically marked by impairments in both visual word recognition and phonological processing. However, there is some debate as to the role that speech perception deficits play in this disorder, and in particular how these are related to these children's phonological awareness difficulties. The primary goal of this study was to examine the preponderance of speech perception deficits in dyslexia. We also examined speech perception in children with SLI, given prior results indicating a stronger tendency toward speech perception impairments in these children. Also of interest was whether the SLI group differed from the dyslexic group in terms of the severity of phonological processing impairments, which again might help elucidate the relationship between phonological awareness and categorical speech perception difficulties.

Results of the speech categorization tests can be summarized as follows: categorization was evenly good across all groups in the baseline condition, where participants heard stimuli in ideal listening conditions (i.e. over headphones at a preferred volume level, within a sound attenuated booth). When noise was added to the stimuli, all groups showed some decline in performance, marked by shallower categorization slopes. However, the SLI group's slopes were significantly less categorical than both control groups, suggesting that they were disproportionately affected by additive noise. In contrast, the dyslexic group did not differ from controls with respect to categorization.

This pattern of results was similar to what was observed in an earlier study (Joanisse *et al.*, 2000), which found that dyslexic children show apparently normal categorization when they are selected in a way that precludes concomitant language impairment. In contrast, language impaired children showed clear deficits on the same measure. This raises the concern that previous findings of poor categorization in dyslexia may have been influenced by concomitant language impairments such as SLI.

Our findings also suggest that deficits are not always apparent when speech is categorized under minimal processing loads. It therefore raises some concern about the assertion that some language impaired children do not show speech perception deficits. While this remains an open possibility, it is also clear that tasks can differ considerably with respect to sensitivity. Thus, our data suggest that subtle speech perception deficits can be revealed when a load is imposed on the auditory system, for instance by adding noise to the stimuli being categorized. Note, however, that even under such a load we failed to observe poor processing in dyslexic children, and that this effect was instead limited to children with language impairment.

The addition of noise may well represent a more realistic test of speech categorization, since listeners rarely hear speech in low-noise situations. It is more typical that listeners must separate speech from irrelevant stimuli such as environmental noise and other speakers' voices. Note that it is unclear whether noise is the only way to increase auditory processing load. Familiarity of the signal might also influence performance. For instance, Coady *et al.* (2007) found better categorization in SLI for familiar words compared to when nonsense syllables were used as stimuli. This suggests that unfamiliar stimuli also place an increased load on the speech processing stream in a way that can draw out subtle impairments. Finally, it is unlikely that the weaker performance in SLI was due to limited language experience or developmental delays, because the RL control group performed at a higher level than the SLI group. Instead, their deficit appears to represent a frank departure from the typical development of speech processing in children.

The discrimination task revealed somewhat less conclusive results. We observed that dyslexic children showed numerically poorer between-category discrimination compared to CA controls, although these effects were only marginally significant. In contrast, we observed clear evidence of an impairment in the SLI group, marked by significantly poorer between-category discriminations in these children compared to the CA control group. Interestingly, the RL control group showed similar between-category discrimination rates to the SLI and dyslexic groups. This might suggest that between-category discrimination performance continues to develop through the school years. As we discuss further below, this has some implications for how we interpret our findings on this task. In general, all groups showed similar performance discriminating within-category pairs, suggesting that group differences were not due to general difficulty with the task, and instead reflect differences in the ability to discriminate phonetically meaningful differences among speech sounds. Note that this finding fails to replicate earlier findings that dyslexic children show higher discrimination rates than controls on such stimuli (Serniclaes *et al.*, 2001; Werker & Tees, 1987).

Overall then, our data suggest that categorical perception deficits can be clearly observed in SLI under the right circumstances. In contrast, children with dyslexia without concomitant receptive language difficulties do not show deficits in categorization, and only marginal effects for discrimination. As we discussed earlier, many studies have found poor categorical perception in either SLI or dyslexia independently (Breier *et al.*, 2002, 2004; Godfrey *et al.*, 1981; Mody *et al.*, 1997; Werker & Tees, 1987; Gerrits, 2003; Serniclaes *et al.*, 2001; Sussman, 1993). Of interest in this study was the finding that, when both groups are considered in parallel, this effect tends to decrease in dyslexia. While this has been observed previously in categorization (Joanisse *et al.*, 2000), our data extend this finding in several important ways; first, the sample size is appreciably larger than in these earlier studies, which helps address the possibility that the effect was being carried by a handful of children. In addition, we used more conservative categorization criteria for dyslexia, yielding children with stronger reading deficits. Finally, three different perception measures were included in the present study – categorization with and without noise, and discrimination. In all respects, the data indicate a stronger tendency toward speech perception difficulties in SLI than in dyslexia.

One issue with studying both SLI and dyslexia in parallel is that the two disorders tend to be comorbid (Catts *et al.*, 2005; McArthur *et al.*, 2000). Consequently, it is unclear whether to categorize children with both significant reading and language difficulties into either the dyslexic or SLI groups, or even into a third separate group. As a whole, the SLI group's reading profiles were rather low, with four children having reading scores that fit the criteria for dyslexia. However, this number was insufficient to include them as a separate group; instead we chose to include these children in the SLI group. One possibility, though, is that the speech perception deficits we observed in SLI were exaggerated by the inclusion of mixed-type individuals in this group. To address this, we examined these effects when these four children were removed from the SLI group. We observed the same pattern of impairment in this subset of language impaired children, which supports our assertion that speech perception deficits are more closely associated with atypical language development.

A potential concern with this study is the extent to which the children in the SLI group fit the definition as laid out in other studies. As mentioned earlier, this group was based on a relatively narrow definition of language impairment as they were selected on the basis of showing deficits in receptive grammatical comprehension. In this sense, our SLI sample represents a relatively homogeneous group of children with marked receptive grammatical impairments and a relatively intact receptive vocabulary. Moreover, the results of the current study are consistent with the speech perception deficits found in children classified with SLI based on a broader set of vocabulary and language production measures (Coady *et al.*, 2007; Sussman, 1993; Ziegler *et al.*, 2005). Whether the severity of speech perception deficits in SLI increases with the breadth of their language impairment is an empirical question for future studies. However, we do not feel it undermines the key finding here, that these children's speech perception abilities differ in important ways from those of children with dyslexia.

Also of interest in this study was the observation that discrimination ability was similar across the dyslexic, SLI and RL control groups, and tended to be better in the CA control group. The data suggest that between-category discrimination rates follow a maturational pathway, or are a consequence of changes in children's reading and language experience over time. This finding might explain why we found small differences between the dyslexic and CA control groups on the discrimination task – speech perception appears to be still developing in children in this age range, and could be characterized as delayed in dyslexia. On the other hand, we did observe that the RL control group performed better than the SLI group on the categorization with noise test. This seems to suggest that the speech perception deficits observed in the SLI group cannot be completely explained as the result of maturational or experiential factors (something that has been observed previously in electrophysiological studies of nonspeech stimuli; Bishop & McArthur, 2004; McArthur & Bishop, 2005).

Relationship to phonological awareness

The second motivation for the present study was to examine the relationship between speech perception deficits and the phonological awareness difficulties commonly associated with reading and language impairment. We assessed phonological awareness using a phoneme elision task, which we found to be equally compromised in dyslexia and SLI such that both groups performed significantly poorer than controls, but failed to differ from each other. This finding is consistent with previous studies that have found phonological awareness deficits in both groups (Joanisse *et al.*, 2000; Kamhi & Catts, 1986).

The similar phonological deficits observed in dyslexic and SLI groups here are inconsistent with the finding reported by Catts *et al.* (2005), in which phonological awareness deficits were stronger in dyslexia than in SLI. However, we do note that dyslexic children showed numerically lower scores than the SLI group on the phoneme elision task; it is possible that differences could emerge in a larger sample, however. More importantly, the strength of these phonological deficits cannot explain the preponderance of speech perception deficits – we found no correlations between the phoneme elision and speech perception measures, and while phonological deficits were observed in both groups, only the SLI group showed clear speech perception deficits. Overall, our data undermine the assumption that speech perception and phonological awareness tasks tap the same types of underlying skill in children. Instead, these results suggest that speech perception and higher-level phonological processing are at least partially independent language abilities (Joanisse *et al.*, 2000; Manis & Keating, 2005).

One interpretation is instead that phonology can be impaired in a variety of different ways. That is, 'phonology' is in fact a complex construct that is composed of multiple dimensions: speech perception measures, such as phoneme categorization; phonological awareness, including comparing, segmenting, and discriminating spoken words based on their phonological structure; and phonological short-term memory, which involves storing and reproducing sequences of phonemes. The processing components across these capacities differ considerably. With this in mind, it may be misleading to expect a direct relationship between speech perception and higher-level phonological processing. It is instead conceivable that different groups of children will have deficits that span different dimensions, due to subtly different neurobiological mechanisms underlying these disorders. In the present study, it appears that the SLI group had difficulties with both perception and phonological awareness components of processing, whereas the dyslexic group showed difficulties that were restricted to phonological awareness. The role of phonological short-term memory to these two disorders is a matter of considerable interest (Catts *et al.*, 2005; Dollaghan & Campbell, 1998; Gathercole & Baddeley, 1990; Montgomery, 1995; Shankweiler, Smith & Mann, 1984), and here again it remains to be seen how this relationship will unfold.

This perspective fits well with the multiple dimension approach of developmental disorders proposed by Pennington (2006) whereby the multifactorial etiologies alter cognitive processes, which in turn produce behavioural symptoms associated with the disorders. This seems consistent with the idea that separate but similar deficits underlie reading and language disorders, and could explain the comorbidity of dyslexia and language impairments as owing to the fact that the two are caused by similar but not identical phonological impairments.

Conclusions

We examined speech perception deficits in dyslexia compared to children with SLI and typically developing controls. Across a range of speech perception tasks, we observed markedly different patterns of results for dyslexic and language impaired children. Specifically, we found much stronger evidence for poor categorical perception in the SLI group, marked by poorer performance on a categorization with noise and discrimination task. Both dyslexic and SLI groups showed deficits in phonological awareness, though this complex form of phonological processing was not significantly related to speech perception. The superior performance of the dyslexic group on speech tasks suggests that there is only a very weak relationship between speech perception and reading failure. Poor language development, however, does appear to be grounded in a broader and qualitatively different deficit in perceiving speech. The findings provide some useful evidence of why SLI and dyslexia represent etiologically distinct disorders in spite of similarities in behavioural profiles, and high levels of comorbidity.

Acknowledgements

This research was supported by grants from the Natural Sciences and Engineering Research Council of Canada and the Canadian Institutes for Health Research. EKR was supported by scholarships from the Scottish Rite Charitable Foundation, and the Ontario Graduate Scholarship in Science and Technology.

References

Bird, J., Bishop, D.V.M., & Freeman, N.H. (1995). Phonological awareness and literacy development in children with expressive phonological impairments. *Journal of Speech and Hearing Research*, **38**, 446–462.

Bishop, D. (1989). *Test of reception of grammar*. Manchester: Department of Psychology, University of Manchester.

Bishop, D.V.M. (1997). *Uncommon understanding*. Hove, England: Psychology Press.

Bishop, D.V.M., Bishop, S.J., Bright, P., James, C., Delaney, T., & Tallal, P. (1999). Different origin of auditory and phonological processing problems in children with language impairment: evidence from a twin study. *Journal of Speech, Language and Hearing Research*, **42**, 155–168.

Bishop, D.V.M., & McArthur, G.M. (2004). Immature cortical responses to auditory stimuli in specific language impairment: evidence from ERPs to rapid tone sequences. *Developmental Science*, **7** (4), F11–F18.

Bishop, D.V.M., & Snowling, M.J. (2004). Developmental dyslexia and specific language impairment: same or different? *Psychological Bulletin*, **130** (6), 858–886.

Blomert, L., & Mitterer, H. (2004). The fragile nature of the speech-perception deficit in dyslexia: natural vs. synthetic speech. *Brain and Language*, **89**, 21–26.

Bradley, L., & Bryant, P.E. (1983). Categorizing sounds and learning to read – a causal connection. *Nature*, **301** (3), 419–421.

Brady, S., Shankweiler, D., & Mann, V. (1983). Speech perception and memory coding in relation to reading ability. *Journal of Experimental Child Psychology*, **35** (2), 345–367.

Breier, J.I., Fletcher, J.M., Denton, C., & Gray, L.C. (2004). Categorical perception of speech stimuli in children at risk for reading difficulty. *Journal of Experimental Child Psychology*, **88**, 152–170.

Breier, J.I., Gray, L.C., Fletcher, J.M., Foorman, B., & Klass, P. (2002). Perception of speech and nonspeech stimuli by children with and without reading disability and attention deficit hyperactivity disorder. *Journal of Experimental Child Psychology*, **82**, 226–250.

Catts, H.W., Adolf, S.M., Hogan, T.P., & Ellis Weismer, S. (2005). Are specific language impairment and dyslexia distinct disorders? *Journal of Speech, Language and Hearing Research*, **48**, 1378–1396.

Chiappe, P., Chiappe, D.L., & Siegel, L.S. (2001). Speech perception, lexicality, and reading skill. *Journal of Experimental Child Psychology*, **80** (1), 58–74.

Coady, J.A., Evans, J.L., Mainela-Arnold, E., & Kluender, K. (2007). Children with specific language impairments perceive speech most categorically when tokens are natural and meaningful. *Journal of Speech, Language and Hearing Research*, **50**, 41–57.

Dollaghan, C., & Campbell, T. (1998). Nonword repetition and child language impairment. *Journal of Speech, Language and Hearing Research*, **41**, 1136–1146.

Dunn, L.M., & Dunn, L.M. (1997). *Peabody Picture Vocabulary Test, Third Edition*. Circle Pines, MN: American Guidance Service.

Gathercole, S.E., & Baddeley, A.D. (1990). Phonological memory deficits in language disordered children: is there a causal connection? *Journal of Memory and Language*, **29**, 336–360.

Gerrits, E. (2003). Speech perception of young children at risk for dyslexia and children with specific language impairment. Paper presented at the 15th International Congress of Phonetic Sciences, Barcelona, Spain.

Godfrey, J.J., Syrdal-Lasky, A.K., Millay, K.K., & Knox, C.M. (1981). Performance of dyslexic children on speech perception tests. *Journal of Experimental Child Psychology*, **32**, 401–424.

Goulandris, N.K., Snowling, M.J., & Walker, I. (2000). Is dyslexia a form of specific language impairment? A comparison of dyslexia and language impaired children as adolescents. *Annals of Dyslexia*, **50**, 103–120.

Griffiths, Y.M., & Snowling, M.J. (2002). Predictors of exception word and nonword reading in dyslexic children: the severity hypothesis. *Journal of Educational Psychology*, **94** (1), 34–43.

Harm, M., & Seidenberg, M.S. (1999). Reading acquisition, phonology, and dyslexia: insights from a connectionist model. *Psychological Review*, **106**, 491–528.

Joanisse, M.F. (2004). Specific language impairments in children: phonology, semantics, and the English past tense. *Current Directions in Psychological Science*, **13** (4), 156–160.

Joanisse, M.F., Manis, F.R., Keating, P., & Seidenberg, M.S. (2000). Language deficits in dyslexic children: speech perception, phonology, and morphology. *Journal of Experimental Child Psychology*, **77**, 30–60.

Joanisse, M.F., & Seidenberg, M.S. (1998). Specific language impairment: a deficit in grammar or processing? *Trends in Cognitive Neuroscience*, **2** (7), 240–247.

Kamhi, A.G., & Catts, H.W. (1986). Toward an understanding of developmental language and reading disorders. *Journal of Speech and Hearing Disorders*, **51**, 337–347.

Klatt, D.H. (1980). Software for a cascade/parallel formant synthesizer. *Journal of the Acoustical Society of America*, **67** (3), 971–995.

Liberman, A.M. (Ed.) (1996). *Speech: A special code*. Cambridge, MA: MIT Press.

Liberman, A.M., Harris, K., Hoffman, H., & Griffith, B. (1957). The discrimination of speech sounds within and across phoneme boundaries. *Journal of Experimental Psychology*, **54**, 358–368.

McArthur, G.M., & Bishop, D.V.M. (2005). Speech and non-speech processing in people with specific language impairment: a behavioral and electrophysiological study. *Brain and Language*, **94**, 260–273.

McArthur, G.M., Hogben, J.H., Edwards, S.M., Heath, S.M., & Mengler, E.D. (2000). On the 'specifics' of specific reading disability and specific language impairment. *Journal of Child Psychology and Psychiatry*, **41** (7), 869–874.

McBride-Chang, C. (1996). Models of speech perception and phonological processing in reading. *Child Development*, **67** (4), 1836–1856.

Manis, F., & Keating, P. (2005) Speech perception in dyslexic children with and without language impairments. In H.W. Catts & A.G. Kamhi (Eds.), *The connections between language and reading disabilities* (pp. 77–99). Wahaw, NJ: Erlbaum.

Manis, F., McBride-Chang, C., Seidenberg, M.S., Keating, P., Doi, L.M., Munson, B., & Petersen, A. (1997). Are speech perception deficits associated with developmental dyslexia? *Journal of Experimental Child Psychology*, **66**, 211–235.

Marshall, C.M., & van der Lely, H.K.J. (2006). A challenge to current models of past tense inflection: the impact of phonotactics. *Cognition*, **100** (2), 302–320.

Mody, M., Studdert-Kennedy, M., & Brady, S. (1997). Speech perception deficits in poor readers: auditory processing or phonological coding? *Journal of Experimental Child Psychology*, **64**, 199–231.

Montgomery, J.W. (1995). Sentence comprehension in children with specific language impairment: the role of phonological working memory. *Journal of Speech and Hearing Research*, **38**, 187–199.

Norbury, C.F., Bishop, D.V.M., & Briscoe J. (2001). Production of English finite verb morphology: a comparison of SLI and mild to moderate hearing impairment. *Journal of Speech, Language and Hearing Research*, **44**, 165–178.

Pennington, B.F. (2006). From single to multiple deficit models of developmental disorders. *Cognition*, **101**, 385–413.

Pollack, L., & Pisoni, D. (1971). On the comparison between identification and discrimination tests in speech perception. *Psychonomic Science*, **24** (6), 299–300.

Rack, J.P., Snowling, M.J., & Olson, R.K. (1992). The nonword reading deficit in developmental dyslexia: a review. *Reading Research Quarterly*, **27** (1), 28–53.

Rice, M.L., & Wexler, K. (1996). Toward tense as a clinical marker of specific language impairment in English-speaking children. *Journal of Speech, Language and Hearing Research*, **39**, 1229–1257.

Serniclaes, W. (2006). Allophonic perception in developmental dyslexia: origin, reliability and implications of the categorical perception deficit. *Written Language and Literacy*, **9** (1), 135–152.

Serniclaes, W., Sprenger-Charolles, L., Carre, R., & Demonet, J.F. (2001). Perceptual discrimination of speech sounds in developmental dyslexia. *Journal of Speech, Language and Hearing Research*, **44** (2), 384–399.

Shankweiler, D., Crain, S., Katz, L., Fowler, A.M., Liberman, A.M., Brady, S.A., Thornton, R., Lundquist, E., Dreyer, L., Fletcher, J.M., Stuebing, K.K., Shaywitz, S.E., & Shaywitz, B.A. (1995). Cognitive profiles of reading disabled children: comparison of language skills in phonology, morphology, and syntax. *Psychological Science*, **6** (3), 149–155.

Shankweiler, D., Smith, S.T., & Mann, V.A. (1984). Repetition and comprehension of spoken sentences by reading disabled children. *Brain and Language*, **23** (2), 241– 257.

Snowling, M.J. (2000). *Dyslexia* (2nd edn.). Malden, MA: Blackwell Publishers.

Snowling, M.J., Bishop, D.V.M., & Stothard, S.E. (2000). Is preschool language impairment a risk factor for dyslexia in adolescence? *Journal of Child Psychology and Psychiatry*, **41** (5), 587–600.

Stanovich, K.E., & Siegel, L.S. (1994). The phenotypic performance profile of reading-disabled children. a regression-based test of the phonological-core-variable-difference model. *Journal of Educational Psychology*, **86**, 24–53.

Stark, R.E., & Heinz, M. (1996). Perception of stop consonants in children with expressive and receptive-expressive language impairments. *Journal of Speech, Language and Hearing Research*, **39**, 676–686.

Sussman, J.E. (1993). Perception of formant transition cues to place of articulation in children with language impairments. *Journal of Speech and Hearing Research*, **36**, 1286–1299.

van der Lely, H., & Ullman, M.T. (2001). Past tense morphology in specifically language impaired and normally developing children. *Language and Cognitive Processes*, **16** (2), 177–217.

Wagner, R.K., Torgesen, J.K., & Rashotte, C.A. (1994). Development of reading-related phonological processing abilities: new evidence of bidirectional causality from a latent variable longitudinal study. *Developmental Psychology*, **30** (1), 73–87.

Wagner, R.K., Torgesen, J.K., & Rashotte, C.A. (1999). *Comprehensive Test of Phonological Processing*. Austin, TX: Pro-Ed Inc.

Wechsler, D.A. (1992). *Wechsler Intelligence Scale for Children-III*. San Antonio, TX: Psychological Corporation.

Wechsler, D.A. (2003). *Wechsler Intelligence Scale for Children-IV*. San Antonio, TX: Psychological Corporation.

Werker, J.F., & Tees, R.C. (1987). Speech perception in severely disabled and average reading children. *Canadian Journal of Psychology*, **41** (1), 48–61.

Woodcock, R.W. (1989). *Woodcock Reading Mastery Tests-Revised*. Circle Pines, MN: American Guidance Service.

Ziegler, J., Pech-Georgel, C., George, F., Alario, F.X., & Lorenzi, C. (2005). Deficits in speech perception predict language learning impairment. *Proceedings of the National Academy of Sciences*, **102** (39), 14110–14115.

Received: 25 August 2007
Accepted: 10 July 2008