Perceptual Discrimination of Speech Sounds in Developmental Dyslexia

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Experiments previously reported in the literature suggest that people with dyslexia have a deficit in categorical perception. However, it is still unclear whether the deficit is specific to the perception of speech sounds or whether it more generally affects auditory function. In order to investigate the relationship between categorical perception and dyslexia, as well as the nature of this categorization deficit, speech specific or not, the discrimination responses of children who have dyslexia and those of average readers to sinewave analogues of speech sounds were compared. These analogues were presented in two different conditions, either as nonspeech whistles or as speech sounds. Results showed that children with dyslexia are less categorical than average readers in the speech condition, mainly because they are *better* at discriminating acoustic differences between stimuli belonging to the same category. In the nonspeech condition, discrimination was also better for children with dyslexia, but differences in categorical perception were less clear-cut. Further, the location of the categorical boundary on the stimulus continuum differed between speech and nonspeech conditions**.** As a whole, this study shows that categorical deficit in children with dyslexia results primarily from an increased perceptibility of within-category differences and that it has a speech-specific component. These findings may have profound implications for learning and re-education.

KEY WORDS: dyslexia, categorical perception, sinewave speech, motor theory

Dyslexia is characterized by a severe reading impairment without any physiological or psychological problems. There is increasing concern about dyslexia, as it has important educational consequences and affects some 8–10% of the population (Shaywitz, 1998). Different forms of dyslexia seem to prevail, one orthographic and one phonological, and each seems to affect a specific aspect of the reading process. Written words can be processed in two different ways, either directly by orthographic processing or indirectly by first transcoding the letters in oral language units (Coltheart, Curtis, Atkins, & Haller, 1993). Surface dyslexics have more difficulties in the reading of irregular words than with pseudowords, which suggests that it is the orthographic route that is most affected (Castles & Coltheart, 1993). Phonological dyslexics have more difficulties in the reading of pseudo-words, thereby indicating that the phonological route is more severely affected. In studies based on accuracy scores with English-speaking children, more phonological dyslexics than surface dyslexics were found as compared to chronological-age controls (Castles & Coltheart, 1993; Manis, Seidenberg, Doi, McBride-Chang, & Petersen, 1996; Stanovich, Siegel, & Gottardo, 1997). However, when compared to reading-age controls, the surface profiles almost disappeared. Similar results were found in a recent study with French-speaking children when processing time was taken into account (Sprenger-Charolles, Colé, Lacert, & Serniclaes, 2000). In the French study, both phonological and surface dyslexics were found to be impaired only in phonological skills when compared to reading level controls, either in processing time (for the phonological dyslexics) or in accuracy (for the surface dyslexics). These results minimize the extent of the dissociation between the two profiles and suggest that developmental dyslexia can be primarily explained by an underlying phonological impairment.

Nature of the Deficit in Dyslexia

There is growing evidence that children with dyslexia do not apprehend speech sounds in the same way as average readers. A striking difference lies in phonemic awareness (i.e., a difference in the conscious access to phonemes), evidenced in tasks involving the manipulation of phoneme segments within words or pseudowords (Liberman, 1973; Liberman, Shankweiler, Fisher, & Carter, 1974). Early phonemic awareness skills are predictive of later reading success (Liberman & Shankweiler, 1979), and a deficit in phonemic awareness has been shown to be one of the most consistent deficits in persons who have dyslexia, whether children or adults (Bruck, 1992; Nicolson & Fawcett, 1994; Wimmer, 1993). Studies have suggested that dyslexics' difficulties are specific to phonemic awareness rather than musical awareness, for example (Morais, Cluytens, & Alegria, 1984). Furthermore, before beginning to learn to read, children who would later become dyslexic have been shown to exhibit impaired skills in phonemic awareness (Liberman, 1973; Sprenger-Charolles et al., 2000; Wimmer, 1996) but not in musical awareness (Sprenger-Charolles et al., 2000). Developmental dyslexia was also found to be associated with a deficit in phonological short-term memory (Brady, Shankweiler, & Mann, 1983; Liberman, Mann, & Werfelman, 1982; Mann & Liberman, 1984; Wagner, Torgersen, & Rashotte, 1994). The number of syllables correctly retrieved shortly after their presentation is smaller for children with dyslexia than for average readers, although results for visual memory tasks with nonverbal material for children with dyslexia are equivalent to those of average readers (McDougall, Hulme, Ellis, & Monk, 1994; Sprenger-Charolles et al., 2000). One less intensively studied aspect of dyslexia, and perhaps the most intriguing one, lies in a deficit in speech perception. A fair proportion of dyslexic children show a weakness in phoneme discrimination. These children make a larger number of errors than do average readers when presented with minimal pairs of syllables (e.g., /ba/ and /da/), which only differ by a single phonetic feature (Adlard & Hazan, 1998; Masterson, Hazan, & Wijayatilake, 1995; Mody, Studdert-Kennedy, & Brady, 1997; Reed, 1989).

Categorical Perception

It is generally agreed that speech sound discrimination is governed by phonemic categories. Acoustic differences between variants of the same phonemic category are usually not perceptible, whereas differences of the same acoustic magnitude between two different categories are perceptible, a property known as "categorical perception" (Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967). As a rule, categorical perception (CP) is more likely to take place in situations where perceptual decoding is more complex. CP is more likely to occur for stop consonant contrasts than for fricative contrasts, for fricative versus vowel contrasts, and for vowels produced at higher articulatory rate versus steady-state vowels. The presence of a discrimination peak for stimuli straddling the phoneme boundary, or "phoneme boundary effect" (PBE), is not sufficient for demonstrating CP. What is further required is the total absence of discriminability between phoneme variants; that is, between sounds located on the same side of the phoneme boundary. This definition conforms to the classic view of CP, dating back to the late 1950s (Repp, 1983). There are many examples in the literature to show that classical CP is often absent in the general population because listeners are sensitive to within-category differences (Grieser & Kuhl, 1989; Repp, 1983; Rosen & Howell, 1987; Volaitis & Miller, 1992). This does not raise problems in studies aimed at comparing different groups of subjects, because it is the relative amount of CP that matters then. In a more recent view of CP, within-category discrimination is related to differences in phonemic identity; that is, to differences in the identification scores collected in labeling experiments. What is required is that discrimination scores are predictable from the corresponding identification data (for a mathematical model, see Fujisaki & Kawashima, 1969, 1970). In this conception, CP is present insofar as within-category discrimination scores are conditioned by differences in phonemic labeling. This "conditional" view of CP is however not very adequate for the study of dyslexia. Enhanced within-category discrimination can be taken as a proof of weakness of phonemic representations irrespective of its predictability from labeling data. In this approach, both discrimination and labeling data are of interest on their own, because each can be used for assessing the consistency of phoneme categories.

Categorical Perception Deficit

Different studies suggest that people with dyslexia are less categorical than average readers in the way they perceive phonetic contrasts. Using the conditional approach for evidencing CP, Werker and Tees (1987) showed that differences between observed and predicted scores were larger for dyslexics than for controls. Further, the degree of within-category discriminability was also larger for dyslexics and the slope of their identification function was shallower. These results suggest that perception is less categorical for people with dyslexia, whatever definition of CP is used. In another study, differences between observed and predicted scores were equivalent for both groups in spite of important between-group differences in both discrimination and identification functions (Godfrey, Syrdal-Lasky, Millay, & Knox, 1981). Although no difference in conditional CP between groups was evidenced, the authors state that "the pattern of identification and discrimination differences suggests an inconstancy in the dyslexics' classification of auditory cues" (Godfrey et al., 1981, p. 401). In still another study, where only labeling data were collected, dyslexics who did not have normal phonological awareness also had shallower identification functions (Manis et al., 1997). Again, no difference in conditional CP between groups was evidenced, but the authors nevertheless stated that, "Dyslexic children showed less sharply defined categorical perception" (Manis et al., 1997, p. 212). A striking common point among these studies is that they all show that children with dyslexia do poorly at discriminating between phonemes from different phonetic categories and that they do *better* at discriminating between acoustic variants of the same phoneme (or are less consistent in labeling them). These are differences in classical CP that are not captured by conditional CP. The interest of such differences is that they might provide a key for explaining the dyslexics' deficit in phonemic awareness and the related difficulty in learning to read. Consistent classification of speech sounds into phonemic categories has functional implications for perceiving spoken language because it allows the listener to discard differences that are irrelevant for word identification. Understanding speech is conceivable without categorical perception, but it might be more demanding in terms of cognitive load due to the greater amount of irrelevant information entering the system. The implication of a categorical perception deficit is probably much more important for conscious access to phonemes. The latter are by no means invariant acoustic segments but rather are abstract linguistic units, which are perceived through complex decoding processes (Serniclaes, 2000; Serniclaes & Wajskop, 1992). These decoding rules have a specific function, which is to extract invariant units from an infinite variety of acoustic variants. A subject who does not possess these rules or who does not possess them in their standard form will not be able to access invariant phonemes from their multiple variants, or at least will perceive some of the variants as distinct units. This might be the decisive obstacle that persons who are affected by dyslexia encounter in the use of alphabetic writing when they have to map grapheme with phoneme.

Origins of the Phonological Deficit

Although there is general agreement that the most prevalent form of dyslexia is related to a phonological deficit, the ontogenesis of the deficit remains controversial. Two different explanations are currently proposed, one relying on auditory processes and the other on phonetic processes. For the proponents of the auditory model, the core of the problem lies in the processing of rapidly changing sounds, whatever their origin (Tallal, 1980), whereas it is specifically the perception of speech sounds that is the cause for proponents of the phonetic model (Mody et al., 1997; Schulte-Körne, Deimel, Bartling, & Remschmidt, 1998; Studdert-Kennedy & Mody, 1995; Tobey & Cullen, 1984). Some experiments previously reported in the literature suggest that dyslexics have problems with categorical perception, yet whether the deficit is specific to the perception of speech sounds or whether it more generally affects auditory functioning remains unknown. Attempts to address the specificity versus nonspecificity of this perceptual deficit have been made in some former studies (Adlard & Hazan, 1998; Mody et al., 1997; Reed, 1989). However, these studies were not directly concerned with categorical perception. Instead of comparing between- and within-category discrimination responses, which is essential to establish the presence of categorical perception, only between-category responses were collected in these studies. Moreover, the paradigm used for establishing the speech specificity of the perceptual deficit was not optimal. In all these studies, the nonspeech stimuli used for examining performance in auditory processing were different from those used for examining speech perception performances. If the results show that perceptual differences between average readers and dyslexics are present for speech stimuli, but not for nonspeech stimuli, as was the case in some studies, this does not specify whether or not the deficit is specific to speech. Indeed, the difference might also be due to a change in the acoustic properties of the stimuli. Even if nonspeech stimuli are fairly similar to stimuli for speech, as was the case in Mody et al. (1997), the acoustic changes necessary to produce the conversion from nonspeech to speech might also be crucial for discriminating between phonetic categories.

The basic difficulty here arises from the absence of one-to-one correspondence between acoustic cues and phonetic features. Although some cues are more important than others for the perception of a given feature, each feature is perceived through the integration of multiple cues, and each cue contributes to the perception of the different features (for a review, see Repp, 1982). Further, these cues are not treated as separate acoustic phenomena but are interactive in their perceptual effects. As a consequence, showing that perception is noncategorical with nonspeech stimuli in which some acoustic cues are lacking (e.g., the first formant, F1), does not, for instance, definitely invalidate an auditory explanation. Indeed, deleting these cues might not only prevent the listeners from perceiving the sounds as speech, but might also affect perceptual processing and, more specifically, auditory processing. Auditory processing of place of articulation cues might, for instance, be qualitatively different for stimuli without F1. Discrimination between categories might be more difficult, or perception might be less categorical, not because the stimuli are not perceived as speech, but because some critical cues are absent. These are classical methodological problems in the study of speech perception in the general population, notably for the interpretation of CP findings.

Auditory Versus Phonetic Basis of Categorical Perception of Speech

In the general population, CP was first evidenced for speech sounds, but was later also obtained for nonspeech continua (Cutting & Rosner, 1974; Miller, Pastore, Weir, Kelly, & Dooling, 1976; Pisoni, 1977). CP was obtained for nonspeech sounds varying along a continuum similar to one of those supporting a phonetic feature. For instance, the voice onset time (VOT) continuum, which supports voicing distinctions between consonants, can be simulated by modifying the onset time of a low-frequency tone (a buzz) relative to a noise burst. Using this continuum, a discrimination peak was obtained at the boundary between stimuli labeled as "buzz followed by noise" and those labeled as "noise followed by buzz" (Miller et al., 1976). This boundary corresponds to a qualitative change on the continuum similar to one used for separating voiced from voiceless stops in speech perception. This lends support to the idea that CP of speech features is based on natural auditory sensitivities (Pastore et al., 1977), rather than being included in speech-specific mechanisms (Liberman et al., 1967). The problem with the auditory interpretation is, however, that the sound continua used for demonstrating CP with nonspeech sounds were not exactly the same as those used for evidencing CP with speech. In these conditions, it cannot be concluded that the same mechanisms are at work for both kinds of stimuli. CP of nonspeech stimuli might be based on stimulus properties that are different from those involved in CP of speech stimuli. It is not possible to decide whether these properties are identical for speech perception and auditory perception unless the same stimuli are used for eliciting both kinds of percepts.

In order to study the differences between the mechanisms involved in the perception of speech and nonspeech stimuli, the most appropriate method is to compare the effect of perceptual processing, whether auditory or speech specific, with exactly the same stimuli. This can be achieved by using a special kind of speech synthesis (Remez, Rubin, Pisoni, & Carrell, 1981) in which the normal frequency structure is replaced by pure tones (sinewaves). Most naive subjects hear sinewave analogues of speech sounds as whistles. But the same stimuli are perceived as speech sounds when the subject's attention is drawn towards their phonetic properties. Different studies suggest that sinewave analogues are processed differently depending on whether they are presented as speech sounds or not. One of the differences between speech processing and nonspeech processing pertains to the integration of contextual information. It has been shown that the perception of a consonant place of articulation contrast depends on the vowel context only when sinewave analogues are perceived as speech (Bailey, Summerfield, & Dorman, 1977). Another difference between speech versus nonspeech processing pertains to CP. Perception of the /r/-/l/ contrast has been shown to be categorical only when sinewave analogues are perceived as speech (Best, Studdert-Kennedy, Manuel, & Rubin-Spitz, 1989). Still another difference is that the categorical boundaries lie at different places on the acoustic continuum when heard as speech or as nonspeech (Best, Morrongiello, & Robson, 1981). This tends to indicate that although there are instances where CP is present for speech and nonspeech distinctions, the underlying mechanisms are different (Liberman & Mattingly, 1985).

The Present Study

The aim of this study was to collect further evidence on the relationship between categorical perception and dyslexia as well as on the nature of the posited deficit in categorization, speech-specific or not. For this purpose, discrimination responses of children with dyslexia and average reader controls to sinewave analogues of speech sounds were compared. Any difference that shows up in these conditions will necessarily arise from a change in perceptual processing, thereby excluding classical alternative interpretations in terms of concomitant acoustical differences between speech and nonspeech stimuli. If the alleged deficit of dyslexics in categorical perception is specific to speech, the difference from average readers should only appear when the sinewave stimuli are perceived as speech sounds. On the contrary, if the deficit is also present in the generalized auditory system, the difference between the two groups should also be found when the sinewaves are perceived as whistles. The discrimination performances of the two groups of children were also tested with modulated sinewave sounds whose acoustic characteristics are closer to natural speech than are the mere sinewave analogues. CP might be present with modulated sinewaves even if it is absent with the unmodulated ones, as the phonemic categories are probably less discriminable for the latter. Therefore, modulated sinewaves provided a safeguard for reaching one of the research objectives, which was to demonstrate differences in CP between groups, irrespective of the speech-specific issue. Further, using both sinewave-speech and modulated-speech is of interest for assessing the impact of stimulus factors on CP differences between dyslexics and average readers.

Method

Participants

The reading level of the dyslexics enrolled in the present study was at least 2 years below their chronological age, and only average readers were included in the control group. All these children had average or above average nonverbal and verbal IQ scores. The criteria used for selecting these children were then the same as those used in most of the studies with dyslexics.

Participants were part of a cohort of 373 children who were followed from kindergarten (5 years old) where they were selected according to the following criteria: (a) they were native speakers of French with no history of neurological or psychological disorders and (b) they came from average or above average socioeconomic families; had average or above average verbal and nonverbal IQ scores; had no language disorders; and had no history of severe hearing, visual, or motor deficits.

This cohort of 373 children was followed up to the age of 8 years; part of this cohort was then followed up to age 13 years, according to the criteria described in Sprenger-Charolles et al. (2000). The important point is that all the children identified as dyslexics were kept in the cohort, together with only a small control group of average readers. The subjects participated in the present study when they were 13 years old. Children classified as dyslexics were those with a reading age at least 2 years below their chronological age. There were 19 dyslexics and 17 average readers. There were 14 boys and 5 girls among the dyslexics and 9 boys and 8 girls among the average readers. All these children were right-handed except 1 boy with dyslexia and 1 girl who was an average reader. Summary statistics of chronological age, reading age, and nonverbal IQ are presented in Table 1 for each group. Nonverbal IQ was assessed on Raven's matrices[1] (Raven, 1976). Reading age was assessed with the Alouette standardized reading test[2] (Lefavrais, 1965). Differences in chronological age and nonverbal IQ between the two groups were non-significant [$t(34) = 1.42$, $p > .05$ and $t(34) = 1.66$, $p > .05$, respectively].

Table 1. Chronological age, reading age, and Raven scores for dyslexics and controls.

	Dyslexics (*n* = 19)		**Controls** (*n* = 17)	
	M	**(*SD*)**	***M***	**(*SD*)**
Chronological Age (in months)	155.0	(3.55)	156.5	(3.14)
Reading Age (in months)	105.6	(11.12)	149.9	(9.13)
WISC-R Vocabulary subtest (verbal IQ)	30.2	(7.00)	38.6	(5.28)
Raven scores (nonverbal IQ)	32.2	(3.42)	33.6	(1.46)

Verbal IQ was assessed both at the beginning of the follow-up study, when the children were 5 years old, and at the moment of the present study, when they were 13 years old. At 5 years old, verbal IQ was measured using a French oral vocabulary test (Deltour & Hupkens, 1980) designed for 5–8 year olds. When the children were 13 years old, verbal IQ was assessed with the vocabulary subtest of the Wechsler Intelligence Scale for Children Revised (WISC-R). Although there was no difference in verbal IQ between the future dyslexics and average readers at the start of the follow-up study, there was a significant difference at the moment of this study. As shown in Table 1, the verbal IQ of the average readers was then significantly larger than that of those affected by dyslexia [$t(34) = 48$, $p < .005$]. This result replicates the well-known "Matthew effect"—that reading level is linked to verbal IQ (Stanovich, 1986, 1993).

Stimuli

The stimuli were sinewave analogues of stop + /a/ syllables varying along a place-of-articulation continuum.

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[1] In the Raven's test, the child has to find the missing piece among six different pieces in order to complete a visuo-spatial pattern. The test includes 36 trials.

[2] The Alouette test provides a reading level from 5.11 to above 14.3 years of reading age. The children have to read aloud a 265-word text as quickly and accurately as possible. The text includes rare words (e.g., "arrimé," meaning "stowed"), words with similar pronunciation (e.g., "Annie-amie" /ani-ami/), as well as words with contextual graphemes (e.g., "gai-geai" /ge-ʒe/). It also attempts to use foils for set phrases (e.g., "au clair de lune" instead of the usual "au clair de la lune") or expected words (e.g,. "cordeau", meaning "gardener's line", after "moineau," meaning "sparrow," instead of the expected "corbeau," meaning "crow"). Errors and reading time are recorded while the child is reading. The child is stopped after 3 minutes. The reading level is obtained either from the reading time (when less than 3 minutes) or from the number of words read in 3 minutes, with points deducted for each error in both cases. This reading level is then transformed into a standardized reading age.

The endpoints were given appropriate values for the perception of a /ba/ syllable at one end and for the perception of a /da/ syllable at the other end. The difference in place of articulation between two initial consonants was created by modifying the onset of the initial frequency transitions (SIN2 and SIN3), which corresponded to those of the second and third formants in natural speech (F2 and F3). The SIN2 onset frequency varied from 700 Hz at the /ba/ endpoint to 2075 Hz at the /da/ endpoint in five equal steps of 275 Hz, yielding a total of six stimuli per continuum. The SIN3 onset frequency varied from 1500 Hz at the /ba/ endpoint to 3875 Hz at the /da/ endpoint in five equal steps of 475 Hz. The end frequencies of SIN2 and SIN3 transition were fixed at 1300 Hz and 2500 Hz, respectively. Schematic spectrograms of the stimuli are presented in Figure 1. The initial frequency of the lowest formant (F1) was 100 Hz, and its end frequency was 750 Hz. The VOT was –100 ms, the duration of all frequency transitions was 40 ms, and the duration of the stable vocalic segment was 170 ms. The choice of the stimulus values was based on a preliminary experiment with average adult readers whose labeling and discrimination data yielded the /ba-da/ boundary (i.e., the point at which the two categories are equally probable in the responses) to lie at the midpoint of the continuum used here (between S3 and S4; see Figure 1).

Two different versions of this continuum were constructed, differing only according to the synthesis method, either pure sinewave synthesis or pitch-modulated sinewave synthesis. The latter was obtained by adding low-frequency amplitude modulation to the sinewave sounds. This had the effect of giving the sounds the equivalent of a voice pitch and made them immediately appear as speech-like sounds. Without modulation, the signal was generated by an amplitude-weighted sum of sinusoids:

$$\begin{aligned}\text{signal} = {} & \text{A1} \times \sin(2\pi t/\text{F1}) + \text{A2} \times \sin(2\pi t/\text{F2}) \\ & + \text{A3} \times \sin(2\pi t/\text{F3})\end{aligned} \tag{1}$$

With modulation, the signal was multiplied by a negative exponential with a time constant of about 50 ms:

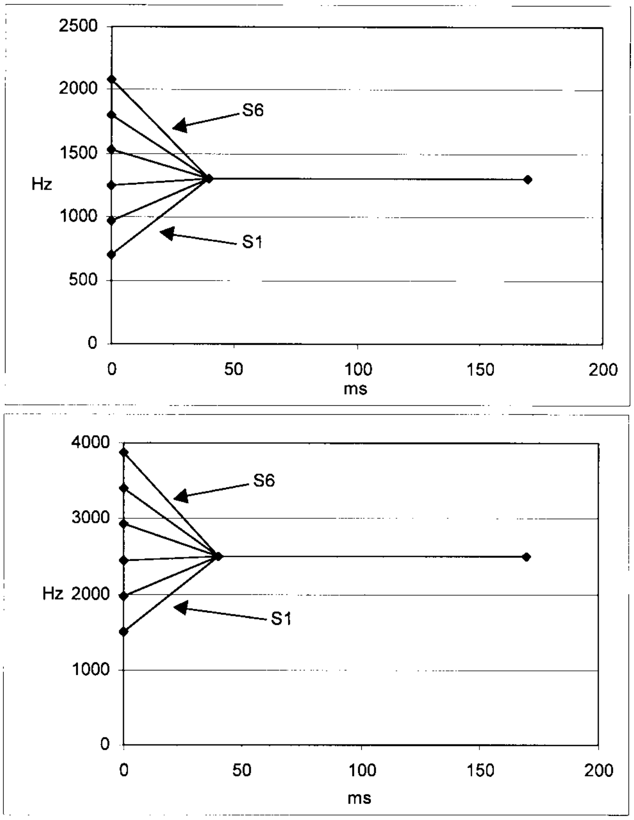
$$\begin{aligned}\text{signal (one period)} = {} & [\text{A1} \times \sin(2\pi t/\text{F1}) + \\ & \text{A2} \times \sin(2\pi t/\text{F2}) + \\ & \text{A3} \times \sin(2\pi t/\text{F3})] \times e^{-t/0.05}\end{aligned} \tag{2}$$

This modulation is reproduced at the F0 frequency, which was constant at 100 Hz. All other parameters were identical for the two synthesis types.

Procedure

The experiment was subdivided into three different conditions. In the first condition, sinewave stimuli were presented as electronic whistles. After completion of this condition, listeners were asked whether they perceived these stimuli as speech sounds. In the second condition, the same stimuli were presented as speech-like sounds. In the third condition, modulated sinewave stimuli were presented as speech-like sounds (see Appendix for further details on the instructions to the listeners). These three conditions are labeled *sinewave-acoustic*, *sinewave-speech*, and *modulated-speech*, respectively. The stimuli were presented in pairs (AX format), and the task of the subject was to decide whether the stimuli within each pair were the same or different by pressing one of two keys on a keyboard. The interstimulus interval within pairs (ISI) was 100 ms, and the intertrial interval (ITI) was 500 ms. In the first condition, the 36 possible pairs of 6 stimuli were presented four times in pseudo-random order, yielding an experimental series of 144 pairs preceded by a "warm-up" run of 20 pairs. In two other conditions, the experimental series of 144 pairs was preceded by a "warm-up" run of 5 pairs. Participants were asked to make their decision as quickly as possible. Correct answers to the pairs of the warm-up series were not provided. Responses to the warm-up series were not taken into account in the results. Only discrimination

Figure 1. Schematic representations of frequency transitions of SIN2 (top) and SIN3 (bottom) in the CV stimuli generated by sinewave synthesis. SIN2 and SIN3 correspond to F2 and F3 in natural speech. S1 and S6 correspond respectively to the /ba/ and /da/ endpoints of the continuum.



data were collected. All the participants were presented the sinewave-acoustic condition first. About one-half of the participants within each group, 9 out of the 19 dyslexics and 8 out of the 17 average readers, experienced the sinewave-speech condition next and received the modulated-speech stimuli last. This order was reversed for the other half of the participants (10 dyslexics and 9 average readers).

Results

After completion of the first condition, in which the sinewave stimuli were presented as electronic whistles, none of the listeners spontaneously reported hearing the sinewave stimuli as speech. Further, all the listeners answered negatively when asked whether they perceived these stimuli as speech sounds. Examination of response scores also supports the effectiveness of the instructions on the apprehension of the sinewave stimuli (see below).

The results were analyzed in terms of percentage correct discrimination scores. For each stimulus pair, these scores were obtained by computing the mean percentage of "different" responses to pairs of acoustically different stimuli (e.g., S3-S4 and S4-S3) and "same" responses to pairs of identical stimuli (e.g., S3-S3 and S4-S4) by the different subjects.

The correct discrimination scores for average readers and dyslexics are presented in Figure 2. Those obtained for the one-step stimulus pairs are presented in Figure 2a for the sinewave-acoustic condition, in Figure 2b for the sinewave-speech condition, and in Figure 2c for the modulated-speech condition. Results obtained for the two-step stimulus pairs are presented in Figure 2d for the sinewave-acoustic condition, in Figure 2e for the sinewave-speech condition, and in Figure 2f for the modulated-speech condition. Data in each condition and for each step size were analyzed separately in two-way ANOVAs with stimulus pair as the within-subject factor and group as the between-subject factor. Between-category discrimination peaks were tested with planned comparisons for pairs. As the S3-S4 pair was the only between-category pair for one-step pairs, the PBE was tested by comparing the S3–S4 score to the mean score of the four within-category pairs (S1-S2, S2-S3, S4-S5, S5-S6). For two-step pairs, the PBE was tested by taking the difference between the mean scores of between-category pairs (S2-S4 and S3-S5) and within-category pairs (S1-S3 and S4-S6). A second planned comparison was used for testing the difference between the two between-category scores (S2-S4 and S3-S5). The motivation for using this comparison was to detect possible differences in the location of the categorical boundary between speech and nonspeech conditions. As the two comparisons were orthogonal, no Bonferroni correction was applied, following usual practice for planned orthogonal comparisons (Hays, 1988, p. 410).

The ANOVAs conducted on one-step pairs showed that:

1. The main effect of group was not significant either in the sinewave-acoustic condition ($F < 1$) or in the modulated-speech condition ($F < 1$) but was significant in the sinewave-speech condition [$F(1, 34) = 9.06$, $p = .005$]. The overall better discrimination performance of dyslexics versus average readers was therefore significant only in the sinewave-speech condition. Figure 2b makes it clear that the better overall discrimination was certainly present for within-category scores in this condition and even more salient than for between-category scores. To allay any doubt, the group effect in this condition was tested separately on within-category scores in a Two-Way Pair × Group ANOVA and was significant as expected [$F(1, 34) = 10.5$, $p < .005$].

2. The main effect of pair was not significant in the sinewave-acoustic condition ($F < 1$) but was significant in the sinewave-speech and modulated-speech conditions [$F(4, 136) = 3.55$, $p = .009$ and $F(4, 136) = 18.8$, $p < .005$, respectively]. More specifically, the comparison for testing the PBE was significant in the sinewave-speech and modulated-speech conditions [$F(1, 34) = 12.3$ and $F(1, 34) = 31.3$, respectively, both $p < .005$]. In short, the PBE was only significant in the speech conditions.

3. The planned comparison for the PBE × Group interaction was nonsignificant in each condition [$F < 1$ for both the sinewave-acoustic and sinewave-speech conditions; $F(1, 34) = 2.12$, $p = .15$ in the modulated-speech condition]. There was therefore no significant difference in PBE between dyslexics and average readers in each of the three conditions.

The ANOVAs conducted on two-step pairs showed that:

1. The effect of group was not significant either in the sinewave-speech condition or in the modulated-speech condition (both $F < 1$) but was just short of significant in the sinewave-acoustic condition [$F(1, 34) = 3.38$, $p = .075$]. This means that the overall discrimination performance of dyslexics tended to be better than that of average readers in the sinewave-acoustic condition, although the effect was only marginally significant (Figure 2d). Figure 2d makes it clear that the better overall discrimination was certainly present for within-category scores in this condition and even more salient than for between-category scores. To allay any doubt, the group effect in this condition was tested on within-category scores only in a Two-Way Pair × Group ANOVA and was clearly significant [$F(1, 34) = 8.95$, $p = .005$].

2. The effect of pair was not significant in the

Figure 2. Percentage correct discrimination for average readers and dyslexics in three different conditions: sinewave-acoustic (top), sinewave-speech (middle), and modulated-speech (bottom). One-step differences between stimuli are shown on the left, 2-step differences on the right.

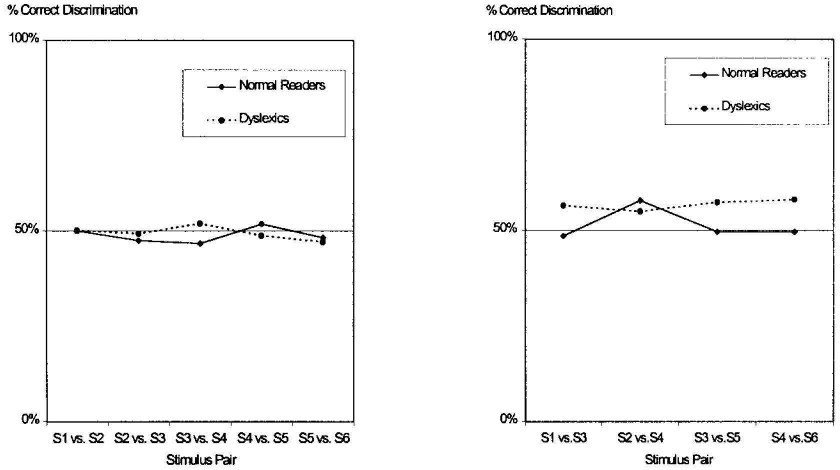


Figure 2a Sinewave-acoustic condition Figure 2d

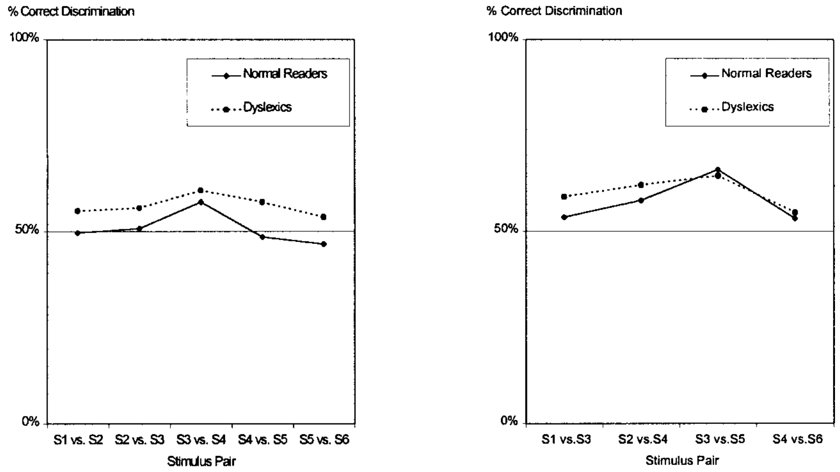


Figure 2b Sinewave-speech condition Figure 2e

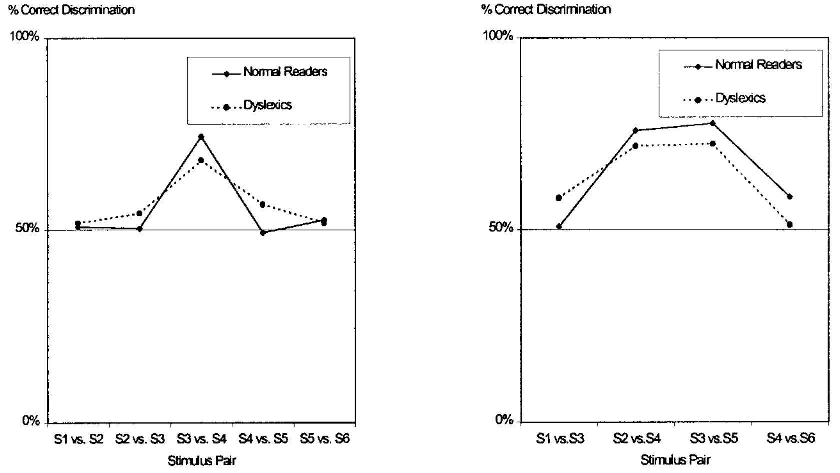


Figure 2c Modulated-speech condition Figure 2f

sinewave-acoustic condition ($F < 1$) but was significant both in the sinewave-speech and modulated-speech conditions [$F(3, 102) = 6.23$ and $F(3, 102) = 26.3$, respectively, both $p < .005$]. The PBE was not significant in the sinewave-acoustic condition [$F(1, 34) = 1.20$, $p = .28$] but was significant both in the sinewave-speech and modulated-speech conditions [$F(1, 34) = 11.5$ and $F(1, 34) = 53.4$, respectively, both $p < .005$]. The difference between peaks (S2-S4 vs. S3-S5) was not significant either in the sinewave-acoustic condition or in the modulated-speech condition (both $F < 1$) but was significant in the sinewave-speech condition [$F(1, 34) = 4.53$, $p = .041$]. This was due to the higher S3-S5 peak versus S2-S4 peak for both groups in the sinewave-speech condition (Figure 2e).

3. The Pair × Group interaction was not significant in the modulated-speech condition [$F(3, 102) = 1.70$, $p = .17$]; neither were the PBE × Group or the Between-Peak Difference × Group interactions (both $F < 1$). Similarly, the Pair × Group and PBE × Group interactions were nonsignificant in the sinewave-speech condition (both $F < 1$), as was the Between-Peak Difference × Group interaction [$F(1, 34) = 1.17$, $p = .29$]. The Pair × Group interaction was also nonsignificant in the sinewave-acoustic condition [$F(3, 102) = 1.86$, $p = .14$], as was the PBE × Group interaction [$F(1, 34) = 1.20$, $p = .28$]. However, the Between-Peak Difference × Group interaction was just short of significant in this condition [$F(1, 34) = 3.37$, $p = .075$]. This arises from the presence of one (S2-S4) of the two between-category peaks for average readers, and not for dyslexics, in the sinewave-acoustic condition. This difference was then tested separately for each group in this condition and was significant for average readers [$F(1, 34) = 4.77$, $p = .044$] but was nonsignificant for dyslexics ($F < 1$).

The outcome of the tests for both step sizes can be summarized as follows. First, the overall discrimination performance of dyslexics, and specifically within-category discrimination, was better than that of average readers in some conditions. This was the case in the sinewave-speech condition for one-step pairs and in the sinewave-acoustic condition for two-step pairs. Second, the PBE was only present in the speech conditions. Third, although there were no significant differences in PBE between groups, one of the two possible between-category discrimination peaks for two-step pairs (the one for S2-S4) was significantly larger for average readers, but not for dyslexics, in the sinewave-acoustic condition.

Another aspect of the results pertains to the effectiveness of the instructions given to the listeners to perceive the sinewaves as electronic whistles in the first place and to perceive them as syllables later. One obvious consequence of this manipulation is the emergence of a PBE in the sinewave-speech condition, that is, the presence of a discrimination peak at the phonemic boundary when sinewaves are presented as speech versus its absence when they are presented as nonspeech sounds. By measuring the difference in PBE between the sinewave-speech and sinewave-acoustic conditions for each listener, the generality of this effect can be assessed. The difference in mean PBE between the sinewave-speech and sinewave-acoustic conditions, for both step sizes taken together, was calculated for each listener. The PBE difference was positive for 15 out of the 17 average readers ($M = .08$, $SD = .10$; range: –.20 to .25) and for 11 out of the 19 dyslexics ($M = .05$, $SD = .14$; range: –.20 to .38). Differences between groups are nonsignificant (for mean PBE difference: Student's t test < 1; for rate of positive PBE differences: Fisher Exact test, $p = .065$). The overall rate of positive PBE differences should therefore be considered as an objective measure of the effectiveness of the instructions, yielding a value of 72% (26 out of 36). Finally, the rate of positive PBE differences did not depend on the order of presentation of the sinewave-speech and modulated-speech conditions (13 positive differences out of 17 for the listeners who were given the sinewave-speech stimuli in second position vs. 13 positive differences out of 19 for the listeners who were given the sinewave-speech stimuli in third position; $\chi^2 < 1$). The similar PBE difference, both for the listeners who had heard the sinewave-speech stimuli immediately after the sinewave-acoustic stimuli and for those who were given the modulated-speech stimuli before hearing the sinewave-speech stimuli, strongly suggests that the improved performance is due to the sinewaves being presented as speech, and not to the effect of practice.

The data collected in this study also included discrimination responses for pairs of stimuli differing by more than two steps. All the other possible pairwise stimulus combinations, from three steps to five steps, were also included. As all these pairs are between-category pairs (i.e., they all straddle the phonemic boundary), these results were not included in the above analyses. Discrimination scores corresponding to the three- to five-step pairs are presented in Table 2 for each stimulus condition and each group of participants. These data were analyzed with a three-way ANOVA with stimulus condition and pair as within-subject factors and group as the between-subject factor. As can be seen in Table 2, discrimination improved from the sinewave-acoustic to the sinewave-speech condition, and from the latter to the modulated-speech condition. The main effect of condition was significant [$F(2, 68) = 20.3$, $p < .005$], as were the planned comparisons for speech mode [comparison between sinewave-acoustic and sinewave-speech conditions: $F(1, 34) = 16.6$, $p < .005$] and for synthesis type [comparison between sinewave-speech and modulated-speech conditions: $F(1, 34) = 9.60$, $p < .005$]. Increasing the step size from three to four steps also improved discrimination, whereas further increase, from four to five steps, did not have a consistent effect. The main effect of pair was significant [$F(5, 170) = 3.53$, $p \le .005$], as was the difference between three-step and four-step pairs [$F(1, 34) = 8.79$, $p = .006$], whereas the difference between four-step and five-step pairs was not significant ($F < 1$). Differences between groups are inconsistent. The main effect of group, the Group × Condition and Pair × Group interactions, as well as the Three-Way Pair × Group × Condition interaction, are each nonsignificant (all $F < 1$).

Discussion

As a whole, the results of the present study show that there are both similarities and differences in the way dyslexics and average readers discriminate speech sounds. Both groups exhibit a PBE (phoneme boundary effect) that is present only when the sounds are perceived as speech. The effect of presenting the sinewaves as speech, rather than as nonspeech whistles, was fairly general, as the difference in PBE was present for 72% of the subjects. This, added to the fact that none of the listeners reported they had heard the sinewave stimuli as speech, supports the contention that listeners were indeed in the nonspeech mode when presented the sinewaves as nonspeech sounds.

The PBE was significant both for sinewaves when presented as speech and for modulated speech, and the magnitude of the PBE was larger for the latter. Although the effects of stimulus presentation and type were similar for average readers and dyslexics, there was an important difference between the discrimination performances of the two groups. Children with dyslexia were *better* at discriminating acoustic differences between stimuli belonging to the same phoneme category than were average readers. This again suggests that the perception of speech sounds is less categorical for dyslexics, as they better perceive within-category differences, in accordance with the results of previous studies (see Introduction: Godfrey et al., 1981; Werker & Tees, 1987; Manis et al., 1997). In this study, the difference between groups was most apparent for one-step pairs in the sinewave-speech condition and for two-step pairs in the sinewave-acoustic condition. No difference was found for one-step pairs in this latter condition, which is obviously due to a floor effect, all the scores being around chance (Figure 2a). The difference between groups was weaker (and nonsignificant) for two-step pairs in the sinewave-speech and for both step sizes in the modulated-speech condition. These three conditions are also those in which the PBE is largest and significantly higher than in the other conditions. It is then specifically in conditions where phonemic categories were weakly perceptible, as for one-step pairs in the sinewave-speech condition, or not perceptible at all, as in the sinewave-acoustic condition, that children affected by dyslexia were more sensitive to nonphonemic differences than were average readers. This might indicate that perception of speech sounds by dyslexics in difficult listening conditions is less immune to the intrusion of acoustic differences irrelevant for linguistic processing.

Although previous studies also suggest that discrimination between phoneme categories depends on the reading level, there was no trace of better discrimination between the endpoints of the /ba-da/ continua in the present study. This might be due to the fairly long interstimulus interval (100 ms) used here. In the study by Mody et al. (1997), below-average readers made substantially more errors in phoneme discrimination than did above-average readers at a very short ISI (10 ms), whereas differences were weaker for longer ISIs (50 or 100 ms). In the study by Adlard and Hazan (1998) where a single ISI of 1 second was used, the phoneme discrimination performance of average readers was not significantly better than that of dyslexics as a group. Reed (1989), who also used an ISI of 1 second, did not obtain a significant difference between reading-disabled children

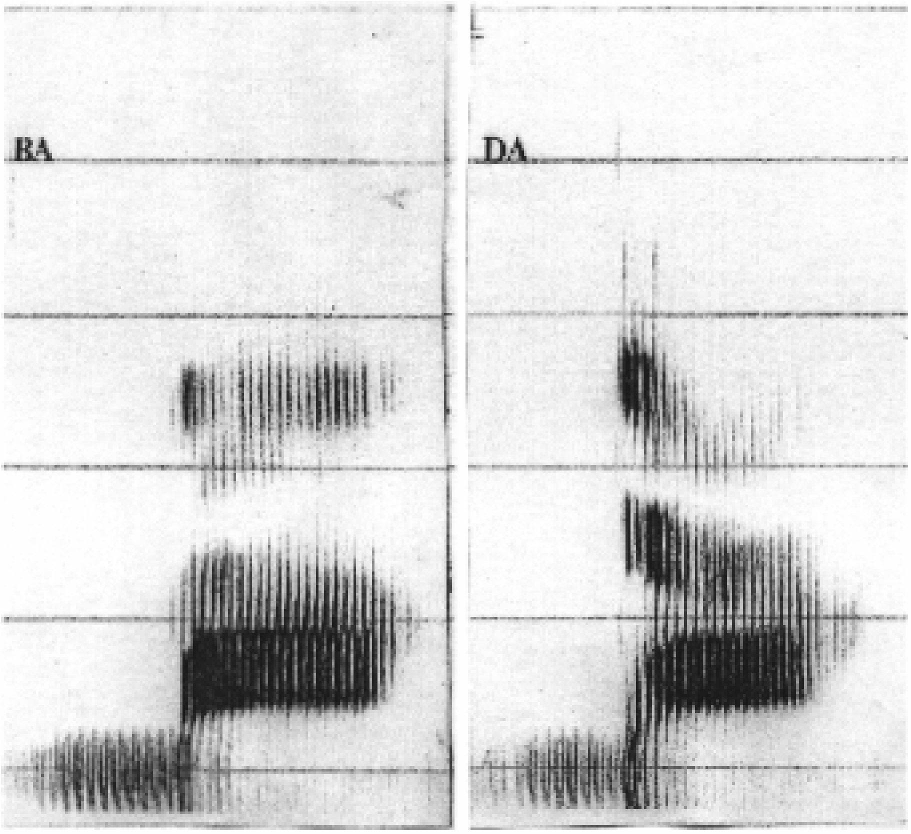
Table 2. Means (and standard deviations) of percent correct discrimination for stimulus pairs differing by more than two steps.

	S1-S4	S2-S5	S3-S6	S1-S5	S2-S6	S1-S6
Sinewave-acoustic						
Average readers	56 (14)	57 (12)	51 (12)	60 (14)	54 (15)	59 (13)
Dyslexics	62 (16)	57 (12)	58 (20)	64 (13)	61 (14)	63 (18)
Sinewave-speech						
Average readers	59 (15)	64 (17)	68 (19)	70 (16)	65 (18)	69 (16)
Dyslexics	66 (19)	70 (16)	65 (17)	65 (16)	69 (15)	69 (18)
Modulated-speech						
Average readers	78 (21)	77 (18)	74 (18)	78 (20)	77 (19)	76 (21)
Dyslexics	75 (10)	69 (16)	67 (19)	75 (17)	70 (15)	72 (15)

and normal readers in the discrimination of stimuli straddling the phoneme boundary.

Although it now seems clear that children who have dyslexia respond less categorically than average readers do, one might wonder whether this is specific to the perception of speech sounds. The absence of PBE in the sinewave-acoustic condition for both groups of listeners shows that the stimuli were not perceived in a categorical way when presented as nonspeech whistles. There were, however, some differences between the two groups in the sinewave-acoustic condition. First, discrimination performances of the dyslexics were better than those of average readers in this condition. Second, one intriguing aspect of the results comes from the discrimination peak for the S2-S4 pair for average readers in this condition (Figure 2d). The S2-S4 peak for average readers was only slightly significant, but it was completely absent for dyslexics. Remembering that the S2-S4 pair straddles the phonemic boundary, the question then is to know what might render it more discriminable, even when the stimuli are presented as *non*speech. The explanation might be given by the examination of the acoustic characteristics of the frequency transitions in the stimuli of this experiment. Figure 1 shows that the SIN2 and SIN3 transitions are almost flat for the S3 stimulus or, in other words, that S3 is close to the point on the stimulus continuum where the direction of the transitions change from rising to falling. The fact that the S2-S4 pair is better discriminated can then be explained by a qualitative difference between rising versus falling frequency transitions. This is not the case for the S3-S5 pair for which the qualitative difference is less clear, as the transition is only slightly rising for S3. Although this contrast is much less obvious on acoustic grounds than that between rising and falling transitions, it is quite appropriate for the perception of the labial-apical place of articulation distinction in French stops in /C + a/ frames. Figure 3 shows that French /ba/ syllables differ from /da/ syllables by a change in F2-F3 transitions from slightly rising to sharply falling. A categorical boundary located between these two configurations is then totally appropriate for perceiving the labial-dental place distinction, although it is acoustically less salient than the rising-falling boundary. And S3-S5 significant discrimination peaks were indeed present for both groups in the sinewave-speech and modulated-speech

Figure 3. Wide-band spectrograms of /ba/ and /da/ syllables produced by a French speaker, giving a time (horizontal axis) versus frequency (vertical axis) representation of the three main formants (F1, F2, and F3). Frequencies are scaled in kilohertz.



conditions. This suggests that the phonetic boundary is specific to the perception of labial-dental place distinctions rather than being determined by qualitative changes in the direction of the transitions.

As mentioned in the introduction, several instances of categorical perception of nonspeech stimuli with speech-like acoustic characteristics have been reported in the literature. Categorical perception of nonspeech sounds can be explained by the presence of natural auditory sensitivities to qualitative changes in the stimuli (Pastore et al., 1977). The discrimination peak obtained here in the sinewave-acoustic condition is located in the neighborhood of a stimulus with flat frequency transitions. This provides a natural boundary for separating sounds with rising transitions from those with falling ones. Sensitivity to qualitative changes can then readily explain categorical perception of the sinewave stimuli used here when presented as nonspeech sounds. Categorical perception of nonspeech contrasts is compatible with the revised version of the motor theory of speech perception (Liberman & Mattingly, 1985), as long as categorical boundaries do not occupy the same position on the acoustic continuum in the speech and nonspeech conditions. As explained above, the /ba-da/ phonemic boundary evidenced in the speech condition here is different from the rising-falling transition boundary that might possibly be categorical for average readers in the nonspeech condition. Categorical perception around the phonemic boundary therefore appears to be speech specific.

Dyslexics do not exhibit any trace of increased discriminability for the difference between rising versus falling transitions (i.e., for the S2-S4 pair) in the sinewave-acoustic condition. This suggests that children with dyslexia are not endowed with increased sensitivity to qualitative acoustic changes. They would then suffer from a general deficit in inhibiting the perception of within-category differences, not only for speech but also for nonspeech. The fact that the inhibition deficit is common to both speech perception and auditory perception in general might be taken as an argument for stating that the speech deficit is entirely due to a deficit in auditory processing. This argument is based on the implicit assumption that speech sounds are apprehended in the same way as other acoustic stimuli before receiving speech-specific treatments. This assumption remains controversial (Liberman & Mattingly, 1985; Best et al., 1989; Remez, Rubin, Berns, Pardo, & Lang, 1994). But even if this assumption were true, assigning the entire deficit to auditory processes is difficult to reconcile with the finding that categorical boundaries are different in the speech and nonspeech conditions. This suggests that two different categorization processes are at work. As a consequence, even if there were auditory precategorization in speech perception, categorization at the speech-specific level need not necessarily be a consequence of mere auditory categorization, and a deficit occurring at the speech level cannot be the mere consequence of an auditory deficit. Therefore, a tentative conclusion is that children who have dyslexia suffer from a double deficit in categorical perception, an auditory one and a speech-specific one. It should, however, be kept in mind that there is no firm evidence in support of an auditory categorical deficit for the moment, given the relatively small differences between groups in the nonspeech condition.

Similar conclusions were reached in a reaction time study (Nicolson & Fawcett, 1994). Dyslexic children appeared to be slower than chronological age controls both in selective choice reactions to pure tones and in lexical decisions to spoken words. However, when compared to reading age controls, only the impairment for lexical decisions was present, which suggests that only the latter is due to a qualitative deficit. This leads the authors to posit two independent deficits, a phonological one and a nonphonological one. It would be interesting to see whether the same difference prevails in the discrimination of speech and nonspeech materials. Comparisons between discrimination of sinewave analogues by dyslexics and both chronological age and reading age controls should allow us to clarify this point in further studies.

Another implication of the present results is that they make it clear that children with dyslexia do not suffer from a deficit in auditory acuity or in perceptual acuity when listening to speech. Instead of performing worse than average readers in the categorization of acoustic cues, such as those provided by rapid frequency transitions in CV syllables, they in fact perform *better* than average readers, as long as the changes remain within the same stimulus category. This confirms the results of previous studies (Godfrey et al., 1981; Werker & Tees, 1987), which have repeatedly shown that discrimination scores for within-category pairs are higher for people affected by dyslexia than for average readers. Notice that this is by no means incompatible with the fact that dyslexics tend to perform worse in the discrimination of between-category differences, as indicated by some studies (for a review, see Bradlow et al., 1999). The reduced discrimination of between-category differences for dyslexics versus average readers, as well as the enhanced discrimination of within-category differences, can be simply accounted for by a common deficit in categorical perception.

However, the fact that perceptual discrimination is not necessarily poorer for children affected by dyslexia allows us to tighten our speculations regarding the nature of the underlying deficit. The better performance of dyslexics in the discrimination of within-category differences between stimuli varying along a stop place-of-articulation continuum makes it clear that they do not have any deficit in the extraction and analysis of rapid transitions, to say the least. This is difficult to reconcile with the hypothesis of a deficit in the processing of rapidly changing information and brief temporal cues, or "temporal processing deficit" (Tallal, 1980). The stimuli in the present study differed in the onset of short frequency transitions (40 ms). The discrimination performance of dyslexics was better than that of average readers, except for those stimulus pairs straddling the phonemic boundary; hence, they certainly do not suffer from a deficit in the processing of brief auditory transitions. Rather, they appear to be unable to use the phonetic cues, such as the brief transitions for perceiving place of articulation in stop consonants for the categorization of speech. Furthermore, there is no reason why this categorical deficit should be restricted to the acoustic cues in brief acoustic segments or to place of articulation in stop consonants. Indeed, the same deficit should be found for individuals affected by dyslexia each time categorical perception is present for average readers, whatever the phonetic feature and its acoustic correlate.

According to the present results, the problem with dyslexia is seemingly not in the processing of rapid incoming sensory information but in the construction of phonemic categories. This might have some implications for rehabilitation methods using slowed-down speech by elongating formant transitions, which are grounded in the hypothesis of a deficit in the processing of brief acoustic events (Merzenich et al., 1996; Tallal et al., 1996). Data from the present results, however, show that this hypothesis does not apply to within-category differences. As a consequence, slowed speech might still improve the discrimination of stimulus differences that are already better segregated by dyslexics. This might be counterproductive, as enhanced discrimination of within-category differences could undermine the categorical perception of speech features. As slowed speech might also enhance between-category discrimination, it is specifically categorical perception that might be affected by slowed speech, whereas PBE would remain unchanged. To sum up, the various implications of these rehabilitation methods remain to be explored in more detail.

As already mentioned in the introduction of this paper, differences in categorical perception between people with dyslexia and average readers might provide a key to explain the formers' deficit in phonemic awareness and their related difficulty in learning to read. Grapheme-phoneme consistency is the major factor in learning to read. Children learning to read must learn to map graphemes to phonemes. To correctly perform this mapping, they must rely on well-specified phonological representations. If the child's phonological representations are not well specified, then the connections between graphemes and phonemes will be difficult to establish. The results of the present study, and the other results previously obtained for the same subjects in the course of a longitudinal study, suggest that phonological representations are indeed deficient for dyslexics. For example, 3 years before the present session of observation, the dyslexics were found to lag behind both same-age and same-reading-level average readers on phonological short-term memory, but not on visual short-term memory. Compared to same-reading-level average readers, the phonological reading skills of the dyslexics were found to be impaired even more, either for processing time or for accuracy, but not for their orthographic reading skills (Sprenger-Charolles et al., 2000). Three years later, when the same children were 13 years old, which is the age at which they also participated in the present study, their reading skills were re-examined (Sprenger-Charolles, 2000). As compared to the 13-year-old average readers, and even as compared to the 10-year-old average readers, the phonological reading skills of the dyslexics were again found to be impaired. The 13-year-old dyslexics lagged even farther behind the same-age average readers according to their results in a phonemic awareness task. Both a phonemic awareness task and a musical awareness task were given to these children when they were 5 and 7 years old. For the phonemic awareness task, the future dyslexics obtained lower scores than the future average readers, whether they were 5 or 7 years old. The results were quite different for the musical awareness task, for which no significant difference between groups was observed (Sprenger-Charolles, 2000).

These longitudinal data show that both before and after they had just begun to learn to read, the future dyslexics exhibited a deficit in phonological awareness, and particularly in phonemic awareness. As for short-term memory, the results of the phonological and musical awareness tasks also suggested that dyslexia is related to a deficit in phonological representations. Now, the categorical perception deficit might affect the robustness of phonemic representations and this would, in turn, disturb the learning of grapheme-phoneme correspondences (Godfrey et al., 1981). Even a small deficit in discriminating between phonemes might have far-reaching consequences in stressful conditions, as underlined by Werker and Tees (1987). Further, sensitivity to phoneme variants by dyslexics might still add to the confusion, especially because this sensitivity is more likely to take place in difficult listening conditions. However, the dyslexics' deficit in categorical perception might also be a consequence of learning to read rather than being the cause of the reading impairment. One does not know whether persons affected by dyslexia already have a categorical perception deficit before learning to read. If not, the categorical perception deficit might be related to the internalization of grapheme-phoneme correspondences.

In conclusion, the present study suggests that children who have dyslexia are less categorical than average readers in the perception of both speech and nonspeech sounds. However, as categorical boundaries are different for speech and nonspeech, there is probably no causal relationship between the two deficits. Finally, the categorical deficit is not only due to a reduced perceptual sensitivity but also to an increased perceptibility of within-category differences. These results have both profound theoretical implications, for the functional link between the perceptual deficiency and the reading deficit, and practical implications, for rehabilitation and treatment methods.

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Appendix

The following instructions were given orally to the participants (translated from French):

Training (before Condition 1): You are going to hear two electronic whistles 20 times. Each time you hear two sounds, immediately say whether they were the same by pressing the green key when they were the same and the red key when they were different.

Sinewave-acoustic condition (Condition 1): You are now going to hear two electronic whistles 144 times. As you just did, immediately say whether they were the same by pressing the green key when they were the same and the red key when they were different.

Sinewave-speech condition (Condition 2 for one half of the participants; Condition 3 for the other half): The electronic whistles you heard before were in fact “ba” or “da” syllables, but they were pronounced in a special way by the computer, just as by Martians. You are going to hear them again. Just as before, say whether you heard the same thing. Whenever you hear the same thing (ba-ba or da-da) press the green key of the computer. If it was not the same thing (ba-da or da-ba) the red key. You will first hear a series of two sounds 5 times, followed by a series of 144.

Modulated-speech condition (Condition 2 for one half of the participants; Condition 3 for the other half): You will now hear “ba” or “da” syllables pronounced a bit as though a little French child was speaking. Just as before, you will have to say whether you hear the same thing twice. Whenever you hear the same thing (ba-ba or da-da), press the green key on the computer. If it was not the same thing (ba-da or da-ba), press the red key. You will first hear a series of two sounds 5 times, followed by a series of 144.