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Language Deficits in Dyslexic Children: Speech Perception, Phonology, and Morphology

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We investigated the relationship between dyslexia and three aspects of language: speech perception, phonology, and morphology. Reading and language tasks were administered to dyslexics aged 8–9 years and to two normal reader groups (age-matched and reading-level matched). Three dyslexic groups were identified: phonological dyslexics (PD), developmentally language impaired (LI), and globally delayed (delay-type dyslexics). The LI and PD groups exhibited similar patterns of reading impairment, attributed to low phonological skills. However, only the LI group showed clear speech perception deficits, suggesting that such deficits affect only a subset of dyslexics. Results also indicated phonological impairments in children whose speech perception was normal. Both the LI and the PD groups showed inflectional morphology difficulties, with the impairment being more severe in the LI group. The delay group's reading and language skills closely matched those of younger normal readers, suggesting these children had a general delay in reading and language skills, rather than a specific phonological impairment. The results are discussed in terms of models of word recognition and dyslexia. © 2000 Academic Press

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Developmental dyslexia is diagnosed in children who fail to acquire age-appropriate reading skills in the absence of other cognitive dysfunctions, such as poor vision or frank neurological deficit (Stanovich, 1988b; Vellutino, 1979). Dyslexic children typically exhibit difficulties in recognizing printed words, and perform poorly on such tasks as nonsense word reading, spelling, and reading comprehension (Lyon, 1995; Rack, Snowling, & Olson, 1992). Dyslexia is sometimes thought to be an impairment that is specific to reading; however, there is now a considerable body of evidence linking dyslexia to impairments in other aspects of language, memory, and perception (Adams, 1990; Snowling, 1987; Stanovich, 1988a; Vellutino, 1979; Wagner & Torgesen, 1987).

A prominent view of dyslexia is that it derives from deficits in the representation and use of phonological information (Liberman & Shankweiler, 1985; Rack et al., 1992; Stanovich, 1988b; Wagner & Torgesen, 1987). Phonological deficits are thought to interfere with learning the correspondences between spelling and sound, an important step in reading acquisition. Several aspects of phonological skill have been shown to be affected. Some studies have focused on dyslexics' poor phonemic awareness, characterized as an inability to segment words into phonemes (Bradley & Bryant, 1983; Bruck, 1992; Manis, Custodio, & Szeszulski, 1993). Phonemic awareness tasks typically involve counting, adding, deleting, or identifying the position of phonemes in familiar words and nonwords. Other studies have examined the effects of phonological impairments on lexical access (Bowers & Swanson, 1991; Denckla & Rudel, 1976; Wolf, 1986) and verbal working memory (Byrne & Shea, 1979; Shankweiler, Liberman, Mark, Fowler, & Fischer, 1979). Prospective studies of phonology and reading support the hypothesis that poor phonological ability can play a causal role in reading deficits. For example, Bradley and Bryant (1983) have shown that prereading children's performance on phonemic awareness tasks is a better predictor of a child's later reading ability than is a measure of general intelligence.

The underlying cause of phonological deficits in poor readers is unclear. One possible source is impaired perception of speech at the phoneme level. Several studies have shown that poor readers as a group tend to perform abnormally on tasks involving the categorization and/or discrimination of speech sounds (Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Manis et al., 1997; Masterson, Hazan, & Wijatilake, 1995; Mody, Studdert-Kennedy, & Brady, 1997; Reed, 1989; Werker & Tees, 1987). The acoustic cues for contrastive speech sounds tend to be continuous, such as voice onset time (VOT), which is relevant to voicing contrasts (e.g., /p/ vs /b/), and the onset frequency of formant transitions, which is relevant to place of articulation contrasts (e.g., /b/ vs /g/). In spite of the acoustic continuity of speech cues, children and adults tend to perceive speech sounds categorically (Liberman, Harris, Hoffman, & Griffith, 1957), with sharp boundaries between phonemic categories. In some studies, dyslexics have shown weak or distorted categorization, in addition to speech discrimination that is different from that of normals (Godfrey et al., 1981; Werker & Tees, 1987). A perceptual deficit of this sort would impair the ability to process speech and could in turn affect the development and use of phonological representations, leading to the commonly observed problems with nonword pronunciation and phonological awareness in dyslexic children.

A problem with this hypothesis is that reader group differences in speech perception tend to be small and not always statistically robust (Manis et al., 1997; Werker & Tees, 1987). For example, in some studies dyslexic children have exhibited poor speech perception for only a subset of the phonemic contrasts on which they were tested (e.g., Godrey et al., 1981). In other studies, case by case analyses revealed abnormal speech perception in only a subset of the dyslexics. Manis et al. (1997) investigated dyslexic children's ability to identify /b/ vs /p/ on the basis of VOT. Dyslexics with low phonemic awareness were more likely to have speech perception deficits than other dyslexics who had reading-level-appropriate phonological abilities. Similarly, Tallal (1980) reported a high correlation between nonword reading skill and temporal order judgments of speech sounds, such that poor nonword readers were poor at perception, while better nonword readers were not. However, the Manis et al. study also indicated that fewer than half of the dyslexics with low phonological skill demonstrated deviant speech categorization profiles on the VOT categorization task. A similar result was reported by Nittrouer (1999), who found appreciable phonological difficulties in a sample of poor readers, but failed to observe significant deficits in both speech and nonspeech perception tasks.

It is possible that the tasks used in these studies were not sensitive enough to detect subtle speech perception difficulties in poor readers. Nevertheless, these studies raise the possibility that speech perception deficits may be observed in only a subset of poor readers. Tallal and Stark (1982) suggested that difficulties on auditory-temporal processing tasks, including tests of speech perception, might be more prevalent among dyslexic children with expressive and/or receptive language delays than among dyslexics without language delays. However, dyslexics with and without language difficulties were not compared within a single study by Tallal and her colleagues, nor were language deficits investigated in the Manis et al. (1997) study.

The goal of the present study was to obtain additional information about the occurrence of speech perception deficits in dyslexia and how they are related to impairments in two other aspects of linguistic knowledge, phonology and morphology. One question is whether dyslexics who exhibit phonological impairments have impaired speech perception. This would be consistent with the idea that phonological impairments are secondary to a speech perception deficit. However, it is also possible that phonological deficits can occur without impaired speech perception. Harm and Seidenberg (1999) simulated phonological dyslexia in a connectionist model by introducing anomalies in phonological processing that were severe enough to affect reading acquisition but not the categorical perception of phonemes. Thus, the model suggests that phonological impairments can have causes other than a speech perception impairment and predicts that at least some phonological dyslexics will have normal speech perception.

We also investigated the possibility that speech perception deficits are limited to dyslexics who exhibit broader impairments in language. Although the evidence for speech perception impairments in dyslexia is mixed, there is much stronger evidence for this type of impairment in children who are categorized as specific language impaired (SLI) or developmentally language impaired (Elliott & Hammer, 1988; Stark and Heinz, 1996; Tallal & Stark, 1980; Thibodeau & Sussman, 1979). Language impaired children tend to be dyslexic (Catts, Hu, Larrivée, & Swank, 1994) in addition to exhibiting impaired acquisition of inflectional morphology and other aspects of grammar (for reviews, see Bishop, 1997b; Leonard, 1998). In these children, speech perception deficits apparently interfere with learning to read as well as with the acquisition of other aspects of language, including morphology (Bishop, 1997b; Kamhi & Catts, 1986; Joanisse & Seidenberg, 1998; Shankweiler et al., 1995; Vogel, 1977; Wiig, Semel, & Crouse, 1973).

Finally, we examined the incidence of speech perception and morphological deficits in dyslexics who do not exhibit specific phonological impairments relative to word reading ability. Studies by Manis, Seidenberg, Doi, McBride-Chang, and Petersen (1996); Castles and Coltheart (1993); Stanovich, Siegel, and Gottardo (1997); and others have identified children, termed “surface” or “delay” dyslexics, whose phonological skills are on par with their word reading skills. These children read below grade level, but their pattern of reading is more like that of younger normal readers than that of phonological dyslexics. In Harm and Seidenberg’s computational model, the delay pattern can be produced by several causes, including lack of experience, learning or visual processing impairments, and reduced computational resources. Our sample of dyslexics also yielded a subgroup of dyslexics fitting this pattern, allowing us to examine whether this subgroup exhibited problems in speech perception.

In addition to individual differences among dyslexics, the weak and inconsistent effects in previous studies of speech perception deficits in dyslexia might be due to a lack of sensitivity in the tasks. The present study addressed this problem by using two separate speech contrasts. The first was a VOT continuum (/d/–/t/), which provided a comparison to our previous work (Manis et al., 1997). A second measure of speech perception was utilized to address the potential criticism that the voicing continuum was not demanding enough. This measure featured a place of articulation (POA) distinction (/p/–/k/) occurring word-medially (in this case, following an /s/ in the words “spy” and “sky”). Perceptual demands should be greater for categorization of consonants within a consonant cluster, particularly the noninitial consonants.

In summary, we addressed relationships among speech perception, phonology, and morphology in a representative sample of third-grade poor readers. Their performance was compared to that of two groups of normal readers, matched for chronological age (CA), and younger children matched for reading level (RL). The RL group was crucial to the design because various cognitive and language skills are related to reading achievement. For example, phonemic awareness is likely affected by degree of literacy (Morais, Cary, Alegria, & Bertelson, 1979), and thus it is possible that some dyslexics' poor performance on phonemic awareness tasks is solely the result of poorer reading skills. Including the RL group allowed us to assess the degree to which low phonemic skill was uniquely associated with performance on other tasks. Similarly, many other language skills could potentially be influenced by a child's literacy; for example, a certain amount of a child's vocabulary is learned through print exposure (Hayes, 1988). Here again, the RL group allowed us to counterbalance any effect reading achievement might have had on the various language skills being measured. To the extent that dyslexics performed more poorly than the RL group, it could be argued that their difficulties on the task in question were not simply related to a general delay in reading ability.

METHOD

Participants

A total of 137 children was selected for this study from a group of 180 children who were participating in a longitudinal study of reading impairments. At the beginning of the school year, third-grade teachers at eight primary schools in the Long Beach, California, area were asked to provide the names of normally achieving and poor readers in their classes. The teachers were asked not to nominate any children who had nonnative proficiency in English, severe cognitive or neurological impairments, or severe hearing loss. In addition, first- and second-grade teachers were also asked to provide normally achieving readers to be used in a younger comparison group. Children who failed to return signed parental consent forms or who did not wish to participate in the study were not included.

The dyslexic group consisted of a sample of 61 third-grade children, ages 7;10 to 9;4 (mean 8;7). Classification as dyslexic was based on teacher referral, and standardized reading scores at or below the 25th percentile on the Woodcock Reading Mastery Task–Revised (Woodcock, 1989). The diagnosis of dyslexia we adopt here is relatively inclusive, as it is based solely on reading delay in the absence of extenuating factors such as neurological disease, social problems, or more global cognitive deficits. Participants were selected from a larger pool of 71 poor readers referred by the teachers. Ten children were excluded from the present analyses when testing revealed them to have nonnative English proficiency (2 cases) or Woodcock reading scores above the 25th percentile (8 cases).

It is common in studies of dyslexia to exclude children whose global IQ score (including verbal and nonverbal ability) falls below average. We did not exclude participants on this basis because we sought to investigate the relationships among broader language skills and other factors, and did not want to restrict the range of language skills within the dyslexic sample. Hence, the sample included some children with very low language skills (in the bottom 5% of the population). However, none of the dyslexics in the present sample were classified as mentally retarded by the schools.

A group of 52 chronological age-matched normal readers (the CA group) was obtained from the sample of 62 third graders nominated as average to above-average readers. Only participants reading at or about the 40th percentile on the Woodcock word reading task and who demonstrated normal language ability, as assessed by standardized language tasks, were included in the study (10 were excluded on these criteria). The mean age of this group was 8;5 (range 7;11–9;3).

The younger normal reader group (the RL group) consisted of 37 younger children who were matched with the dyslexic group on Woodcock Word Identification grade level. This group was selected from a total of 47 first- and second-grade children in the larger sample, all scoring at or above the 40th percentile on the Woodcock task. Mean age for this group was 6;11 (range: 6;1–8;1). Ten of the 47 children originally nominated by the teachers were excluded from the present analyses, as they were reading above the grade level range for dyslexics.

Procedures

Participants were tested individually over five sessions, all during normal school hours. Sessions lasted on average 30 min, though the participants were encouraged to take breaks or discontinue the session whenever they desired.

Reading tasks. Three reading tasks were administered to each participant. The first was Form G of the Word Identification subtest of the Woodcock Reading Mastery Test–Revised. In this task, participants read words presented in isolation, with stimuli consisting of words that varied in spelling-to-sound regularity, complexity, and familiarity. An exception word reading task was also administered, in which stimuli consisted of 70 exception words such as HAVE, ISLAND, and YACHT, also presented in isolation. The task was discontinued when children read 6 consecutive words incorrectly. Finally, a nonword reading task was administered, consisting of 70 nonsense words such as NUP and CLEESH presented in isolation. The task was discontinued when children made 10 consecutive mistakes.

Phonemic awareness. A phoneme deletion and blending task of the type originally devised by Bruce (1964) was administered in two parts (more information on this task, including test items, can be found in Keating & Manis, 1998). In the first subtask, participants were asked to repeat a familiar word that was spoken on a tape. The speaker on the tape then asked the participant to repeat the word, but with part of it missing. Each prompt was in the following form:

Say mat. (pause for child to repeat)
Now say it without the /m/. (pause for child to respond)

The prompts were recorded by a trained phonetician. In cases where the target phoneme was a voiced consonant, care was taken to produce it with as little and as neutral following vocalic sound as possible. As well, onset and coda allophones (most importantly pre- and postvocalic /l/ and /r/) were produced as appropriate. Target phonemes included stops, fricatives, and sonorants. They included simple onsets and codas, along with all or part of an onset or coda cluster. Thus, some stimuli required simply deleting a phoneme of the target word, while others also required phoneme blending, such as saying *float* without /l/. All stimuli were monosyllables, and were devised in such a way that all answers, along with the most likely incorrect answers, were real words.

Participants were given 4 practice items, followed by 25 experimental items. Feedback was provided for practice items, but not for experimental items. Stimuli were presented in order of difficulty, based on piloting data. The task was discontinued after five consecutive errors. One repetition was allowed per item, in cases where the participant forgot the stimulus.

The second subtest was identical to the first, but here stimuli consisted of 15 monosyllable nonwords, following 3 practice items. In both subtasks, the deletion targets varied from simple onsets and codas of words to all or part of a word-initial or word-final cluster. Correct responses and most of the likely incorrect responses were also nonwords, to prevent biases toward real-word responses.

Inflectional morphology. A test of inflectional morphology similar to the one originally devised by Berko (1958) was administered in order to assess each child's ability to apply proper past tense agreement rules to familiar and nonsense words. The task consisted of both plural noun and past tense verb marking. The plural noun subtask consisted of eight familiar nouns and four nonsense words; four of the real-word nouns were regularly marked as plurals (e.g., face–faces), while four were irregularly marked as plurals (e.g., foot–feet). Regular and irregular words were equated for frequency and phonological complexity. The nonword items were equated with the real-word stimuli for phonological complexity. Four practice items with feedback were administered for both tasks.

Participants were presented target nouns as part of a sentence, accompanied by picture stimuli showing just one picture of that noun. They were then shown a picture of two or more of the same object and prompted to provide the plural of the noun, as follows:

Here is a fish (experimenter points to picture of a fish).

Now there are two of them. There are two . . . (pause for child to respond).

Testing proceeded similarly in the case of nonwords, where participants were shown pictures of fictitious creatures and told that the nonword was the name of that creature.

The past tense verb subtask proceeded similarly. Stimuli consisted of 16 familiar verbs, of which half were regularly marked for past tense using one of the "-ed" allomorphs (/-t/ /-d/ /-ld/), for example, "bake–baked." The other half consisted of irregularly marked verbs, such as “drive–drove,” matched for frequency and phonological complexity with the regularly marked verbs. A set of 8 nonsense verbs was also presented, for example, “filp–filped.” All verbs were presented as part of a sentence completion task, where the experimenter asked the participant to repeat a word used in the first sentence to finish the second sentence. Visual stimuli were provided for the nonword items, consisting of pictures depicting fictional creatures doing various activities.

CELF Word Structure task. Participants were also administered the Word Structure component of the CELF language assessment battery (Semel, Wiig, & Secord, 1995), to assess grammatical skill. In this task, children were shown pictures and were then read sentences that they had to complete based on examples shown by the experimenter. Most English morphological markings were represented in this task, including tense and number, along with other morphosyntactic markers such as pronouns, comparatives, and superlatives.

WISC-III Vocabulary task. The vocabulary subtask of the Wechsler Intelligence Scale for Children–III (WISC-III; Wechsler, 1992) was administered, to assess any semantic and lexical difficulties. Stimuli consisted of a standardized list of words that participants were asked to define as best they could.

Speech perception. Two tests of speech perception were administered to participants. Both were in the form of a single stimulus categorization task, in order to minimize any effect of attention or memory. Previous studies have used tasks in which participants were asked to indicate the temporal order of two auditory stimuli (Mody *et al.*, 1997; Tallal, 1980); this places a load on working memory, and as such does not differentiate between deficits in processing speech and the ability to maintain phonological representations in working memory while operating upon them. The categorization tasks used in the present study allowed us to assess children’s perceptual abilities under a minimal working memory load. We chose to test participants on two separate contrasts, voicing and POA. Perception of these two types of contrasts is well known to be categorical in nature (Liberman, 1996), and they are the contrasts most commonly tested in previous studies of speech perception by dyslexics.

The stimuli constructed for these contrasts differed in their expected perceptual demands. The VOT continuum, made from natural speech and with the test consonant in initial position (“dug–tug”), was expected to be readily categorized. In contrast, the POA stimuli have the test consonant as the second member of a consonant cluster (“spy–sky”). These could be more difficult to categorize for the following reasons: perceptual attention must be focused on a noninitial segment; the onset of the second consonant could potentially be masked by the noise of the preceding [s]; the stimuli were synthesized and therefore less natural; dyslexics sometimes have difficulty segmenting consonant clusters, and therefore might have trouble processing these items.

In the first task, “dug–tug,” stimuli were created by cross-splicing progressively more “tug” into “dug” from natural speech. The result was 8 different

VOT values from about 10-ms to 80-ms voicing lag, in roughly 10-ms increments (the exact values depended on the fundamental frequency of the voice, since pitch pulses were kept intact in the splicing). This formed a continuum of words identifiable as either *dug* or *tug.* Participants were given 6 practice items with feedback, consisting of endpoint stimuli. During experimental trials, no feedback was given. All stimuli were presented in random order, and each participant heard each stimulus 5 times, for a total of 40 trials.

The second task, "spy–sky," manipulated a consonant's perceived POA based on the onset frequency of second formant (F2) transition sweeps in the second consonant of the target word. This produced a continuum between the labial /p/ and dorsal /k/ phonemes. F2 onsets ranged from 1100 to 1800 Hz. Formant transition duration was 45 ms. The closure duration of 30 ms was chosen to be long enough to produce a clear stop percept, but short enough to make listeners vulnerable to effects of masking or to other auditory difficulties in processing too-short intervals between successive components of speech segments. This resulted in eight words discriminable as either *spy* or *sky*. 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.

Stimuli were presented using a Macintosh Powerbook with 16-bit audio and an active matrix screen. On each trial, participants were presented with two pictures, and an auditory stimulus were presented over Shure SM-2 headphones. All auditory stimuli were played as 16-bit, 22.05-kHz audio files. Participants were told to point to the picture of the word that they heard. Six practice items were presented with feedback, consisting solely of endpoints of the continuum. Test stimuli were then presented in random order, and each participant heard each stimulus 4 times, for a total of 32 trials. Feedback was not given during experimental trials.

Both tasks were expected to yield response profiles which could be characterized as categorical S-curves. To better quantify these data, each child's categorization curve was fitted to a logistic function using the Logistic Curve Fit function in SPSS. This procedure was used to estimate logistic curve functions for each categorization curve, including a slope coefficient. Valid coefficients tend to be between 0 and 1.0, where higher values represent shallower slopes. However, the logistic curve estimation procedure yields poor estimates for nonlogistic data (for example, random and near-random responses at endpoints), which results in positively skewed data violating the assumptions of normality necessary for reliable statistical analysis. To control for this, we excluded all coefficients of 1.2 or more.

RESULTS

Mean scores for the combined group of dyslexics and the two normal reader groups are presented in Table 1. The dyslexic group scored significantly below the CA group on nearly every task (Word Identification $t(111) = 20.16$, $p <$

TABLE 1
Mean Task Scores for the Dyslexic Group and the Two Normal Reader Groups

	Group		
Task	Dyslexics (N = 61)	CA (N = 52)	RL (N = 37)
Mean age	8;7	6;11	8;6
Grade	3	3	1 & 2
Woodcock[a]			
Grade Equivalent	2.1 (0.38)	4.0 (0.60)	2.2 (0.38)
Percentile	8.4 (5.4)	68.2 (16.4)	79.9 (15.5)
Nonwords (/70)	9.8 (8.0)	36.3 (12.4)	15.2 (10.1)
Exception words (/70)	19.5 (8.1)	44.3 (7.1)	21.7 (8.5)
Phoneme Deletion			
Words (/25)	10.8* (5.2)	17.2 (5.8)	13.1 (4.5)
Nonwords (/15)	4.7* (2.9)	9.0 (3.3)	7.2 (3.9)
Total (/40)	15.4* (7.4)	26.2 (8.3)	20.2 (8.0)
WISC Vocabulary			
Standard score	8.2* (2.7)	10.2 (2.9)	11.8 (3.8)
Raw score	17.9 (4.6)	21.5 (4.7)	17.4 (5.0)
CELF Word Structure			
Standard score	8.7* (2.9)	11.7 (2.9)	12.6 (2.3)
Raw score	24.0 (4.9)	28.1 (3.2)	25.0 (3.1)
Inflectional Morphology[b]	64.5* (19.0)	82.0 (13.2)	69.5 (15.8)
Speech Perception			
POA[c]	0.213 (0.17)	0.253 (0.03)	0.119 (0.03)
VOT[d]	0.231 (0.12)	0.213 (0.02)	0.200 (0.01)

Note. Asterisks indicate significant differences between the dyslexic and reading-level-matched normal reader group, $p < .05$. (Woodcock percentiles and raw scores for the CELF Word Structure and WISC Vocabulary tasks are listed for convenience only; no pairwise t tests were performed for them.) Standard deviations are indicated in parentheses. RL = reading-level-matched normal readers; CA = chronological age-matched normal readers.

[a] Word Identification subtask of the Woodcock Reading Mastery Task–Revised Form G.

[b] Percent correct, combined Noun and Verb tasks.

[c] Mean categorical slope, place of articulation task.

[d] Mean categorical slope, voice onset time task.

.0001; Nonword Reading $t(111) = 13.74$, $p < .0001$; Exception Word Reading $t(111) = 17.20$, $p < .0001$; Phoneme Deletion word subtask $t(111) = 6.92$, $p < .0001$, nonword subtask $t(111) = 6.79$, $p < .0001$, and overall score $t(111) = 7.46$, $p < .0001$; CELF Word Structure (standard score) $t(111) = 5.47$, $p < .0001$; WISC Vocabulary (standard score) $t(98) = 3.77$, p < .0001; Inflectional Morphology (combined noun and verb subtasks) $t(111) = 5.07$, $p < .0001$).

These differences are consistent with the studies reviewed above indicating that phoneme awareness and inflectional morphology are deficient in dyslexic children (e.g., Bruck, 1992; Manis et al., 1993; Shankweiler et al., 1995; Vogel, 1977). In contrast, the dyslexic group did not differ significantly from the CA

TABLE 2
Pearson Correlation Coefficients of the Tasks in this Study

	1	2	3	4	5	6	7	8	9
1. Woodcock Reading Level	—	.44**	.11	.37*	.53**	.52**	.35*	.11	−.25
2. Nonword Reading Accuracy	.43**	—	.26	.42**	.26	.10	.25	.26	−.08
3. Exception Wd. Reading Accuracy	.81**	.30*	—	.14	−.19	−.01	.19	.04	−.05
4. Phoneme Deletion Accuracy	.29*	.38**	.24	—	.43**	.25	.30	.09	.07
5. CELF Word Structure	.23	.45**	.14	.31*	—	.36*	.55**	−.07	−.10
6. WISC-II Vocabulary	.17	.25*	.06	.18	.42**	—	.39*	−.20	−.00
7. Inflectional Morphology (composite)	.40**	.22	.27*	.51**	.58**	.47**	—	−.06	−.28
8. Categorical Perception—POA	−.13	−.22	−.04	−.07	−.40**	−.21	−.30*	—	−.30
9. Categorical Perception—VOT	.00	−.23	−.11	.04	−.35**	−.29*	−.08	.31*	—

Note. The lower left triangle represents the dyslexics only ($N = 61$); the upper right triangle represents the RL group only. The inflectional morphology factor represents the overall mean on both the noun and the verb subtasks. POA = place of articulation; VOT = voice onset time.

* $p < .05$.

** $p < .01$.

group on either speech perception task (VOT $t(111) = 0.80$, $p = .43$; POA $t(111) = 1.11$, $p = .27$). The low scores by dyslexics on the standardized language measures indicate that a significant number of dyslexics had low language ability for their age, making it possible to investigate relationships among various aspects of language and speech perception.

The dyslexic group was also compared to the RL group on the same tasks. The two groups differed significantly on Nonword Reading ($t(96) = 2.96$, $p < .01$) and Phoneme Deletion (word subtask $t(96) = 2.01$, $p < .0001$; nonword subtask $t(96) = 3.90$, $p < .0001$; overall $t(96) = 2.99$, $p < .01$). Dyslexics scored significantly below the RL group on CELF Word Structure standard score ($t(83) = 6.81$, $p = .0001$) and WISC-III Vocabulary standard score ($t(83) = 5.22$, $p = .0001$). No other raw score group means differed significantly, including scores on the two speech perception tasks (VOT $t(93) = 0.42$, $p = .68$; POA $t(106) = 0.80$, $p = .43$).

As an initial investigation of the relationships among phonological, other language, and speech perception variables in this study, two sets of Pearson correlations were performed for all tasks. The first correlation matrix was done for all dyslexics. The second coefficient matrix used the same variables as the first, but was done only for the RL group. The purpose of this second matrix was to provide us with an overview of how intercorrelated the reading, language, and speech perception tasks tend to be in children with the same degree of reading achievement. Both matrices are presented in Table 2.

The bottom left half of Table 2 demonstrates that the reading and language measures tended to be moderately correlated with each other in dyslexics. In particular, Nonword Reading and Phoneme Deletion scores appeared to be predictive of language and overall reading ability. A similar pattern was observed for the RL group, indicating that for children reading at the level of the dyslexic group, reading and language abilities were similarly correlated.

The speech perception tasks were not correlated with any reading tasks, for either the dyslexic or the RL group. In the dyslexic group, however, these two tasks did tend to be significantly correlated with CELF Word Structure, WISC-III Vocabulary, and Inflectional Morphology. The negative *r* values indicated that children scoring lower on these tasks tended to have higher (and therefore less categorical) slope values. These relationships did not occur for the RL group.

From the results presented thus far, it appears the dyslexic group as a whole had difficulty with phonological tasks, including phonemic awareness and non-word decoding. Less severe deficits were also seen on three measures of oral language skill, though these difficulties did not appear to extend for the group as a whole to speech perception. Nevertheless, the significant correlations between the standardized language tasks and the speech perception scores for dyslexics are consistent with the hypothesis stated earlier that a subgroup of dyslexics with low language skill might have speech perception impairments.

Analysis of Subgroups

To better investigate the hypothesis that speech perception deficits were specific to dyslexics with either phonological impairments or broader language impairments, the dyslexic group was separated into three subgroups: phonological dyslexics, delay-type dyslexics, and language impaired dyslexics. The third subgroup also allowed us to explore the possibility that speech perception deficits might be specific to, or stronger in, dyslexics with language deficits extending beyond phonology.

The subgrouping methodology used in the present study was intended to yield groups of children similar to those in Manis et al. (1996) and Stanovich et al. (1997). As such, phonological dyslexic and delay-type dyslexic groups were obtained based on phonological decoding and phonological awareness abilities. Four dyslexic children were not included in the subgroup analyses because of extremely low reading achievement (Word Identification scores below the 1st percentile) that made subgrouping impractical.

Phonological dyslexics in previous studies have been characterized by deviant nonword reading and phonological awareness ability. Thus, the 24 dyslexics who scored one standard deviation or more below the RL group mean on either Nonword Reading or Phoneme Deletion were classified as phonological dyslexic. As described below, the 8 children in this group who also fit the criteria for the language impaired group were excluded from the phonological dyslexic group. The remaining 16 participants were classified in the phonological dyslexic group. Mean age was 8;7 (range 7;11–9;0).

Though two separate criteria were used to include children in the phonological dyslexic group, 11 of the phonological dyslexic children met both the low Nonword Reading and low Phoneme Deletion criteria. Another 4 children met only the low Nonword Reading criterion, and 1 met only the low Phoneme Deletion criterion.

The main purpose for defining a delay-type dyslexic group was to provide a sample of poor readers whose phonological skills were on a par with their overall reading level, and who were similar to the phonological dyslexic group on reading level. Accordingly, all dyslexics ($n = 33$) who demonstrated Phoneme Deletion and Nonword Reading profiles within one standard deviation of the RL group mean were included in the Delay group.[1] One also fit the criteria for the language impaired group as described below, and thus was not included in the delay group. An additional 9 dyslexic children were excluded in order to obtain matching means and standard deviations with the phonological dyslexic group on Word Identification. The result was a group of 23 children whose reading achievement was very similar to children in the phonological dyslexic group, but who showed reading-age-appropriate Nonword Reading and Phoneme Deletion scores. The mean age for this group was 8;7 (range 7;10–9;4). Most of the delay group fell below the CA group on Nonword Reading and Phoneme Deletion, indicating they had mild phonological difficulties. However, what was of interest in the present study was that their phonological skill was comparable to their word identification skill.

The language impaired group was identified based on scores obtained from two standardized language subtasks known to be highly correlated with overall language ability and verbal IQ: the CELF Word Structure and WISC Vocabulary tasks. A total of nine dyslexics scoring below a standardized score of 7 on both tasks were classified as language impaired; for both tasks, these represented a score of greater than one standard deviation below the normative mean. Only dyslexic children were included in this sample; one nondyslexic who also fit the language impairment criteria was not included in the language impaired group. Mean age for this group was 8;8 (range 7;11–9;4). Because this group was intended to represent any dyslexic children with broad language difficulties, participants fitting the criteria for *either* dyslexic subgroup were considered. As indicated above however, eight of the nine children in this group also fit the criteria for the phonological dyslexic group.

It should be pointed out that the criteria used in classifying the language impaired group did not include phonological ability measures. This is in keeping with the traditional definition of language impairment (or SLI) that includes only children with grammatical deficits, although phonological deficits also tend to cooccur with these (Bishop, 1997b). Thus, while this group's language problems

[1] An initial investigation of dyslexics who were very low on exception word reading but normal on phonemic awareness and nonword reading—that is, children who constituted very pure cases of delay or "surface" dyslexia—yielded a relatively small group of dyslexics ($N = 5$). This group also had very poor Woodcock reading scores compared to other dyslexics, making it difficult to compare them to the RL group. For this reason, we opted to include a broader range of dyslexics in the delay group, including those scoring similarly to the phonological dyslexic group on exception word reading.

could also extend into phonology, children who demonstrated *only* phonological deficits were excluded from this group. One difference between the language impaired group and typical SLI groups is that measures of nonverbal intelligence were not included in the present study.[2] Table 3 presents the means for the three dyslexic subgroups. The CA and RL group means are repeated here for convenience.

Subgroup comparisons on the defining tasks. The subgroups and the two normally achieving groups were compared on the defining measures to confirm the distinctiveness of the groups. Planned comparisons were conducted for the defining measures (Word Identification, Nonword Reading, Phoneme Deletion combined score, CELF Word Structure Standard Score, and Vocabulary Standard Score). Ten possible pairwise comparisons were possible. However, performing each of these comparisons involved an unacceptable level of Type I error, and while corrective post hoc tests can help control for this, there was the real possibility of failing to detect small yet reliable between-group differences. In order to balance these two considerations, four Bonferroni-corrected t tests were performed for each task. We performed the following four comparisons: language impaired vs RL, phonological dyslexic vs RL, delay vs RL, and CA vs RL. Significant effects were reached at $p < .0125$, based on dividing a significance level of .05 by the total number of comparisons. As was discussed earlier, many different skills are related to reading experience, including phonological and morphological ability and phonological awareness. Comparing the three dyslexic groups to the RL group, in addition to the CA group, allowed us to take this into consideration when assessing any dyslexic group's difficulties on a given task.

The results of the pairwise comparisons on the Woodcock and nonword tasks were as follows. Only the CA group's mean Woodcock grade level was significantly different from that of the RL group, $t(87) = 16.83$, $p < .0001$. However, both the phonological dyslexic and CA groups were different from the RL group on the nonword reading task: phonological dyslexic vs RL, $t(51) = 4.28$, $p < .0001$; CA vs RL, $t(87) = 8.56$, $p < .0001$. No other group differences were significant for these two tasks.

Planned comparisons were also performed for the real-word and nonword subtasks of the phoneme deletion task. The phonological dyslexic group was

[2] To better assess the language impaired group's cognitive status, participants in all five groups were tested on the Visual Closure subtask of the Woodcock–Johnson Psycho-Educational Battery–Revised to assess nonverbal intelligence. This task was used in a follow-up study. Due to normal attrition several of the participants in this study were thus no longer available for testing. Mean standardized scores for all five groups were well within normal limits (language impaired 98.9 (12.9), $N = 7$; phonological dyslexic 93.7 (13.5), $N = 13$; delay 98.1 (14.0), $N = 16$; CA 101.0 (10.3), $N = 44$; RL 103.6 (13.6), $N = 22$; standard deviations are indicated in parentheses). This was confirmed by five one-sample t tests which indicated that no group mean differed significantly from the mean standard score of 100. In addition, all children in the language impaired group who were retested scored above 90 on this task. These results indicate that the language impaired group was not composed of children with disproportionately poor cognitive skills.

TABLE 3
Mean Task Scores for the Dyslexic Subgroups

Task	LI (N = 9)	PD (N = 16)	Delay (N = 23)	CA (N = 52)	RL (N = 37)
Woodcock[a]					
Grade Equivalent	2.1 (0.28)	2.1 (0.31)	2.1 (0.23)	4.0* (0.60)	2.2 (0.38)
Percentile	6.3 (5.9)	8.3 (6.2)	9.3 (4.4)	68.2 (16.4)	79.9 (15.5)
Nonwords (/70)	7.0 (7.5)	4.1* (3.4)	14.0 (6.8)	36.3* (12.4)	15.2 (10.1)
Exception words (/70)	18.7 (7.3)	18.2 (7.0)	19.8 (5.0)	44.3* (7.1)	21.7 (8.5)
Phoneme Deletion					
Words (/25)	8.4 (5.9)	5.5* (3.4)	14.2 (2.6)	17.2* (5.8)	13.1 (4.5)
Nonwords (/15)	3.9* (3.2)	2.6* (2.4)	5.8 (1.9)	9.0 (3.3)	7.2 (3.9)
Total (/40)	12.3 (8.7)	8.0* (4.9)	20.0 (3.6)	26.2 (8.3)	20.2 (8.0)
WISC Vocabulary					
Standard score	5.1* (0.9)	8.1 (3.2)	9.1 (2.7)	10.2* (2.9)	11.8 (3.8)
Raw score	12.9 (1.6)	17.2 (4.9)	19.7 (4.8)	21.5 (4.7)	17.4 (5.0)
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)
Raw score	17.4 (3.5)	22.3 (4.4)	26.4 (3.8)	28.1 (3.2)	25.0 (3.1)
Inflectional Morphology[b]	44.2* (15.0)	58.2 (20.2)	72.6 (11.7)	82.0* (13.2)	69.5 (15.8)
Speech Perception					
POA[c]	0.410* (0.12)	0.171 (0.02)	0.181 (0.02)	0.253 (0.03)	0.119 (0.03)
VOT[d]	0.289* (0.05)	0.223 (0.03)	0.215 (0.02)	0.213 (0.02)	0.200 (0.01)

Note. Asterisks indicate significant differences from the reading level-matched normal reader group, $p < .0125$. (Woodcock percentiles and raw scores on the CELF Word Structure and WISC Vocabulary tasks are listed for convenience only; no pairwise *t* tests were performed for them.) Standard deviations are indicated in parentheses. PD = phonological dyslexics; LI = language impaired dyslexics; RL = reading-level-matched normal readers; CA = age-matched normal readers.

[a] Word Identification subtask of the Woodcock Reading Mastery Task–Revised Form G.

[b] Percent correct, combined Noun and Verb tasks.

[c] Mean categorical slope, place of articulation task.

[d] Mean categorical slope, voice onset time task.

significantly different from the RL group on both the word subtask, $t(51) = 4.72$, $p < .001$, and the nonword subtask, $t(51) = 5.03$, $p < .001$. The language impaired group also differed from the RL group on the nonword subtask, $t(44) = 2.68$, $p < .01$. Differences between the CA and RL groups were also significant for the real-word subtask, $t(87) = 3.77$, $p < .001$. No other differences were significant.

The standardized language measures also showed the expected differences among groups (standard scores). On the CELF Word Structure task, significant differences were obtained for the language impaired vs RL, $t(44) = 6.44$, $p < .001$, and CA vs RL, $t(87) = 4.46$, $p < .001$, comparisons. On the WISC Vocabulary task, significant differences were obtained for the language impaired vs RL comparison, $t(36) = 2.62$, $p < .0125$, and the CA vs RL comparison, $t(87) = 3.96$, $p < .001$.

Subgroup comparisons on validating tasks. Planned comparisons were also performed for the two tasks that were not used in the classification phase, Exception Word Reading and Inflectional Morphology. The CA group was superior to the RL group on Exception Word Reading ($t(87) = 13.70$, $p < .001$); no other comparisons reached significance. The similarity of the dyslexic groups to the RL group on this measure indicates that the process of equating reading levels using Woodcock Word Identification was validated by an independent measure of word reading.

The inflectional morphology task was of interest for two reasons. First, it provided a check on the classification process for language deficits using a focused test of one of the central language skills thought to be involved in language difficulties. Mean scores combining across nouns and verbs are shown in Table 3. Planned comparisons were performed, and they indicated significant differences between the language impaired and RL groups, $t(44) = 3.11$, $p < .001$, and the CA and RL groups, $t(87) = 4.04$, $p < .001$. The delay group did not differ from the RL group (and in fact was quite similar to the RL group on this measure). These results confirm the classification of the language impaired group, and support the definition of the delay group as showing reading-level-appropriate levels of language skill.

The inflectional morphology task also provided a test of the hypothesis that phonological difficulties in reading were associated with poor knowledge of inflectional morphology. The phonological dyslexic–RL comparison was marginally significant, given the degree of Bonferroni correction ($t(51) = 2.21$, $p < .03$), providing limited support for this hypothesis.

Speech Perception Tasks

Identification functions for the *dug–tug* VOT categorization task were obtained by calculating the proportion of *tug* responses (out of five) for each stimulus along the continuum of eight items. When these were plotted, the result was an S-shaped curve, where high values along the *y* axis would indicate a greater proportion of *tug* responses at that VOT; lower values would indicate more *dug* responses. A narrower, steeper crossover between the two endpoint regions would indicate sharper overall categorization, whereas a wider and flatter crossover would indicate a greater number of inconsistent responses, suggesting weak categorization. Completely random responses would result in a flat line across the continuum.

Figure 1 shows the mean categorization curves on this task for the normal readers compared to each of the three dyslexic groups. To simplify the graph, the normal reader curve represents the mean of the CA and RL groups, which did not differ in slope. Overall curves for the phonological dyslexic and delay groups appeared relatively consistent with those for the normal readers, showing similar

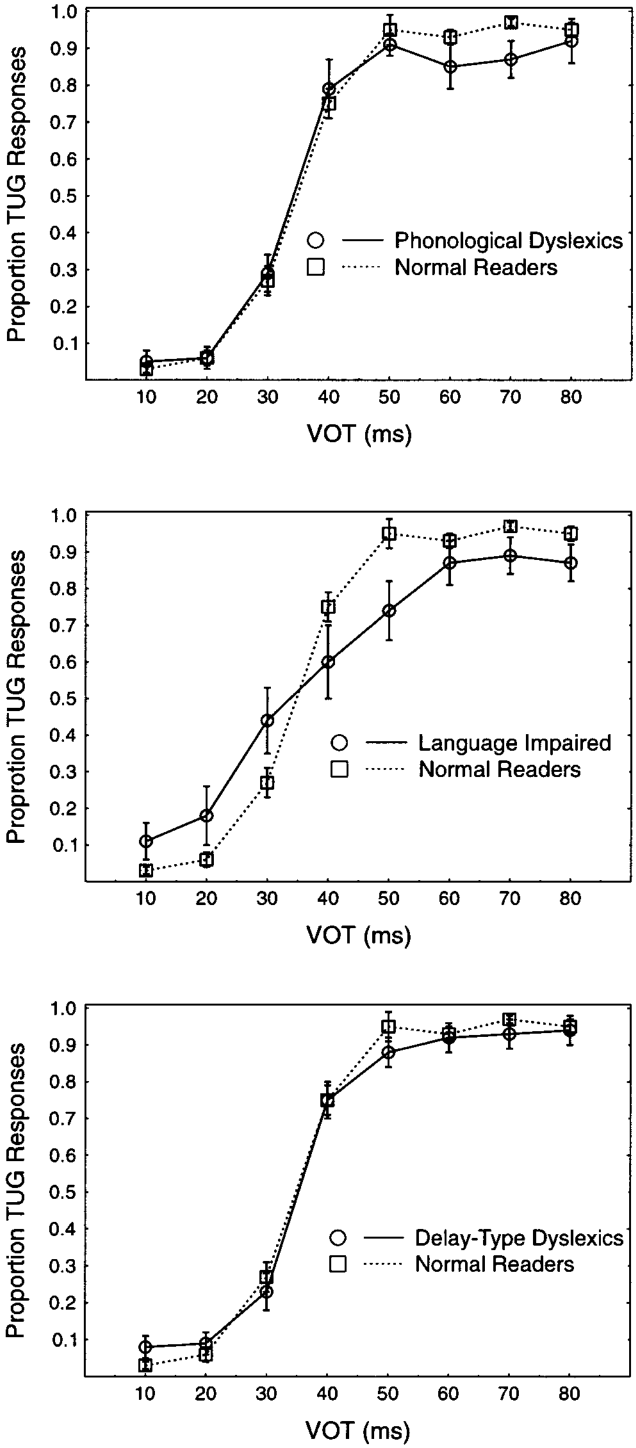

FIG. 1. Comparison of group curves on the voice onset time (VOT) categorization task.

crossover points between 30 and 40 ms. In contrast, the language impaired group curve indicated slightly weaker categorization between 40- and 60-ms VOT.

To assess the reliability of these differences, mean logistic slope values were calculated for each participant as described under Method. Group means are presented in Table 3. As mentioned above, slope coefficients above 1.2 were trimmed to control for positively skewed distributions. This meant excluding one from the CA group for this analysis only. This participant was also excluded from Fig. 1. Bonferroni-corrected planned comparisons were used to compare slope means for the language impaired, phonological dyslexic, delay, and CA groups to that of the RL group. The language impaired group showed a significantly higher slope parameter than the RL group, $t(43) = 2.68$, $p < .01$. No other differences were significant.

Analyses of the *spy–sky* POA task proceeded similarly. Categorization scores were obtained by calculating the proportion of *spy* to *sky* responses at each stimulus value. Figure 2 plots the language impaired, phonological dyslexic, and delay group curves relative to the normal readers (here again, the mean of the CA and RL groups was plotted). Each participant's categorization curve was fitted to a logistic function, yielding mean slope coefficients for each group (Table 1). To control for outlier effects, participants with slope coefficients greater than 1.2 were again excluded. This ruled out two phonological dyslexic and two delay subjects from this analysis. Data from these subjects were also excluded from plots in Fig. 2. Planned comparisons were performed on the mean slope coefficients. As with the VOT task, the language impaired group's mean slope was significantly different from that of the RL group, $t(41) = 2.71$, $p < .01$. No other group's slope was significantly different from the RL group.

These results show that, on both speech categorization tasks, the language impaired group demonstrated distorted or weakened perceptual categories for speech sounds. This result is similar to what has been found in other studies of stop consonant categorization in groups of poor readers (Godfrey et al., 1981; Masterson et al., 1995; Reed, 1989; Werker & Tees, 1987). However, it also goes beyond these studies by finding only one subgroup of dyslexics that departed from the normal pattern of categorical perception. This is consistent with results reported in Manis et al. (1997), where it was found that only a subset of the children who manifested phonologically based reading difficulties (phonological dyslexia) demonstrated measurable speech perception deficits. The present results suggest this subgroup in the Manis et al. sample included language impaired children.

Regression Analyses

While the comparison of dyslexic subgroups on the speech perception tasks is theoretically interesting, the subgroup divisions were arbitrary, and it is of interest to examine the relationship between the defining measures and speech perception treated as continuous variables. We therefore conducted separate

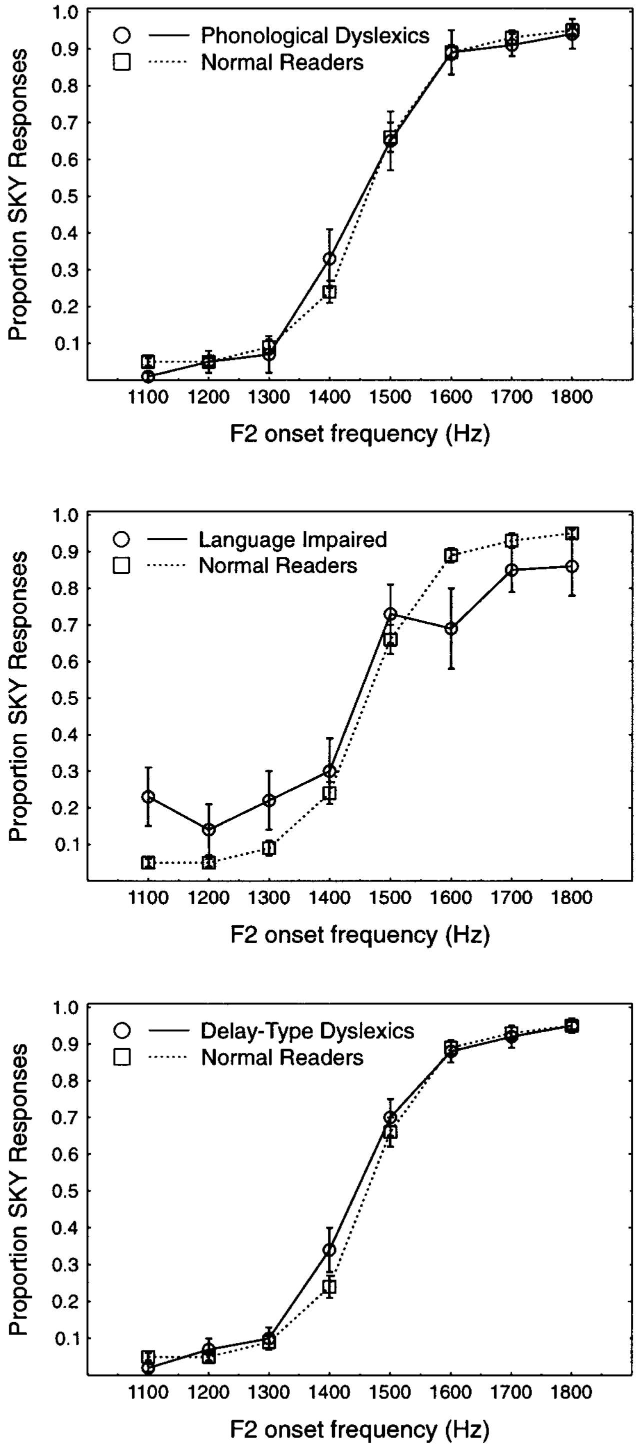

FIG. 2. Comparison of group curves on the place of articulation (POA) categorization task.

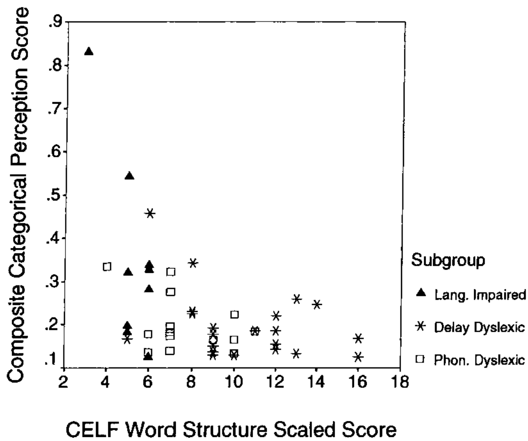

FIG. 3. Scatter plot of mean slopes on the two categorical perception tasks and the CELF Word Structure task.

hierarchical regression analyses for the dyslexics as a combined group, and for the RL group. Given the subgroup results, we would expect phonological skill among dyslexics to account for less variability in speech perception than the CELF and Vocabulary measures. No strong relationships between the predictor variables and speech perception would be expected for the RL group, as few or none of these children performed poorly on the speech perception tasks.

As in the previous analyses, slope scores exceeding 1.2 for the VOT or POA tasks were treated as outliers and eliminated. Phonological variables (Phoneme Deletion and Nonword Reading) were entered first as a block, followed by CELF and Vocabulary as a block. For dyslexics, the phonological variables accounted for less than 7% of the variance in either slope value, and the coefficients were not significant. When CELF Word Structure and WISC Vocabulary scores were added, these two variables accounted for significant additional variance (11.8% for VOT slope and 12.9% for POA slope). In both analyses, CELF Word Structure was the only variable that was significant in the regression analyses ($p < .05$ for VOT and $p < .025$ for POA). In contrast, similar analyses conducted for the RL group revealed that neither the phonological nor the language variables accounted for reliable variance in speech perception slopes.

The form of the relationship between CELF Word Structure (the strongest predictor of speech perception performance) and the mean slopes from the two speech perception tasks is shown for the dyslexic subgroups in Fig. 3. There was a weak negative linear relationship between CELF scores and mean slopes (slopes get smaller as CELF score increases). Six of the language impaired participants showed moderately high to high mean slope values; in addition, several delay and phonological dyslexic children also showed mean slopes above

0.25, though it is interesting that most of these participants also showed abnormally low scores on the CELF task. It is possible that these participants are children with milder language impairments who were not included in the language impaired group due to marginally better scores on the WISC-II vocabulary task.

To better characterize the relationship between performance on the language and speech perception tasks, curve-fitting procedures were applied to the data. These revealed that the linear component and the quadratic component were both significant at $p < .05$, but the best fitting function was the inverse. The inverse function has very high y values closer to the x axis, with y values approaching zero as x values increase. The results indicate that abnormalities in speech perception occur only for a minority of children, those with low language skills. Slopes were uniformly low (indicating strongly categorical speech perception) among the rest of the participants and unrelated to language ability.

The results of these regression analyses make it clear that only a minority of dyslexic participants showed abnormal speech perception, and these children were primarily found among dyslexics with broader and more severe language impairments. Severity of the phonological deficit was not related to categorical speech perception among dyslexics, and in fact accounted for less than 7% of the variance in speech perception slopes. Thus, treating the subgrouping variables (phonological skill and language skill) as continuous variables did not substantially alter the group results reported above.

DISCUSSION

The principal goal of this study was to investigate the occurrence of speech perception deficits in developmental dyslexia, and their relationship to knowledge of phonology and other aspects of language, particularly morphology. We found that the children exhibited considerable heterogeneity (Fig. 4). They differed with respect to both their pattern of reading and the extent to which speech perception, phonology, and morphology were impaired. We analyzed the results with respect to several subgroups defined by theoretically relevant aspects of performance. Defining subtypes in this way clearly imposes somewhat artificial categorical distinctions on the participants. However, the purpose of this subgrouping was to facilitate investigating the contributions of several distinct factors to dyslexic reading acquisition rather than to define diagnostic categories. We can now discuss the results for the different subtypes using theories of reading to explain why specific factors tend to give rise to different behavioral patterns.

One implication of the present study, consistent with previous research (e.g., Manis et al., 1997; Tallal, 1980; Tallal & Stark, 1982), is that only a small minority of dyslexics appear to have perceptual difficulties. This implies that researchers must look beyond speech perception for the source of reading difficulties in the majority of dyslexics with phonological awareness and non-

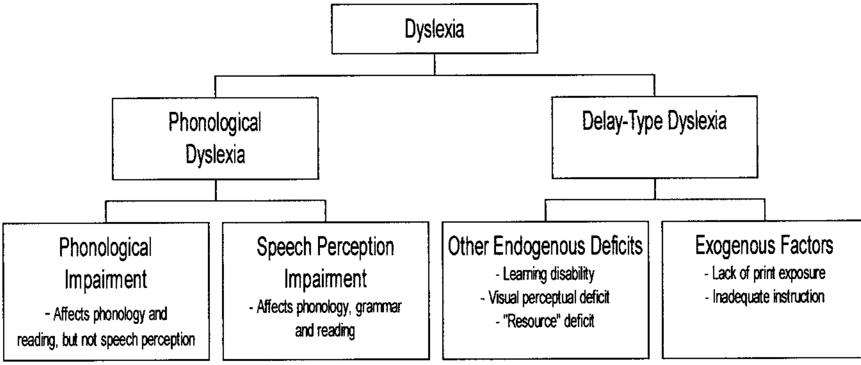

FIG. 4. Summary of dyslexic subgroups.

word reading difficulties. In addition, a sizable number of dyslexics, here represented in the delay subgroup, do not have phonological skills that are out of line with their word recognition skills. This suggests that other factors beyond phonological ability may be relevant to variation among dyslexics (Manis et al., 1996; Stanovich et al., 1997).

Phonological Dyslexics

The phonological dyslexics in this study exhibited a behavioral profile observed in many previous studies. They were poor at reading both exception words and nonwords, but they were much worse on the latter. As in previous studies, their performance was markedly dissimilar to that of younger normal readers, suggestive of a deviant developmental trajectory. These children exhibited a phonological deficit, performing more poorly than younger normal readers on Phoneme Deletion and Nonword Reading. This pattern has been widely acknowledged as the dominant profile for children with moderate to severe reading disabilities (e.g., Liberman & Shankweiler, 1985; Shankweiler et al., 1995; Wagner & Torgesen, 1987). There are explicit theories of how this problem might develop. Skilled reading and the ability to pronounce nonwords depend on representing phonological information segmentally. Impaired development of segmental phonology interferes with the acquisition of word recognition skill, but it especially affects the capacity to use knowledge of spelling–sound correspondence in pronouncing novel words. Harm and Seidenberg (1999) present simulations using a connectionist model of word recognition that demonstrate such effects of phonological impairment on reading acquisition.

Our study provides evidence about two additional aspects of phonological dyslexia. First, although this group of dyslexics exhibited impaired knowledge of phonology, their performance on two speech perception tasks was normal. These results suggest that phonological representations can be impaired independently of speech perception. Simulations in Harm and Seidenberg (1999) illustrate this point. They introduced anomalies in the processing of phonological information that were severe enough to yield reading impairments but did not affect the model's performance on simulated speech perception tasks. These anomalies were specific to the phonological component of their network model: they affected the capacity of the network to represent phonological information and the dynamics of phonological processing.

Because we have not tested all aspects of speech perception, we cannot be sure that the phonological dyslexics' speech perception was normal in all respects. Nevertheless, the present study and Manis et al. (1997) together indicate that on three separate speech contrasts, a large number of dyslexics, many of them with severe phonological deficits, performed normally. Hence, researchers will need to examine other aspects of phonological processing to better understand phonological deficits in dyslexia.

A second finding is that the phonological dyslexic group's knowledge of inflectional morphology was below normal for age (though not significantly so for reading grade level), indicating that their behavioral impairment was not limited to reading and phonemic awareness. These morphological difficulties are likely to be another consequence of the children's phonological impairment. Morphological regularities such as the ones involved in the formation of English past tense verbs have a significant phonological component. Specifically, the past tense "-ed" morpheme surfaces in three forms (-t/-d/-Id, as in BAKED, TUGGED, and PATTED), with the correct surface variant determined by the phonological structure of the verb stem. Difficulty analyzing phonological structure can therefore affect the acquisition of morphological patterns such as past tenses. The main impact of the phonological impairment is on generalization. Thus, although it is commonly observed that phonological dyslexics are poor at pronouncing nonwords such as WUG, they are also poor at generating novel past tenses such as WUGGED; the two deficits have a common phonological basis. Joanisse and Seidenberg (1999) describe a computational model illustrating the effects of a phonological impairment on past tense generation. Consistent with the present data, a phonological impairment in the model had a bigger impact on generating past tenses for nonwords than irregular past tenses.

An important caveat should be noted, which is that the development of phonological representations and the use of this information in reading most likely are affected by the method of reading instruction (Byrne, Fielding-Barnsley, Ashley, & Larsen, 1997; Olson, Wise, Ring, & Johnson, 1997). Many children are exposed to whole language methods that discourage the use of phonological decoding strategies. The school district from which the children in the present study were obtained relied strongly on these methods during the period in which the dyslexics were in grades K–2. Hence, it is possible that some children classified in the phonological dyslexic subgroup had low nonword reading or low phonological awareness because of the curriculum. Alternatively, a low emphasis on phonics instruction might have combined with otherwise mild phonological deficits to produce more serious difficulties in nonword reading. These difficulties might be expected to lessen as children are given special education services focusing on phonics. Until such instructional variables are examined carefully, theoretical explanations for phonological dyslexia may be incomplete.

Language-Impaired Dyslexics

A second subgroup of dyslexics fit some of the criteria typically used in studies of developmental language impairments (Leonard, 1998). These children scored poorly on two separate standardized language tests, yet had not been categorized as mentally retarded or low in English proficiency by their schools. Follow-up testing also suggested that these children had normal nonverbal cognitive abilities. Past research has indicated a strong tendency for language impaired children to have significant reading difficulties (Bishop & Adams, 1990; Catts et al., 1994; Scarborough, 1990), and the present results are consistent with this observation; only one nondyslexic reader in the overall sample also fit the language score criteria for the language impaired group. (As we noted earlier, this child was not included in analyses.) All other children with language difficulties had significantly impaired reading.

In many respects the language impaired group's performance was like that of the phonological dyslexics. In fact, eight of the nine children in the language impaired group met the criteria we used in identifying the phonological dyslexic group. Like the children in the phonological dyslexic group, children in the language impaired group were impaired in reading both exception words and nonwords, with a more severe deficit on the latter. Both groups performed poorly on the phoneme deletion task and were below average in morphological knowledge. However, the two groups differed in important ways.

The language impaired group exhibited clearly deviant performance on the speech perception tasks, whereas the phonological dyslexic subjects did not. The results for this group are consistent with previous studies implicating speech perception impairments in this population (Elliott & Hammer, 1988; Stark & Heinz, 1996; Tallal & Piercy, 1974). These children also exhibited broader language impairments than the phonological dyslexics. Thus, in the language impaired group, impaired language and reading may be sequelae of a basic information processing deficit involving phoneme perception, as suggested by Bishop (1997a), Leonard (1998), and Tallal and Stark (1980), among others. This deficit appears to be severe enough to interfere with the development of phonological representations and with learning systematic aspects of linguistic structure (Joanisse & Seidenberg, 1998).

The phonological dyslexic group differed from the language impaired group insofar as their performance on the speech perception tasks was apparently normal. There are two explanations for the difference between the phonological dyslexic and language impaired subgroups. One is that the phonological dyslexic group merely has a milder form of a speech perception deficit that does not disrupt categorical perception severely enough to be observed experimentally. By hypothesis, this deficit is severe enough to interfere with the difficult task of learning to read and with some aspects of language acquisition (e.g., learning inflectional morphology), but it is not as severe as in developmentally language impaired children. The other possibility is that the phonological dyslexic group's speech perception is genuinely normal and their deficit is localized to the representation and processing of phonology. The latter alternative suggests that although both groups have phonological impairments, they derive from different causes. Harm and Seidenberg's (1999) model is suggestive in this regard, showing three different types of phonology-based anomalies which produced the phonological dyslexic reading pattern; not all of these anomalies resulted in a deficit to categorical perception in the model.

Data relevant to the two alternatives are provided by the finding that children in the language impaired group were more impaired than the phonological dyslexics on the speech perception and morphology tasks, but the groups did not differ on the phoneme deletion and nonword reading tasks. In fact, the language impaired group was numerically *better* on both the latter tasks (though preliminary analyses indicated these differences were not statistically significant). These results favor the second of the two alternatives listed above. They suggest that although the language impaired and phonological dyslexic groups exhibit similar deficits in phonology and reading, their causes may differ, with one involving a speech perception deficit, and the other involving higher level differences in phonological representation or processing. Speech perception deficits may have a broad impact on spoken language acquisition, affecting vocabulary, phonology, morphology, and syntax (Bishop, 1997b), whereas the effects of higher level phonological processing deficits in phonological dyslexic children may be more limited. Caution needs to be exercised because of the small sample sizes in the present study. These issues need to be investigated further with a larger number of participants and additional measures of phonological skill and speech perception.

There is also uncertainty about how children in the language impaired group in the present study compare to those in other studies of developmental language impairments. Since we did not test children in this study on overall IQ, and since several children in the language impaired group had not been previously identified with specific language deficits by their schools, it is difficult to determine how they would compare to children who meet the classic definition of SLI. In some respects, the language impaired children in the present study fit a broad definition of SLI; they are children with no frank cognitive or neurological deficits who scored poorly on standardized tasks of language skills, and demonstrated poor morphological, phonological, and speech perception abilities. In addition, while these children's nonverbal cognitive profiles were not fully assessed, they scored normally on a follow-up test of nonverbal cognitive ability (see footnote 2), suggesting general retardation was not a factor in this group's reading and language profiles. Nevertheless, the relatively small sample size suggests the need for caution in generalizing to the broader population of language impaired children. As well, this group's large standard deviations on many tasks suggests that the language impaired group was to some degree heterogeneous. While this is often observed in populations of language impaired children (Aram & Nation, 1975; Bishop, 1997b), future research will need to examine the degree to which this variability affects the phonological, speech perception, and reading measures examined in this study.

Delay Dyslexics

A third subgroup of dyslexics, whom we have labeled delay dyslexics, was also quite prominent in our sample of poor readers. Unlike the performance of language impaired and phonological dyslexic groups, these children's performance on the reading, phonology, morphology, and speech perception tasks was like that of younger normal readers. Hence at the point they were tested they appeared to be developmentally delayed with respect to reading, phonology, and morphology, although their speech perception was within normal limits. While it is clear that these children's behavior differs in many respects from that of the phonological dyslexics, the basis for their impaired performance is unclear. One possibility is that this is a heterogeneous group of poor readers whose developmental delay has a variety of causes (Harm & Seidenberg, 1999; Manis et al., 1996; Stanovich et al., 1997). These may include a learning impairment not specific to reading, a visual processing deficit, a cognitive resource limitation, and environmental factors such as lack of experience. Harm and Seidenberg's simulations show how such factors would produce the delay pattern.

A second possibility is that these children's impaired performance is related to a milder form of phonological impairment. The results indicate that the delay group performed more poorly than same-aged controls on the Nonword Reading and Phoneme Deletion tasks but better than the phonological dyslexics. Thus these children's mild phonological impairment may be a consequence of their other behavioral deficits. Our study does not rule out this possibility, which needs to be investigated further. However, this hypothesis runs into two problems. First, it suggests that the delay group should have exhibited the same kinds of impairments as the phonological dyslexics but to a lesser degree of severity. However, the delay dyslexics' behavioral profile was not a less-impaired version of the phonological dyslexics'; in particular, both groups were reading at a similar grade level, as assessed by the Woodcock Word Identification test, and also had similar scores on the Exception Word Reading task. It would then have to be explained why the mild and severe forms of phonological impairment fail to give rise to differences on such tasks. Second, the simulation modeling results of Harm and Seidenberg (1999) contradict the hypothesis in two respects. The modeling demonstrates that the delay pattern can arise from nonphonological impairments, such as inefficient learning, a resource deficit, or lack of experience. There is no comparable account of how a mild phonological deficit could give rise to the delay pattern. In addition, the modeling shows that a mild impairment on phonological tasks (such as Nonword Reading) is one of the consequences of these nonphonological impairments. Segmental phonological representations normally emerge in the course of learning to read an alphabetic writing system. These will affect the course of acquisition and are in turn modified by the knowledge that is acquired (Morais et al., 1979; Wagner, Torgesen, & Rashotte, 1994). Nonphonological factors that delay the course of acquisition also affect progress in developing these representations. Thus, the mild phonological impairments seen in the delay group are a consequence of other factors that are the proximal cause of the behavioral delay.

The causes of the impairments observed in the delay group are less well understood than the causes of phonological dyslexia. One question that needs to be addressed in future research is whether the delay group differs with respect to etiology. There is a need to use other behavioral measures to differentiate between very different causes, such as a visual processing impairment vs a lack of experience, that nonetheless give rise to similar behavioral patterns. A second question concerns the nature of the phonological deficit in the delay group: Is it a cause or an effect of their impaired reading acquisition? If the deficit is a consequence of another problem, it might be expected to resolve in children whose reading skills eventually improve. True phonological deficits, in contrast, seem constitutional in nature, are difficult to remediate, and tend to persist even in adult dyslexics who eventually acquire greater reading proficiency (Bruck, 1992).

CONCLUSIONS

This research, along with earlier research by Manis et al. (1996), Castles and Coltheart (1993), Murphy and Pollatsek (1994), Stanovich et al. (1997), and others, suggests there is considerable variability among children who are classified as dyslexic, with regard to both the pattern of impaired reading and the extent to which they exhibit impaired use of language. In addition, however, the present results indicate that there is also variability with respect to the speech perception abilities of dyslexics, and that this variability is related to language deficits in dyslexics.

As Fig. 4 illustrates, there is a major break between phonological and nonphonological (delay) types of dyslexia. Within the phonological subtype, there is a standard pattern in which the reading impairment is secondary to impaired phonology. Other phonological dyslexics exhibit broader language impairments;

their deficits appear to be strongly related to impaired speech perception.[3] Children on the delay side exhibit a different pattern of impairment. Both their reading (e.g., exception words and nonwords) and their language (e.g., phonology, morphology) are like that of younger normal readers. As we have suggested, this pattern may have several causes including mere lack of reading experience or failure to learn efficiently.

Although there are two broad behavioral patterns in dyslexia, both the empirical results presented here and the results of simulation modeling suggest that each pattern can have more than one underlying cause. Phonological dyslexia, for example, may derive from deficits in either speech perception or other aspects of phonology. The delay pattern can be produced by both endogenous factors (such as a lack of computational resources) and exogenous factors (such as a lack of experience). These results suggest that it may not be valid to assume that children who exhibit similar patterns of impaired reading have the same underlying deficits. The different potential causes of a given pattern can be differentiated by using additional measures that assess other aspects of language and experience.

REFERENCES

Adams, M. (1990). *Beginning to read.* Cambridge, MA: MIT Press.

Aram, D. M., & Nation, J. E. (1975). Patterns of language behavior in children with developmental language disorders. *Journal of Speech and Hearing Disorders,* **18,** 229–241.

Berko, J. (1958). The child's learning of English morphology. *Word,* **14,** 150–177.

Bishop, D. V. M. (1997a). Listening out for subtle deficits. *Nature,* **387,** 129–130.

Bishop, D. V. M. (1997b). *Uncommon understanding: Development and disorders of language comprehension in children.* Hove, UK: Psychology Press.

Bishop, D. V. M., & Adams, C. (1990). A prospective study of the relationship between specific language impairment, phonological disorders, and reading retardation. *Journal of Child Psychology and Psychiatry,* **31,** 1027–1050.

Bowers, P. G., & Swanson, L. B. (1991). Naming speed deficits in reading disability: Multiple measures of a single process. *Journal of Experimental Child Psychology,* **51,** 195–219.

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

Bruce, D. (1964). The analysis of word sounds. *British Journal of Educational Psychology,* **34,** 158–170.

Bruck, M. (1992). Persistence of dyslexics' phonological awareness deficits. *Developmental Psychology,* **28,** 874–886.

Byrne, B., Fielding-Barnsley, J., Ashley, L., & Larsen, K. (1997). Assessing the child's and the environment's contribution to reading acquisition: What we know and what we don't know. In B. Blachman (Ed.), *Foundations of reading acquisition and dyslexia.* Mahwah, NJ: Erlbaum.

Byrne, B., & Shea, P. (1979). Semantic and phonetic memory codes in beginning readers. *Memory and Cognition,* **7,** 333–338.

[3] As we mentioned above, there might exist a third group of "instructional" phonological dyslexics who have normal phonological processing capacities but are behaviorally impaired because of teaching methods that strongly discourage reliance on phonological information in reading (e.g., Smith, 1983). We would expect these children to benefit greatly from appropriate types of remediation and so their deficits may only be temporary.

Castles, A., & Coltheart, M. (1993). Varieties of developmental dyslexia. *Cognition,* **47,** 149–180.

Catts, H., Hu, C.-F., Larrivée, L., & Swank, L. (1994). Early identification of reading disabilities in children with speech–language impairments. In R. Watkins & M. Rice (Eds.), *Specific language impairments in children* (pp. 145–160). Baltimore, MD: Paul H. Brookes.

Denckla, M., & Rudel, R. (1976). Rapid automatized naming (R.A.N.): Dyslexia differentiated from other learning disabilities. *Neuropsychologia,* **14,** 471–479.

Elliott, L. L., & Hammer, M. A. (1988). Longitudinal changes in auditory discrimination in normal children and children with language-learning problems. *Journal of Speech and Hearing Disorders,* **53,** 467–474.

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

Harm, M. W., & Seidenberg, M. S. (1999). Phonology, reading, and dyslexia: Insights from connectionist models. *Psychological Review,* **163,** 491–528.

Hayes, D. (1988). Speaking and reading: Distinct patterns of word choice. *Journal of Memory and Language,* **27,** 572–585.

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

Joanisse, M. F., & Seidenberg, M. S. (1999). Impairments in verb morphology following brain injury: A connectionist model. *Proceedings of the National Academy of Science, USA,* **96,** 7592–7597.

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.

Keating, P., & Manis, F. (1998). The Keating–Manis phoneme deletion test. In *UCLA working papers in phonetics* (Vol. 96, pp. 162–165). Los Angeles: UCLA Phonetics Laboratory.

Klatt, D. (1990). Analysis, synthesis, and perception of voice quality variations among female and male talkers. *Journal of the Acoustical Society of America,* **87,** 820–857.

Leonard, L. (1998). *Children with specific language impairment.* Cambridge, MA: MIT Press.

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

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

Liberman, I., & Shankweiler, D. (1985). Phonology and the problems of learning to read and write. *Remedial and Speech Education,* **6,** 8–17.

Lyon, G. R. (1995). Toward a definition of dyslexia. *Annals of Dyslexia,* **45,** 3–27.

Manis, F. R., Custodio, R., & Szeszulski, P. (1993). Development of phonological and orthographic skill: A 2-year longitudinal study of dyslexic children. *Journal of Experimental Child Psychology,* **56,** 64–86.

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.

Manis, F., Seidenberg, M. S., Doi, L., McBride-Chang, C., & Petersen, A. (1996). On the basis of two subtypes of developmental dyslexia. *Cognition,* **58,** 157–195.

Masterson, J., Hazan, V., & Wijatilake, L. (1995). Phonemic processing problems in developmental phonological dyslexia. *Cognitive Neuropsychology,* **12,** 233–259.

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

Morais, J., Cary, L., Alegria, J., & Bertelson, P. (1979). Does awareness of speech as a sequence of phones arise spontaneously? *Cognition,* **7,** 323–331.

Murphy, L., & Pollatsek, A. (1994). Developmental dyslexia: Heterogeneity without discrete subgroups. *Annals of Dyslexia,* **44,** 120–146.

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

Olson, R. K., Wise, B. W., Ring, J., & Johnson, M. (1997). Computer-based remedial training in phoneme awareness and phonological decoding: Effects on the post-training development of word recognition. *Scientific Studies of Reading,* **1,** 235–253.

Rack, J., Snowling, M., & Olson, R. (1992). The nonword reading deficit in developmental dyslexia: A review. *Reading Research Quarterly,* **27,** 29–53.

Reed, M. A. (1989). Speech perception and the discrimination of brief auditory cues in reading disabled children. *Journal of Experimental Child Psychology,* **48,** 270–292.

Scarborough, H. (1990). Very early language deficits in dyslexic children. *Child Development,* **61,** 1728–1743.

Semel, E., Wiig, E., & Secord, W. (1995). *Clinical evaluation of language fundamentals* (3rd ed.). San Antonio, TX: Psychological Corporation.

Shankweiler, D., Crain, S., Katz, L., Fowler, A. E., 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,** 149–156.

Shankweiler, D., Liberman, I. Y., Mark, L. S., Fowler, C. A., & Fischer, F. W. (1979). The speech code and learning to read. *Journal of Experimental Psychology: Human Learning and Memory,* **5,** 531–545.

Smith, F. (1983). Twelve easy ways to make learning to read difficult. In F. Smith (Ed.), *Essays into literacy* (pp. 11–25). London: Heinemann.

Snowling, M. (1987). *Dyslexia: A cognitive developmental review.* Oxford: Blackwell.

Stanovich, K. E. (1988a). Explaining the differences between the dyslexic and the garden-variety poor reader: The phonological-core variable-difference model. *Journal of Learning Disabilities,* **21,** 590–604.

Stanovich, K. E. (1988b). The right and wrong places to look for the cognitive locus of reading disability. *Annals of Dyslexia,* **38,** 154–177.

Stanovich, K., Siegel, L., & Gottardo, A. (1997). Converging evidence for phonological and surface subtypes of reading disability. *Journal of Educational Psychology,* **89,** 114–127.

Stark, R., & Heinz, J. M. (1996). Vowel perception in children with and without language impairment. *Journal of Speech and Hearing Research,* **39,** 860–869.

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

Tallal, P., & Piercy, M. (1974). Developmental aphasia: Rate of auditory processing and selective impairment of consonant perception. *Neuropsychologia,* **12,** 83–94.

Tallal, P., & Stark, R. E. (1980). Speech perception of language-delayed children. In G. H. Yeni-Komshian, J. F. Kavanagh, & C. A. Ferguson (Eds.), *Child phonology: Vol. 2. Perception* (pp. 155–171). New York: Academic Press.

Tallal, P., & Stark, R. E. (1982). Perceptual/motor profiles of reading impaired children with or without concomitant oral language deficits. *Annals of Dyslexia,* **32,** 163–176.

Thibodeau, L. M., & Sussman, H. M. (1979). Performance on a test of categorical perception of speech in normal and communication disordered children. *Journal of Phonetics,* **7,** 379–391.

Vellutino, F. R. (1979). *Dyslexia: Theory and research.* Cambridge, MA: MIT Press.

Vogel, S. A. (1977). Morphological ability in normal and dyslexic children. *Learning Disorders,* **10,** 41–49.

Wagner, R. K., & Torgesen, J. K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychological Bulletin,* **101,** 192–212.

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

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

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

Wiig, E., Semel, E., & Crouse, M. (1973). The use of morphology by high risk and learning disabled children. *Journal of Learning Disabilities,* **6,** 457–465.

Wolf, M. (1986). Rapid alternative stimulus naming in the developmental dyslexias. *Brain and Language,* **27,** 360–379.

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

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