In Search of the Auditory, Phonetic, and/or Phonological Problems in Dyslexia: Context Effects in Speech Perception

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There is a growing consensus that developmental dyslexia is associated with a phonological-core deficit. One symptom of this phonological deficit is a subtle speech-perception deficit. The auditory basis of this deficit is still hotly debated. If people with dyslexia, however, do not have an auditory deficit and perceive the underlying acoustic dimensions of speech as well as people who read normally, then why do they exhibit a categorical-perception deficit? A potential answer to this conundrum lies in the possibility that people with dyslexia do not adequately handle the context-dependent variation that speech signals typically contain. A mathematical model simulating such a sensitivity deficit mimics the speech-perception deficits attributed to dyslexia. To assess the nature of the dyslexic problem, the authors examined whether children with dyslexia handle context dependencies in speech differently than do normal-reading individuals. Contrary to the initial hypothesis, children with dyslexia did not show less context sensitivity in speech perception than did normal-reading individuals at auditory, phonetic, and phonological levels of processing, nor did they reveal any categorization deficit. Instead, intrinsic properties of online phonological processes, not phonological representations per se, may be impaired in dyslexia.

KEY WORDS: developmental dyslexia, speech perception, categorical perception, context effects, phonological deficit

Developmental dyslexia refers to poor reading and writing abilities in spite of adequate intelligence and in the absence of any sensory disorder or neuropsychological signs. People with dyslexia, however, not only are impaired in reading but also show subtle deficits on a range of tasks that probe phonological processing and do not involve written material. People with dyslexia have been shown to be subtly impaired on tasks that involve repeating words and nonwords (Brady, Poggie, & Rapalla, 1989; Brady, Shankweiler, & Mann, 1983; Snowling, 2000), the retention of verbal material in working memory (Snowling, Nation, Moxham, Gallagher, & Frith, 1997; Witruk, Ho, & Schuster, 2002), rapid naming (Bowers & Swanson, 1991; Denckla & Rudel, 1976; Wolf, Bowers, & Biddle, 2000), and object naming (Katz, 1986) and on metalinguistic tasks that involve the manipulation of phoneme size units (i.e., phoneme awareness tasks; Adams, 1990; Bradley & Bryant, 1983; Wagner & Torgesen, 1987). These lines of research have led to a general acceptance of the assumption that the core problem in dyslexia is best described as a phonological deficit (Catts, 1989; Shaywitz, 1998).

In search for the cause of this phonological deficit, some investigators have postulated a significant role for auditory and speech perception. McBride-Chang (1996), for instance, conducted a structural linear equations analysis that showed that the variance in phoneme-awareness tasks could be accounted for by the performance on categorical-perception tasks. In a categorical-perception task, participants have to classify a continuum of speech sounds as belonging to one of two phoneme categories, which are represented by contrasting good exemplars at each end of the continuum (e.g., /ba/ to /da/). Usually, most stimuli of such a continuum are perceived consistently as either /ba/ or /da/, and only a small range of stimuli is perceived as ambiguous. People with dyslexia, however, tend to deviate from this pattern. They tend to show less categorical perception of short speech sounds. That is, they perceive a wide range of speech-sound continua as potentially ambiguous. Several studies investigating categorization performance found people with dyslexia to exhibit such problems, particularly with stop consonants. Godfrey, Sydral-Lasky, Millay, and Knox (1981) showed that phoneme categories of reading-disabled children were less well separated than those for normal-reading children when they were presented with synthetic speech /ba/–/da/ and /da/–/ga/ continua. Also, these children were less able to discriminate between /ba/ and /da/, even at the extremes of the continuum. Reed (1989) used /ba/–/da/ stimuli that differed in F2 and F3 frequency during the first 35 ms. Under these conditions, reading-disabled individuals were impaired in discriminating between /da/ and /ba/. Overall, however, the results of categorization studies are equivocal. Some studies found phoneme discrimination and categorization deficits among dyslexics (e.g., Tallal, 1980; Werker & Tees, 1987), whereas others did not (e.g., Snowling, Goulandris, Bowlby, & Howell, 1986).

The nature of the phonological-awareness and the categorization problem is still fiercely debated (e.g., Studdert-Kennedy, 2002). Some investigators (Stein & Walsh, 1997; Tallal, 1980; Tallal, Miller, & Fitch, 1993) have argued that the problems in handling speech sounds may be attributed to a general perceptual deficit in temporal processing, especially in the perception of brief auditory events. Indeed, a number of studies reported that people with dyslexia show subtle anomalies in the perception of brief acoustic events, as found in stop-vowel syllables (see McBride-Chang, 1995). Such observations have led to the theory that people with dyslexia are impaired in the processing of rapid auditory events. However, other research not only revealed that people with dyslexia have discrimination problems with brief formant transitions but also showed them to have impaired performance with longer transition times. In a magnetoencephalographic study, Heim, Eulitz, Weinbruch, and Elbert (1999) presented /ba/ and /da/ stimuli with CV transition times of 43 and 93 ms, respectively, which were modeled after the Tallal and Piercy (1975) stimuli. The electrophysiological data revealed no differences between people with dyslexia and controls, but the behavioral results revealed significant differences for both the short and long transition times. This result clearly poses a problem for a temporal-processing deficit account, which predicts unimpaired performance for long transition times.

The temporal-processing deficit theory has also been challenged on theoretical grounds. Studdert-Kennedy and Mody (1995) argued that the temporal processing construct is not well defined and that the evidence in favor of impaired temporal perception in dyslexia is inconclusive. Results ostensibly showing impaired processing of rapid sequences of auditory events do not necessarily imply a temporal-processing deficit. Such findings also can be explained if one assumes that auditory recognition is impaired for the subcomponents of rapid auditory sequences. Moreover, findings of subtly deviant speech perception in people with dyslexia do not necessarily imply that there is a perceptual deficit. An alternative view is that the perception of acoustic cues is unimpaired but that the use of these cues for the categorization of a speech sound differentiates people with dyslexia from normal-reading controls. This assumption gains credibility from the fact that there is no one-to-one correspondence between an acoustic cue and a phoneme category. For example, what differentiates the phonemes /b/ and /p/ is not only voice-onset time (VOT), but, among other cues, also length and f0 of the adjacent vowel. Therefore, categorizing acoustic events into phonological categories implies more than the application of a simple decision rule (e.g., if VOT is greater than –20 ms, then /b/) and requires the application of a multidimensional nonlinear function to a multidimensional stimulus pattern.

In an insightful article, Mody, Studdert-Kennedy, and Brady (1997) tried to tease apart whether the differences between people with dyslexia and normal-reading controls on categorical-perception tasks are caused by a general auditory problem or a speech-specific deficit. To this end, they used a synthetic /ba/–/da/ continuum that varied in F2 onset frequency. In line with earlier results, they found that people with dyslexia differ from normal-reading controls in the perception of this continuum. They then presented the isolated F2 transitions of the speech sounds, which were completely unlike speech and were not categorizable. If people with dyslexia were impaired in the perception of short transitions in acoustic events, then they should also be impaired in perceiving these isolated formant transitions. However, people with dyslexia and normal-reading controls performed equally well when discriminating isolated second-formant transitions taken from the speech continuum. Mody et al. concluded that people with dyslexia may have trouble identifying phonetically similar, but phonologically contrastive, synthetic syllables.

Although the validity of Mody et al.'s (1997) result was disputed (e.g., Dennenberg, 1999), a similar result was obtained by Rosen and Manganari (2001), who found evidence for a perceptual deficit with speech sounds. This deficit was markedly reduced if nonspeech sounds were used. Moreover, Nittrouer (1999) showed that people with dyslexia rely more strongly on formant transitions than on spectral cues for speech-sound identification in certain paradigms. Most notably, Serniclaes, Sprenger-Charolles, Carre, and Demonet (2001) reported that people with dyslexia are better than normal-reading controls in discriminating within-category differences. This result argues against the assumption that people with dyslexia are impaired in the perception of acoustic transients. If people with dyslexia were impaired in perceiving acoustic transients, then their sensitivity to within- and between-category differences should be smaller than that of normal-reading controls. None of these results are compatible with the assumption that people with dyslexia have a general temporal-auditory deficit.

If people with dyslexia perceive the underlying dimensions of speech as well as do normal-reading participants, then why do they show a categorical-perception deficit at all? A plausible alternative to the auditory-perception account is the hypothesis that people with dyslexia have less well defined phonological categories (Snowling, 2000). This reason might explain why people with dyslexia show less categorical perception in spite of adequate perception of the acoustic cues. In addition, Brady (1997) argued that such an assumption also might explain other phonological deficits that are associated with dyslexia, including impaired phoneme awareness and verbal short-term memory. However, it is now unclear why people with dyslexia develop less sharply defined phonological categories. Even Mody et al. (1997) left open this question: "speech categories may be for unknown reasons, broader and less sharply separated in reading disabled than in normal children" (p. 201) and that "the nature, origin, and extent of the perceptual deficit remains to be determined" (p. 227).

In this study, we hypothesize that people with dyslexia may be impaired in coping with the enormous variation inherent in fluent speech (see, e.g., Farnetani, 1997). Such a deficit would lead to less well defined phonological categories. This point is illustrated in Figure 1. Consider the width dimension of Figure 1A to be one acoustic dimension that differentiates the syllables /ta/ and /ka/ in terms of F3-onset frequency. The height dimension represents the probability of a certain phoneme, with the white function depicting the probability for /ta/ and the gray-shaded function reflecting the probability for /ka/. The depth dimension represents a context variable that influences how strongly a given F3 value is associated with a certain syllable. A prime candidate for this depth dimension is the place of articulation required by the previous segment. If the previous phoneme has an alveolar place of articulation—with a high F3—then a following F3 of medium frequency value is more likely to be associated with the velar /k/ because of the coarticulation of the preceding alveolar segment and the velar segment. This context dependency, illustrated in Figure 1A, is only defined for a finite space, because of the articulatory nature of the width and depth dimension.

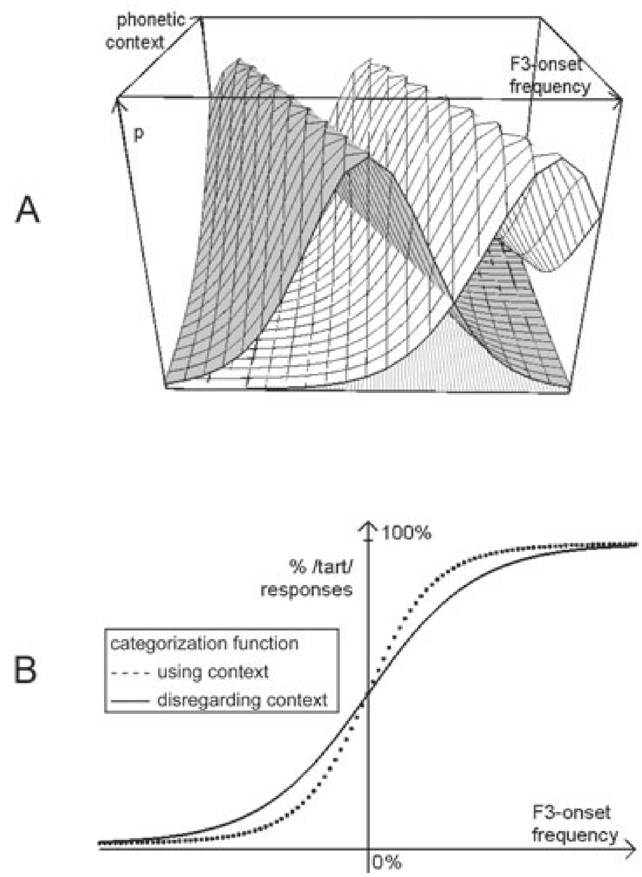


Figure 1. A: The two functions represent a theoretical probability distribution of /t/ and /k/ utterances, with probability represented in the *z*-dimension. The *x*-axis represents a major cue differentiating /t/ and /k/ (e.g., F3-onset frequency), and the *y*-axis represents a context sound influencing the F3-onset frequency. B: The two classification functions resulting from an optimal classification of the data in Panel A. The dotted line represents the classification when context is used; the continuous line represents the best classification when the context dimension is disregarded.

The optimal categorization function for the two overlapping distributions in Figure 1A is given by $p_t / [p_t + p_k]$ (Rojas, 1996), which represents the probability for /t/ divided by the sum of probabilities. Consider what would happen if the context variable (the depth dimension) were not used in categorization. Then, the probability that a certain F3 value is associated with /t/ or /k/ would be given by its mean value over all context positions. This result would increase the overlap between the two categories and, as shown in Figure 1B, would lead to a shallower identification function than the identification function using the context dimension. (The calculations for both categorization functions are provided in the Appendix.) This outcome brings us back to the earlier problem, namely, why do people with dyslexia show a shallower than normal categorization function when they seem able to perceive the underlying acoustic distinction at normal levels? One possible answer to this question is that people with dyslexia handle context-dependent variation in speech inadequately. Therefore, they show the shallower identification function, represented by the continuous line in Figure 1B.

In this article, we investigated whether this hypothesis can be supported. Context effects in speech perception have been stipulated at multiple levels of processing. First of all, context dependencies have been observed at auditory levels of perception (Delgutte, 1997; Lotto & Kluender, 1998). Nevertheless, some context sensitivities seem to arise at speech-specific processing levels (see Fowler, Brown, & Mann, 2000), which we denote here as phonetic-context effects. Finally, Gaskell and Marslen-Wilson (1996, 1998) proposed that some context sensitivities in speech perception arise at a phonological-processing level. Therefore, we examined the extent to which speech perception in children with dyslexia and in normal-reading children is susceptible to influences from the auditory, phonetic, and phonological contexts in Experiments 1, 2, and 3, respectively.

Experiment 1: Effect of Acoustic Context

Overview

In this first experiment, we compared the use of acoustic context information in the identification of a speech sound by children with dyslexia and by normal-reading children. The basis for the identification of the speech sounds is *spectral contrast* (see Holt & Lotto, 2002; Lotto & Kluender, 1998; Lotto, Kluender, & Holt, 1997). Ostensibly, the perceptual system takes into account the acoustic parameters of the context when evaluating a speech cue. A prototypical example is the contrast between an alveolar stop (/d/) and a velar stop (/g/). In prevocalic position, the main cue for this contrast is the onset of the third formant (F3), which is higher in frequency in a /da/ syllable than in a /ga/ syllable. According to the contrast framework, a preceding pure tone should influence the perception of a syllable with an ambiguous "medium" F3 onset in the following ways: If the preceding tone is lower in frequency than that of the F3 onset, then the F3-onset frequency will be judged "high" in comparison to the lower frequency tone, and perceived as /da/, which is characterized by a high F3 onset. Vice versa, the same syllable should be perceived as /ga/ if the preceding tone is higher in frequency than that of the F3 onset of the syllable. Lotto and Kluender (1998) verified both of these predictions.

Such spectral-contrast enhancement would be functionally important in speech perception. Because of coarticulation, contrasts between adjacent speech sounds diminish, especially when two adjacent sounds require quite different positions of the articulators (e.g., tongue tip, jaws, etc.), which leads to noncanonical productions of the speech sounds involved. A mechanism enhancing spectral contrasts should then effectively increase the "production diminished" contrast between two adjacent segments. However, in the case of two speech sounds, which require similar positions for the articulators, the speech sound will be produced in a more or less canonical manner. Because two speech sounds require similar positions of the articulators, no spectral contrast arises. Therefore, a mechanism enhancing spectral contrast will "correct" non-canonical productions of speech sounds while leaving canonical productions unaffected. The resulting representations of the speech sounds, in turn, are more stable over different productions.

To investigate the use of acoustic context by children with dyslexia and normal-reading children, we adopted the paradigm used in by Lotto and Kluender's (1998) Experiment 4 and investigated whether children with dyslexia and normal-reading children differ in the way they use auditory context when identifying speech sounds. Because Dutch does not have a velar voiced plosive, we used a continuum ranging from the unvoiced velar to an unvoiced alveolar plosive (/t/ vs. /k/). In contrast to Lotto and Kluender, we used words instead of nonsense syllables to make the task requirements more transparent for the young participants. In addition, we used natural stimuli. With this design, we made two predictions. First, we predicted that children with dyslexia would have shallower identification functions than normal-reading children. Second, we predicted that auditory context would influence speech-sound identification more strongly in normal-reading children than in children with dyslexia.

Method

Participants

Forty-two second- and third-grade children between the ages of 7;3 (years; months) and 9;10 (mean age = 8.5) participated in the study. Fourteen participants were recruited from the Regional Institute for Dyslexia (RID) in Arnhem and Maastricht, The Netherlands. These 14 participants had been diagnosed as having dyslexia prior to the present study by the RID, which is one of the major specialized dyslexia institutes in The Netherlands. In addition, 28 children were recruited from public schools. These children were tested on two reading tests, two phonological tests (a standardized auditory synthesis test from van Bon's [1982] Taaltest voor Kinderen [Language Test for Children] and an unpublished phoneme-deletion task devised by the RID). Two hearing tests were performed, a pure-tone hearing test at 0.5, 1, 2, and 4 kHz and a speech audiogram in which words had to be identified at levels down to 20 dB. In order to be included in the study, children had to perfrorm at pure-tone tresholds of 20 dB or less and identify at least 50% of the phonemes at 42 dB in the speech audiogram, which is within 15 dB of the age-appropriate norm level. Ten children were excluded from the study; 5 did not reach the criteria set for the hearing test and an additional 5 performed more than 1 *SD* below the age-appropriate mean on one of the reading tests. The descriptive data are shown in Table 1.

The participants with dyslexia had undergone an extensive cognitive diagnosis at the dyslexia institute. This testing protocol included two reading tests, a number of tests for phonological processing (three subtests from the Taaltest voor Kinderen and a phoneme-deletion task devised by the RID). The three standardized subtests were an auditory-synthesis task, an auditory-discrimination task, and a word-recognition task. The auditory-synthesis task asks participants to produce verbally words upon hearing a sequence of phonemes (e.g., /k/ + /a/ + /t/ = *cat*). The auditory-discrimination task requires the child to decide whether two utterances, one from a male and the other from a female, are the same word. In the word-recognition task, spoken words are presented with one or two phonemes deleted (e.g., “ele_ant”), and the child has to pronounce the intended word (e.g., “elephant”).

Children with dyslexia were selected for inclusion in this study based on performance at least 1 *SD* below the age-appropriate mean on two standardized reading tests (Brus & Voeten's [1972] Een-minuut leestest [One-Minute-Reading Test] and the KLEPEL, a pseudoword reading test devised by van den Bos, Lutje Spelberg, Scheepstra, & de Vries, 1994). Moreover, performance had to be within 1 *SD* of the age-appropriate mean on the Dutch version of the Wechsler Intelligence Scale for Children–Revised (WISC-R; WISC-R Projectgroep, 1986) and on a standardized visual-form perception test. In addition, the children with dyslexia had to pass the same hearing tests as the control children in order to be included in the study.

Table 1. Means (and standard deviations) of sample characteristics for both children with dyslexia (CWD) and normal-reading children (NRC).

	CWD		NRC		
	M	*SD*	*M*	*SD*	*t*(30)
Age (years; months)	9.1		8.6		*ns*
IQ (Dutch WISC-R)	105	9.2	—		
Reading level words[a]	6.0	2.7	11.6	2.6	5.9**
Reading level nonwords[a]	6.6	2.8	12.7	2.6	6.1**
Phoneme deletion[b]	17.2	6.4	24.9	4.09	3.9**
Auditory synthesis[a]	11.0	2.9	10.9	3.7	*ns*
Word recognition[a,c]	7.7	—			
Auditory discrimination[a]	7.6	—			

Note. WISC-R = Wechsler Intelligence Scale for Children–Revised (Dutch version).

[a]Standardized scores ($M = 11$, $SD = 2$). [b]Number of correct items (maximal = 28). [c]Norms for 7-year-olds (oldest age range available).

$^{**}p < .01$.

Design

The experiment consisted of two tasks. First, we assessed whether participants were able to discriminate between the endpoints of a speech-sound continuum. Discrimination was measured using a two-alternative forced-choice (2AFC) task with feedback. If participants made more than four errors on the first 20 stimuli, then another 20 stimuli were presented, with a maximum of 60 training stimuli. Participants then listened to the whole continuum of seven speech sounds and identified the speech sounds as either “tart” [“cake”] or “kart” [“card”]. The speech sounds were presented first in isolation. Then the speech sounds were preceded by either a high-frequency sinusoid or a low-frequency sinusoid. The various stimulus combinations yielded a 3 × 7 factorial structure.

Stimuli

A female natural speaker of standard Dutch was recorded digitally (Sony, Model PCM-R500) using a table microphone (Sennheiser, Model K6). The speaker was instructed to say /tart/ and /kart/. The recordings were digitized with a sampling frequency of 44.2 kHz, low-pass filtered at 6.5 kHz, and resampled to 22.1 kHz. A /tart/

utterance was used as a template for the construction of the continuum. The formants of the utterance were estimated using linear predictive coding (LPC) analysis implemented in the software package PRAAT 3.8 (Boersma & Weenink, 1999) with 14 prediction coefficients. The LPC coefficients were used to estimate the glottal source by inverse filtering of the original sound. Because the estimated source did not contain any aperiodic noise, broadband noise was added to the source for the first 25 ms of the source, emulating a 25-ms VOT observed in the original utterance. The LPC-based formants were edited, and a continuum of seven stimuli was created by using seven different formant transitions. In the original utterance, the third formant started at 3.4 kHz. Six variants were created by reducing systematically the step size for the start of the formant transitions by 0.330 bark, thereby preserving the nonlinearity of the original formant transition. This process leads to F3 onset frequencies at 3.40, 3.23, 3.07, 2.92, 2.77, 2.63, and 2.50 kHz for the seven filters. Seven seminatural speech sounds were generated using each of these edited formant filters and the estimated source.

The sinusoids used as context sounds had frequencies of 2.58 and 3.15 kHz, which were just above the lowest F3 onset and just below the highest F3 onset, respectively. Each sinusoid had a duration of 125 ms and was clipped linearly for the first and last 25 ms to prevent audible transients. There was a 25-ms gap of silence between each tone and speech sound.

Apparatus

The experiments were conducted with a mobile lab. Stimulus presentation was controlled from a laptop computer with DELPHI 5.0 software (Borland, Inc., 1999). The sound output of the computer was amplified (Radio Design Labs, Model ST-PH 1) and played to the participants via a headphone (Sony, Model MDR-V900). Experiments were performed in a quiet room with only the experimenter and the participant present.

Procedure

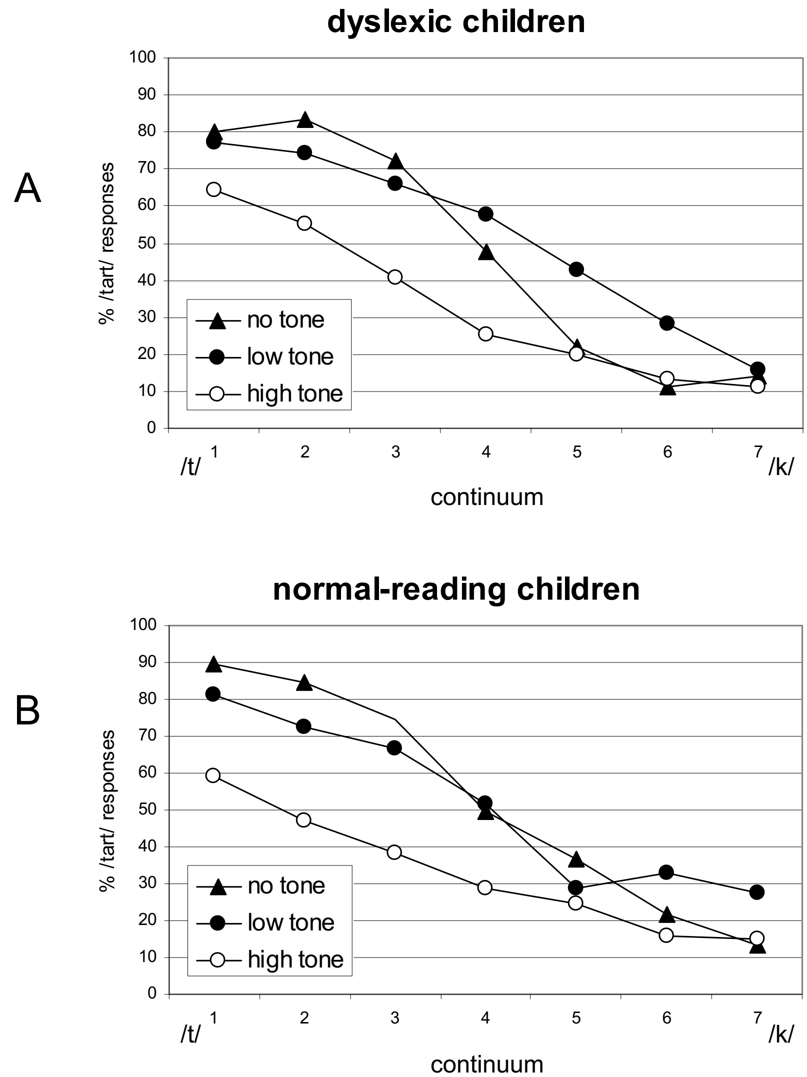
All children were acquainted first with the 2AFC procedure using the pair "huis"–"muis" ["house"–"mouse"]. Two pictures representing the two words were displayed in the upper-left and upper-right corners of the computer screen. Participants were instructed that upon hearing a word, they should indicate which word they heard by pressing an upper-left (q) or an upper-right (p) key of the computer keyboard. (A custom-made cover left only these two keys available for pressing.) After each response, a smiley face indicated to the child whether the choice was correct. None of the children displayed any problems in understanding and performing the 2AFC task. After this practice, children performed a 2AFC task with feedback using only the two endpoints of the seminatural "tart"–"kart" continuum. Two pictures on the computer screen indicated which key was associated with which word. If more than four errors were made on the first 20 trials, then another 20 stimuli were presented, with a maximum of 60 stimuli. Subsequently, all seven seminatural stimuli along the continuum were judged in a block without any precursor sound. In this and the following phase of the experiment, the smiley face only "looked" in the direction of the picture corresponding to the child's response. This procedure did not provide performance-related feedback, but instead stimulated motivation and indicated to the participant that the response was registered. Each stimulus was presented 10 times in random order. The seminatural stimuli then were presented with one of the two precursor tones. Each of the 14 (seven words × two precursor tones) stimuli was presented 15 times in random order. The children were given a short break after every 70 trials. The experiment lasted about 20 min.

Results

The diagnostic testing (see Table 1) revealed that the selection criteria resulted in a clear difference in reading proficiency between the groups. In addition, the sample with dyslexia sample performed significantly worse or below average on three of the four phonological tests.

The individual data from the experimental task were transformed into percent /t/ responses (see Figure 2). These data were subjected to an analysis of variance (ANOVA) with two within-subject variables (context: none, high tone, and low tone; continuum: the seven seminatural stimuli) and one between-subjects variable (group: children with dyslexia and normal-reading children). The ANOVA revealed a significant effect of the continuum, $F(3, 75) = 161.5$, $p < .001$, and a main effect of the context, $F(2, 48) = 21.9$, $p < .001$. Post hoc Bonferroni tests ($p < .05$) revealed that, overall, participants gave fewer /t/ responses in the high-tone condition (32.8%) than in either the low-tone (53.2%) or no-context (50.4%) conditions. The latter two conditions did not differ significantly. There also was a significant interaction of the two within-subjects factors, $F(6, 182) = 7.8$, $p < .001$. To investigate this interaction, we conducted seven ANOVAs comparing the three context conditions at all levels of the continuum with each other. Although context influenced the responses at all levels, post hoc Bonferroni tests showed that the high-tone condition differed from the two other conditions on the first four levels of the continuum (the "/t/ end"). The low-tone condition differed from the other two conditions at the

Figure 2. Mean percentage of /tart/ responses in Experiment 1 as a function of stimulus continuum for the parameter acoustic context by the children with dyslexia (Panel A) and the normal-reading children (Panel B). The seven-step /tart/–/kart/ continuum is shown along the bottom axis of each panel.



last three levels of the continuum (the "/k/ end"), with the exception of the comparison between low tone and no context at the seventh level (the most /k/-like stimulus). However, neither the between-subjects factor (F < 1) nor its interaction with any of the other factors was significant: Continuum × Group, $F(3, 75) = 1.14$, $p = .332$; all other Fs < 1.

The absence of an effect of group might possibly be an artifact of averaging over participants. We therefore fitted a logistic function with two free parameters ($1 / [1 + \exp(-ax + b)]$) to the three individual identification functions in the three different context conditions (see Table 2). These estimates were used in an ANOVA with group as the between-subjects variable and context as the within-subject variable. Context significantly influenced the slope parameter, $F(2, 48) = 15.0$, $p < .001$. Post hoc tests showed that the slope in the no-context condition ($m = 3.65$) was larger than in either the high-tone ($m = 2.01$) or the low-tone ($m = 1.96$) context. The

Table 2. Slope parameters as a function of context parameter for the group with dyslexia and the normal-reading group in Experiment 1.

Group	Context: No tone	Low tone	High tone	*M*	*SD*
Dyslexic	4.033	2.314	1.905	2.751	1.577
Normal reading	3.272	1.717	2.020	2.130	1.589

latter two conditions did not differ significantly. The between-subjects variable did not have a significant effect or an interaction with the context variable (Fs < 1). Notably, the participants with dyslexia had a larger mean slope value in the no-context condition. Therefore, the fact that we did not find a speech-perception deficit cannot be attributed to lack of statistical power.

Discussion

The diagnostic testing showed large differences in reading ability between the groups, which was part of the selection criterion. This testing also revealed that the sample of children with dyslexia exhibited clear deficits on phonological-processing tasks. These deficits were evident in a phoneme-deletion task, an auditory word-discrimination task, and a word-recognition task. The finding of no differences on the auditory-synthesis task may be explained by the fact that training in auditory synthesis is an important part of the school curriculum and the remediation program of the dyslexia institute (RID).

The experiment revealed the expected main effects: First, changing the F3-onset frequency influenced the perception of the initial stop (i.e., either /t/ or /k/). Second, the precursor sounds influenced the perception of the speech sounds in line with the frequency-contrast model. Participants were more likely to produce a /t/ response, associated with a high F3-onset frequency, after a low-frequency precursor tone than after a high-frequency precursor tone. Therefore, the experimental stimuli and procedure met the expectations for this experiment, despite the fact that both groups performed similarly in this experiment. We could find neither any evidence for a speech-perception deficit nor evidence that the group with dyslexia made less use of the context. One possibility why we did not find a speech-perception deficit might be that the formant transition of the stop was too long (80 ms). Tallal (1980) proposed that the speech-perception problems of people with dyslexia are restricted to brief transitions, shorter than 50 ms. There is, however, evidence showing that speech-perception problems can be found with long-lasting stimulus differences. de Gelder and Vroomen (1998) found a speech-perception deficit using a synthetic /ba/–/da/ continuum with a transition time of 80 ms, which is equal to the transition time used here (see also Heim et al., 1999). Masterson, Hazan, and Wijayatilake (1995) reported problems with steady-state fricatives, and Post, Foorman, and Hiscock (1997) reported problems in vowel perception. Therefore, the relatively long formant-transition times used in this experiment do not seem to be responsible for the present failure to find a speech-perception deficit in the group with dyslexia.

The other finding contradicting our initial hypotheses was that children with dyslexia and normal-reading children did not differ in their use of acoustic context information. This result, however, does not rule out our initial hypothesis that people with dyslexia may make less use of context in the identification of speech sounds. It is conceivable that the use of the acoustic context may not be impaired, but that the use of speech-specific context on higher levels of processing may be impaired. Such an argument is buttressed by the findings of Fowler et al. (2000). They showed that speech-specific context effects may be dissociated from auditory-context effects. Fowler et al. also argued that spectral-contrast effects result from forward masking. If auditory context effects are based on different mechanisms than are speech-specific context effects, then it is possible that children with dyslexia and normal-reading children differ in their use of speech-specific context. This idea was tested in Experiment 2.

Experiment 2: Effect of Phonetic Context

Overview

In this experiment, we investigated the influence of phonetic context information on speech-sound identification in children with dyslexia and in normal-reading children. Here we made use of the compensation-for-coarticulation paradigm, which is one of the cornerstones of the direct-perception theory for speech perception (Fowler, 1996). As in Experiment 1, the target sounds were drawn from a continuum ranging from /ta/ to /ka/. We used the syllables /al/ and /ar/ as context sounds. Mann (1980) showed that such precursor syllables influence the perception of the velar–alveolar distinction in stops. Participants are more likely to hear a speech sound as /ta/ after /ar/ than after /al/. This may be explained in terms of the direct-perception theory: Specifically, participants are more likely to hear an ambiguous stop as /t/ after /ar/ than after /al/ because /r/ requires a tongue position very different from the prototypical tongue position for a /t/. In contrast, a /k/ requires a similar tongue position as /r/. Therefore, it is more likely after /ar/ that the ambiguous stop is a non-canonical version of /t/ rather than of /k/. Vice versa, the same ambiguous stop is interpreted as a /k/ after /al/ because an /lt/ sequence affords less movement from the articulators than an /lk/ sequence.

Like the auditory-context effects, compensation for coarticulation is functional in speech perception, in as much as it compensates for context-dependent variance that arises in speech production. This compensation, in turn, allows a more narrowly defined representation of the speech sounds in question. Most important for current purposes, it seems that such phonetic-context effects are distinct from auditory-context effects (Fowler et al., 2000). Therefore, we hypothesized that children with dyslexia and normal-reading children may differ in their use of phonetic-context information, even though they did not differ in the use of an auditory context.

Method

Participants and Apparatus

The participants and apparatus were the same as in Experiment 1.

Design

The experiment consisted of two tasks. First, we acquainted the participants with the stimuli in a 2AFC discrimination task with feedback. For this task the children had to discriminate each of the endpoints of the continuum, which were preceded by one of the two precursor syllables. The second task began after 20 trials. In this second task, participants had to categorize the seven stimuli in the continuum, each of which was preceded by one of the precursor syllables. No feedback was given. This design produced a 2 (/ar/ vs. /al/ precursor syllable) × 7 (continuum stimuli) factorial structure.

Stimuli

The same /tart/–/kart/ continuum was used as in Experiment 1. The precursor syllables were synthesized by applying different filters to the source of the vocal portion of the /tart/ utterance used for the continuum. Therefore, the precursor syllables and the stimuli of the continuum sounded as if they were coming from the same speaker in a single utterance. The precursor syllables had a duration of 300 ms. The filters for both syllables were identical for the first 170 ms, with F1 = 900, F2 = 1500, F3 = 3200, and F4 = 4900. At t = 170 ms, the filter settings started to differ between the /al/ and /ar/ syllable. The formants for the /al/ syllable changed linearly to reach F1 = 630, F2 = 1020, F3 = 3740 at t = 0.3 s. For the /ar/ syllable, the formants changed linearly to reach F1 = 585, F2 = 2060, and F3 = 2360 at t = 0.3 s. These formant transitions indicate a movement of the tongue to the front of the mouth in the case of the /al/ syllable and a movement to the back of the mouth for the /ar/ syllable (cf. Ladefoged, 1996). The interstimulus interval (ISI) was adjusted to achieve a natural sounding bisyllable with an appropriate closure time, which was given at 50-ms ISI.

Procedure

Experiment 2 was performed in a second session at least 1 week after Experiment 1. All children were familiar with the display and the response mode. The experiment started with 20 training trials, in which participants classified the endpoints of the /tart/–/kart/ continuum, which were preceded by one of the precursor syllables. A smiley face indicated whether the classification was correct. In the main experiment all seven stimuli of the continuum were presented, each preceded by one of the precursor syllables. In this part, the smiley face looked in the direction of the picture corresponding to the response of the child. Each of the 14 experimental stimuli was presented 15 times in randomized order. At the conclusion of the experiment, the participants performed a 20-trial posttest to identify the precursor syllables as either /al/ or /ar/ in a 2AFC task with feedback. The whole experimental session lasted about 15 min.

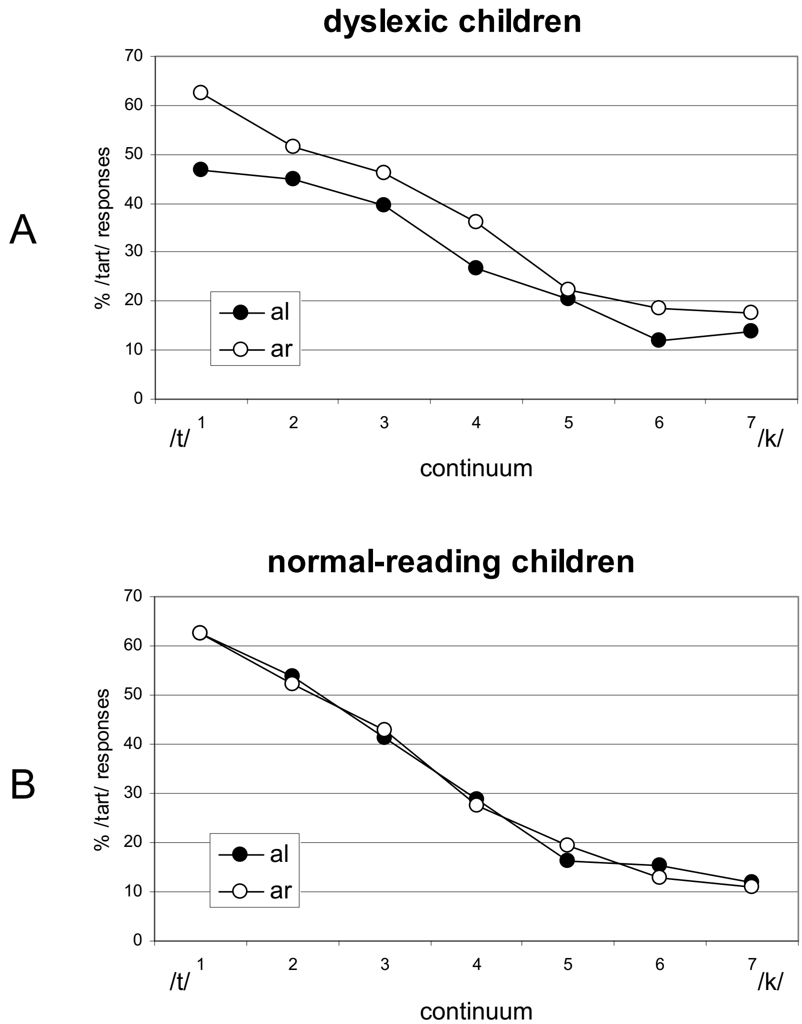
Results

The posttest data showed that all participants perceived the precursor syllables as intended. The mean percentage correct score was 94.4% (children with dyslexia: 93.6%; normal-reading: 95%), which is equivalent to one error on the 20-trial test. Twenty-four of the 32 participants did not make more than one error; the maximum number of errors was four.

The data from the experimental session were transformed into percentage of /tart/ responses for each individual in each condition. These data (see Figure 3) were subjected to a repeated measures ANOVA with context (/al/ vs. /ar/) and continuum (the seven stimuli of the continuum) as within-subjects factors and group (children with dyslexia vs. normal-reading) as the between-subjects factor. Both within-subjects factors were significant: $F(1, 30) = 5.5$, $p < .05$, for context; $F(2, 60) = 41.0$, $p < .001$, for continuum, while their interaction was not significant ($F < 1$). Moreover, the interaction between context and the group factor was significant, $F(1, 60) = 5.7$, $p < .025$. To investigate the nature of this interaction, we tested the effect of context in both groups separately. Context did affect responses in the group with dyslexia, $F(1, 13) = 8.4$, $p < .025$, but not in the normal-reading group ($F < 1$). In the group with dyslexia, the context effect was in the expected direction. Namely, after /al/ there were more /kart/ responses than after /ar/, indicating compensation for coarticulation. The between-subjects factor and the three-way interaction were not significant (Fs < 1).

In the absence of a context effect in the normal-reading group, we also analyzed the training data for context effects. The mean percentage of correct responses

Figure 3. Mean percentage of /tart/ responses in Experiment 2 as a function of stimulus continuum for the parameter phonetic context by the children with dyslexia (Panel A) and the normal-reading children (Panel B). The seven-step /tart/–/kart/ continuum is shown along the bottom axis of each panel.



for each of the four stimuli is shown in Table 3. An ANOVA revealed that all participants generally made more errors for /tart/ (66.0% correct) than for /kart/ (88.9% correct), $F(1, 30) = 28.1$, $p < .001$, whereas the precursor phoneme did not have an influence ($F < 1$).

Table 3. Percentage correct /t/ and /k/ (stop) responses as a function of context parameter for the group with dyslexia and the normal-reading group.

	Context			
	/al/		/ar/	
Group	/t/	/k/	/t/	/k/
Dyslexic	52.9	90.0	68.7	82.9
Normal reading	68.8	98.8	74.1	83.5

Most important, the interaction between target and context was significant, $F(1, 30) = 8.8$, $p < .01$. Specifically, /tart/ was more often recognized correctly in the /ar/ context than in the /al/ context, whereas /kart/ was more often recognized correctly in the /al/ context than in the /ar/ context. This trend is in line with compensation for coarticulation. An /al/ context biases perception toward /kart/, whereas an /ar/ context biases responses toward /tart/. These effects did not interact with the group factor (Fs <1).

In addition, we analyzed the individual classification functions by fitting a logistic curve (see Table 4). The individual slope parameters were then analyzed with an ANOVA using context and group as factors. Neither factor influenced the slopes (Fs < 1), nor did the interaction reach significance, $F(1, 30) = 2.36$, $p < .138$. In addition, participants were overall more likely

Table 4. Slope parameters as a function of context parameter for the group with dyslexia and the normal-reading group in Experiment 2.

	Context			
Group	/al/	/ar/	*M*	*SD*
Dyslexic	3.089	1.870	2.480	2.740
Normal reading	2.239	2.876	2.557	2.416

to respond /kart/ in both context conditions of this experiment than in the no-context condition of Experiment 1, $t(31) = 5.3$, $p < .001$.

Discussion

As in the previous experiment, individuals with dyslexia did not show shallower identification functions in a speech-sound classification task. That is, we again failed to find evidence to support the hypothesis that dyslexia is associated with a speech-perception deficit. However, children with dyslexia and control children differed in the way phonetic context information was used. Contrary to our expectations, context influenced identification more strongly in the group with dyslexia than in the control group. The control group only showed a context effect in the easier training part of the experiment, when only the continuum endpoints were presented. The group with dyslexia showed a context effect in both the training and the experimental phases.

The shallower identification function in this experiment indicated that the task was more difficult for the children to perform than that in the first experiment. Perhaps the difficulty of the task in Experiment 2 obliterated a context effect for the control group, which held up for the children with dyslexia both in the training and experimental phases. This last result parallels a report by Nittrouer (1999). She found that children with dyslexia used the range of acoustic cues for a given phonemic distinction differently than did normal-reading children. Children with dyslexia children placed a heavier weight on a context-dependent cue, the formant transition, than on a local cue, the spectral composition of the noise, whereas normal-reading children showed the opposite pattern. Similarly, the control group in the present experiment did put less weight on a contextual cue than did the group with dyslexia. The pattern of our group with dyslexia resembles the results obtained with preschool children, described by Nittrouer (e.g., 1992) in her developmental-weighting-shift model. This may indicate that children with dyslexia fail to develop optimal speech-recognition routines.

Again, however, the present results fail to support our initial hypothesis about context effects in speech perception. As in the Experiment 1, the group with dyslexia used the context information in speech-sound classification in a way that is appropriate for compensation for coarticulation.

Experiment 3: Effects of Phonological Context

Overview

Up to this point, we investigated the use of acoustic and phonetic context information in the identification of speech sounds. The results did not show the expected effect of less context sensitivity in the dyslexic group. Nevertheless, such an effect might be found when a context effect is examined that arises at a higher level of processing. An example of such high-level, context sensitivity is the "phonological-inference" mechanism proposed by Gaskell and Marslen-Wilson (1996, 1998). This mechanism is supposed to aid the recognition of words that have undergone phonological assimilation. Phonological assimilations are similar to coarticulation in that the acoustic manifestation of a phoneme is influenced by adjacent phonemes. In contrast to coarticulation, the influence from phonological assimilation is so strong that it blurs phonological contrasts—at least superficially. To give an example of a phonological assimilation, consider the utterance "garden bench." The /n/ in "garden" may be assimilated by the /b/ in "bench" leading to the utterance "gardembench." This change of the final nasal sound in "garden" to become an /m/ occurs only if the next segment is a labial obstruent. That is, the /n/ does not change in the utterance "garden chair." Hence, *"gardemchair" is a forbidden form.

According to the model of phonological inference, the perceptual system evaluates assimilated word forms by using the phonological context of the assimilated segment. Hence, in perception, assimilated forms as "gardem" are only accepted as instances of the respective canonical form, if the phonological context allows the assimilation. Therefore, "gardem" is accepted as an instance of "garden" in "gardembench" but not in *"gardemchair." Thus, phonological inference is an instance of a context effect. The context determines whether the assimilated form is recognized as an instance of a canonical form.

This context effect is conceptually different from the compensation for coarticulation effect that was the subject of the previous experiment. In compensation for coarticulation, it is the phonetic gesture of the context sounds that drives the context sensitivity. In the model of phonological inference, it is not the phonetic gesture, but rather the abstract phonological features, that are crucial. The assimilation is compensated for only if the phonological feature values of the context are such that the assimilation is allowed. Given these conceptual differences, we may expect phonological context effects caused by phonological inference to dissociate from acoustic and phonetic context effects. Accordingly, we tested whether this phonological context effect was different in children with dyslexia and normal-reading children.

To this end, we applied a method of testing phonological inference established by Mitterer and Blomert (2003). They showed that the context sensitivity in the perception of phonological assimilation could be probed with a 2AFC task. Their results showed that participants, when asked to indicate whether they heard the Dutch word "tuin" ["garden"] pronounced properly or wrongly with a final /m/, were readily able to do so. Performance also was near ceiling level when the composite "tuinstoel" ["garden chair"] was used. However, the results were different when the composite "tuinbank" ["garden chair"] was used. In this case, the pronunciation with /m/ might be the consequence of place assimilation. Indeed, it turned out that participants made a significant number of errors by misperceiving the stimulus "'tui<u>m</u>bank' as "tui<u>n</u>bank." That is, they compensated for the possible assimilation. The change from /n/ to /m/ in production is countered by a change from /m/ to /n/ in perception. Mitterer and Blomert showed this effect cannot be attributed to a lexical top-down effect or to decision-making processes. Rather, the effect seems to be prelexical. Here, we used the same 2AFC paradigm to compare phonological context sensitivity in children with dyslexia and normal-reading children.

Method

Participants and Apparatus

The participants were the same as in the previous experiments. The experiment was conducted in the same session as Experiment 2. The apparatus was the same as in the previous experiments.

Design

The design entailed three factors, two within-subjects factors and a between-subjects factor, group (children with dyslexia vs. control). The first within-subjects factor was the identity of the word-final nasal of the target word "tui…," which could be /n/ or /m/. The second within-subjects factor was the context following the target word. There could be no context, a viable context ("bank") in which assimilation ("tuimbank") may occur in natural speech, and an unviable context ("stoel") in which assimilation is not allowed to occur. This leads to a 2 × 2 × 3 design with the factors group, nasal murmur (/n/ vs. /m/), and context (none, viable [i.e., "bank"], and unviable [i.e., "stoel"]).

Stimulus Material

A male native speaker of Dutch was recorded uttering "tuinbank" [tœynbaŋk], "tuimbank" [tœymbaŋk], "tuinstoel" [tœynstuˑl], and "tuimstoel" [tœymstuˑl] several times. The speaker was chosen because of his low f0 (75–80 Hz), which did not vary greatly between utterances. Therefore, cross-spliced utterances sounded natural. The context words "stoel" [stuˑl] and "bank" [baŋk] were spliced from two other utterances. By cutting 5 ms of the friction noise of the /s/ in [stuˑl], the length of this sound was made equivalent to the length of the [baŋk] sound. This duration includes a silent period of 25 ms before the onset of the /b/, which is an appropriate closure duration in natural utterances of [tœynbaŋk]. The stimuli differed slightly in length (<1 ms) because of the constraint of splicing at zero crossings. The onset and nucleus of [tœyn] then were spliced from the nasal murmur, using the lowest amplitude between the vowel and nasal part as cutting point. This "tui" [tœy] utterance was concatenated with an /n/ and /m/ nasal murmur spliced from two other tokens, resulting in tokens of [tœyn] and [tœym] that differed only in nasal murmur. These tokens then were concatenated with "stoel" [stuˑl] and "bank" [baŋk], leading to three [tœyn] and [tœym] stimulus pairs: one without context, one with a "stoel" [stuˑl], and one with a "bank" [baŋk] context.

Procedure

Participants looked at the computer screen displaying a large *n* in the upper-left corner and a large *m* in the upper-right corner. They were instructed to press the upper-left key of the computer keyboard (q) upon hearing "tui<u>n</u>" and the upper-right key (p) upon hearing "tui<u>m</u>." A custom-made shell left only these two keys available for pressing. Participants first went through a short training phase of six trials with feedback provided by a smiley face on the computer screen to clarify any problems with the task instruction. All children understood the nature of the task without any problems. The utterances "tuin" and "tuim" were presented in isolation in this training phase.

In a second phase, no explicit feedback was given to the children. Instead, the smiley face looked in the direction of the picture associated with the response. All participants started with the no-context condition ([tœyn] "tuin" and [tœym] "tuim"). After presenting the block with the targets in isolation, the orders of presentation of the viable-context block ("tuinbank" vs. "tuimbank") and unviable-context block (“tuinstoel” vs. “tuimstoel”) were counterbalanced. One block consisted of 50 stimuli presented in randomized order. The experiment lasted about 10 min.

Results

The average results of both groups coded as percentage correct responses are shown in Table 5. These data were evaluated with an ANOVA, which revealed significant main effects of nasal murmur, $F(1, 30) = 11.7$, $p < .005$, and context, $F(3, 43) = 100.3$, $p < .001$, and a significant interaction between the main effects, $F(1, 42) = 23.3$, $p < .001$. This interaction indicates phonological inference. In the viable-context condition, participants showed a bias toward (mis)perceiving “tuimbank” as “tuinbank.” Neither the main effect for group ($F < 1$) nor any of the interactions with a within-subjects variable attained significance: Nasal Murmur × Group, $F(1, 30) = 2.7$, $p > .1$; all other Fs < 1).

Discussion

The results replicated the patterns observed with adult participants (Mitterer & Blomert, 2003). The identification task was more difficult in the viable context than in either the unviable context or without a context. In addition, there was a bias toward responding with “tuinbank,” the canonical form, in the viable condition. However, as in the previous experiments, the group factor did not have a measurable influence on the responses. The children with dyslexia did not make more errors in classifying the two nasal murmurs and this was not due to a ceiling effect. Most participants found the task challenging, and this fact is reflected in scores that were just over 80% correct performance in the no-context condition. In addition, there was a similar bias towards the canonical form “tuinbank” in both the group with dyslexia and the control group.

Controlling for a Speech-Perception Deficit

In three experiments, we did not find any effect for a speech-perception deficit in our sample with dyslexia. Several studies have reported that perhaps only a subgroup of people with dyslexia show speech-perception deficits (Joanisse, Manis, Keating, & Seidenberg, 1999; Ramus, Rosen, Dakin, Day, Castellote, White, & Frith, 2003; for a review, see Ramus, 2003). It is thus conceivable that we, due to a sampling error, might have included an atypical sample of individuals with dyslexia. To test this hypothesis, we tried to replicate a well-controlled study by Reed (1989), which reported a speech-perception deficit. We included the same children with dyslexia who participated in Experiments 1, 2, and 3 in this study (Blomert & Mitterer, 2004). Presumably, if we had included a biased sample of participants with dyslexia in our current study (i.e., a sample without a low-level speech perception problem), then we should not have been able to replicate Reed’s results.

Table 5. Mean of the percentages of correct /n/ and /m/ responses as a function of context parameter for the group with dyslexia and the normal-reading groups in Experiment 3.

	Context					
	None		Unviable: /stoel/		Viable: /bank/	
Group	/n/	/m/	/n/	/m/	/n/	/m/
Dyslexic	81.7	78.3	79.7	77.1	68.9	34.3
Normal reading	81.6	84.6	75.3	81.1	67.8	44.7

In this replication study, Blomert and Mitterer (2004) tested 10 of the 14 children with dyslexia who participated in Experiments 1, 2, and 3. Furthermore, 12 normal-reading children, who did not take part in any of the previous studies, were recruited as a control group. These normal readers also completed the cognitive testing and the categorical-perception task with the [tart]–[kart] stimuli, which the participants with dyslexia had already performed as participants in Experiment 1 of the present study. In addition, both groups completed a categorical-perception task with speech stimuli based on the parameters in Reed (1989). These were synthetic-speech syllables ranging from /ba/ to /da/. The majority of the original sample of children with dyslexia participated in this task. The diagnostic testing of these children with dyslexia showed that this group did not differ from the original sample. Furthermore, the differences between the experimental and control groups in reading level and phonological skills were comparable to the original samples. Thus, this latter study appears to rule out a sampling bias among our children with dyslexia. Our current study replicated two main results reported by Blomert and Mitterer (2004). First, the results with the speech-sound continuum used in Experiment 1 again revealed no differences between children with dyslexia and control participants (who were a completely new sample). Second, we replicated a speech-perception deficit with a synthetic speech continuum as reported by Reed, which is in agreement with most studies reporting speech-perception deficits in people with dyslexia (e.g., Hurford & Sanders, 1990; Tallal & Piercy, 1974, 1975). Thus, the results revealed that the current sample of children with dyslexia is not an atypical subsample of dyslexia. That is, they showed expected perceptual deficits, but only when tested in the way described in previous studies (i.e., Reed, 1989). It seems therefore that this deficit is more subtle and stimulus-dependent than would be predicted by a hypothesis based on an auditory (temporal) processing deficit.

General Discussion

A number of studies have suggested that people with dyslexia suffer from a subtle speech-perception deficit, which becomes evident in categorical-perception tasks (Godfrey et al., 1981; Hurford & Sanders, 1990; Reed, 1989). Recent results (Mody et al., 1997; Nittrouer, 1999; Rosen & Manganari, 2001; Serniclaes et al., 2001) indicate that sensitivity to speech cues is not impaired in people with dyslexia and, therefore, the nature of the speech-perception deficit remains elusive.

First, we investigated whether the speech-perception deficit displayed by children with dyslexia is a consequence of insufficient context sensitivity in speech perception. Although it may not be immediately apparent how insufficient context sensitivity could lead to a speech-perception deficit, a simulation of the effects of a context-sensitivity deficit on the performance in a categorical-perception task showed that inadequate handling of context leads to shallower identification curves (see Figure 1). The studies that assumed a comprehension deficit in dyslexia often reported shallower identification curves for participants with dyslexia. Accordingly, we performed three experiments probing acoustic, phonetic, and phonological context sensitivity (Experiments 1, 2, and 3, respectively) in children with dyslexia and control children. We found no evidence for either a speech-perception deficit or insufficient compensation for context-dependent variation in natural speech by children with dyslexia in any of the three experiments. Nevertheless, one group difference was found in Experiment 2, in terms of a phonetically based context effect. Namely, children with dyslexia were influenced more strongly by the context than were their normal-reading peers. This finding is in line with a result obtained by Nittrouer (1999). In her view, people with dyslexia do not integrate speech cues properly to achieve phonological categorization and may weight the coarticulatory cue in the context more strongly than the cues in the segment itself.

Our sample of children with dyslexia was not an atypical group of individuals with dyslexia, based on evidence reported by Reed (1989). Our sample clearly showed problems on phonological-processing tasks and speech-perception deficits when synthetic speech was used, thus replicating the main finding of Reed. Therefore, it is unlikely that the current results may be explained by a random sampling error.

The null results in this study with regard to the use of context in speech perception are intriguing. Mody et al. (1997) noted that heretofore the nature of the speech-perception deficit in people with dyslexia had not been explored. Because the hypothesis that people with dyslexia suffer from low-level acoustic deficits has serious problems explaining recent data, we explored the possibility that children with dyslexia suffer from insufficient context sensitivity and obtained "conclusive" null results. We found that the children with dyslexia did not show less context sensitivity than the normal-reading control group. Therefore, a speech-perception deficit in dyslexia apparently cannot be explained by insufficient compensation for variance in the speech signal. People with dyslexia adequately use acoustic, phonetic, and phonological context information when identifying a given speech sound.

In this context, we note that McQueen and Cutler (2001) argued that normalization processes in speech perception reflect some form of intermediate representations. By filtering variance out of the input signal, normalization processes yield an abstract code that is instrumental in lexical access. Although many different versions of this abstract code are possible (e.g., phonological features, phonemes, demisyllables), these abstract representations are much closer to a representation of phonemes than the raw acoustic input. Hence, the present results indicate that children with dyslexia may develop nonimpaired intermediate representations based on adequate normalization processes. Therefore, it seems worthwhile to consider the possibility that it is the processing of phonological information to achieve lexical access, and not the phonological representations per se, that is impaired in children with dyslexia. If some aspect of online phonological processing is slowed down or otherwise deviant from the time-locked obligatory processes for word recognition, then this may just be as devastating for the global phonological process as inadequate phonological representations (e.g., recently we found event-related electrophysiological evidence for deviances in early phonological processing during word recognition in dyslexia [Bonte & Blomert, in press]).

A second related finding of the current study is that we not only found null effects for context sensitivity but also did not find a categorical speech perception deficit when using seminatural speech. Blomert and Mitterer (2004) replicated this finding in an independent study. However, they also showed that the same group with dyslexia exhibited a speech-perception deficit when presented with a synthetic speech-sound continuum very similar to the continuum used by Reed (1989). This difference between seminatural and synthetic speech may be associated with the processing of familiarity of the stimulus material. The seminatural speech used here is of similar quality to that encountered in everyday life (e.g., in telephone conversations). This realistic quality is not afforded by synthetic speech stimuli, especially if qualitative typical distortions of natural voice sources are missing from the stimuli (see Klatt & Klatt, 1990). This qualitative difference may account for discrepancies between our studies and those of Reed (1989) or Hurford and Sanders (1990).

Summary and Conclusion

In this study, we explored two aspects of speech perception in children with dyslexia. We tested first the acuity of speech perception and second the ability to use acoustic, phonetic, and phonological contexts in speech-sound identification. The children with dyslexia did not show any speech-perception deficit for natural speech stimuli. Moreover the children with dyslexia showed sensitivity to acoustic and phonological contexts that was similar to that measured for normal reading children. In addition, they used the phonetic context to a greater extent than did the control children. This last result is consistent with Nittrouer's (1999) finding that children with dyslexia weigh contextually dependent cues more strongly than they do local, context-independent cues. Most important, however, the current study indicates that the quality of the phonemic representations used in speech perception may be similar in children with dyslexia and normal-reading children. That is, the context compensation processes that are instrumental in building and maintaining phonemic representations seem to function properly for children with dyslexia. We therefore suggest that the phonological core deficits in developmental dyslexia may be attributed to deviancies in online phonological processing rather than to a phonological-representation deficit per se.

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Appendix. Equations for the probability and categorization funciton in Figure 1.

The two distributions are quasinormal distributions using the derivative of the logistic function. This makes the equations and integration in Step 2 more manageable than the use of a Gaussian distribution. The probability distribution is then given by Equation A1, which is only defined for [$-5 > x > 5$] and [$-2 > y > 2$]:

$$p_1(x, y) = \frac{\exp(-x + y + \mu)}{[1 + \exp(-x + y + \mu)]^2} \tag{A1}$$

where p_1 is the probability of a given phoneme, x is a variable representing the major acoustic cue for a phoneme distinction (e.g., F3-onset frequency), y is a variable for the phonetic context (e.g., backness of the preceding phoneme), and μ is the phoneme-specific mean of the x-axis.

Using this equation with the $\mu_t = -2$ and $\mu_k = 2$ gives rise to the distributions in Figure 1A. If the distribution of /t/ and /k/ is calculated just along the x-dimension, disregarding the y-dimension, then the probability for a given phoneme at any x is the mean value of $p_1(x, y)$ in Equation A1 in the interval $-2 < y < 2$. For a given value of x, this is the area under p_1 at x in the interval $-2 < y < 2$ divided by four, the length of the interval.

$$\begin{aligned} p_2(x, y) &= \frac{1}{2 - (-2)} * \int_{-2}^{2} \frac{\exp(-x + y + \mu)}{[1 + \exp(-x + y + \mu)]^2}\, dy \\ &= \frac{1}{4} * \frac{1}{1 + \exp(x + \mu - 2)} - \frac{1}{4} * \frac{1}{1 + \exp(x + \mu + 2)} \end{aligned} \tag{A2}$$

where x, y, and μ are the same variables as in Equation A1.

To calculate the optimal categorization, we have to compute $p(k) / [p(t) + p(k)]$, in which $p(t)$ and $p(k)$ are given by putting in the appropriate mean in Equation A1. Because the overlap of the three-dimensional function is identical for all y, we can calculate the categorization function for any value of y. For $y = 0$, the categorization function is given by Equation A3, which is represented by the dotted line in Figure 1B.

$$C_1(x) = \frac{\dfrac{\exp(-x + 2)}{[1 + \exp(-x + 2)]^2}}{\dfrac{\exp(-x + 2)}{[1 + \exp(-x + 2)]^2} + \dfrac{\exp(-x - 2)}{[1 + \exp(-x - 2)]^2}} \tag{A3}$$

where x is the same variable as in Equation A1.

The optimal categorization function when disregarding the phonetic-context variable y can be calculated using probability distribution given in Equation A2 with the appropriate means for $p(t)$ and $p(k)$. Again, we calculate $p(k) / [p(t) + p(k)]$, but now with the probability function given in Equation A2. The continuous line in Figure 1B represents this function.

$$\begin{aligned} C_2(x) &= \frac{\dfrac{1}{4} * \dfrac{1}{1+\exp(x+2-2)} - \dfrac{1}{4} * \dfrac{1}{1+\exp(x+2+2)}}{\dfrac{1}{4} * \left(\dfrac{1}{1+\exp(x+2-2)} - \dfrac{1}{1+\exp(x+2+2)} + \dfrac{1}{1+\exp(x-2-2)} - \dfrac{1}{1+\exp(-x-2+2)} \right)} \\ &= \frac{\dfrac{1}{1 + \exp(x)} - \dfrac{1}{1 + \exp(x + 4)}}{\dfrac{1}{1+\exp(x-4)} - \dfrac{1}{1+\exp(x+4)}} \end{aligned} \tag{A4}$$

where x is the same variable as in Equation A1.