

Performance of Dyslexic Children on Speech Perception Tests

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Several researchers who have compared the performance of dyslexic and normal-reading children on a variety of different tasks have suggested that dyslexic children may have subtle deficits in the phonemic analysis of spoken as well as written language. Thus it is of interest to know how children who have extraordinary difficulty learning to read can perform explicitly auditory-phonetic tasks. Seventeen dyslexic children (10 years of age) and a group of 17 controls were administered tests of identification and discrimination of synthesized voiced stop consonants differing in place of articulation. These were tests of the type used to study categorical perception in adults, adapted for use with young children. Significant differences between dyslexics and controls were found in both kinds of tasks; the pattern of identification and discrimination differences suggests an inconsistency in the dyslexics' phonetic classification of auditory cues. A significant relationship was found between reading level and speech discrimination.

Although the normal process of reading is far from being completely understood, considerable progress has been made in recent years by the use of experimental techniques developed in the study of perception and memory, and by the application of insights gained in the study of speech perception. Reviews of this literature can be found in Gibson and Levin (1975), Kavanagh and Mattingly (1972), and Reber and Scarborough (1977). That the process of speech perception has relevance to understanding the normal development of reading cannot be doubted. Logically, given the relatively sophisticated ability of a 6-year-old to perceive speech, the visual input from reading ought to be converted to a form

This work was partially supported by a grant from the National Institute of Child Health and Human Development (NIH HD-10422). Some of the results of this work were reported at the 1979 meeting of the American Speech-Language-Hearing Association in Atlanta. We would like to thank Miss Esther Hansen, Director of Behavior Associates Reading Clinic, Tucson, and Mrs. Glen Holmes, Director of St. John's Episcopal School, Dallas, without whose generous cooperation the research reported here could not have been done. Requests for reprints should be sent to John J. Godfrey, Callier Center for Communication Disorders, University of Texas, 1966 Inwood Road, Dallas, TX 75235.

appropriate for the speech perception system at the earliest stage possible, to avoid duplicating any of its complex and highly interdependent processing steps.

Studies investigating possible relationships between speech and reading have found, for example, that children reading simple words make comparatively few errors due to the visual confusability of letter shapes, but a substantial number of errors reflecting phonetic confusions (Conrad, 1972; Fischer, Liberman, & Shankweiler, 1977; Liberman, Shankweiler, Orlando, Harris, & Bell-Berti, 1971). Moreover, when groups of better and poorer readers were given the task of recalling strings of letters either immediately or after a short delay, where half of the strings contain phonetically confusable letters (i.e., letters whose names rhyme), performance of better readers was more adversely affected than that of poorer readers' by the phonetic confusability condition, and much more so by the addition of a short delay, allowing for rehearsal (Liberman, Shankweiler, Liberman, Fowler, & Fisher, 1977; Shankweiler & Liberman, 1976; Shankweiler, Liberman, Mark, Fowler, & Fischer, 1979). This interesting effect suggests that the habit of coding letters phonetically in short-term memory (STM), which is responsible for the better readers' reading success, makes them more vulnerable to its experimental manipulation. Furthermore, good and poor readers not only show differences with phonetic coding in STM when material is presented visually in script, but also when material is presented auditorily (Shankweiler et al., 1979). The fact that poor readers have difficulty with phonetic representation apart from its conversion or recoding from print strongly suggests that their deficit is of a more general nature.

The close functional relationships between speech perception and learning to read justify a study comparing the speech perception skills of dyslexic and normal children. Researchers from several different perspectives have suggested that dyslexic children may have subtle deficits in the phonemic analysis of spoken as well as written language (Boder, 1971, 1973; Monroe, 1932; Myklebust, 1965; Savin, 1972; Shankweiler et al., 1979; Tallal, 1980; Zurif & Carson, 1970). Thus, it is reasonable to conduct experiments concentrating on the perception of speech sounds apart from higher-level linguistic variables. Clinical observations that a dyslexic child "hears normally" and understands spoken language are not necessarily sufficient; the ability to perceive speech sounds should be tested in a way that precludes the use of linguistic redundancy, contextual clues, or visual aids, focusing instead on the capacity to recognize essential auditory cues to particular phonetic distinctions.

The importance of this ability for learning to read is apparent in the fact that letters are normally converted to some phonetic equivalent, such as segmental phonemes, in order for linguistic units, such as words,

to be reconstructed for recognition. This, in turn, requires the availability of some long-term representation of the phonetic units, independent of contextual variations, which must have been formed by abstraction in the process of perceiving speech. Abnormality in either the conversion to phonetic form or in the long-term stored "image" could cause problems in the process of learning to read.

Shankweiler et al. (1979) discuss the need for research to examine whether children with reading disabilities may also have subtle deficits in their perception of the acoustic cues for speech. They specifically propose the use of speech identification and discrimination tests like those used to study categorical perception in adults. Similarly, Tallal (1980) cites the need for research employing receptive and expressive speech and language tests for children with reading disorders.

This study constitutes an attempt to identify such deficits in the perception of speech in dyslexic children. In the experiments to be described, identification and discrimination tests with synthesized speech sounds, such as are frequently used in perceptual experiments with adults, were modified for use with normal and dyslexic children as young as 7 years of age. Such tests offered the advantage of precise computer control of stimulus properties, so that neither the variability nor the redundancy of natural human speech could affect performance. Instead, a single acoustic cue at a time was varied, and the discriminability of that change, or its effect on the perceived identity of the stimulus, was determined. The resulting functions show how sounds varying by a given acoustic parameter are classified phonetically, how consistent the judgments are, and what magnitude of change in the parameter can be discriminated.

Besides comparing the performance of a group of dyslexic children with that of matched normal controls on several speech perception tasks, the following experiments attempted to compare the performance of two clinically identified dyslexic subgroups, "dysphonetic" and "dyseidetic," on these tasks. Boder's diagnostic test (1971, 1973) is intended to differentiate between dyslexic children whose errors on reading and spelling tests are primarily based on auditory and phonetic confusions and those whose errors reflect primarily visual and spatial confusions. Boder's screening test was used to classify a population of dyslexic children into subgroups. If the phonetic skills, in which "dysphonetics" were judged deficient on the basis of reading and spelling screening procedures, are closely related to the auditory-phonetic processing abilities relevant to speech perception, one might expect that the "dysphonetics" but not the "dyseidetics" (who presumably have deficits principally in the perception of visual forms) would differ from normal controls.

METHOD

Subjects

The dyslexic population tested was composed of 17 children (11 boys and 6 girls) diagnosed as severely dyslexic, who attended a private reading clinic in Tucson, Arizona. They were of average or higher intelligence, and had no apparent emotional problems or other complicating conditions. These children were administered the Boder Diagnostic Screening Procedure (Boder, 1971, 1973) in an attempt to classify dyslexics into subgroups on the basis of error patterns in reading and spelling tests. On the basis of this procedure, 11 children (4 girls and 7 boys) were classified as "dysphonetic dyslexics" because of the apparently phonetic nature of their errors, and 6 children (2 girls and 4 boys) were classified as "dyseidetic dyslexics" because their errors suggested greater difficulty with the visual forms of letters in reading and writing.

A control group of 17 normal readers was chosen from the students in a private school in Dallas, Texas. They also were of average or above-average intelligence and were matched individually in age (within 6 months), sex, and hand preference with the dyslexic children.

Summary statistics of age, reading level on the Boder Diagnostic Screening Procedure, and Boder reading level minus expected reading grade based on chronological age, are listed in Table 1 for the two subgroups of dyslexic children, the dyslexics overall, and the control group.

Stimuli. Two series of eight consonant-vowel stimuli were synthesized, using a Rockland Model 4516 Digital Speech Synthesizer (Rabiner, 1968), controlled by a DEC PDP-11/45 computer. These stimuli were designed to present the subjects with necessary and sufficient cues to the place of articulation distinction, with acoustic variation confined to the minimum number of parameters. One series varied from /ba/ to /da/ by changing the starting frequencies of the second and third formants from 800 and 1800 Hz, respectively, to 1700 and 2600 Hz in equal logarithmic steps. The second series varied from /da/ to /ga/ by changing the starting frequency of the third formant from 2600 to 1700 Hz in equal logarithmic steps, while the second formant started at 1500 Hz for all eight stimuli; formant frequency transitions occurred in the initial 45 msec of the formants. The 190-msec steady-state frequency of the second formant was 1200 Hz, and of the third formant, 2163 Hz, for all stimuli. Fourth and fifth formants remained constant at 3500 and 4500 Hz, respectively, for all stimuli. In both sets of syllables, 95 msec of prevoicing preceded formant onset. Fundamental frequency rose from 100 to 111 Hz during prevoicing, remained constant at 111 Hz while formant frequency transitions occurred, and then gradually fell from 111 to 91 Hz during the remainder of the syllable. Each stimulus was 330 msec in

TABLE 1
 DESCRIPTIVE STATISTICS FOR "DYSPHONETICS," "DYSSEIDETICS," "DYSLEXICS AS A SINGLE GROUP, AND CONTROLS

| Group | Age (years:months) | | | Boder reading level (grade) | | | Boder reading level—grade expected by age | | |
|------------------------|--------------------|-----|-------------|-----------------------------|-----|-----|---|-----|-----|
| | Mean | SD | Range | Mean | SD | SD | Mean | SD | SD |
| Dysphonetics (N=11) | 10:10 | 2:6 | 7:4 to 15:1 | 3.3 | 1.6 | 1.6 | -2.7 | 1.8 | 1.8 |
| Dyseidetics (N=6) | 9:5 | 1:1 | 7:9 to 11:0 | 2.8 | 1.6 | 1.6 | -1.7 | 0.8 | 0.8 |
| Dyslexics (N=17) | 10:5 | 2:2 | 7:4 to 15:1 | 3.1 | 1.6 | 1.6 | -2.4 | 1.6 | 1.6 |
| Controls (N=17) | 10:5 | 2:1 | 7:3 to 15:0 | 7.9 | 2.9 | 2.9 | +2.8 | 2.3 | 2.3 |

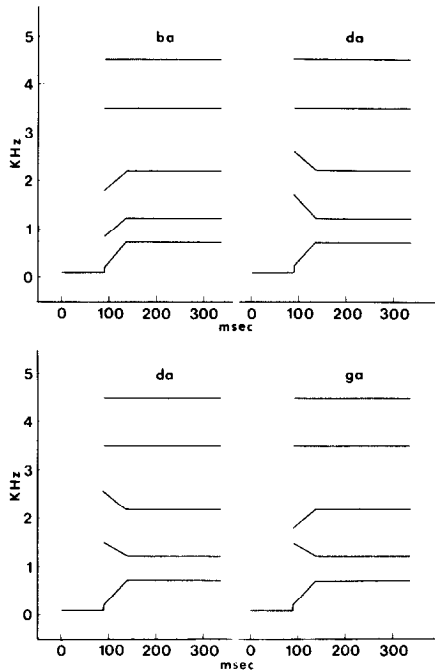


FIG. 1. Schematic spectrograms of the extreme stimuli (Nos. 1 and 8) of the /ba-da/ series (top) and the /da-ga/ series (bottom).

overall duration. Figure 1 shows schematic spectrograms of the endpoint stimuli (the first and eighth) of each series.

Identification tests consisted of four repetitions of each of the eight stimuli of a series in random order; the 32 items of each test were presented in succession with an interstimulus interval of 5 sec. Discrimination tests were conducted on pairs from a series which differed by three steps (stimulus 1 paired with stimulus 4, 2 with 5, etc.), using an AX ("same-different") paradigm. All five possible three-step pairings in both orders (1-4, 4-1, etc.), with an equal number (10) of identical pairings (1-1, 2-2, etc.) as foils, yielded 20 discrimination items per test, presented in random order with 1-sec interstimulus intervals within pairs and 5-sec interstimulus intervals between pairs.

Apparatus. Tape-recorded tests were played over a Sony TC-353 D stereo tape deck, through a special purpose amplifier box which permitted field calibration of each channel's output in SPL. Subjects listened monaurally with the right ear at 75 db SPL (re: 0.0002 μ bar) over TDH-49 headphones. Output level was calibrated by means of a 5-sec steady-state vowel, identical to the /a/ of the stimulus series, recorded at the beginning of each tape. Both groups were tested in quiet environments.

Procedures. All subjects were screened for normal hearing at 0.5, 1, 2, and 4 kHz before taking any experimental tests.

The speech perception tests were administered in the following order (subject to restrictions discussed below):

1. /b-d/ Identification Criterion Test
2. Three /b-d/ Identification Tests
3. /b-d/ Discrimination Criterion Test
4. Six /b-d/ Discrimination Tests
5. /d-g/ Identification Criterion Test
6. Three /d-g/ Identification Tests
7. /d-g/ Discrimination Criterion Test
8. Six /d-g/ Discrimination Tests

In the absence of normative data on young children's performance on speech perception tasks such as these, our procedures were designed to make the tests as easy to take as possible, even at the risk of obscuring potential intergroup differences through a ceiling effect. The intention was to reduce the chances of type I error by avoiding task factors unrelated to speech perception which might nevertheless affect performance in certain children.

Children were tested individually with an experimenter present throughout the procedure; tests normally were completed in two sessions of 30 to 45 min each, but if the experimenter judged that fatigue or boredom was affecting performance, a session would be terminated early and testing finished in a third session.

The purpose of the Criterion Tests was to assure that each child understood the nature of the task and how to perform it before taking each test. The protocol for all Criterion Tests began with an explanation by the experimenter of the kinds of sounds to be heard, with a few recorded examples, followed by instructions on the task. Finally, responses were made to 24 recorded items. In the /b-d/ Identification Criterion Test, there were 24 randomized presentations of stimuli 1 and 8, the extreme /ba/ and extreme /da/ from the continuum. Subjects responded by identifying each item verbally as "ba" or "da," and the experimenter recorded the response. The /d-g/ Identification Criterion Test had the same format, with 24 randomized presentations of stimuli 1 and 8 from the /d-g/ continuum, to be identified as "da" or "ga." The Discrimination Criterion Tests followed the same protocol, except that each item was a pair of stimuli from the respective test series, and subjects were instructed to respond verbally "same" or "different" depending on whether they heard any difference between the two. Of the 24 pairs, 12 were identical and 12 were pairs of stimuli differing by four steps on the eight-step continuum, which were very easy to discriminate.

To "pass" any Criterion Test required 12 consecutive correct responses. If a subject failed to accomplish this in the 24 trials of a Criterion

Test, the test was repeated a second time, and, if necessary, a third time. Subjects were not given feedback on their responses. If the child still could not get 12 consecutive responses correct after 72 presentations, that particular Criterion Test was discontinued, the corresponding speech perception test (Identification or Discrimination) for that stimulus set was not immediately attempted, and the experimenter proceeded to the next Criterion Test. Those subjects who did not pass a particular Criterion Test were, in a later session, retested on both the Criterion Test and, regardless of its outcome, the corresponding Identification or Discrimination Test. This procedure was adopted on the grounds that the nature of their extreme difficulty with the acoustic-phonetic distinction might thereby be better revealed.

Whenever a child passed a Criterion Test, the experimenter immediately began the corresponding Identification or Discrimination Tests. An Identification Test, as described above under *Stimuli*, contained 32 randomized items at 5-sec intervals; subjects heard each test three times (recorded separately so that there was no clue the same test was being repeated) for a total of 96 identification responses per stimulus set, 12 responses per stimulus. Each Discrimination Test was given six times (again, with repetitions recorded separately) for a total of 120 responses, 12 responses per stimulus pair. Half of these were identical pairs, used as foils in the "same-different" paradigm.

Children were told during the first session that they would earn a prize (their choice of one of several popular games) after taking all the tests; during the testing sessions the experimenter frequently offered verbal encouragement.

RESULTS

Criterion Tests

Whereas all children in the control group passed all Criterion Tests during initial testing, 8 (47%) of the dyslexic children were initially unable to pass one or more Criterion Tests.

For /ba-/da/ Identification Criterion Tests, all 17 control group children passed initially with a mean number of trials to criterion of 12 (12 was the minimum number possible); for the dyslexic group, 15 children (88%) passed initially and had a mean number of 19 trials to criterion. The 2 dyslexic children who failed criterion were able to be retested, and both eventually passed. The mean number of trials to criterion over all 17 dyslexic subjects was 25. In the case of the /ba-/da/ Discrimination Criterion Test, all 17 control group children and all 17 dyslexic children passed initially, each with a mean number of 14 trials to criterion.

In /da-/ga/ Identification Criterion Tests, all 17 control group children passed initially with a mean number of 16 trials to criterion, but only 10 (59%) of the dyslexic children passed initially and they had a mean

number of 29 trials to criterion. Of the 6 failing dyslexic children available for later retesting, however, only 1 still failed to pass criterion. The dyslexic group as a whole had a mean number of 46 trials to criterion. For /da-/ga/ Discrimination Criterion Tests, again, all 17 controls passed initially; their mean number of trials to criterion was 22. Eleven children from the dyslexic group (65%) initially passed criterion, and their mean number of trials to criterion was 29. Of the 6 who failed initially but were available for later retesting, 5 subsequently passed criterion. The mean number of trials to criterion was 42 for the dyslexic group overall.

A 2 (Group) \times 2 (Stimulus Set) \times 2 (Task) Analysis of Covariance was performed, with number of trials to criterion on the four tests the dependent variables, Reading Level the covariate, and Stimulus Set and Task the repeated measures. There was a significant Group effect, $F(1, 31) = 4.67, p < .04$, because dyslexics had a higher number of trials to criterion overall than did their controls. The effect of the covariate, Reading Level, was not significant ($F(1, 31) = .86, p < .40$). There was a significant main effect of Stimulus Set, $F(1, 32) = 25.16, p < .00005$, because both groups of subjects required more trials to reach criterion on /da-/ga/ tests than on /ba-/da/ tests. The Stimulus Set \times Group interaction was also significant, $F(1, 32) = 9.03, p < .005$, reflecting the fact that dyslexics required disproportionately more trials to reach criterion on /da-/ga/ tests than were required on /ba-/da/ tests or by the Control group with either stimulus set. Finally, there was a significant Task \times Group interaction, $F(1, 32) = 4.57, p < .04$, due to the differences in difficulty of identification versus discrimination tasks between dyslexic and control groups; dyslexic children required more trials to reach identification criteria than to reach discrimination criteria, whereas control group children required more trials to reach discrimination criteria than to reach identification criteria. There were no significant differences between "dysphonetic" and "dyseidetic" dyslexics in number of trials the subgroups required to reach criterion, $F(1, 14) = .86, p < .37$, nor any significant effects of the covariate Reading Level, $F(1, 14) = .18, p < .68$.

Identification

The upper halves of Figs. 2 and 3 display the group identification functions for all the dyslexics tested and for the matched control group ($N = 17$ for /ba-/da/; $N = 16$ for /da-/ga/). The eight stimulus values of each continuum are on the abscissa, and the ordinate shows the percentage of tokens of each stimulus identified as /ba/ in the /ba-da/ test (Fig. 2) and as /da/ in the /da-ga/ test (Fig. 3). Each data point is the mean of 204 judgments for /ba-da/ and of 192 judgments for /da-ga/ (four tokens per test \times three test sessions \times number of subjects). The control group identification functions indicate that children as young as

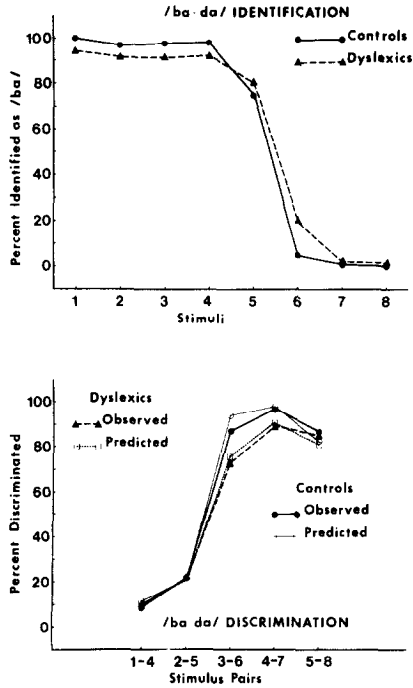


FIG. 2. Performance of control and dyslexic groups on /ba-da/ Identification and Discrimination Tests. Top: Percentage identified as /ba/ in the /ba-da/ Identification Tests. Bottom: Predicted and obtained percentages correctly discriminated in /ba-da/ Discrimination Tests.

7 years old can indeed identify these synthetic speech sounds as adults do. For both continua, the stimuli at the ends of the series are virtually unanimously labeled, and the slope of the function in the region of the phoneme boundary is characteristically sharp. Particularly in the case of /ga/, which is normally heard with an initial burst in natural speech, but was synthesized without one, it is interesting that these children readily accept the formant transition cue as sufficient, as adults also do (Stevens & Blumstein, 1978).

The dyslexic children differed from the controls in their labeling of the stimuli of both the /ba-da/ and the /da-ga/ series. Although their majority vote for each item agreed with the controls', their classification of the stimuli at the ends of both series is less consistent than the normal children's, and the crossover slope near the phoneme boundary, especially for /da-ga/, is more gradual. Two types of statistical analyses were performed on results from the identification tests. First, the dyslexic and control group data for /ba-da/ and /da-ga/ tests were submitted to probit transformations (Finney, 1964), from which the values of the phoneme boundaries, standard deviations, and slopes were obtained. These are

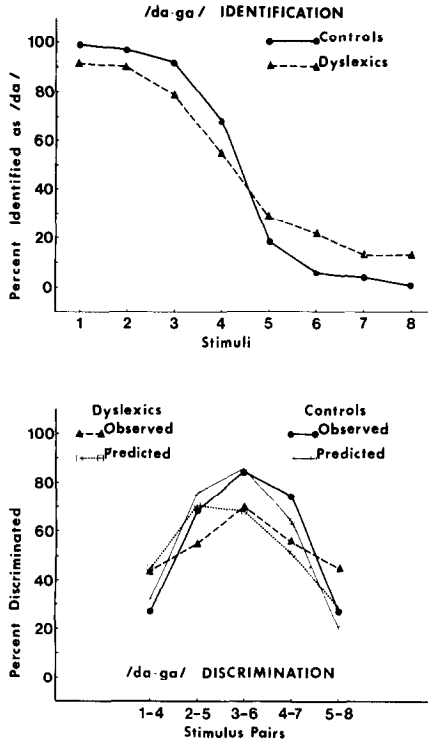


FIG. 3. Performance of control and dyslexic groups on /da-ga/ Identification and Discrimination Tests. Top: Percentage identified as /da/ in the /da-ga/ Identification Tests. Bottom: Predicted and obtained percentages correctly discriminated in /da-ga/ Discrimination Tests.

determined in the probit method by regressively computing the cumulative normal distribution which is closest, by a maximum likelihood estimate, to the data. The mean of the resulting distribution is the interpolated 50% crossover point (phoneme boundary), its standard deviation is a measure of the variability of identification scores around the mean, and the slope, which in a probit transformation is the reciprocal of the standard deviation, is a measure of the degree of "sharpness" with which phoneme categories are distinguished from one another. The /ba/-/da/ phoneme boundaries (expressed in stimulus units) were 5.20 for the control group and 5.18 for the dyslexic group; they did not differ significantly. Group differences in slopes, because of their reciprocal relationship to standard deviations, were tested by an *F* test of the ratio of the variances; the differences approached significance, $F(7, 7) = 3.12$, $p < .08$. The /da/-/ga/ phoneme boundaries, 4.36 for the controls and 4.35 for the dyslexics, did not differ significantly. Group differences in /da/-/ga/ slopes, however, did approach significance, $F(7, 7) = 3.34$, p

< .07. In the second type of statistical analysis, 2 (Group) \times 8 (Stimuli) repeated measures analyses of variance, with the number of trials a stimulus was identified as /da/ the dependent variable and Stimuli the repeated factor, the differences appear as highly significant Stimulus \times Group interactions: for the /ba-da/ test, $F(7, 224) = 3.49$, $p < .001$, and for the /da-ga/ test, $F(7, 210) = 4.60$, $p < .0005$. On the whole, these results can be taken as an indication that the dyslexics were less certain, hence more variable, in their identification of the speech sounds.

Similar analyses of variance and appropriate Tukey test of specific contrasts were performed comparing the identification performance of dyseidetic, dysphonetic, and control subjects, and it was found that both dyslexic subgroups differed significantly from the control group on both identification tests: for /ba-da/ Stimulus \times Group interaction, $F(14, 217) = 2.01$, $p < .018$; for /da-ga/, $F(14, 203) = 3.10$, $p < .005$. In addition, analyses of variance performed with data from only those dyslexics (and their controls) who passed Criterion Tests during initial testing indicated that they also differed significantly from controls: for /ba-da/ Stimulus \times Group interaction, $F(7, 210) = 2.86$, $p < .007$; for /da-ga/, $F(7, 154) = 3.85$, $p < .001$. Thus the overall group differences were not due to the addition of those dyslexic subjects who had the greatest difficulty passing Criterion Tests.

Discrimination

The discrimination data are shown in the lower halves of Figs. 2 and 3; on Fig. 2, the scores for the /ba-da/ stimuli, and on Fig. 3, those for /da-ga/ stimuli. On the abscissa are found the five three-step pairings of stimuli used to test discrimination, and on the ordinate the percentage of different pairs which were correctly called "different."

The solid lines connect the actual data points obtained in the tests. The dashed lines connect discrimination scores which are predicted by the classical assumption of categorical perception, namely, that stimulus pairs will be discriminable only to the extent that the individual stimuli are identified, when presented singly, as members of different phonetic categories. Specifically, the predicted discrimination scores were obtained from the identification data by the formula:

$$\text{proportion discriminated} = (P_{1a} \times P_{2b}) + (P_{1b} \times P_{2a}),$$

where

P_{1a} = proportion of time stimulus 1 was identified as "a",

P_{2b} = proportion of time stimulus 2 was identified as "b",

P_{1b} = proportion of time stimulus 1 was identified as "b",

P_{2a} = proportion of time stimulus 2 was identified as "a".

This formula predicts discrimination scores strictly on the basis of phonetic categorization, without incorporating assumptions about guessing

probabilities. The only two previous studies on categorical perception by children (Wolf, 1973; Brandt & Rosen, 1980) also employed "same-different" discrimination tasks and found the use of this type of absolutely categorical prediction formula appropriate. In addition, this prediction formula agrees with Pollack and Pisoni's (1971) treatment of the 21AX ("same-different") paradigm.

As would be expected from adult data collected with similar stimuli (Pisoni, 1971), discrimination scores generally fit the description of categorical perception: discrimination is very good between stimuli which are identified with different phonetic labels (e.g., the 3-6 pair from either series) but poor between stimuli which are labeled the same phonetically (e.g., the 1-4 pair from either series). In 2 (Group) \times 2 (Predicted versus Observed Discrimination Functions) \times 5 (Stimulus Pairs) repeated measures analyses of variance, with number of correct discrimination responses per pair the dependent variable and Functions and Stimulus Pairs as repeated factors, there were no significant differences of any kind between observed and predicted discrimination functions in /ba-da/ tests, but in the case of /da-ga/, there was a significant Function \times Stimulus Pair interaction, $F(4, 120) = 5.87, p < .005$, because summing across both groups, predicted and obtained scores differed significantly for pairs 2-5 and 5-8, but not for other pairs.

The difference in discrimination scores obtained from the dyslexic children and their controls was significant as a main Group effect in the /ba-da/ analysis of variance, $F(1.32) = 5.13, p < .03$; in the /da-ga/ tests, due to the higher within-category discrimination of the dyslexics on the 1-4 and 5-8 pairs, the group difference shows up as a significant Stimulus Pair \times Group interaction, $F(4, 120) = 5.12, p < .001$.

As was the case with identification data, when dysphonetic and dysideitic dyslexics were considered separately, both subgroups differed about equally from the normal controls in their discrimination performance. In /ba-da/ analyses, the main Group effect was weaker than when dyslexics were treated as a single group, $F(2, 31) = 2.52, p < .097$, and dysphonetics and dysideitics were equally poorer than controls in overall discrimination. In /da-ga/ analyses, there was a significant Stimulus Pair \times Group interaction, $F(8, 116) = 3.68, p < .001$, and both dyslexic subgroups individually differed from the control group. Again, group differences in both /ba-da/ and /da-ga/ tests were maintained when only data from the dyslexics who passed Criterion Tests initially (and their controls) were analyzed: for the /ba-da/ main Group effect, $F(1, 30) = 6.12, p < .019$, for /da-ga/ Stimulus Pair \times Group interaction, $F(4, 80) = 3.40, p < .013$, indicating that the group differences observed were present for even the initially better-performing dyslexic children and their controls.

Signal Detection Analyses

To examine whether the speech discrimination differences between dyslexics and controls were essentially perceptual in origin or could be explained by nonperceptual task performance variables, signal detection analyses of the discrimination data were also made. The d' scores were determined on the basis of the proportion of "different" judgments when the stimuli were actually different (hits) and the proportion of "different" judgments when the stimuli were actually the same (false alarms) according to the Yes-No procedure (Swets, 1964). Figure 4 shows discrimination functions, in terms of group d' scores, for the dyslexic and control groups in the /ba-da/ tests (above) and the /da-ga/ tests (below). Because each subject made only 12 discrimination judgments per different pair, d' scores for individual subjects for the purposes of analyses were calculated on the basis of their performance across all discrimination pairs (a total of 60 judgments each for different pairs and for same pairs).

Five 2 (Group) \times 2 (Test) repeated measures analyses of covariance were performed with /ba-/da/ and /da-/ga/ d' scores the dependent variables and Test the repeated factor. In one analysis, the covariates were number of trials required to reach /ba-/da/ and /da-/ga/ identifi-

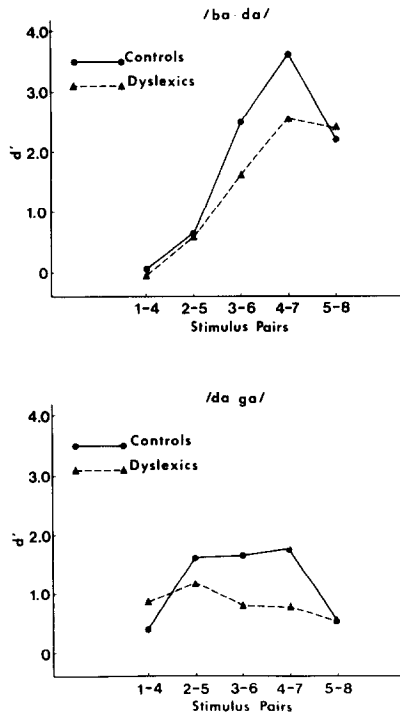


FIG. 4. Discrimination data of Figs. 2 and 3 expressed in terms of d' scores.

cation criteria; there was a significant Group effect indicating d' scores were significantly higher for control subjects than for dyslexics, $F(1, 31) = 4.43, p < .04$, and a significant Test effect indicating d' scores were significantly higher for /ba-da/ tests than for /da-ga/ tests, $F(1, 31) = 39.43, p < .00005$, but no significant effects of the covariates. Similar results were obtained from an analysis in which trials to discrimination criteria were the covariates; the Group effect closely approached significance, $F(1, 31) = 3.78, p < .06$, the Test effect was highly significant, $F(1, 31) = 28.89, p < .00005$, and the effect of the covariates was nonsignificant. These two analyses indicate that the differences in d' scores between dyslexic and control groups cannot be accounted for by the differences they also showed in number of trials to criterion. A third analysis used Boder reading level as the covariate. In this case, the Group effect was no longer significant, $F(1, 31) = .06, p < .80$, the Test effect remained significant, $F(1, 32) = 63.04, p < .00005$, and the effect of the covariate approached significance, $F(1, 31) = 3.36, p < .08$. Another analysis was performed with Boder reading level minus expected grade the covariate; the Group effect approached significance, $F(1, 31) = 2.84, p < .10$, the Test effect was significant, $F(1, 32) = 63.04, p < .00005$, and the effect of the covariate was not significant. The latter two analyses indicate that differences in d' between dyslexics and their controls could also be accounted for by the differences in reading level between the groups, but not by differences in the extent of reading impairment or advancement. Finally, a similar analysis was performed on d' scores of the dysphonetic and dyseidetic subgroups of dyslexics, with Boder reading level the covariate; there was neither a significant Group effect, $F(1, 14) = .13, p < .73$, nor a significant effect of the covariate, $F(1, 14) = 1.53, p < .24$, although the Test effect was significant, $F(1, 15) = 21.25, p < .0003$. These results indicate that neither classification into dysphonetic or dyseidetic subgroups nor differences in reading level can account for the variations in d' scores within the dyslexic group. The analysis of d' scores is important because it provides assurance that the discrimination differences observed were not due to different rates or strategies of guessing.

False positive discrimination responses (that is, "different" responses when the two stimuli were actually identical) were also analyzed in two 2 (Group) \times 2 (Test) analyses of covariance with Test the repeated factor. In the first analysis the number of trials to discrimination criteria were the covariates; the Group effect approached significance, $F(1, 31) = 3.50, p < .07$, indicating that after adjusting for differences in trials to criteria, dyslexics tended to make more false positive discrimination responses than did normal controls; there was a significant Test effect, $F(1, 31) = 22.30, p < .00005$, because both groups of subjects made more false positive responses on /da-ga/ than on /ba-da/ tests; and there

were no significant effects of the covariates. Boder reading level was used as the covariate in the second analysis. In this case, neither Group nor the covariate had significant effects, although Test remained significant, $F(1, 32) = 49.58, p < .00005$, and there was a significant Group \times Test interaction, $F(1, 32) = 4.63, p < .04$, indicating that dyslexics made significantly more false positive judgments than controls for the more difficult /da-ga/ test but not for the /ba-da/ test. The group differences in false positive responses suggest a basic difference in discrimination performance between dyslexic and normal children; dyslexics not only discriminated true differences between stimuli more poorly than controls, but they also reported identical stimuli to be different more often than did controls. Clearly, a difference in general response bias between dyslexic and control groups could not account for these results.

Because of the close interrelationship between membership in the dyslexic or the control group and reading level, it is very difficult to determine whether the differences observed in the children's performance on speech perception tests are more closely related to the continuous variable of reading level or to qualitative differences between dyslexic and control groups. As can be easily seen from the Boder reading level means and standard deviations for dyslexic and control children listed in Table 1, reading levels for the two groups are significantly different. The correlation between group and reading level is highly significant, $r = .73, F(1, 32) = 36.22, p < .000005$. Overall correlations are slightly higher between reading level and d' scores (for /b-d/, $r = .38, F(1, 32) = 5.34, p < .03$; for /d-g/, $r = .44, F(1, 32) = 7.84, p < .01$) than between group and d' scores (for /b-d/, $r = .26, F(1, 32) = 2.40, p < .13$; for /d-g/, $r = .39, F(1, 32) = 5.64, p < .02$), but that may be explained because reading levels range from 0 to eleventh grade, whereas groups are limited to two categories. When partial correlations between d' scores and reading level were performed after removing the linear effects of the group variable, and when partial correlations between d' scores and group were performed after removing the linear effects of reading level, neither set of correlations remained significant. Correlations between reading level and d' scores within the dyslexic group (for /ba-da/, $r = .41, F(1, 15) = 3.03, p < .11$; for /da-ga/, $r = .06, F(1, 15) = .05, p < .82$) and within the control group (for /ba-da/, $r = .24, F(1, 15) = .90, p < .36$; for /da-ga/, $r = .35, F(1, 15) = 2.11, p < .17$) were not significant, but since some of the correlations are similar to those computed for the total subject sample, lack of significance may be due to the smaller sample size involved when each group was considered separately.

Given the difficulties in separating and interpreting the effects of reading level and of dyslexia with our subject groups, we conclude that it would be desirable to employ two control groups, one matched with the

dyslexics on the basis of chronological age, as in the present study, and another matched for reading level. Only a small subgroup of the dyslexics and normal readers tested in this study could be regrouped according to reading level: two dyslexics and one control subject performed at the second-grade reading level; four dyslexics and two controls, at the fourth-grade reading level; two dyslexics and one control, at the fifth-grade reading level, and one dyslexic and two controls, at the sixth-grade reading level. The normal readers had higher d' scores than the dyslexic readers at the same reading level (for /ba-da/ discrimination, the mean d' score was 1.64 for the control subgroup and 1.53 for the dyslexic subgroup; for /da-ga/ discrimination, the mean d' scores were 1.12 for controls and 0.83 for dyslexics); although these differences were not statistically significant, they were only slightly smaller than the significant d' differences between the larger age-matched groups (for /ba-da/ tests, 1.74 for controls and 1.50 for dyslexics; for /da-ga/ tests, 1.20 for controls and 0.90 for dyslexics). Thus the results from such a small sample of reading-level-matched dyslexics and control subjects, while suggestive, are insufficient to aid in determining whether the group differences in speech perception are a cause or an effect of the reading problems.

DISCUSSION

Dyslexic children differed from normal children in every speech perceptual test the two groups were administered. Our results did not, however, reveal any differences in auditory-phonetic perception between clinically identified "dysphonetic" and "dyseidetic" subgroups of dyslexics; both subgroups differed from the control group in the same general respects. On the basis of their phonetic identification and discrimination performances, we found no reason to consider the dyslexics to be composed of these different subgroups.

Experiments similar to ours were recently reported by Brandt and Rosen (1980), who concluded that dyslexic children identify and discriminate consonants categorically, just as normal children and adults do. Their results and ours are not necessarily in conflict, however. First, neither dyslexic nor normal subjects were reported by Brandt and Rosen to fail preliminary criterion tests, but their criterion was four correct responses in six trials (thus the probability of reaching or exceeding criterion by chance alone was $p = .34$), a much less difficult task than 12 consecutive correct responses (with guessing probability of $p < .001$), as employed in the present study. Second, the only direct statistical comparison Brandt and Rosen made between the identification test results of their dyslexic and control groups was that of phoneme boundaries, which did not differ between groups in their study or in ours. Their only direct statistical group comparison for discrimination tests was of correct "same" discrimination responses, which did not differ between

groups in their study but whose inverse value, false positives, approached significance in our study. Brandt and Rosen did not make statistical group comparisons of other aspects of their data analogous to those made in the present study, but if they had, it seems likely, judging from inspection of their graphs, that they would have found many of the same group effects. For example, normal subjects in Brandt and Rosen's study had discrimination peaks of about 85% for the /ba-da/ boundary and about 75% for the /da-ga/ boundary, whereas dyslexic subjects had lower peaks, about 65% for /ba-da/ and about 60% for /da-ga/. Analogous group differences were found and tested for statistical significance in the present study. Although the many significant group differences observed have led us to conclude that dyslexic and normal children differ in certain aspects of their performance on speech identification and discrimination tests, it is also true that the dyslexic children's results were not grossly abnormal, such as those reported for children with severe language impairment (Tallal & Piercy, 1973, 1974, 1975) or for hearing-impaired adults (Godfrey & Millay, 1978, 1980; Van de Grift Turek, Dorman, Franks, & Summerfield, 1980). Indeed, it would be surprising if deficits in auditory processing of phonetic information revealed on such speech identification and discrimination tasks, but not otherwise readily apparent in the children's linguistic behavior, were of an extreme nature.

The dyslexics' frequent failure to pass Identification and Discrimination Criterion Tests contrasts with the consistently and more readily successful performance of the control group. It is noteworthy that, for both groups of children, the /ba-da/ Criterion Tests were more easily passed than the /da-ga/ Criterion Tests. Similarly, identification functions had steeper slopes for /ba-da/ than for /da-ga/ tests and d' scores were significantly higher for /ba-da/ than for /da-ga/ tests. If the poorer performance of the dyslexics on Criterion Tests (and on subsequent tests) were due to some kind of general difficulty with the task, rather than a perceptual difficulty, one would expect the same level of poorer performance on both /ba-da/ and /da-ga/ Criterion Tests (or possibly worse performance on /ba-da/ tests, as they were given first). However, /da-ga/ tests were more difficult for both groups for perceptual reasons: the /da-ga/ distinction was cued by changes in only one aspect of the stimulus—the third formant transition; on the other hand, /ba/ and /da/ were differentiated by changes in both the second and third formant transitions. Furthermore, the absence of stop consonant release bursts in all synthetic stimuli would be most noticeable in /ga/ syllables. Thus the /ba-da/ series might sound more natural than the /da-ga/ series, as well as contain more acoustic cues on which to base the phonetic distinction.

In Identification Tests, dyslexic children were less consistent in their classification of stimuli and changed more gradually from one phonetic category to another than normal children. These differences were most

apparent in the perceptually more difficult /da-ga/ series. Brandt and Rosen (1980) also noted steeper /ba-/da/ phoneme boundaries than /da-/ga/ phoneme boundaries for both normal and dyslexic children in their study, and for normal adult listeners studied by Blumstein, Stevens, and Nigro (1977), whose synthetic stimuli they used. Both the Blumstein et al. stimuli and our independently synthesized stimuli used changes in both F2 and F3 transitions to differentiate between /ba/ and /da/, but changes in only F3 transitions to differentiate between /da/ and /ga/. Neither set of stimuli contained release bursts. Results of all three studies substantiate the phenomenon and support an explanation based on number of acoustic cues and/or naturalness.

The dyslexic group did not discriminate between syllables from different phonetic categories as well as the control group did, as indicated by their lower discrimination peaks in both series. In addition, the dyslexics' inconsistency in phonetic classification produced higher within-category discrimination in the /da-ga/ test for the dyslexics than for the controls. Both these discrimination differences are predictable from the groups' identification performances. The dyslexics' lower between-category discrimination peaks can be related directly to their more gradual perceptual crossover between phonetic categories. For example, consider a hypothetical case of the /da-ga/ discrimination pair 3-6. Compare the predicted discrimination score for a group that identified stimulus 3 as /da/ 100% of the time and stimulus 6 as /ga/ 100% of the time (proportion correctly discriminated = $(1.0 \times 1.0) + (0 \times 0) = (1.0) + (0) = 1.0$) to the predicted discrimination score for a group that identified stimulus 3 as /da/ 75% of the time and stimulus 6 as /ga/ 75% of the time (proportion correctly discriminated = $(.75 \times .75) + (.25 \times .25) = (.5625) + (.0625) = .625$). In the case of discrimination between a pair of stimuli both identified as belonging in the same phonetic category, inconsistent identification would result in higher discrimination performance than consistent identification. For example, consider a hypothetical case of /da-ga/ discrimination pair 1-4. If stimuli 1 and 4 are both identified as /da/ 100% of the time, it would be predicted that the 1-4 pair would not be discriminable (proportion correctly discriminated = $(1.0 \times 0) + (1.0 \times 0) = (0) + (0) = 0$). However, if stimulus 1 were identified as /da/ 90% of the time, and stimulus 4 were identified as /da/ 90% of the time, the two would be predicted to be discriminated that proportion of the time that they would be identified differently (proportion correctly discriminated = $(.9 \times .1) + (.1 \times .9) = (.09) + (.09) = .18$).

That the group differences in discrimination performance are predictable from their identification performance is evident from comparison of the predicted and obtained discrimination functions, which closely correspond for both groups. Because of this correspondence, group differences in Discrimination Tests can be considered to reflect the same

types of phonetic perceptual differences between dyslexics and controls observed in the Identification Tests, despite the procedural differences between Identification and Discrimination tasks. This fact, and the observation that the same group differences are also evident in signal detection analyses of the discrimination data, support the conclusion that the group differences observed in these tests are indeed perceptual in origin, i.e., differences in the way the stimuli are registered by the auditory system and/or phonetically coded.

In order to determine whether the dyslexics' difficulties with the speech identification and discrimination tests were due primarily to auditory or more strictly phonetic factors, an additional test should be made with the same task and perceptual demands as the speech tests, but using nonspeech acoustic stimuli. We did not perform exactly analogous nonspeech identification or discrimination tests with these children; however, subjects were administered an environmental sounds dichotic test (Knox, 1980; Knox & Kimura, 1970), in which they were asked to identify dichotically presented common sounds (e.g., telephone ringing, dog barking). Overall performance on this test was slightly, but not significantly, higher for the control group (55%) than for the dyslexic group (49%) ($F(1, 28) = .97; p = .33$). While this test did not provide an ideal control for the speech tests, it suggests that the focus of the problem observed in poor readers may be phonetic rather than auditory. Tallal (1980), on the other hand, has recently reported that although reading-impaired and control children performed similarly on nonverbal auditory discrimination and temporal order perception tests in which complex tone stimuli were presented at slow rates, the reading-impaired group made significantly more errors than the controls when the same stimuli were presented with shorter interstimulus intervals. Furthermore, she found phonetic reading skills were highly correlated with auditory processing abilities for rapidly presented stimuli. Tallal hypothesized that a basic auditory perceptual dysfunction led to impairment in the phonemic analysis of speech, which could underlie some of the difficulties in phonemic segmentation and recoding that Liberman, Shankweiler, Fischer, and Carter (1974) and Liberman et al. (1977) have found in poor readers.

The pattern of results by which dyslexics differed from normals in speech perception tasks indicates that they were inconsistent in their phonetic classification of auditory cues. Inconsistency in phonetic categorization might affect the dyslexics' ability to learn to read through the formation of inadequate long-term representations of phonetic units. Any such abnormality in the long-term stored "image" could be expected to adversely affect reading processes that involve the transformation of script to phonetic units of speech, as well as the ordering and combining of those units that make up words.

If reading normally involves the transformation of the printed word into a phonetic representation before it is processed semantically, then in the normal process of learning to read the child must become conscious of the individual phonetic units of speech and be able to manipulate an abstract auditory-phonetic representation of each stored in long-term memory. Our results demonstrate a correlation, though not necessarily a causal relationship, between speech perception performance and reading performance. In other words, one explanation of these results could be that learning to read causes the child to create or to refine his or her mental abstraction of a phoneme, and failure to learn to read may therefore result in poorer performance on auditory speech perception tasks in which individual phonemes are contrasted. An alternative explanation is that learning to read presupposes long-term memory representations of phonemes acquired through experience with speech, so that failure to learn to read may be caused by more fundamental auditory-phonetic perceptual problems. The question could be approached empirically in several ways. As previously discussed, reading-level-matched as well as age-matched control groups could be compared with dyslexics; alternatively, the correlation between reading level and speech perception performance in a sufficiently large and otherwise homogeneous group of children could be examined.

Another approach would be to test speech perception skills before children begin reading, and then observe their subsequent performance in learning to read. A procedure of this kind was in fact followed by Venezky, Shiloah, and Calfee (1972) and by Liberman and her colleagues. Venezky et al. found that the performance of prereaders on a rhyming task (which required the concept of phonetic similarity) correlated highly with their reading ability at the end of first grade. Liberman et al. (1974) tested whether children from 4 to 6 years of age could segment words into syllables or into phonemes, using a game in which the children tapped out the number of segments. None of the nursery school children could segment by phonemes, although 46% could segment by syllables. At the kindergarten level, 17% of the children could perform phonemic segmentation, while 48% of the children at that level could segment syllabically. By the end of first grade, 70% succeeded in phoneme segmentation, and 90% were successful in the syllable task. A follow-up study with these same children showed a high correlation between the ability to segment by phonemes and early reading success (Liberman & Shankweiler, 1979). The assumption here is that the beginning reader must, in a sense, "discover the phoneme" in order to effect a conversion from perceived letter shapes to phonetic entries for lexical search; yet the speech signal itself often lacks simple positive cues to phonemic segmentation, and normal auditory perception of speech appears to oper-

ate on at least syllable-size units. Before the child can even face the problems of English orthography, therefore, it would seem necessary to achieve an awareness of the separability of the consonants and vowels that, in speech, are quite effectively fused in individual syllables. This ability to single out the phonetic segment must be developed in the presence of the enormous variability of highly encoded acoustic cues, and the often asymmetrical effects of coarticulation. Such a skill could be critical to the conversion of visual text into a phonetically based code; thus failure to develop it fully might well underlie some cases of failure to learn to read.

While our results do not establish conclusively a cause-effect relationship between speech perception performance and reading ability, we believe they should be weighed in support of the view that difficulties in the perception of speech may cause difficulties in learning to read. The apparently perceptual origin of the differences we observed between dyslexic and normal readers on speech identification and discrimination tests, the differences Tallal (1980) reported between normal and impaired readers on rapidly presented nonverbal auditory perception tasks, and the longitudinal data collected by Venezky et al. (1972), Liberman et al. (1974), and by Liberman and Shankweiler (1979) showing high correlations between early rhyming and phonemic segmentation abilities and later reading performance, lead us to favor the interpretation that auditory-phonetic perceptual difficulties may underlie reading disabilities. This position certainly also seems more intuitively plausible than its converse, since under normal circumstances, the naturally acquired abilities to understand and produce speech unquestionably precede the formally learned abilities to read and write. While it is possible that inability to read causes (or is related to the cause of) poor performance on particular speech perception tasks, it seems reasonable to suppose that the process of learning to read serves rather as the occasion for children to become consciously aware of phonemic units of speech (Mattingly, 1972), and that, without such experience, they might never do so. Although speech can obviously be perceived and spoken adequately without a conscious awareness of its phonetic structure, it is also possible that this awareness may involve or initiate perceptual learning (Gibson & Levin, 1975), improving one's ability to make fine auditory-phonetic perceptual distinctions.

Whether the locus of difficulty is on an "auditory" or a "phonetic" level of representation, our results indicate that dyslexic children perform more poorly than normal children on speech perception tests, that these differences appear to be perceptual in origin, and that there is a significant relationship between reading ability and the perception of speech, the nature of which should be explored in future research.

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RECEIVED: June 3, 1980; REVISED: March 6, 1981.