Speech Perception in Dyslexic Children

With and Without Language Impairments

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Developmental dyslexia refers to a group of children who fail to learn to read at the normal rate despite apparently normal vision and neurological functioning. Dyslexic children typically manifest problems in printed word recognition and spelling, and difficulties in phonological processing are quite common (Lyon, 1995; Rack, Snowling, & Olson, 1992; Stanovich, 1988; Wagner & Torgesen, 1987). The phonological processing problems include, but are not limited to difficulties in pronouncing nonsense words, poor phonemic awareness, problems in representing phonological information in short-term memory and difficulty in rapidly retrieving the names of familiar objects, digits and letters (Stanovich, 1988; Wagner & Torgesen, 1987; Wolf & Bowers, 1999).

The underlying cause of phonological deficits in dyslexic children is not yet clear. One possible source is developmentally deviant perception of speech at the phoneme level. A number of studies have shown that dyslexics' categorizations of speech sounds are less sharp than normal readers (Chiappe, Chiappe, & Siegel, 2001; Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Maassen, Groenen, Crul, Assman-Hulsmans, & Gabreels, 2001; Reed, 1989; Serniclaes, Sprenger-Charolles, Carré, & Demonet, 2001;Werker & Tees, 1987). These group differences have appeared in tasks requiring the labeling of stimuli varying along a perceptual continuum (such as voicing or place of articulation), as well as on speech discrimination tasks. In two studies, there was evidence that dyslexics showed better discrimination of sounds differing phonetically within a category boundary (Serniclaes et al, 2001; Werker & Tees, 1987), whereas in one study, dyslexics were poorer at both within-phoneme and between phoneme discrimination (Maassen et al, 2001). There is evidence that newborns and 6-month olds with a familial risk for dyslexia have reduced sensitivity to speech and non-speech sounds (Molfese, 2000; Pihko, Leppanen, Eklund, Cheour, Guttorm & Lyytinen, 1999). If dyslexics are impaired from birth in auditory processing, or more specifically in speech perception, this would affect the development and use of phonological representations on a wide variety of tasks, most intensively in phonological awareness and decoding.

Although differences in speech perception have been observed, it has also been noted that the effects are often weak, small in size or shown by only some of the dyslexic subjects (Adlard & Hazan, 1998; Brady, Shankweiler, & Mann, 1983; Elliot, Scholl, Grant, & Hammer, 1990; Manis, McBride-Chang, Seidenberg, Keating, Doi, Munson, & Petersen (1997); Nittrouer, 1999; Snowling, Goulandris, Bowlby, & Howell, 1986). One reason for small, or variable effects, might be that the dyslexic population is heterogeneous, and that speech perception problems are more common among particular subgroups of dyslexics. A specific hypothesis is that speech perception problems are more concentrated among dyslexic children showing greater phonological deficits. McBride-Chang (1996) reported structural equation analyses indicating that speech perception was not directly related to word recognition among third graders. Instead, phoneme awareness acted as a mediator for the relationship of speech perception and word reading. She proposed that poor perception of the phoneme might impede the development of phoneme awareness, which in turn interfered with early word decoding and word reading development.

Evidence in support of this view was provided by Manis et al. (1997). They tested older (age 10-14 years) dyslexic children who had serious delays in word recognition, but who varied in the degree of deficit in phoneme awareness. About half of the sample of dyslexics fell within the normal range for chronological age on a measure of phoneme awareness. Manis et al. (1997) found that dyslexics with low phoneme awareness were more likely to have speech perception deficits on a task requiring them to identify /b/ vs. /p/ on the basis of VOT. Five of the thirteen cases with low phoneme awareness had abnormal categorical perception functions, as opposed to only two of the twelve cases with normal phoneme awareness. Only one of 25 cases in the CA group and three of 24 cases in the RL group showed abnormal categorical perception, and these were minor deviations from normal compared to what was seen in the low phoneme awareness subgroup. It is possible that past studies finding a significant group difference in speech perception had a greater concentration of dyslexic children with problems in phonological awareness. However, findings inconsistent with this viewpoint have been reported. Nittrouer (1999) studied a sample of poor readers with considerable phonological difficulties, but failed to observe deficits in auditory processing or speech perception.

Another possibility is that speech perception difficulties might be more common among dyslexics with broader impairments in language. The selection criteria used in past studies of dyslexia (e.g., typically scores within the normal range on a full-scale IQ test or on a short-form of the IQ test) allow for the possibility that some dyslexics have mild to moderate language delays. There is strong evidence that speech perception problems are implicated in children categorized as specific language impaired (SLI) (Elliot & Hammer, 1988; Stark & Heinz, 1996; Tallal & Stark, 1980; 1982; Thibodeau & Sussman, 1979). Many, but not all SLI children tend to be dyslexic (Catts, Fey, Tomblin, & Zhang, 2002; Kamhi & Catts, 1986; Goulandris, Snowling, & Walker, 2000).

The purpose of the studies described in this paper was to investigate the relationships among reading difficulties, phonological processing, language impairments and speech perception. We first present data from Joanisse, Manis, Keating & Seidenberg (2000), including re-analyses of the data, as well as data from a follow-up study on the same subjects, administered a year later.

Dyslexia and Specific Language Impairment

The specific question we address in this paper is why speech perception difficulties are not consistently found in a majority of dyslexic children. One possibility is that they are associated more with phonological deficits, as hypothesized by a number of investigators (Adlard & Hazan, 1998; McBride-Chang, 1995; Manis et al., 1997). Still another is that speech perception problems are part of broader language deficits found in some dyslexic children, as hypothesized by investigators exploring the correlates and sequelae of specific language impairment (Elliot & Hammer, 1988; Leonard, 1998; Tallal & Stark, 1980). A third view is that the varying results of speech perception tasks in the dyslexic population might be due to lack of sensitivity in the tasks. With a sufficiently sensitive task, it might be found that all or nearly all dyslexics have a speech perception deficit (Serniclaes et al., 2001).

Phonological dyslexia is prominent in studies exploring heterogeneity within the dyslexic population. Investigations by Castles and Coltheart (1993) and others (Boder, 1973; Stanovich, Siegel, & Gottardo, 1997) as well in our lab (Manis, Seidenberg, Doi, McBride-Chang, & Peterson, 1996; Manis, Seidenberg, Stallings, Joanisse, Bailey, Freedman, Curtin, & Keating, 1999) have identified children, termed phonological dyslexics, who exhibit specific phonological impairments relative to word reading ability. This sub-sample of dyslexics, who often form the majority of cases in a dyslexic sample, fit the profile of phonological impairments that is often associated more generally with dyslexia (Rack, Snowling, & Olson, 1992; Stanovich, 1988; Wagner & Torgesen, 1987). Surface or "delay" dyslexics, have phonological skills that are on a par with their word reading skills. These children read as far below grade level as children typically included in dyslexia samples, but their profile of reading and phoneme awareness skills resemble those of younger normal readers.

While phonological processing problems are found in a majority of dyslexic children, it is also the case that a number of children with dyslexia have a history of language impairments. Research on specific language impairment has often been carried out somewhat independently of studies of dyslexia, even though 50% or more of a sample of children manifesting language delays in early childhood eventually meet the criteria for dyslexia in middle childhood (Catts et al., 1994; Goulandris et al., 2000). Specific language impaired children typically exhibit normal nonverbal intelligence, but have delayed or deficient development of inflectional morphology and other aspects of grammar, as well as difficulties with phonological processing and aspects of speech perception (Catts et al., 1994; Dollaghan & Campbell, 1998; Elliot & Hammer, 1988; Leonard, 1998; Stark & Heinz, 1996; Tallal & Stark, 1980; Thibodeau & Sussman, 1979). Evidence of deficits in phonological processing and speech perception raise the issue of the similarity of dyslexia and SLI.

Despite the relatively independent development of the two lines of research on SLI and dyslexia, there is evidence that dyslexia and SLI may share some characteristics, or that SLI may be a part of one developmental pathway to dyslexia. Scarborough (1990) found that nearly 60% of a sample of children who were deemed at risk for dyslexia because of a dyslexic family member qualified as dyslexic at age 8. Data collected at age 2 1/2, 4 and 5 years of age indicated that children who later became dyslexic had delays in the development of expressive morphology, articulation, word retrieval, and phonological awareness compared to at-risk children who did not qualify as dyslexics as well as children without a familial risk. Moreover, the syntactic problems predicted unique variance in later word recognition scores, partialling out the contribution of phonological awareness and other language variables. These data indicate that language delays are a common predecessor of reading difficulties, suggesting a common cause for both dyslexia and the language difficulties. Whether the cause could be localized in phonological processing or more specifically in speech perception remains to be seen.

Goulandris et al (2000) followed a sample of children identified at age 4 as SLI. They compared children with resolved SLI (n = 19), those with persistent SLI (n = 20) and a group of dyslexic children (n = 20) at the age of 15-16 years on a battery of tasks. The dyslexics had the same level of oral language skill (including phonological skill) as the resolved SLI children but were lower in word and nonword reading and spelling. Dyslexics were equivalent to the persistent SLI children in word and nonword reading, lower in spelling, and higher in reading comprehension. Dyslexics were also higher in phonological and other language skills. The data present a complex picture of the relationships between SLI and dyslexia. It is possible that what are traditionally thought of as separate disorders of SLI and dyslexia are better conceptualized as a spectrum of language and phonological processing problems that put a child at risk for reading and language difficulties (Snowling, Gallagher, & Frith, 2003).

Identification Functions in Dyslexics and Normal Readers: Joanisse et al. (2000)

We will report the results of a study by our group (Joanisse et al., 2000) in some detail. This was an initial study exploring the role of phonological impairments and broader language impairments in speech perception. We divided dyslexics into three subgroups: a group with delayed nonword reading or phoneme awareness (as measured by experimental tasks of nonword pronunciation and phoneme deletion) relative to a reading-level comparison group (phonological dyslexic, or PD group, n = 16), a group with delays in both phonological skill and oral language, as measured by tests from the CELF (Semel, Wiig & Secord, 1995) and the WISC-III (Wechsler, 1992) of morphology and vocabulary, respectively (language impaired, or LI group, n = 9), and a group whose language scores were normal for chronological age, and whose phonological skill was within the range of the reading-level group (Delayed group, n = 23). The three dyslexic subgroups were equally impaired in word reading (scoring on the 8th, 6th and 9th percentiles, respectively). The PD and LI groups were quite impaired in nonword reading and phoneme awareness, with the PD group tending to have the more severe impairment. Groups of 52 chronological-age matched normal readers (CA group) and 37 reading-level matched normal readers (RL group) were also tested. The RL group allowed us to some extent to balance effects of reading achievement on phonological or language variables. If dyslexics perform more poorly than the RL group on a given measure, it can be argued that the dyslexics' difficulties are not simply a byproduct of low reading achievement. Subjects had to score at the 40th percentile or higher on the Woodcock Reading Mastery Test, Word Identification subtest (Woodcock, 1989) to qualify for the CA and RL group. In addition, the RL group was matched to the dyslexic group as a whole for mean and range of Word Identification grade-equivalent scores. The mean age for the dyslexic group was 8;7 (range 7;10 to 9;4), for the CA group it was 8;5 (range 7;11 to 9;3) and for the RL group it was 6;11 (range 6;1 to 8;1). Descriptive data for the groups are shown in Table 1.

Joanisse et al. (2000) explored categorical perception along a VOT (/d/-/t/) continuum ("dug"-"tug") and a place of articulation (POA) (/p/-/k/) continuum ("spy"-"sky"). Perception of VOT and POA contrasts has been found to be categorical in nature in past studies of speech perception in both normal listeners and dyslexics (e.g., Godfrey et al., 1981; Liberman, 1996; Maassen et al., 2001; Werker & Tees, 1987). For the /d/-/t/ contrast, "dug"-"tug" stimuli were constructed by cross-splicing progressively more components of "tug" into "dug" from natural speech. The result was a continuum of eight different VOT values ranging from 10 ms. to 80 ms. voicing lag, in roughly 10 ms. increments. The subjects heard six practice items at the endpoints, with feedback, and simply pointed to a picture representing the correct word (a cartoon figure digging or tugging on a rope). There were 40 experimental trials, with each point on the continuum represented by 5 tokens, administered in random order. The /p/-/k/ contrast was presented as a contrast between the words “spy” and “sky”. The place of articulation contrast was created by varying the onset frequency of the second formant (F2) transition sweep in the second consonant of the target word. This produced a continuum from the labial /p/ to the dorsal /k/ phoneme. F2 onsets varied from 1100 to 1800 Hz in 100 ms. steps. Formant transition duration was close to that of natural speech, 45 ms. A closure duration of 30 ms was chosen to be long enough to produce a clear stop consonant percept, but short enough to present problems if listeners had difficulty responding to stimuli presented at short intervals (Reed, 1989; Tallal, 1980). These stimuli were produced synthetically using the Klatt hybrid synthesizer on a PC (Klatt, 1990) and recorded as 16-bit, 22.05 kHz digital sound files. There were six practice trials with endpoint stimuli, and 32 experimental trials, four at each of eight F2 onset frequencies.

Stimuli were presented using a Macintosh Powerbook with 16-bit audio and an active matrix screen. The responses were expected to conform to the S-shaped identification curves typical of categorical perception tasks. To quantify the data, each child's categorization data was fitted to a logistic function using the Logistic Curve Fit function in SPSS. This yielded a logistic slope coefficient. Valid coefficients tend to be between 0 and 1.0, with higher values representing shallower slopes. To control for positive skew, which can invalidate logistic functions, we excluded coefficients of 1.2 or more.

We found speech perception deficits only in the LI subgroup. This group had an identification function with a shallower slope than that of normal readers on both the VOT and place of articulation dimension (see Figures 1 and 2, which were not printed in the original paper). The critical comparison is between each of the dyslexic subgroups and the RL group. The only significant difference for “dug”-”tug” involved the LI and RL group, where the LI group showed higher mean slopes, indicating a shallower slope. Likewise, the only significant difference for “spy”-“sky” resulted from the LI group having a higher slope than the RL group.

Inspecting the identification functions in Figures 1 and 2, the cross-over point appeared to be similar in the LI group and the other groups, but the LI group was more likely to label clear instances of /d/ as /t/ and vice versa, and likewise for /p/ and /k/. The findings are consistent with broader or less distinct categories for phonemes.

However, an alternative possibility is that LI children experience generalized auditory processing problems that affect attentiveness to subtle auditory distinctions. According to this line of argument, the deficit is not as noticeable at intermediate values on the continuum, since all of the children have difficulty categorizing those stimuli, but becomes apparent at the ends of the continuum. This possibility can be addressed by administering a discrimination task using stimuli along the same continuum. In addition, the discrimination task provides a method of validating the subgroup distinctions in speech perception obtained for the identification task.

Speech Discrimination in Dyslexic and Normal Readers

Previous studies exploring speech discrimination in dyslexic and normal readers have yielded an interesting mixture of results. In this task, subjects typically are given pairs of stimuli from a VOT or place of articulation continuum, and asked to judge whether they are the same or different. Discrimination of pairs that are different is expected to be poor for within-category pairs (e.g., two different stimuli from the /ba/ end of the /ba/ - /da/ continuum). Discrimination of pairs that cross a category boundary is expected to be much better. Brandt and Rosen (1980) reported no difference between dyslexic children and CA controls for both an identification and a discrimination task given for each of three continua, /ba/ -/da/, /da/-/ga/ or a VOT continuum. However, as noted by Godfrey et al. (1981), the identification and discrimination functions were slightly flatter for dyslexics. Godfrey et al. (1981) reported weaker discrimination across the categorical boundary for /ba/ - /da/ and /da/ - /ga/ for dyslexics compared to CA controls. In addition, dyslexics were found to discriminate better than the controls for within-category items on the /da/ - /ga/ continuum. This finding is of particular interest, as it indicates dyslexics may be as sensitive as normal readers to subtle differences in the phonetic values of the stimuli. An inference can be made that dyslexics perceive the physical differences among the stimuli as well as the control group, but their phoneme boundaries are less sharp. Godfrey et al. (1981) classified dyslexics into dysphonetic and dyseidetic subgroups, using Boder's (1973) criteria, but no differences in speech perception were found between these two subgroups. However, the number of subjects in each group (11 dysphonetics, 6 dyseidetics) was fairly small.

Werker and Tees (1987) collected both identification and discrimination data. They found that the slope of the identification function for /ba/ - /da/ was shallower in the dyslexics. Dyslexic children performed more poorly than age-matched controls at discriminating "different" pairs for both 1- and 2-step pairings. Group differences were larger, favoring the control group, for cross-boundary pairs. Inspection of the figures indicates that there was a trend for dyslexics to discriminate within-category pairs better than the controls, but only at the /ba/ end of the continuum. The results replicate Godfrey et al.'s (1981) findings showing better within- and poorer between-phoneme discrimination.

Maassen et al (2001) compared dyslexic children to both CA and RL control groups on a voicing (/bak/ - /pak/) and a place of articulation (/bak/ - /dak/) continuum using both identification and discrimination tasks. They found no differences in the mean slope for the identification function between dyslexics and either control group on the place of articulation continuum. Dyslexics and the RL group differed from the CA group but not each other on the voicing continuum, with dyslexics and RLs showing shallower slopes than the CA group. Dyslexics demonstrated a lower level of performance on the discrimination task than both control groups for the place of articulation as well as the voicing continuum. Inspection of the discrimination curves indicates that dyslexic-control group differences favoring the controls were found for stimulus pairs that crossed the categorical boundary, but also for pairs that were within-category. This study replicated Godfrey et al.'s (1981) and Werker and Tees (1987) findings of poorer cross-phoneme boundary discrimination in dyslexics, but not their findings of better within-category discrimination.

Serniclaes et al. (2001) utilized sine-wave analogues to speech stimuli to create a place of articulation continuum, in order to determine whether the deficit in categorical perception was specific to speech. The sine-wave stimuli were designed so that subjects could perceive them as tones or as speech stimuli (/ba/ and /da/), depending on instructions. An additional set of modulated sine-wave stimuli that sounded more like the natural speech versions of /ba/ and /da/ were utilized. Serniclaes et al. (2001) found that the sine-wave stimuli designated as “tones” to the subjects were not perceived categorically (discrimination functions were flat for both dyslexics and normal readers). In contrast, the identical sine-wave stimuli designated as “speech” showed a peak for discrimination accuracy at the typical boundary for /ba/ and /da/ obtained for adult speakers of French. The third stimulus type, modulated sine-waves, were apparently treated as even more speech-like by the children, as the peaks were steeper at the phoneme boundary. Dyslexics showed less peaked discrimination curves, consistent with weaker phoneme boundaries, and were better at perceiving differences within-category for the sine-wave “speech” stimuli. A trend in this direction was found for the modulated sine-wave speech stimuli. Serniclaes et al (2001) concluded that dyslexics' auditory discrimination is as good as that of normal readers, but their phoneme boundaries are less sharp.

Although they did not utilize categorical perception tasks, Adlard and Hazan (1998) contrasted dyslexics and CA and RL controls on a wide range of auditory and phoneme discrimination tasks. They reported no overall group differences on speech and auditory discrimination tasks. However, a subset of the dyslexics (4 out of 13) were poor at speech discrimination, particularly when it involved pairs of words that were not only phonetically similar (i.e., they differed by one phonetic feature), but in which the phonetic contrast was not acoustically salient (e.g., *sue/shoe, fine/vine, still/spill* and *smack/snack*). Adlard and Hazan (1998) found no difference between the subgroup of four dyslexics and either normal reader control group in detecting differences among non-speech auditory stimuli. Adlard and Hazan's (1998) findings suggest once again that only a small subgroup of dyslexics has difficulty with speech perception.

Follow-Up Study of Speech Discrimination

In the present study, we were able to retest some of the children participating in the Joanisse et al (2000) study 9-10 months later on speech discrimination, using the "spy" - "sky" continuum. The children were also retested on Woodcock Word Identification (Woodcock, 1989), WISC-III Vocabulary (Wechsler, 1992), Nonword Reading and Phoneme Deletion.

The dyslexic and CA groups were all fourth graders. All dyslexic children had to score at or below the 25th percentile on the Woodcock Word Identification Test (Woodcock, 1989) in the retesting to qualify for the study. Criteria for classifying children as LI, PD or Delayed dyslexics were the same as Joanisse et al. (2000). LI dyslexics scored at or below a scaled score of 6 on both WISC-III Vocabulary and CELF Word Structure in the previous year. Their scores from the 3rd and 4th grade on Vocabulary and for 3rd grade for CELF Word Structure are shown in Table 2 along with the other scores from the 4th grade testing. It can be seen that the LI children remained well below average in WISC-III Vocabulary at the second testing. The LI group consisted of 7 of the 9 classified as LI in Joanisse et al. (2000). PD dyslexics had to score one standard deviation or more below the original RL group (n = 37) in the previous year on either Nonword Reading (an experimental list of 70 nonsense words) or Phoneme Deletion (an experimental list of 24 real words and 14 nonwords). All but two of the LI dyslexics also would have qualified as PD dyslexics. The PD group consisted of 13 of the 16 originally classified as PD in Joanisse et al. (2000). Delayed dyslexics scored within one standard deviation of the RL group on both Nonword Reading and Phoneme Deletion in the previous year. The delayed subgroup consisted of 15 of the 22 classified in this group in Joanisse et al. (2000). The three subgroups were very similar in overall word identification skill. The CA control group consisted of 20 children selected at random from the original group of 52 children. The RL group consisted of 10 children in second grade selected to have the same mean and range of Woodcock Word Identification grade-equivalent scores as the dyslexics. Descriptive data for all of the groups is shown in Table 2.

It is apparent from the Nonword Reading and Phoneme Deletion z-scores collected at the time of the discrimination task testing that the PD and LI groups were the only groups with a phonological deficit (about one standard deviation below the original RL group across tasks). The delayed group was still well within the range of the RL group and did not differ from this group by Bonferoni-corrected t-tests on either measure. All three dyslexic groups scored significantly below the range of the CA group on both measures (p-values all less than .001).

Other findings of note are that the PD group was intermediate in Vocabulary scores between the LI and delayed groups. The overall group comparison on Vocabulary was significant, F (4, 61) = 3.92, *p* < .01. Tukey post hoc tests revealed the only significant differences to be between the LI group and each of the other groups (p-values all less than .025). There were no differences in Woodcock Word Identification grade equivalent or percentile scores between the subgroups, and none of the groups differed from the RL group on the grade-equivalent score by t-test. CAs were higher than the other four groups on the grade-equivalent score (p-values all less than .001).

The speech discrimination task required children to judge whether stimuli along the "spy" - "sky" (place of articulation) continuum were the same or different. The children heard two words spaced 400 ms apart and responded "same" or "different". The words were played by a Macintosh Powerbook computer over headphones. The word stimuli were identical to those used in the identification task of Joanisse et al. (2000). There were six practice trials using endpoint stimuli (2 same and 4 different). This was followed by 52 experimental trials. The experimental trials consisted of eight "same" trials, four pairs of stimuli repeated twice each at F2 onset frequencies of 1100, 1400, 1500 and 1800 Hz. There were 44 "different" trials. Twenty-eight trials consisted of pairs separated by one step at each of seven points on the continuum (1100-1200 Hz, 1200-1300 Hz, etc.). There were four repetitions of each one-step pair, two in one order (e.g., 1100-1200) and two in the opposite order (e.g., 1200-1100). There were sixteen trials of pairs differing by four steps on the continuum, four each at stimulus values of 1100-1500, 1200-1600, 1300-1700 and 1400-1800 Hz. Based on the identification data, we anticipated that the phoneme boundary would be located between 1400 and 1500 Hz. Thus, there was one pair in the one-step set that crossed the phoneme boundary (1400-1500), and six pairs that were within the boundary. All four pairs in the four-step set involved comparisons across the phoneme boundary. It should be noted that there were many more actual "different" trials than "same" trials. However, many times the children perceived stimuli differing by one step as "same", so from the child's point of view, there was not a huge discrepancy in the number of "same" and "different" responses.

The results are displayed separately for “same” trials (Figure 3), four-step “different” trials (Figure 4), and one-step “different” trials (Figure 5). Performance was fairly good on the “same" trials for all groups, except that the groups showed a dip in performance near the middle of the continuum (i.e., on the 1400-1400 and 1500-1500 Hz items), with the LI group performing the poorest on these items. In fact the LI group's score of 50% correct and the CA group's score of 58% correct on the 1500-1500 item did not differ significantly from chance. F-tests comparing the five groups at each of the four points on the continuum revealed group differences only for the 1800-1800 Hz pairs. This appeared to be due to lower performance by the LI and to some extent the Delayed groups relative to the other groups. However, the only pairwise comparison to attain significance by Tukey post hoc test was the PD vs. LI comparison. The general lack of group differences on the "same" trials indicates that the dyslexic groups understood the task, and were able to judge pairs that were acoustically identical with roughly the same accuracy as the control groups. The dip in performance at or near the category boundary (1400-1500 Hz) probably reflects unstable perception of items that are intermediate on the /p/-/k/ continuum. It makes sense that children would be more certain that pairs on the ends of the continuum matched one another, as they should tend to encode these items most of the time as the same word. Pairs in the middle of the continuum might sometimes be encoded as one word and sometimes as the other, even within the same trial, resulting in more guessing or more "different" responses.

Figure 4 shows the percentage of correct "different" responses made on four-step pairs as a function of F2 onset frequency. These pairs should have been fairly easy to discriminate on two grounds, the fact that they crossed the phoneme boundary, and that they were acoustically quite distinct (i.e., F2 onset frequency differed by 4-steps on the continuum). It can be seen in Figure 4 that all groups achieved better than 70% accuracy across all four pair types, with mean accuracy on the 1300-1700 Hz pair exceeding 90% for all groups. There is a trend for the PD group and the LI group to be somewhat lower in accuracy than the other groups. However, none of the F-tests conducted for any of the four pairs revealed significant group differences. Results for the 4-step comparisons once again illustrate that the children generally understood the task and were able to distinguish items differing by 4-steps on the continuum. However, since all of the items were both acoustically and phonemically distinct, it is not possible to determine whether this performance reflected categorical perception. The one-step items made this determination possible.

Figure 5 depicts the percentage of correct responses on one-step trials (a correct response is a response of "different"). The curve shows that a sharp phoneme boundary at about 1400 or 1500 Hz exists for some of the groups, with performance rising from less than 10% correct at the end-points to 50-60% correct for items crossing the phoneme boundary. The peak appeared to be between 1500 and 1600 ms for the CA and RL groups, and between 1400 and 1600 ms for the PD and Delay groups. The most interesting finding is that the LI group showed a very broad peak that extended to items that were clearly within the /p/ phoneme category for the other groups (e.g., 1200-1300 ms). The LI group appeared to show better discrimination of the items at 1200-1300 and 1300-1400 Hz than the other groups.

F-tests conducted at each point on the continuum revealed group differences at the 1200-1300 Hz pair, F (4, 61) = 3.99, $p < .01$, and at the 1300-1400 Hz pair, F (4, 61) = 3.03, $p < .025$. Pairwise comparisons of each group, using the Tukey HSD test to control for cumulative Type I error, revealed that LIs performed better than the CA (p < .01), RL (p < .05) and PD (p < .025) groups at the 1200-1300 Hz pair, and better than the CA (p < .05) and RL (p < .025) groups at the 1300-1400 Hz pair. Although the CA group appears to have a higher peak at 1500-1600 Hz than the other groups, this difference was not significant.

The results for the LI group parallel previous findings reported for dyslexics as a whole by Serniclaes et al (2001) and noticeable in the graphed results of Werker and Tees (1987). The central finding is that the category boundary for the place of articulation phoneme is not as sharp for dyslexics as for normal readers. However, in the present case, the findings can clearly be attributed to the LI subgroup of dyslexics - the PD and Delayed subgroups overlapped substantially with the normal reader groups. The finding of better discrimination by the LI group for two within-category pairs indicates that LI dyslexics do not have less acute auditory discrimination. Based on their superior performance, an argument could be made that their auditory discrimination is more acute than that of normal readers. However, the more reasonable interpretation of the data is that normal readers (and the PD and Delayed groups of dyslexics) have a sharp phoneme boundary, and tend to ignore acoustic differences among pairs that are perceived as within the /p/ or /k/ categories. In contrast, LI dyslexics could not ignore these acoustic differences because they had not established a sharp phoneme boundary.

Regression Analyses: Joanisse et al (2000) Re-Examined

Although it is apparent from the Joanisse et al. (2000) study and the follow-up speech discrimination study that group differences between dyslexics and normal readers were concentrated among dyslexics with language impairments, an important question is whether the speech perception, language and phonological deficits are part of the same underlying problem, such as poor phonological representations for familiar words. If this were the case, the speech, language and phonological processing tasks should account for considerable common and very little unique variance in word reading skill.

To address this question, data from the original Joanisse et al (2000) data set were subjected to additional regression analyses for the present paper. We conducted commonality analyses on the language tasks (CELF Word Structure and WISC-III Vocabulary), on phonological awareness (Phoneme Deletion) and on speech perception ("spy"-"sky" identification slope). These tasks were entered as independent variables in regressions predicting Woodcock Word Identification at grade 3. All of the third graders participating in the Joanisse et al. (2000) study (48 dyslexics and 52 CA controls) and the 37 RL controls (who were in grades one and two) were included in these analyses.

Results are summarized in Table 3. The total amount of variance in Word Identification accounted for by all of these variables was 47.8%, with 22.9% common across the tasks, and the remainder unique variance. Phoneme Deletion accounted for the largest share of independent variance. The other three variables entered into the regression equations, spy-sky slope, CELF Word Structure, and WISC-III Vocabulary, accounted for small but statistically significant amounts of variance.

The fact that about half of the variance accounted for was common variance suggests a construct such as phonological skill could underlie some of the variables' relationships to word reading. However, there was considerable unique variance. Phoneme awareness and speech perception were partially independent sources of word identification skill. The two language measures were also partially independent of the speech and phoneme awareness tasks. However, these tasks do not represent all aspects of language functioning. It would be interesting to see whether other language tasks would show more overlap with the speech and phoneme awareness measures.

Conclusions

The studies reviewed here, and the data from the two investigations we have conducted indicate that different kinds or degrees of phonological impairment exist in dyslexic children. The commonly perceived "core" profile of a phonological processing deficit (e.g., poor nonword reading and phoneme awareness) was indeed observed in over half of the dyslexic children tested by our research group. However, the delayed profile (phonological skill below age level, but on a par with overall reading skill) was almost as common in our sample. A subset of children with phonological impairments was found to have deficient speech perception. The experiments discussed here suggest strongly that this subset of dyslexic children also have significant problems in certain other aspects of language.

One of the most interesting findings in the study was that LI dyslexics were actually superior to the other groups at within-category discriminations (see Figure 5). This finding is quite problematic for the view that specific language impairment and phonological dyslexia result from basic auditory processing problems (Ahissar, Protopapas, Reid, & Merzenich, 2000; Kujala, Myllyviita, Tervaniemi, Alho, Kallio, & Naatanen, 2000; Tallal, 1980; Tallal, Miller & Fitch, 1993; Tallal & Stark, 1982). Instead, our results are consistent with the view that auditory processing problems among dyslexics are limited to speech stimuli (Mody et al. 1997; Serniclaes et al., 2001).

Our findings are consistent with the view that categorical speech perception difficulties are associated with broad language deficits in a dyslexic sample. What is not clear is the direction of causality. One hypothesis is that poor phonological representations cause a cascading series of problems in language and reading development (Goswami, 2002; Snowling, 2000; Vellutino, 1979). Children who don't develop sharp phonemic boundaries might experience difficulty perceiving the small but critical sound-elements that define grammatical inflections in English, resulting in delays in morphological development (e.g., Scarborough, 1990) and poor performance on the morphology tasks utilized by Joanisse et al. (2000). Poor phonological representations might interfere with the process of vocabulary acquisition, either because they hinder the encoding and comparison of phonologically similar, but semantically distinct words, or because they lead to general word-name retrieval problems that interfere with oral communication and performance on verbal ability tests.

It is possible that there is a continuum of severity in phonological deficits, with the most severe problems manifesting themselves as speech perception difficulties early in development (e.g., Molfese, 2000; Pihko et al., 2000) that persist into the school years in the most extreme cases. If this were the case, one might argue that LI dyslexics were the most impaired, followed by the PD and then the Delayed groups. However, this prediction does not fit our data, as the LI dyslexics were **not** the most impaired group on nonword reading, phoneme awareness and word identification, the three tasks most commonly associated with developmental dyslexia. LI dyslexics performed at about the same level as the PD dyslexics. This argument is further complicated by the observation that the Delayed dyslexics were as impaired in word reading as the other groups at both test-times (third and fourth grade - see Tables 1 and 2).

An alternative argument is that there are multiple factors associated with the occurrence of word reading problems in children. Speech perception problems might be uncommon in dyslexics, and when present, lead to wider language delays. The most common profile among dyslexics might entail difficulties in developing segmental representations, rather than deficits at the level of the individual phoneme or in overall phonological representations. Dyslexics who fail to develop segmental representations would tend to show the classic phonological dyslexia profile, involving interrelated problems in developing phoneme awareness, learning grapheme-phoneme associations, and spelling (Castles & Coltheart, 1993; Manis et al., 1996; Stanovich et al., 1997)), but would not necessarily perform poorly on speech perception tasks. In other cases (such as the Delayed dyslexics), factors affecting the encoding and storage of item-specific word knowledge (such as poor letter recognition, low print exposure) might combine with mild phonological deficits to produce what appear to be general delays in reading (Bailey, Manis, Pedersen, & Seidenberg, 2004). In still other cases, language problems might involve aspects of language other than phonology and phoneme awareness (e.g.., receptive vocabulary) and hence interfere with higher order aspects of reading (comprehension rather than word recognition and decoding).

Dyslexia is a dynamic, developmental disorder. It is likely that the importance of different language skills (phoneme perception, representation of word phonology, segmental phonology, and semantic representations) will vary with development. It will be important to investigate speech and language skills in individuals of a variety of ages (from infancy to adulthood) in order to shed further light on the etiology of this complex problem.

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Table 1. Means and standard deviations for the identifying tasks in the Joanisse et al. (2000) study

			GROUP		
	LI (n = 9)	PD (n = 16)	Delay (n=23)	CA (n = 52)	RL (n = 37)
Woodcock Word Iden.					
- Grade Equivalent	2.1 (0.3)	2.1 (0.3)	2.1 (0.2)	4.0 (0.6)	2.2 (0.4)
- Percentile	6.3 (5.9)	8.3 (6.2)	9.3 (4.4)	68.2 (16.4)	79.7 (15.5)
Nonword z-score	-0.9 (0.7)	-1.1 (0.3)	-0.1 (0.7)	2.1 (1.2)	0 (1.0)
Phon. Del. z-score	-0.9 (1.0)	-1.5 (0.6)	-0.02 (0.4)	0.7 (1.0)	0 (1.0)
WISC Vocabulary Standard Score	5.1 (0.9)	8.1 (3.2)	9.1 (2.7)	10.2 (2.9)	11.8 (3.8)
CELF Word Structure Standard Score	5.2 (1.0)	7.7 (1.9)	10.3 (2.9)	11.7 (2.9)	12.6 (2.3)

Table 2. Means and standard deviations for the identifying tasks in the discrimination study (scores obtained in 4th grade unless otherwise indicated)

			GROUP		
	LI (n = 7) (grade 4)	PD (n = 13) (grade 4)	Delay (n=15) (grade 4)	CA (n = 20) (grade 4)	RL (n = 10) (grade 2)
CELF Word Structure Stan. Score (3rd grade)	5.2 (1.0)	7.5 (2.1)	10.3 (2.9)	12.3 (2.8)	12.6 (2.3)
WISC Vocabulary Stan. Score (3rd grade)	5.1 (0.9)	8.2 (2.6)	9.6 (2.2)	10.0 (1.9)	11.8 (3.8)
WISC Vocabulary Stan. Score (4th grade)	5.9 (2.3)	9.1 (2.8)	10.1 (3.2)	10.1 (2.6)	10.2 (2.1)
Woodcock Word Iden. (4th grade)					
- Grade Equivalent	2.7 (0.3)	2.6 (0.4)	2.9 (0.5)	5.2 (1.2)	3.0 (0.3)
- Percentile	8.1 (7.8)	7.2 (5.1)	12.7 (9.6)	69.8 (12.7)	82.8 (14.1)
Nonword z-score (4th grade)	-0.8 (1.0)	-1.1 (0.5)	-0.1 (0.7)	1.6 (0.8)	0.7 (0.7)
Phon. Del. z-score (4th grade)	-1.1 (1.5)	-1.0 (1.0)	.1 (0.8)	1.3 (0.7)	.2 (0.7)

Table 3. Common and Unique Variance for 3rd grade variables in the prediction of 3rd grade Word Identification

Variable	Variance Explained	Significance
Spy-sky slope (unique)	2.8 %	$p < .05$
Phoneme Deletion (unique)	17.3 %	$p < .001$
CELF Word Structure (unique)	2.7 %	$p < .05$
WISC Vocabulary (unique)	2.1 %	$p < .05$
Total Unique	24.9 %	
Total Common	22.9 %	

Figure Captions

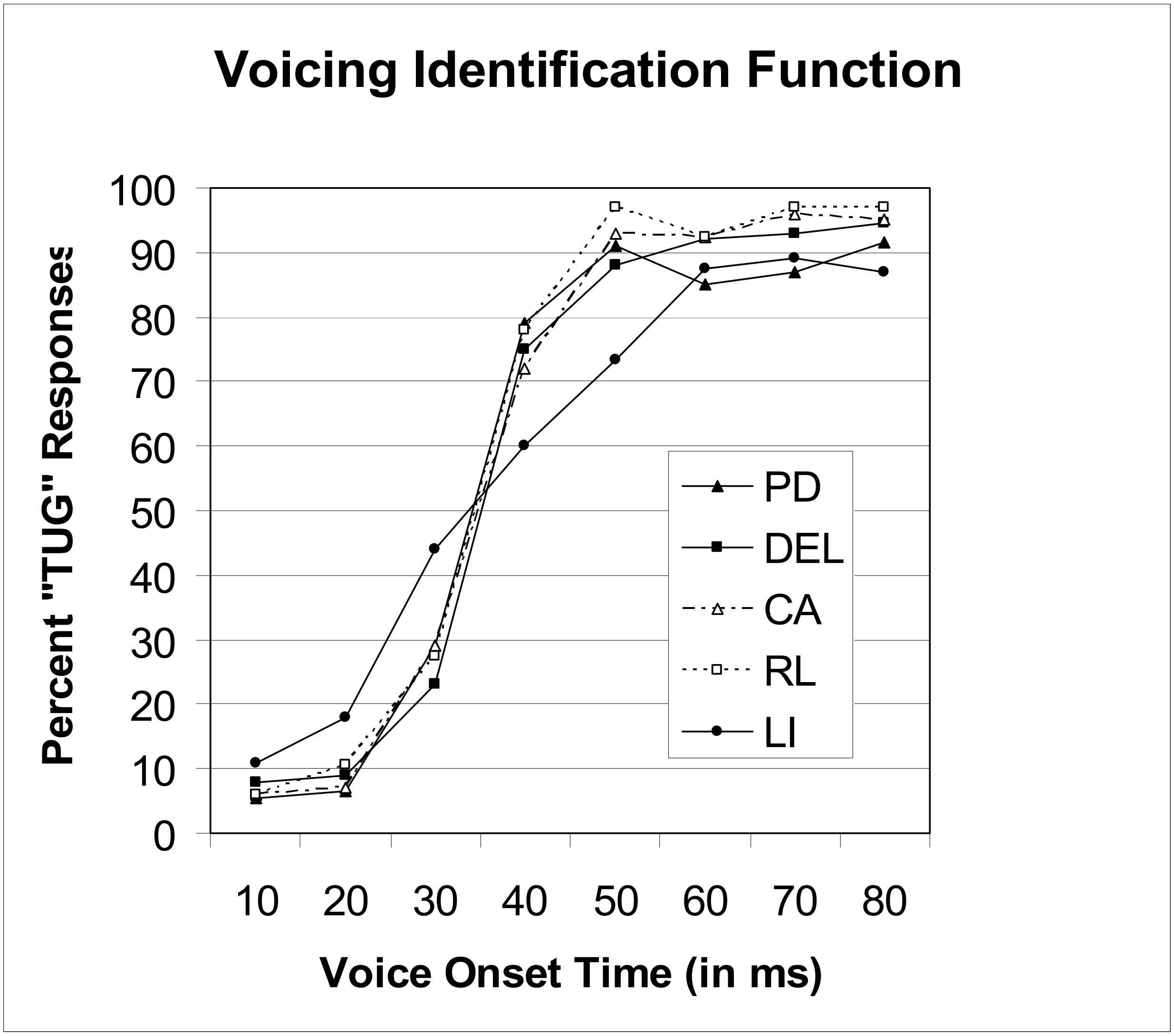
Figure 1. Voicing (""dug"-"tug"") identification functions for the five groups in the study.

Figure 2. Place of articulation ("spy-sky") functions for the five groups in the study.

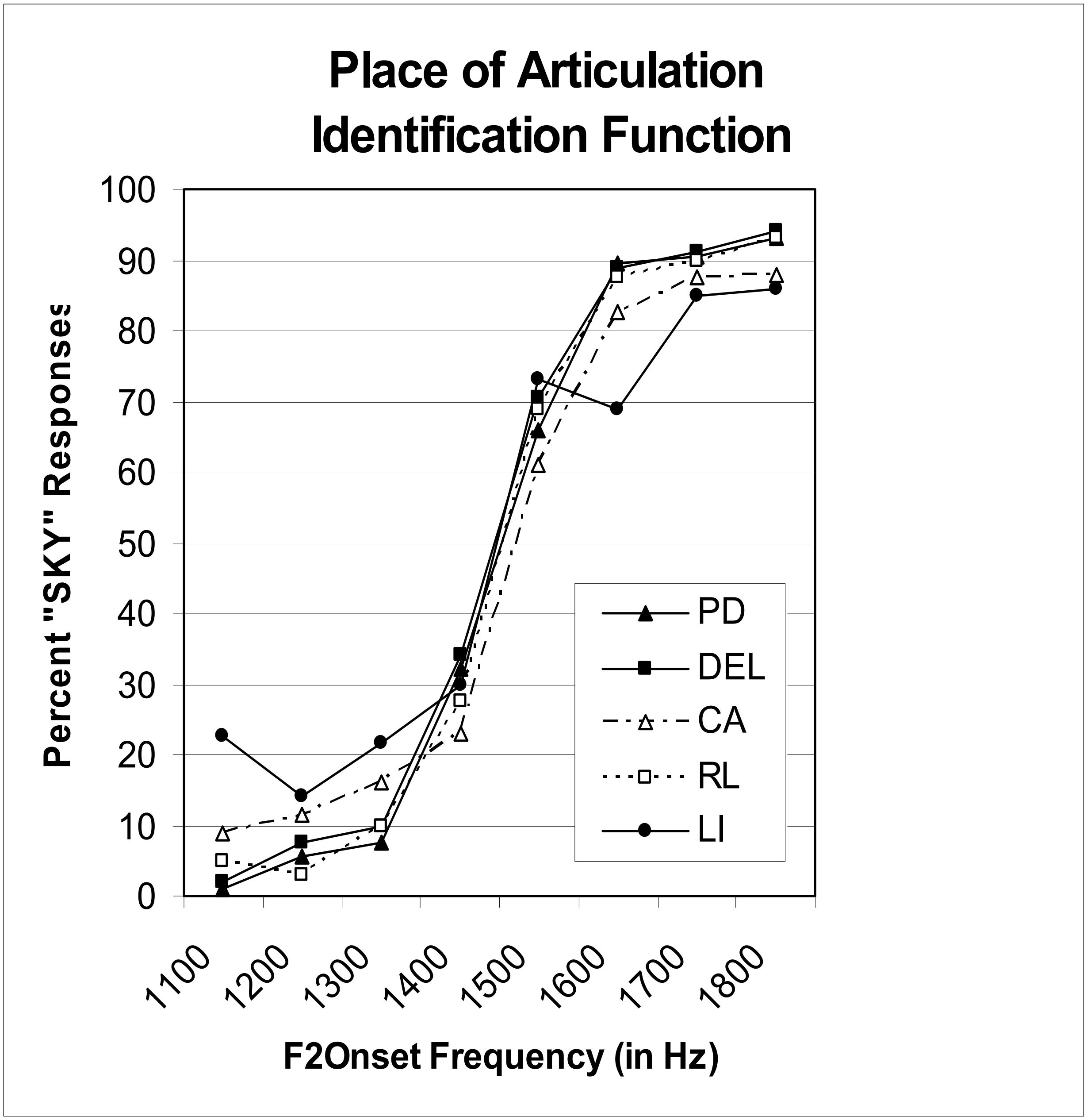
Figure 3. Discrimination task ("spy-sky") - same trials (percent correctly matched)

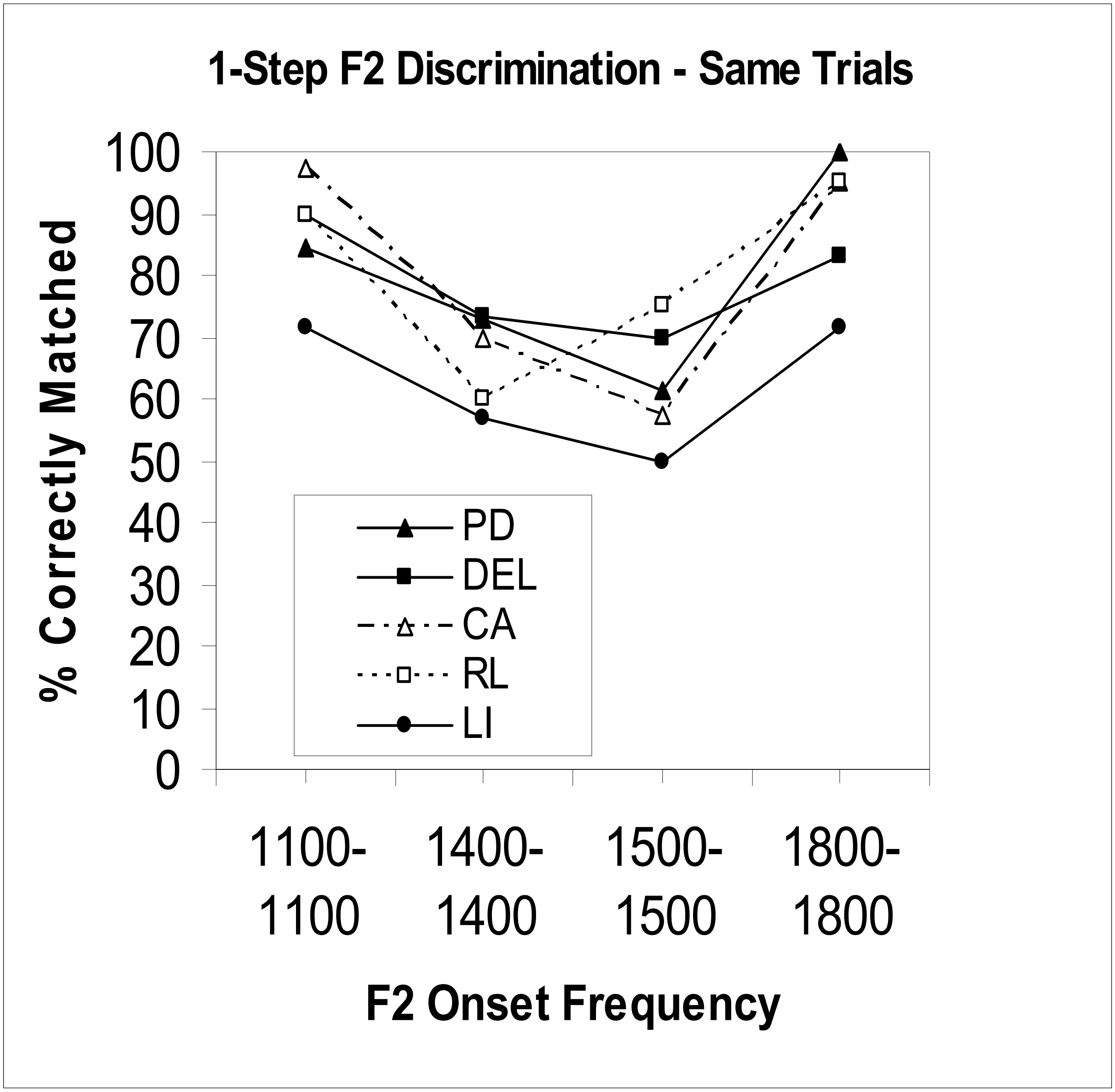
Figure 4. Discrimination task - four-step different trials (percent correctly discriminated)

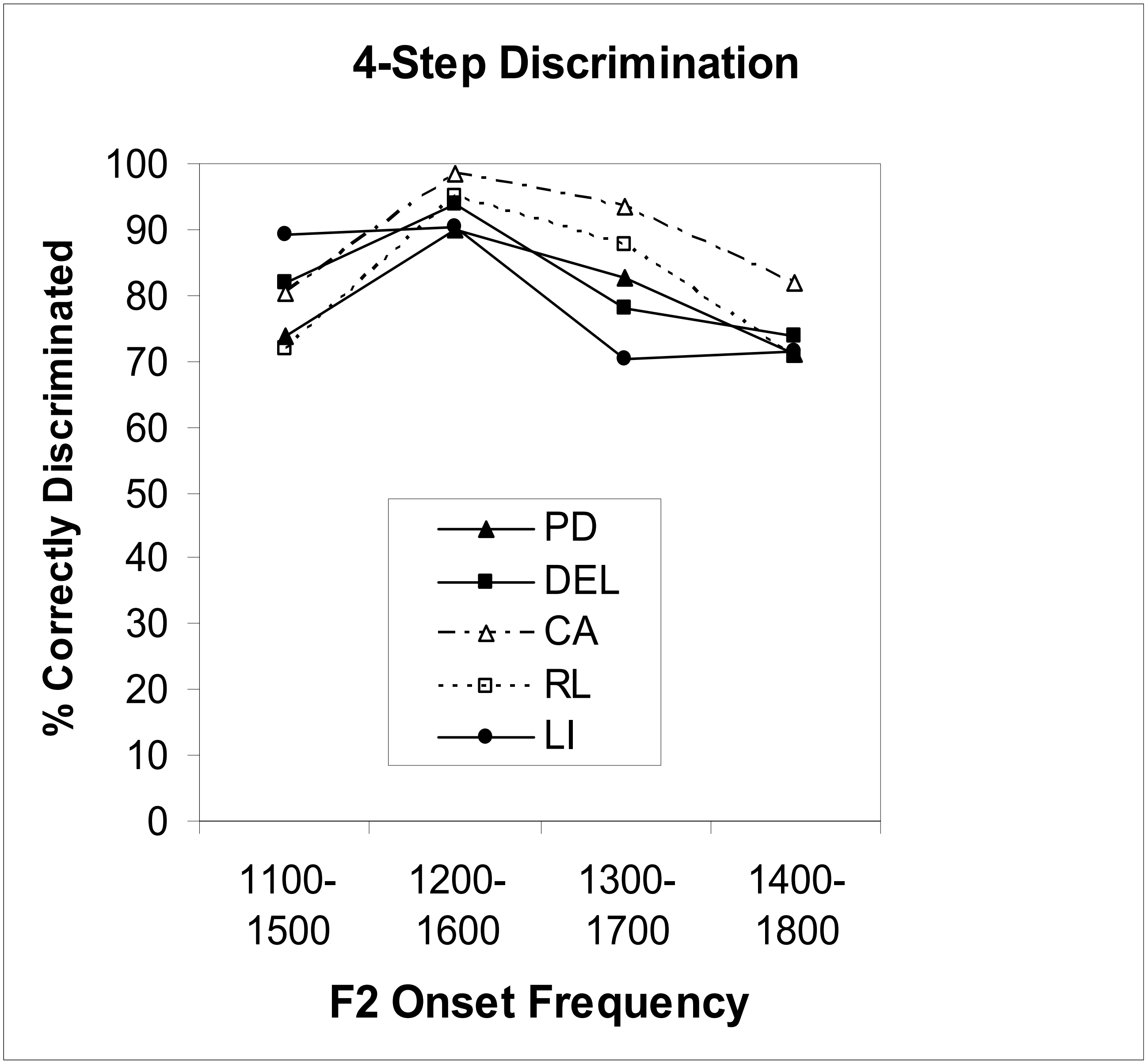
Figure 5. Discrimination task - one-step different trials (percent correctly discriminated)

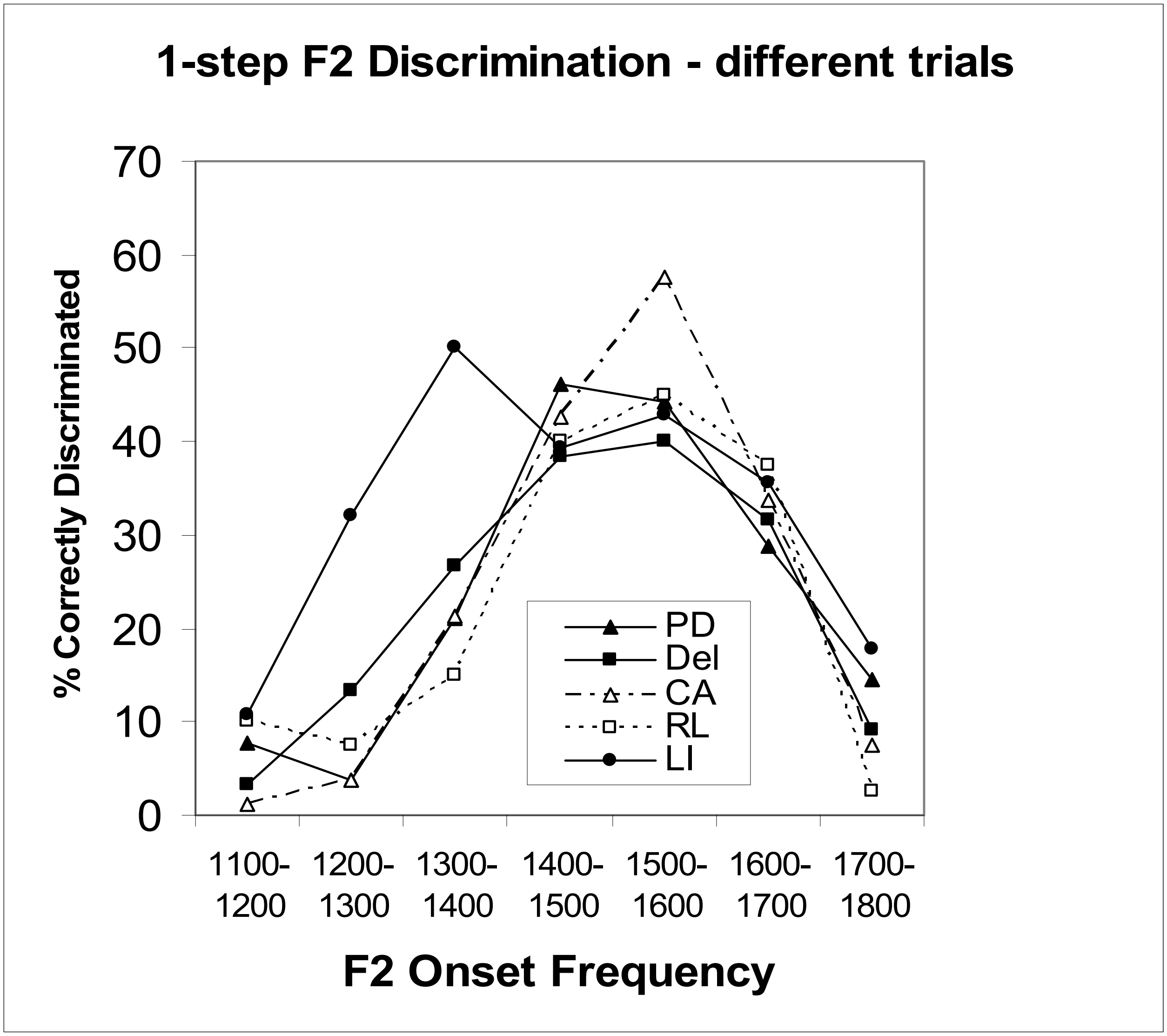


Voicing Identification Function
Percent "TUG" Responses
0
10
20
30
40
50
60
70
80
90
100
10
20
30
40
50
60
70
80
Voice Onset Time (in ms)
PD
DEL
CA
RL
LI


Place of Articulation
Identification Function
Percent "SKY" Responses
100
90
80
70
60
50
40
30
20
10
0
1100
1200
1300
1400
1500
1600
1700
1800
F2Onset Frequency (in Hz)
PD
DEL
CA
RL
LI


1-Step F2 Discrimination - Same Trials
% Correctly Matched
100
90
80
70
60
50
40
30
20
10
0
PD
DEL
CA
RL
LI
1100-1100
1400-1400
1500-1500
1800-1800
F2 Onset Frequency


4-Step Discrimination
% Correctly Discriminated
100
90
80
70
60
50
40
30
20
10
0
1100-1500
1200-1600
1300-1700
1400-1800
F2 Onset Frequency
PD
DEL
CA
RL
LI


1-step F2 Discrimination - different trials
% Correctly Discriminated
70
60
50
40
30
20
10
0
1100-1200
1200-1300
1300-1400
1400-1500
1500-1600
1600-1700
1700-1800
F2 Onset Frequency
PD
Del
CA
RL
LI