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# Identification and discrimination of voicing and place-of-articulation in developmental dyslexia

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**Abstract**

Problems in reading and spelling may arise from poor perception of speech sounds. To study the integrity of phonological access in children with developmental dyslexia (mean age 8 years, 9 months) as compared to two control groups of children (age-matched and matched on reading level), identification and discrimination functions of the features voicing and place-of-articulation were assessed. No differences were found between groups with respect to identification of place-of-articulation. With respect to identification of the voicing contrast, children with developmental dyslexia performed poorer than age-matched controls, but similar to reading-level controls. For the voicing as well as the place-of-articulation contrast, children with developmental dyslexia discriminated poorer than both control groups. This pattern of identification and discrimination performance is discussed relative to the multidimensionality of the speech perception system. The clinical relevance of these perception tasks could be demonstrated by significant negative correlations between performance on the perception tasks and reading and spelling ability. This provided additional support for a functional relation between speech perception and reading and spelling in developmental dyslexia.

*Keywords*: developmental dyslexia, phonological processing, categorical speech perception.

## Introduction

The process of reading and writing demands the integration of skills, which are specific to the process of written language with skills developed for the perception and production of speech. Developmental dyslexia is a disorder manifested by

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difficulties in learning to read and write despite conventional instruction, adequate intelligence, and sociocultural opportunity (Critchley, 1975). It has been associated with deficits in central auditory function, deficits in phonological short-term memory, and specific language impairments (Tallal, 1980; Steffens, Eilers, Gross-Glenn and Jallad, 1992). A major issue in the literature is whether auditory perception deficits in the reading-impaired are of a general nature, or are specific to speech perception (Siegel, 1993; Stanovich, 1993; Studdert-Kennedy and Mody, 1995; Mody, Studdert-Kennedy and Brady, 1997; Tallal, Merzenich, Miller and Jenkins, 1998).

Several studies have demonstrated reduced auditory sensitivity in adult dyslexics (Menell, McAnally and Stein, 1999), children with developmental dyslexia (Farmer and Klein, 1995; Hugdahl, Heiervang, Nordby, Smievoll, Steinmetz, Stevenson and Lund, 1998; Cacace, McFarland, Ouimet, Schrieber and Marro, 2000) or new-borns and 6-month-old infants, who had a familial risk for dyslexia (Pihko, Leppänen, Eklund, Cheour, Guttorm and Lyytinen, 1999; see also Benasich, 1998). This supports a general, auditory processing account of developmental dyslexia. On the other hand, there is evidence that developmental dyslexia can be largely accounted for by an underlying phonological impairment or by a deficient phonological awareness or phonological sensitivity (Sprenger, Cole, Lacert and Serniclaes, 2000).

In the present study we focus on the possible role of phoneme perception in developmental dyslexics. Brandt and Rosen (1980) failed to demonstrate speech perception problems in children with dyslexia. Children with reading impairments labelled and discriminated speech sounds much like normal-reading children and adults. Lieberman, Meskill, Chatillon and Schupack (1985), however, demonstrated that adult subjects with dyslexia show deficits in the identification of vowels and the feature place-of-articulation in consonants. Steffens *et al.* (1992) found that the overall performance in identification and discrimination by adults with dyslexia was generally less accurate. Godfrey, Syrdal-Lasky, Millay and Knox (1981) investigated the perception of place-of-articulation in children with dyslexia. They concluded that the pattern of identification and discrimination differences between dyslexic and control children suggested an inconsistency in the dyslexics' phonetic classification of auditory cues. In the present study, the quality of the perception of speech sounds in children with developmental dyslexia is studied on an identification and a discrimination level. Identification and discrimination tap into the access and the integrity of phonemic units.

There is evidence that poor phonological access reflects problems in processing brief acoustic cues (Tallal, 1980; Reed, 1989; Tallal, Miller, Bedi, Byma, Wang, Nagarajan, Schreiner, Jenkins and Merzenich, 1996). In Tallal (1980), these brief acoustic cues basically concerned formant transitions. Reed (1989) mentioned the importance to understand the generality of dyslexia; it may affect only certain types of speech sounds. To address more than one type of speech sound, in the present study the perception of formant transitions as well as voicing cues in children with developmental dyslexia was investigated. As a cue in the domain of formant transitions, place-of-articulation was studied; whereas, as a cue in the voicing domain, voice onset time was studied.

Language-delayed children seem to rely more on redundancy in the acoustic signal than normally developing children do (Tallal and Stark, 1980). Brady, Shankweiler, and Mann (1983) suggested that poor readers require more complete auditory stimulus information than good readers in order to apprehend the phonetic shape of words. Degraded speech stimuli with a reduced redundancy, therefore, could prove to have differential value and to be a sensitive means for assessing perceptual problems in developmental dyslexia. In the present study, the speech signal was degraded not in a psychophysical, but a psycholinguistic way by reducing the phonetic redundancy of the speech sounds, resulting in speech sound continua (Groenen, 1997). A speech continuum consists of a series of speech tokens that vary acoustically for a single phonological contrast. A speech sound continuum contains words of varying phonemic ambiguity. The endpoint tokens are most representative with regard to phonemic clarity. The intermediate tokens vary in phonemic clarity and as such can be interpreted as reflecting a certain level of stimulus degradation. By using speech sound continua containing degraded speech tokens, a sensitive test for the perception of speech was developed.

A major issue in studies on deficits underlying dyslexia is whether these deficits should be considered as developmental delay or deviance. A methodological consequence is the choice of the control group. Both Brandt and Rosen (1980) and Godfrey *et al.* (1981) used control groups matched on the basis of chronological age. This design is not decisive for the delay versus deviance issue. Thus, in Brandt and Rosen (1980) and Godfrey *et al.* (1981), the lack of a reading-level-matched control group made it impossible to determine whether any observed differences in perception were caused by developmental delay or by functional differences in perception. Ziegler, Tallal and Curtiss (1990) and Schmitt and Meline (1990) emphasised the need for appropriate variables on which to match groups. One of the suggestions made by Watson and Willows (1995) concerned the employment of a reading-level match instead of the traditional chronological-age match when studying children with learning disabilities who have general reading problems. Vellutino and Scanlon (1989) acknowledged the importance of a reading-level match design, but also warned for the risks in drawing conclusions via this methodology. They mentioned that the general concern is the ambiguity inherent in interpreting results comparing chronological age and reading level matched groups on cognitive tasks that could be affected by reading disability. Manis, Szeszulski, Holt and Graves (1990) proposed to use both designs in developmental research, until problems of chronological age and reading-level control designs are resolved. Therefore, in the present study, both control measures were used; the children with dyslexia were compared to a control group matched on chronological age, and a younger control group matched on reading-level.

To summarize, the aim of the present study was to determine if poor perception of speech sounds underlies developmental dyslexia in children. To determine the clinical value of the perceptual tasks, perception ability was related to reading and spelling level. Thus, our study extends previous research in combining:

(a) identification and discrimination tasks;
(b) sensitive measurement materials and procedures (speech continua);
(c) tests of two general dimensions (spectral cues: place-of-articulation, and temporal cues: voicing); and
(d) two control measures that compared dyslexics to control groups matched both on chronological age and reading-level.

## Method

### *Subjects*

The subjects with developmental dyslexia were eight children (five boys and three girls, mean age 8;9 (8 years, 9 months), range 7;7 to 9;11) of which four children attended schools specialized in the remediation of learning disabilities and four children attended regular elementary schools. All schools were in the south and east of the Netherlands within 40 kilometres from the city Nijmegen. In the pre-selection phase, information was obtained from medical and educational records. Inclusion and exclusion criteria were used with reference to suggestions made by Ziegler *et al*. (1990).

The criteria for inclusion were:

(1) Diagnosis of developmental dyslexia according to the pedagogue for special education.
(2) Confirmed heredity of dyslexia. There were multiple cases of dyslexia in the family.
(3) Problems in reading and spelling. Reading level was assessed with the one-minute-test for speed-reading of words of Brus and Voeten (1973) and the 'AVI'-reading test for sentences of Van den Berg and Lintelo (1977). The spelling level was assessed with dictation tests for words of In den Kleef (1988) and Geerling and Geurts (1986) and the Van der Wissel (1963) spelling test for sentences. Scores were expressed in educational age-equivalent. Subtraction of the educational age-equivalent in months from the educational age (10 months per school year) yielded the educational delay. For all reading and spelling tests an educational delay of at least 6 months was required.
(4) Normal intelligence, as measured by the WISC-R intelligence test (Wechsler Intelligence Scale for Children, 1986). Performance IQ above 90 was required.
(5) Significantly lower verbal than performance IQ on the WISC-R intelligence test.

In table 1, the mean scores for the children with dyslexia on the tests are presented. In addition, information derived from the medical and educational records was used to determine exclusion criteria. This information indicated that each selected child:

(a) had no structural organic problems,
(b) did not have otorhinolaryngologic problems, and

Table 1. *Descriptive statistics for the dyslexic group*

| | Mean | SD | Range |
|---|---|---|---|
| Age (months) | 105.4 | 9.2 | 91–119 |
| WISC-R | | | |
| Verbal IQ | 94.7 | 7.7 | 87–110 |
| Performance IQ | 113.8 | 22.5 | 90–158 |
| Performance—Verbal | 21.0 | 13.7 | 10–48 |
| Reading (educational delay in months) | | | |
| Words | 16.5 | 7.0 | 6–24 |
| Sentences | 16.5 | 7.0 | 6–24 |
| Spelling (educational delay in months) | | | |
| Words | 13.2 | 4.8 | 6–24 |
| Sentences | 13.2 | 4.8 | 6–18 |

Note. The reading level was assessed with the one-minute-test for words of Brus and Voeten (1973) and the AVI-test for sentences of Van den Berg and te Lintelo (1977). The spelling level was assessed with tests for words of In den Kleef (1988) and Geerling and Geurts (1986) and a test for sentences of Van der Wissel (1963).

(c) did not suffer from severe attention deficits, as tested with the Bourdon-Vos test for visual attention (Vos, 1992).

Because of these strict inclusion and exclusion criteria, including the consistent verbal vs. performal IQ-discrepancy, the group of dyslexic children was rather homogeneous. Therefore, no subtypes of dyslexia were distinguished.

There were two control groups. One was matched on chronological age, and the other was matched on reading level. The age-matched group of control subjects were 12 children (mean age 8;9, range 7;7 to 10;1) attending a regular elementary school. The group matched on reading level consisted of eight subjects (mean age 7;0, range 6;3 to 8;2). Each subject was matched on reading level with a subject with dyslexia on the assessed educational age-equivalent. The mean reading delay across subjects with dyslexia was 16.5 months (SD = 6.8).

The children of both control groups were selected by their teachers. The teachers were instructed to select moderately achieving children who were not outstanding with regard to social classroom behaviour and cooperativeness. The children showed no evidence of learning disabilities, a history of hearing problems, speech and language problems, or speech-limiting structural abnormalities. Based on school performance and information from the classroom teachers, normal levels of cognitive, motor, and perceptual functioning could be assumed.

The children in both the experimental and the control groups met the following selection criteria:

(a) absence of hearing loss on bilateral pure tone audiometric testing with air-conduction thresholds at 250, 500, 1000, 2000, 4000 Hz (ISO, 1985) at the time of testing; the maximally allowed hearing loss was 25 dB HL for either ear;
(b) no previous exposure to synthesized speech;
(c) Dutch as the native language; and
(d) no bilingualism.

In addition, only children who could correctly identify 11 out of a series of 12 words consisting of six random repetitions of two speech tokens representing the perceptually clearest ends of the speech continua (i.e., /bɑk/ and /dɑk/, or /bɑk/ and /pɑk/) were admitted to the study. All three endpoint tokens were Dutch words. The probability of obtaining 11 correct responses out of 12 trials based on chance alone was 0.003. The subjects had to pass this pretest so that children who had difficulties accommodating to artificial speech could be excluded. The pretest was administered prior to actual testing, and all of the children with developmental dyslexia and all the children in the control groups passed the pretest.

### *Stimuli*

The original stimulus signal for both the place-of-articulation and the voicing continuum was an adult male utterance of a single word /bɑk/ (the Dutch word for 'box'). Both the place-of-articulation and the voicing continuum originated from this stimulus /bɑk/. After A/D conversion with a DASH-16 data-acquisition board (12 bit sampling at 10 kHz; band-pass filtering between 40 and 5000 Hz, low-pass cut-off frequency 5000 Hz with a decline of 60 dB/octave), the Interactive Laboratory System (ILS-PC, V6.1, 1989) was used to manipulate the spectral structure of the initial formant transitions. Only the vocalic portion (formant transitions plus steady state vowel) was analysed with pitch-synchronous linear predictive coding (covariance method: pre-emphasis factor 0.98, Hamming window), which yielded 12 reflection coefficients (Markel and Gray, 1976). The locations of the spectral peaks, their bandwidths, and their intensities were estimated by transforming the reflection coefficients to autoregressive coefficients and then performing a fast Fourier transformation (FFT). The result was smoothed spectrally by interactively adjusting the formant frequencies. F0 for all words was 104 Hz.

*Place-of-articulation continuum*[1]

The consecutive stimuli of the continuum ranged perceptually from /bɑk/ to /dɑk/ (i.e., the Dutch word for 'roof') and differed from one another in the starting value and slope of the transitions of the second and third formant. The onset frequencies of the F2 and F3 for each stimulus are shown in table 2. F1 always started at 400 Hz. The transition of the first formant was 20 ms in duration. The transitions of the second and third formants were 52 ms in duration. All transitions were linear. The final 98 ms of the vowel consisted of steady-state formants appropriate for the Dutch vowel /ɑ/ with centre frequencies at 750 Hz (F1), 1150 Hz (F2) and 2500 Hz (F3). The sampled data were resynthesized with a pitch-synchronous synthesis procedure by transforming the manipulated reflection coefficients to inverse filter coefficients. Pitch period excitation used a unit pulse. The resynthesized vowel parts were spliced back into the original utterance /bɑk/, which produced seven stimuli ranging from /bɑk/ to /dɑk/.[2] The total length of each stimulus was 381 ms, consisting of

(a) voice-lead 71 ms;
(b) burst 10 ms;
(c) vowel /ɑ/ 150 ms, divided into 52 ms transition duration and 98 ms steady state;
(d) silence interval (occlusion period /k/) 70 ms; and
(e) release /k/ 80 ms.

In figure 1 waveforms and spectrograms of the resynthesized endpoints of the continuum are presented.

*Voicing continuum*

An 8-step /b-p/ continuum was generated. The stimuli of the continuum ranged perceptually from /bɑk/ to /pɑk/ (i.e., 'package') and differed from one another in Voice Onset Time (VOT) values of about 10 ms. The endpoints of the continuum are presented in figure 2. Voice lead was cut back in steps of about 10 ms. Voice lag

Table 2. *Onset frequencies (in Hz) for the second and third formant transitions of the stimuli of the place-of-articulation continuum*

| Stimulus | F2 | F3 | |
|---|---|---|---|
| 1 | 1000 | 2150 | /bɑk/ |
| 2 | 1083 | 2317 | |
| 3 | 1167 | 2483 | |
| 4 | 1250 | 2650 | |
| 5 | 1333 | 2817 | |
| 6 | 1417 | 2983 | |
| 7 | 1500 | 3150 | /dɑk/ |

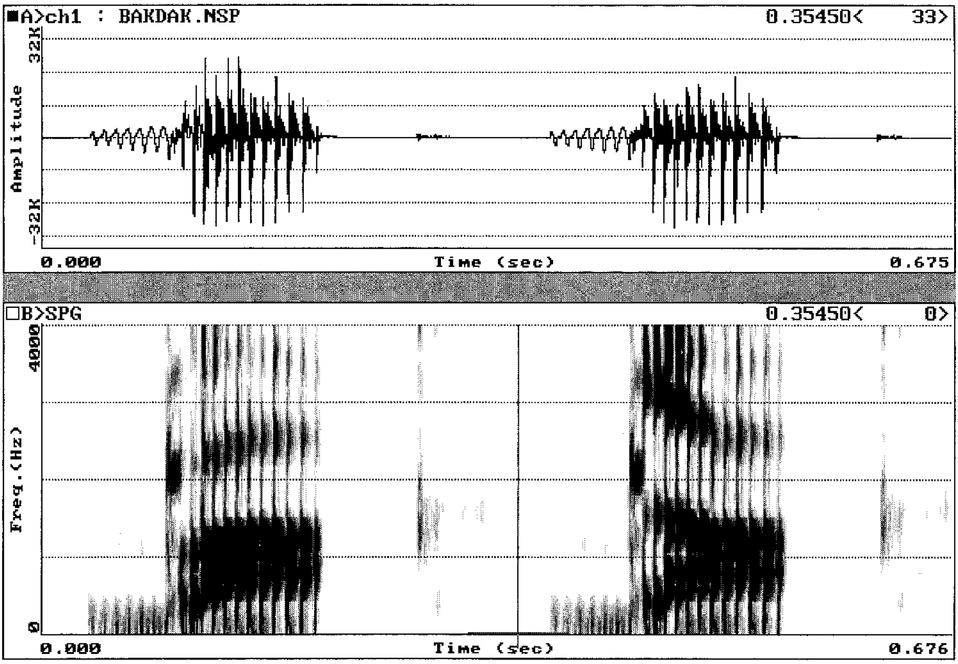


Figure 1. *Waveform and spectrogram of the place-of-articulation endpoint tokens /bɑk/ (left panel) and /dɑk/ (right panel).*

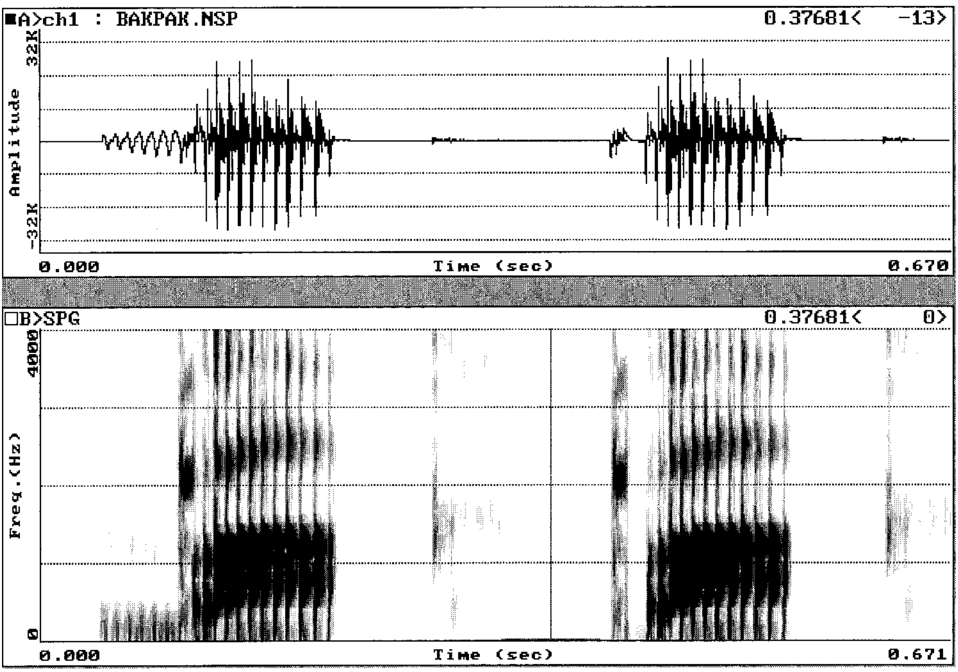


Figure 2. *Waveform and spectrogram of the voicing endpoint tokens /bɑk/ (left panel) and /pɑk/ (right panel).*

was implemented by inserting increasing silent intervals between the burst and the vocalic portion. The consecutive eight stimuli had VOTs of – 52.7, – 40.9, – 29.1, – 19.1, – 10.8, 0, + 8.0 and + 16.0 ms.

Stimulus phonemic quality was checked by having 10 adults label 10 repetitions of each of the stimuli of both continua presented in random order. For individual subjects, the phoneme boundary was located between stimulus 3 and 5 on the place-of-articulation continuum. The mean phoneme boundary for the voicing contrast occurred at a VOT of – 11.31 ms. The shape of the identification function was representative for the Dutch language (Slis and Cohen, 1969). These results indicated a valid choice of values in the spectral and temporal manipulations.

### *Procedure*

The stimuli were recorded and played back using an Ampex 467 DAT-tape on a Grundig Fine Arts digital audio tape recorder (type DAT-9000: 16 bit D/A converter, 2-fold oversampling, sampling frequency 48 kHz). Presentation was via a Beyer-dynamic closed headphone (type DT770). The playback level was set at a listening level judged by the subject to be comfortable (approximately 70 dB HL). Subjects were tested in a quiet room.

Each subject was examined once. In order to get accustomed to the artificial speech, the subject first listened to six repetitions of each of the four endpoint stimuli. The subject then had to identify 11 out of a series of 12 endpoint stimuli correctly for both continua (see subject selection criteria). After this, the subject was administered the main experimental tasks: two identification and two discrimination tasks.

The identification task was based on a two-alternative forced choice response procedure and consisted of ten repetitions of each of the stimuli of the continuum presented in a random order in five series. This resulted in five series of 14 stimuli for the place-of-articulation continuum and five series of 16 stimuli for the voicing continuum. The stimuli were separated by an interstimulus interval of 5000 ms. For the place-of-articulation condition, the subjects could identify the stimulus by pointing to one of two pictures: a picture of a box, representing the stimulus /bɑk/, or a picture of a roof, representing the stimulus /dɑk/. For the voicing condition, the subjects could identify the stimulus by pointing to either a picture of a box, representing the stimulus /bɑk/, or a picture of a package, representing the stimulus /pɑk/.

The discrimination tasks consisted of same-different (AX) judgements. In order to obtain a bias-free measure of discriminability, the discrimination tasks were set up in such a way that signal detection analysis could be applied (Coombs, Dawes and Tversky, 1970). For this, each task contained physically different as well as identical pairs. In the place-of-articulation condition, subjects were presented three series of 15 stimulus pairs. Each series consisted of one identical pair for each of the seven stimuli, one physically different pair for each of the five possible 2-step comparisons (1–3, 2–4, 3–5, 4–6, 5–7), and one physically different pair for three 3-step comparisons (2–5, 3–6, 4–7). The 3-step comparisons were treated as dummies explicitly intended to elicit more 'different' responses. In the voicing condition, subjects were presented three series of 17 stimulus pairs. Within each series, there was one identical pair for each of the eight stimuli, one physically different pair for each of the six 2-step comparisons (1–3, 2–4, 3–5, 4–6, 5–7, 6–8) and one physically different pair for three 3-step comparisons (2–5, 3–6, 4–7). In each series, the pairs were randomly ordered with an intrapair interstimulus interval of 600 ms and an interpair interval of 5000 ms. An intrapair interstimulus interval value of 600 ms had proven to be a sensitive one in previous studies by Groenen, Maassen, Crul and Thoonen (1996) and Groenen, Crul, Maassen and Van Bon (1996). To avoid difficulties with the verbal concepts of 'same' and 'different', the subjects were required to point to one of two pictures after hearing a pair of stimuli: a picture of a triangle and a circle, representing the concept 'different', or a picture of two circles, representing the concept 'same'.

Half of the subjects began with the place-of-articulation condition while the other half began with the voicing condition. The subjects always participated in the identification task before the discrimination task. The children were encouraged to respond but never received differential feedback for particular responses.

### *Statistical analysis*

Each individual identification curve was submitted to probit transformations (Finney, 1971). The probit method determines the value of the phoneme boundary and slope by iteratively computing the cumulative normal distribution that comes closest to the data, using a maximum likelihood criterion. The resulting distribution has a mean (i.e., the interpolated 50% crossover point or phoneme boundary) and a standard deviation (i.e., a measure of the variability of scores around the mean). The slope is the reciprocal of the standard deviation and indicates the range of uncertainty in distinguishing one phoneme category from another. A high slope value indicates a small uncertainty range and suggests a highly consistent ability to categorise a speech contrast; whereas, a low slope value indicates a large range of uncertainty and suggests difficulties in identifying the speech stimuli.

The discrimination scores (proportions 'different'-responses) were converted to a nonparametric estimate of discriminability $d'$ (-ln eta, Wood, 1976) as a function of stimulus pair. Discriminability equals zero when performance is at chance. It increases with increasing discrimination accuracy without influences of bias to respond 'same' or 'different'. Discriminability is maximal at the -ln eta value of 4.6; this value is obtained when the probabilities for the correct 'difference' and correct 'same' responses are both 0.99, the value assigned (for computational purposes) when the actual probabilities were 1.00.

Differences between groups with respect to mean slope and phoneme boundary were tested with one-factor ANOVA (with Subject Group being the factor with 3 levels: Dyslexic, Age-matched controls, Reading-level-matched controls). A two-factor ANOVA (subject group × stimulus pair) with repeated measures on Stimulus Pair was performed for discriminability scores. To compare pairs of Subject Groups, Tukey's studentized range post-hoc analyses were conducted. All analyses were performed for voicing and place-of-articulation separately.

In order to determine the relation between perception ability on the one hand and reading and spelling ability on the other, the data of the subjects with dyslexia were used to cross-correlate mean discriminability for voicing and place-of-articulation with educational delay in (a) reading, (b) spelling, and (c) mean educational delay in reading and spelling (all scores were averaged across words and sentences). Pearson product-moment correlation coefficients were calculated. If perception is related to reading and spelling (i.e., high level of mean discriminability and low score in educational delay), then the correlations should be significantly negative.

## Results

### *Identification*

In table 3, the mean phoneme boundary and slope scores for the developmental dyslexic and the control groups are presented for both the perception of place-of-articulation and voicing.

*Place-of-articulation*
In figure 3, the mean identification curves for the children with developmental dyslexia and the control children for the stimuli differing in place-of-articulation are presented. According to a one-factor ANOVA analysis, there were no significant differences in mean slope between the dyslexic and the control groups. This indicates that the children with developmental dyslexia performed as consistently as the control children. The mean phoneme boundary for the dyslexic group was shifted to the left compared to that of each control group. This difference approached significance ($F(2)=2.93$, $p=0.072$).

*Voicing*
In figure 4, the mean identification curves for the children with dyslexia and the control children for the stimuli differing in voicing are displayed. A one-factor ANOVA showed the difference between groups for slope to be significant ($F(2)=4.94$, $p<0.05$). A Tukey's studentized range test showed that the dyslexic group and the control group matched on reading level demonstrated lower slope values than

Table 3. *Mean identification results and discriminability scores for the children with developmental dyslexia and the control children on the place-of-articulation and voicing stimuli*

| | Phoneme boundary | Slope | Discriminability |
|---|---|---|---|
| Place-of-articulation (stimulus number) | | | |
| Dyslexic | 3.75 | 2.68 | 0.84 |
| | *0.52* | *1.06* | *0.71* |
| Reading-level-matched control | 4.24 | 2.50 | 1.48 |
| | *0.45* | *1.12* | *0.37* |
| Age-matched control | 4.19 | 2.85 | 1.54 |
| | *0.41* | *1.04* | *0.42* |
| Voicing (voice onset time) | | | |
| Dyslexic | – 10.39 | 0.12 | 0.41 |
| | *7.29* | *0.08* | *0.72* |
| Reading-level-matched control | – 9.60 | 0.11 | 1.12 |
| | *6.49* | *0.04* | *0.57* |
| Age-matched control | – 9.88 | 0.22 | 1.20 |
| | *9.97* | *0.11* | *0.39* |

Notes: Voice Onset Time is not evenly distributed along the x-axis. The consecutive stimulus intervals are approximately 10 ms in the voice-lead phase and 8 ms in the voice-lag phase; standard deviations are printed in *italics*.

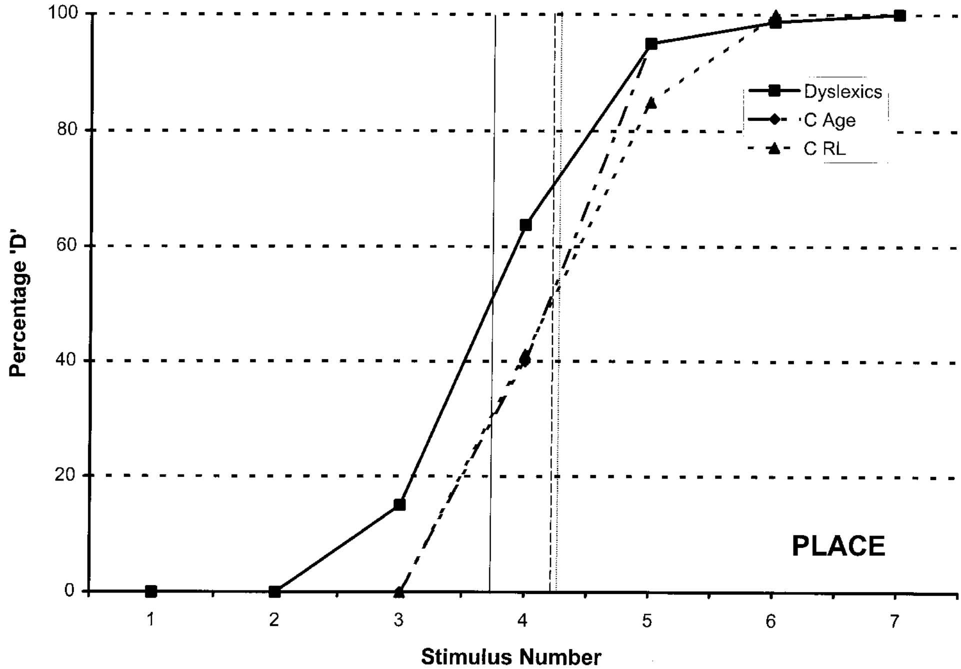


Figure 3. *Mean percentages 'D' responses as a function of stimulus number of the place-of-articulation continuum for the children with developmental dyslexia and control children. Vertical lines indicate the location of the mean phoneme boundary.*

the control group matched on age ($p < 0.05$). The dyslexic group and the control group matched on reading level were not different from each other. This indicated that the children with developmental dyslexia and the children matched on reading level labelled less consistently than the control children matched on chronological age. There were no significant differences in phoneme boundary.

### *Discrimination*

The discrimination functions plot the discriminability, which is corrected for response bias, of each 2-step pair in terms of a nonparametric estimate of d' (-ln eta, Wood, 1976). Mean discriminability scores per group for both continua are also presented in table 3.

#### *Place-of-articulation*

In figure 5, the mean discriminability functions for the dyslexic and the control groups are presented. A two-factor ANOVA (subject group × stimulus pair) showed a significant effect of subject group ($F(2,25) = 5.13$, $p < 0.05$). Post-hoc analyses showed that the dyslexic group demonstrated a lower level of discrimination than both the control groups ($p < 0.05$). The age-matched and reading-level-matched control groups were not different from each other.

#### *Voicing*

In figure 6, the mean discriminability functions for the children with dyslexia and the control children are displayed. A two-way ANOVA (subject group × stimulus

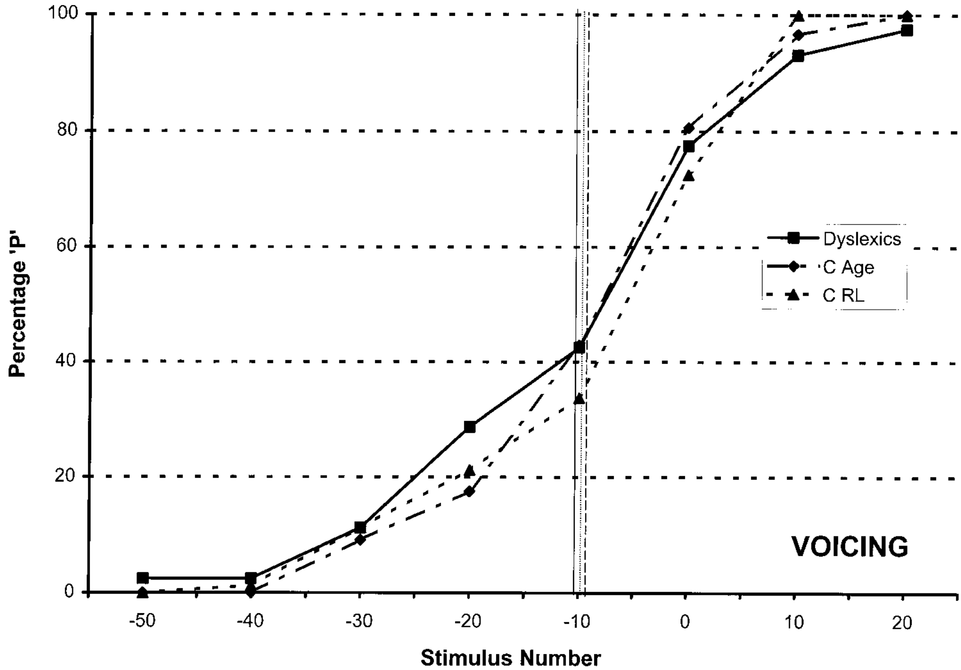


Figure 4. *Mean percentages 'P' responses as a function of VOT (voicing continuum) for the children with developmental dyslexia and control children. Vertical lines indicate the location of the mean phoneme boundary.*

pair) showed a significant effect of subject group ($F(2,25) = 5.45$, $p < 0.05$). Post-hoc analyses showed that the dyslexic group demonstrated a lower level of discrimination than both the control groups ($p < 0.05$). The age-matched and reading-level-matched control groups were not different from each other.

### *Clinical value*

Correlations between perception ability on the one hand and reading and spelling ability on the other are presented in table 4.

The correlation coefficients for all comparisons were high and reached significance, except for the relation between reading ability and discrimination of place-of-articulation (there was a trend, however). The mean discriminability scores for place-of-articulation and voicing were negatively related to the mean educational delay in reading and spelling ($r = -0.77$, $p < 0.05$ and $r = -0.82$, $p < 0.05$, respectively). The correlations revealed a firm relationship between discriminability of place-of-articulation and voicing on the one hand and reading and spelling ability on the other.

In the scatterplot presented in figure 7 discriminabilities of voicing and place-of-articulation are presented. As can be seen in this plot, the voicing continuum is more discriminative between children and groups than the place-of-articulation continuum. Six children of the dyslexic group performed poorly on the combination of discriminability scores, as did one child of the reading-level-matched group. The distribution of scores from the remaining reading-level-matched control children is

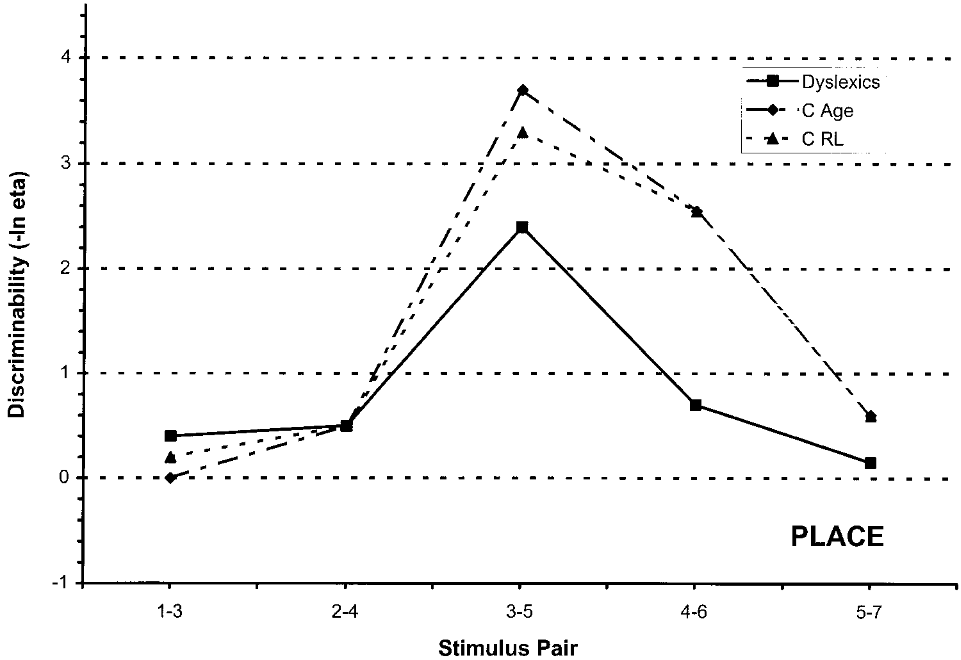


Figure 5. *Mean discrimination scores as a function of stimulus pair of the place-of-articulation continuum for the children with developmental dyslexia and control children.*

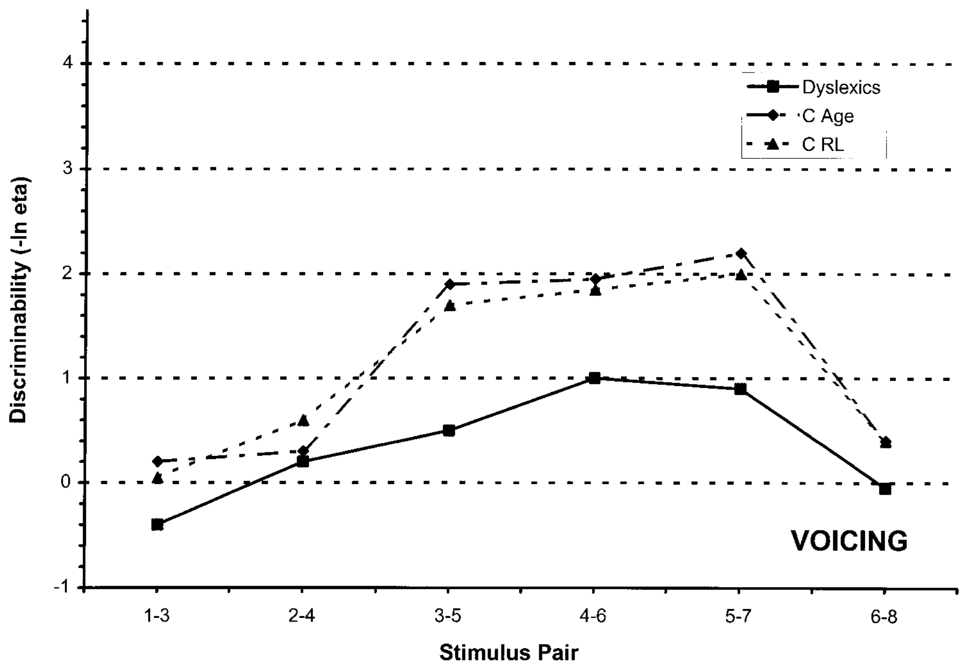


Figure 6. *Mean discrimination scores as a function of stimulus pair of the voicing continuum for the children with developmental dyslexia and control children.*

Table 4. *Pearson product-moment correlation coefficients of the reading and spelling measures with the mean discriminability for voicing and place-of-articulation*

| | Reading | Spelling | Mean reading/spelling |
|---|---|---|---|
| Mean discriminability | | | |
| Voicing | – 0.76* | – 0.76* | – 0.82* |
| Place-of-articulation | – 0.62(*) | – 0.87** | – 0.77* |

Note: The individual reading and spelling levels were computed by taking the mean educational delay in word and sentence performance.
$^{**}p < 0.01$
$^{*}p < 0.05$
$^{(*)}p < 0.1$

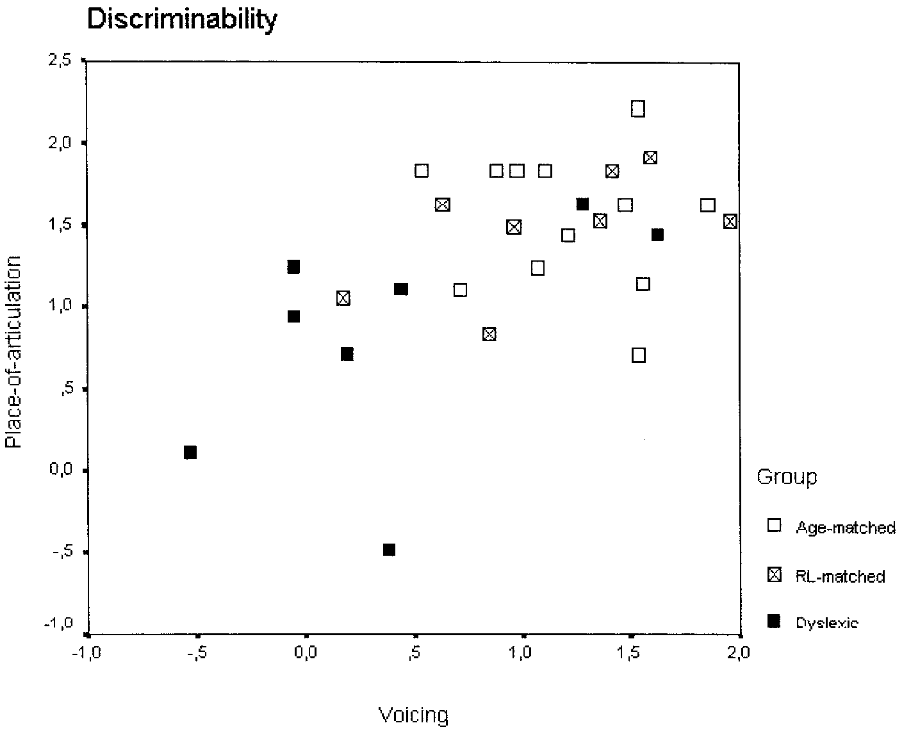


Figure 7. *Scatterplot of discriminability scores for children in the dyslexic group, and the age-matched and reading-level-matched control groups. Plotted are the discriminabilities of the voicing and place-of-articulation continua.*

indistinguishable from the age-matched group. Two dyslexic children showed no evidence of poorer discrimination ability. No explanation could be found for this difference from an analysis of the reading and spelling scores from these two children as compared to the other six. It should be mentioned that these 2 children obtained slope scores on the voicing continuum that was below the mean of the dyslexic group. We return to this result below.

**Discussion**

To answer the question whether children with developmental dyslexia have poorer perception of speech sounds, we have to distinguish between identification and discrimination performance. With regard to identification, children with developmental dyslexia demonstrated slopes for place-of-articulation which were not significantly different from the age-matched and reading-level-matched control children. For voicing, children with dyslexia showed a less steep identification curve than the age-matched controls. However, there was no difference in slope compared with the younger control group matched on reading-level. This seems to suggest that identification differences between groups can be attributed to developmental aspects associated with reading-level and not to qualitative functional differences between dyslexic and nondyslexic groups.

Discrimination performance of children with developmental dyslexia and control children was reflected in discriminability differences. For the perception of both voicing and place-of-articulation, children with developmental dyslexia demonstrated poorer discrimination than the age-matched as well as the reading-level-matched control children.

The clinical value of speech discrimination tasks was demonstrated by the six children in the dyslexic group who performed relatively poorly on the combination of both discrimination tasks (figure 7). There are only three children out of 18 from both control groups, who come close to these poor scores. Furthermore, the clinical relevance is supported by the negative correlations between the mean discriminability data and the reading and spelling data within the dyslexic group (table 4). Speech sound discrimination explains 36% to 64% of the reading and spelling abilities, thus addressing issues of potential theoretical importance.

On the other hand, the clinical value should not be overestimated. First, the number of children was small. Second, variability within groups and overlap between groups is quite substantial. For instance, two children of the dyslexic group obtained discriminability scores within the regions of the control groups. These two children performed relatively poorly on voicing identification. Analyses of their reading and spelling abilities did not yield any difference from the remaining children in the dyslexic group. These results corroborate the study of Adlard and Hazan (1998), in which also among children with dyslexia two subgroups could be distinguished. One subgroup performed poorer on speech discrimination tasks but did not differ from controls in their performance on non-speech psychoacoustics tasks, whereas the other group performed within normal limits overall. Moreover, the subgroups could not be distinguished on the basis of their reading and spelling abilities. Further research is needed to assess the validity of discrimination tests for distinguishing between groups.

Our data are consistent with recent studies suggesting that children with secondary linguistic problems are significantly impaired in specific aspects of auditory and phonetic analysis. Tallal and Stark (1980) and Tallal *et al.* (1996) suggested that lower-level auditory and phonetic disabilities directly affect these children's ability to perform higher-level perceptual, cognitive, and linguistic tasks. This view is adhered to by Godfrey *et al.* (1981). In contrast, Brady *et al.* (1983) suggested that perceptual difficulties in poor readers are specific to speech. The issue is still controversial, and clinically important in relation to the problem of early detection and diagnosis (Denenberg, 1999; Studdert-Kennedy and Mody, 1995). In this study, we did not compare the perception of speech and non-speech stimuli. However, we did test the children with two different speech contrasts, and found different results for identification, but equal results for discriminibality. We therefore conclude that as long as the issue of a phonetic–phonological versus an underlying auditory explanation is not resolved, psycholinguistic assessment must comprise diverse material. No controversy exists with respect to the result that if stable auditory processing of speech sounds has not been developed problems in reading and spelling may arise.

### *Speech processing levels*

At the theoretical level, our results pose some interesting problems. It may be useful to characterize speech perception as a series of processes, including a preliminary auditory analysis, further auditory and phonetic feature analysis, and the combination of phonetic features into a phonemic representation (Pisoni and Sawusch, 1975; Cutting and Pisoni, 1978). At any stage in the process of speech perception, information can be placed in short-term memory. Auditory processing includes a preliminary analysis and is related to auditory short-term memory; whereas, phonetic processing includes phonemic labelling strategies and is related to phonetic memory. For a detailed discussion on short-term memory and its role at different stages of processing, we refer to Baddeley (1992) and Liberman (1996).

According to a dual-coding structure of auditory and phonetic processing (see e.g., Sawusch and Nusbaum, 1983; Sawusch and Mullennix, 1985), it is not likely for phonetic identification to be normal while auditory discrimination is disturbed. The question is whether or not phonetic identification can develop with problems of auditory processing. Groenen, Crul *et al.* (1996) and Groenen, Maassen *et al.* (1996) proposed that the validity of classical models of speech perception should be questioned. If the dysfunctional discrimination profile of children with developmental dyslexia is a reflection of an abnormal discrimination strategy, then it is not unlikely that the auditory dysfunction may be the result of selective attention. Nittrouer and Studdert-Kennedy (1987) and Nittrouer (1992) demonstrated that children show different cue weighting strategies than adults. Dysfunctional speech perception may be determined by the process of attributing different (yet valid and adequate) weights to acoustic cues in the process of categorisation as compared to the cues on which discrimination was based. This would allow discrimination performance to be affected while identification was not. Such a viewpoint is highly compatible with the concepts of the WRAPSA model (Word Recognition and Phonetic Structure Acquisition) of Jusczyk (1993). According to Jusczyk, preliminary auditory analysis reflects the inherent organisation of the human auditory system. The auditory analysers belong to the innate endowment of the infant. After the development of a weighting scheme, language-specific phonetic decisions can be made. Selective attention within a set of intraphonetic cues, then, seems likely to play a role in phonetic processing. It is possible that for children with dyslexia, cues playing a minor role are weighted less in the identification process. Thus, problems with discrimination of these minor cues may not have as much importance for the identification process as problems in discrimination of more important speech cues. This standpoint seems highly plausible to us because it accounts for the multidimensionality of the speech signal as well as the multidimensionality of the speech processing system. Future research with a focus on cue weighting strategies in the perception of multiple-cue speech signals could well provide insight in selective attention by dyslexic subjects and, in general by subjects with language problems.

### *Sensitive measures*

Brandt and Rosen (1980) studied reading-disabled children who were at least 2 years behind their age mates in reading level and found no perceptual deficits; whereas, in the present study, perceptual effects were found in children who were at least six months behind their age mates. A reason for this apparent discrepancy in results could be that Brandt and Rosen (1980) statistically compared only phoneme boundaries. In the present study, no differences in phoneme boundaries were found either. For discrimination, Brandt and Rosen (1980) used correct 'same' responses; whereas, we used measures of discriminability (-ln eta). Measures based on signal detection theory are likely to be more sensitive and less prone to contaminating effects of response bias.

Brady *et al.* (1983) suggested that deficits characteristic of poor readers may stem from material-specific problems of perceptual processing. In most studies on speech perception the stimuli are produced by synthesis procedures. Brandt and Rosen (1980) used a computer controlled parallel resonance synthesiser; Godfrey *et al.* (1981) used a Rockland Model 4516 digital speech synthesizer (Rabiner, 1968); Lieberman *et al.* (1985), Reed (1989) and Steffens *et al.* (1992) used the Klatt (1980) cascade-parallel synthesizer. Our choice for using resynthesized instead of synthesized stimuli was based on results of Groenen, Maassen *et al.* (1996) who directly compared the perception of resynthesized and synthesized speech. For the synthesized speech, a text-to-speech system that followed the principles of allophonic synthesis was used (Loman, Kerkhoff and Boves, 1989). Labelling and discriminability turned out to be poorer for synthetic than for resynthetic stimuli. The value for distinguishing a pathological from a control group, however, was not increased by using synthetic speech stimuli, indicating no increase in sensitivity. Thus, we conclude that the way in which stimuli are constructed has no major influence on the sensitivity of the perceptual tasks.

### *Deviance or delay*

Our results add to those of Godfrey *et al.* (1981) and Reed (1989). Decreased overall levels of discriminability were found for the subjects with dyslexia. Both studies reported less consistent identification near the phoneme boundary. However, both studies compared identification results of the experimental group to those of a control group matched on chronological age. The results of Godfrey *et al.* (1981) and Reed (1989), therefore, could be a consequence of reading development. In the present study, a similar result was obtained for the identification performance. It was shown that for voicing, the children with dyslexia showed a greater degree of ambiguity in identification than the age-matched control group. This indicates a deficiency in perception ability. However, the dyslexic children performed no worse than subjects matched on reading level which indicates that the level of development in perception is no worse than that of nondyslexic readers. This suggests that the deficiency is developmental in nature and implies that neither the dyslexic nor the subjects matched on reading level have the prerequisite skills necessary to learning to read better. For voicing as well as place-of-articulation, the children with dyslexia showed poorer discrimination than both control groups. This suggests discrimination problems to underlie developmental dyslexia.

The problems associated with dyslexia have proven neither to be of uniform aetiology nor to be completely individualised (Ellis, 1984; Lieberman *et al.*, 1985; Watson and Willows, 1995). There have been several attempts to achieve greater specificity in comparisons between dyslexic and non-dyslexic groups. The group of subjects with dyslexia in our study was too small to reveal any differences between subgroups as far as reading and spelling abilities is concerned (e.g., dysphonetic and dyseidetic dyslexics, Boder, 1973). The present study, however, demonstrates that speech perception of children with developmental dyslexia may be affected. Adlard and Hazan (1998) identified subgroups differing on perceptual processing and non-word reading. For a better understanding of the aetiology of specific developmental language disabilities such as dyslexia, it seems recommendable to consider the child's identification and discrimination abilities. This could result in improved diagnosis of the underlying deficits in developmental dyslexia. Hence, the diagnostic identification of those children with dyslexia that show underlying deficits in speech perception may serve as a guide for therapeutic remediation.

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## Notes

1. Important acoustic cues carrying place-of-articulation information are the transitions of the second and third formants and the spectrum of the release burst. We decided to manipulate the formant transitions. Decisions regarding the voiced-voiceless distinction are based on the perceptual integration of several distinct acoustic properties. The major acoustic cue carrying voicing information in Dutch is voice onset time (VOT). In addition to the major cue VOT, other minor cues appear to contribute to the voiced-voiceless distinction, such as the length of the noise burst, the intensity of the noise burst, the formant transition duration of F1, F2, and F3, and the range of the frequency shift of F1. We chose for manipulating VOT.
2. We used a burst appropriate for a /b/ in all the tokens of the place-of-articulation continuum. Dyslexic subjects showed a tendency for lower phoneme boundaries for the place-of-articulation continuum than the nondyslexic subjects. It has been suggested that children pay more attention to formant transitions and pay less attention to static cues (such as burst spectra) than adults. Dyslexic subjects may have affected speech perception abilities and so pay less attention to burst spectra than the control children. Ignoring the burst information could explain why they were identifying the stimuli as starting with /d/ earlier than the other subjects.

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