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# Discrimination of speech sounds by children with dyslexia: Comparisons with chronological age and reading level controls

C. Bogliotti<sup>a,\*</sup>, W. Serniclaes<sup>b</sup>, S. Messaoud-Galusi<sup>c</sup>, L. Sprenger-Charolles<sup>b</sup>

<sup>a</sup>Laboratoire de Sciences Cognitives et Psycholinguistique, EHESS–ENS–CNRS, 75005 Paris, France

<sup>b</sup>Laboratoire de Psychologie de la Perception, CNRS–Université Paris Descartes, 75006 Paris, France

<sup>c</sup>Department of Phonetics and Linguistics, University College of London, London WC1E 6BT, UK

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### ABSTRACT

Previous studies have shown that children suffering from developmental dyslexia have a deficit in categorical perception of speech sounds. The aim of the current study was to better understand the nature of this categorical perception deficit. In this study, categorical perception skills of children with dyslexia were compared with those of chronological age and reading level controls. Children identified and discriminated /do-to/ syllables along a voice onset time (VOT) continuum. Results showed that children with dyslexia discriminated among phonemically contrastive pairs less accurately than did chronological age and reading level controls and also showed higher sensitivity in the discrimination of allophonic contrasts. These results suggest that children with dyslexia perceive speech with allophonic units rather than phonemic units. The origin of allophonic perception in the course of perceptual development and its implication for reading acquisition are discussed.

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### Introduction

Dyslexia is characterized by a severe reading impairment without other physiological or psychological problems (Lyon, Shaywitz, & Shaywitz, 2003; Shaywitz, 1998; Stanovich, 1996). There is a growing amount of evidence that phonological factors play a crucial role in the acquisition of normal

\* Corresponding author. Fax: +33 144 322 630.

E-mail addresses: caroline.bogliotti@ens.fr, caroline.bogliotti@gmail.com (C. Bogliotti).

reading and that phonological processes are impaired in children affected by dyslexia (Ramus, 2003; Ramus, Pidgeon, & Frith, 2003; Ramus, Rosen, et al., 2003; Snowling, 2000; Sprenger-Charolles, Colé, & Serniclaes, 2006). Indeed, it is now well established that to learn to read in alphabetic orthographies, it is necessary to learn to map graphemes with phonemes. This process is easier when children can use a shallow orthography than when they are faced with an opaque orthography (e.g., in Spanish vs. English; for a review, see Sprenger-Charolles et al., 2006). However, whatever the opacity of the orthography, it has nonetheless been shown that early reliance on grapheme–phoneme correspondences is a bootstrapping mechanism for future reading acquisition. For instance, children who were the best early decoders of grapheme–phoneme correspondences turned out to be the best readers. Evidence of this is provided by longitudinal studies (Share, 1995; Sprenger-Charolles et al., 2006) and by the fact that training based on grapheme–phoneme correspondences is the most effective (Ehri, Nunes, Stahl, & Willows, 2001; Ehri, Nunes, Willows, et al., 2001). In addition, dyslexics experience great difficulties when they need to rely only on grapheme–phoneme correspondences to read without the help of their lexical knowledge (i.e., for the reading of unknown words or pseudowords). Indeed, such a deficit is the key characteristic of developmental dyslexia, for this deficit is consistently found in group studies even as compared with reading level controls (Rack, Snowling, & Olson, 1992; Van Ijzendoorn & Bus, 1994; for French data, see Sprenger-Charolles, Colé, Lacert, & Serniclaes, 2000) and is systematically observed in most participants in single and multiple case studies (Sprenger-Charolles et al., 2006).

Finally, a good level in phonemic awareness seems indispensable for making appropriate use of grapho-phonemic correspondences. Indeed, among the prereading abilities linked to reading acquisition, phonemic awareness has been shown to be the best predictor of future reading level, whereas evidence for the unique contribution of syllabic awareness and rhyme awareness is very limited (for a review, see Sprenger-Charolles et al., 2006). In addition, deficits in phonemic awareness have been found to be more reliable across studies than have deficits in phonological short-term memory (STM) or in rapid naming (e.g., in English: Bruck, 1992; Chiappe, Stringer, Siegel, & Stanovich, 2002; Pennington, Cardoso-Martins, Green, & Lefly, 2001; in German: Wimmer, 1993). However, some discrepancies between the results of dyslexics faced with a transparent orthography have been reported in regard to phonemic awareness. Indeed, such a deficit was not observed in some studies (e.g., Landerl & Wimmer, 2000), whereas it was in other studies (e.g., in Spanish: Jimenez-Gonzalez & Ramirez-Santana, 2002; in Czech: Caravolas, Volin, & Hulme, 2005; in German: Landerl, Wimmer, & Frith, 1997; Wimmer, 1993; in French: Sprenger-Charolles et al., 2000; Ziegler et al., 2008). Nevertheless, it seems difficult to argue that the dyslexic's deficit in phonemic awareness is a mere consequence of reading acquisition given that in some of these studies that deficit was observed relative to reading-matched (or spelling-matched) control peers (e.g., in English: Bruck, 1992; Chiappe et al., 2002; Pennington et al., 2001; in Spanish: Jimenez-Gonzalez & Ramirez-Santana, 2002; in Czech: Caravolas et al., 2005) and even before reading acquisition in future dyslexics compared with future average readers (e.g., Sprenger-Charolles et al., 2000).

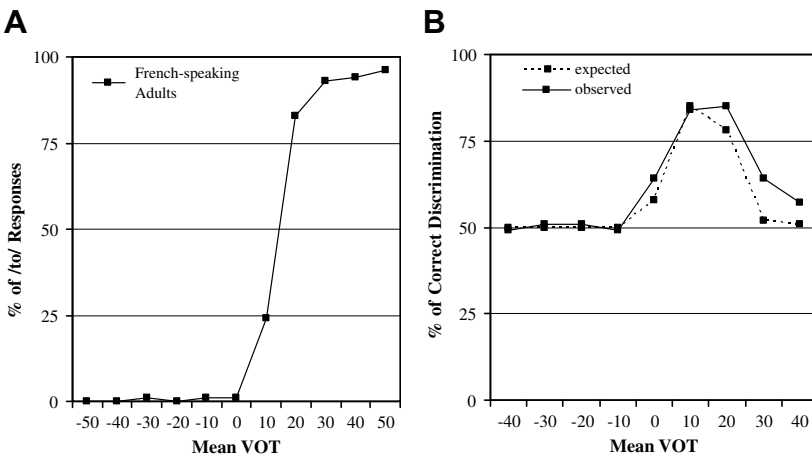
Most of the studies in this field have used tasks involving the explicit segmentation of spoken words (phonemic counting, phonemic deletion, and phonemic inversion). However, there is also some evidence for implicit phonological deficits in dyslexic children. Boada and Pennington (2006) showed that children affected by dyslexia performed consistently worse than controls when more segmental representations were required in lexical gating, priming, and syllable similarity tasks. This might reflect either a specifically segmental deficit or a core deficit in phoneme representation, with the latter having in turn several different consequences for achieving segmentation and other tasks. Interestingly, the results of speech discrimination experiments suggest that dyslexic children indeed have a deficit in phoneme representation that would be characterized by the use of allophonic, rather than phonemic, representations of speech sounds (Serniclaes, Van Heghe, Mousty, Carré, & Sprenger-Charolles, 2004). Allophones correspond to mere contextual variants of phonemes in the language of interest while being phonemic in other languages. For instance, some languages display a twofold distinction between /d/ (voiced), /t/ (voiceless), and /t<sup>h</sup>/ (voiceless aspirated) stops, whereas other languages have only a single d/t<sup>h</sup> distinction. However, in these languages, the /t/ consonant is also present as an allophone of either the /d/ or /t<sup>h</sup>/ phoneme.

### Categorical perception deficits in dyslexia

A fairly large number of studies on the perceptual discrimination of speech sounds have reported categorical perception deficits in people affected by developmental dyslexia (Brandt & Rosen, 1981; De Weirtdt, 1988; Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Reed, 1989; Serniclaes, Sprenger-Charolles, Carré, & Démonet, 2001). The data presented in the current article lend further support to the existence of a phonemic discrimination deficit in dyslexia and also to the claim that this deficit reflects a specific mode of speech perception based on allophonic units rather than phonemic units. Before examining the arguments in support of the allophonic explanation of dyslexia, we first provide a unified view of the categorical perception deficits.

Three different kinds of speech categorization deficits have been evidenced in people affected by dyslexia, depending on the experimental paradigm under use: discrimination alone, labeling alone, and discrimination versus labeling. Although each of these three deficits is somehow related to “categorical perception”, there are also important differences among them. Discrimination between stimuli that lie across a phoneme boundary is normally better than discrimination between stimuli located within a category (see Fig. 1). Furthermore, the observed discrimination scores should normally coincide with those expected from labeling. The magnitude of the boundary discrimination peak (Wood, 1976) and the correspondence between the observed and expected discrimination scores (Liberman, Harris, Hoffman, & Griffith, 1957) are two different indexes of categorical perception, and both have been used in the studies on dyslexia. In the current article, the categorical perception deficit refers to a reduction in discrimination peak unless otherwise specified. Still another index of categorical perception is based on the slope of the labeling function, a shallower slope indicating a lesser degree of categorical “precision” (Simon & Fourcin, 1978). We refer to the reduction in the slope of the labeling function as the “categorical labeling” deficit.

Various studies have evidenced a categorical perception deficit by showing that the phoneme discrimination peak was smaller in dyslexics than in chronological age controls (Brandt & Rosen, 1981; De Weirtdt, 1988; Godfrey et al., 1981; Reed, 1989; Serniclaes et al., 2001). Some studies also have compared observed discrimination scores with those expected from labeling data, and they showed that the discrepancy was larger for the children affected by dyslexia, revealing another form



**Fig. 1.** Criteria for assessing categorical perception as illustrated by data collected from French-speaking adults on a /do-to/ VOT continuum (Bogliotti, unpublished manuscript). Labeling responses (A) indicate the location of the perceptual boundary (i.e., the 50% do-to response point, 15 ms VOT) and are also used for computing expected discrimination scores (B, dotted line). Pairwise discrimination responses were collected with a 20-ms VOT difference between stimuli in a pair. The observed discrimination scores (B, solid line) are fairly close to the expected scores (B, dotted line), indicating nearly perfect categorical perception in the classical sense (Liberman et al., 1957). The magnitude of the phonemic peak, the difference between across- and within-category discrimination scores, is an index of categorical perception.

of categorical perception deficit (Brandt & Rosen, 1981; Godfrey et al., 1981; Werker & Tees, 1987). Finally, the slope of the labeling function was also found to be shallower in dyslexics than in chronological age controls, thereby evidencing a categorical labeling deficit (Chiappe, Chiappe, & Siegel, 2001; Joanisse, Manis, Keating, & Seidenberg, 2000; Maassen, Groenen, Crul, Assman-Hulsmans, & Gabreëls, 2001; Manis et al., 1997; Reed, 1989).

Furthermore, studies with adult developmental dyslexics have not found either a categorical perception or a labeling deficit in the behavioral responses, although categorical differences were present in the neuronal recordings (Dufor, Serniclaes, Balduyck, Sprenger-Charolles, & Démonet, 2006; Ruff, Cardebat, Marie, & Demonet, 2002; Ruff, Marie, Celsis, Cardebat, & Demonet, 2003).

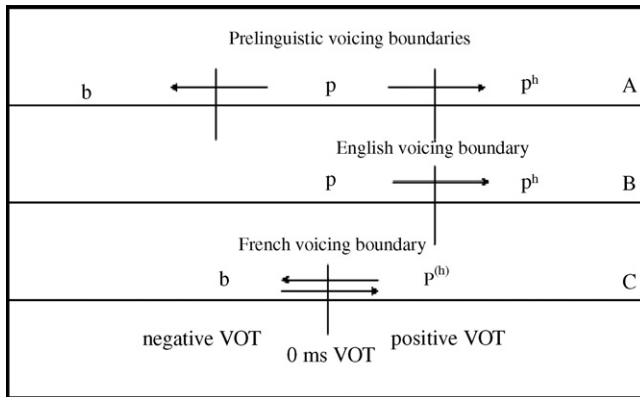
Most of the previous studies dealing with the categorical perception deficit in dyslexia have used only chronological age controls. The presence of a categorical perception deficit in dyslexics relative to chronological age controls is commonplace in the literature on dyslexia (Maassen et al., 2001; Serniclaes et al., 2001; Serniclaes et al., 2004; Werker & Tees, 1987). The few studies that used both chronological and reading level controls failed to find significant differences in categorical perception between dyslexics and reading level controls (in French: Boissel-Dombreval & Bouteilly, 2003; in Dutch: Foqué, 2004; in English: Manis & Keating, 2004). However, the deficit was present, albeit not significant, in one of these studies (Foqué, 2004), and a strong categorical perception deficit was found for those dyslexics who also had specific language impairment (SLI) in another study (Manis & Keating, 2004). This suggests that a categorical perception deficit might also be present when comparing dyslexic children with reading level controls. Comparisons with reading level controls allow one to discard differences in reading level as a possible cause of the deficits associated with dyslexia (e.g., Bryant & Impey, 1986). One of the objectives of the current study was to provide a further test of the differences in categorical perception between dyslexics and reading level controls.

#### *Origin of categorical perception deficit: Allophonic mode of speech perception*

The categorical perception deficit in dyslexia is characterized not only by reduced discrimination of across-category differences between stimuli straddling the phonemic boundary but also by increased discrimination of within-category differences (Serniclaes et al., 2001). Furthermore, dyslexics exhibit a higher sensitivity to phonetic distinctions between different members of the same phoneme category (Serniclaes et al., 2004).

The enhanced sensibility to phonetic components of phonological contrasts could originate from an allophonic mode of perception. Allophonic perception means that phonetic features that are not relevant for native language phonology remain discriminable, possibly as a consequence of deviant perceptual development during early childhood. Infants are born with the ability to distinguish all of the phonetic contrasts in the world's languages (Aslin, Pisoni, Hennessy, & Perey, 1981; Eimas, Siqueland, Jusczyk, & Vigorito, 1971; Lasky, Syrdal-Lasky, & Klein, 1975; Streeter, 1976). This ability would be either enhanced or somehow neutralized, depending on the relevance of the contrasts in the linguistic environment of the listener (Werker & Tees, 1984; Werker & Tees, 1999). For example, infants younger than 6 months of age are able to discriminate three voicing categories separated by two voice onset time (VOT) boundaries<sup>1</sup> (Lasky et al., 1975; Streeter, 1976) (see Fig. 2A). However, after approximately 6 months of age, voicing perception differs according to native language. Infants raised in an English environment react more to the positive VOT boundary than to the negative VOT boundary (Aslin et al., 1981) (see Fig. 2B). However, the enhancement of a boundary is not the only possible developmental pathway; in languages such as French and Spanish, boundaries that are not present in infants' predispositions emerge from couplings between predispositions (Hoonhorst, Colin, Deltenre, Radeau, &

<sup>1</sup> There are three possible voicing categories across languages, and these categories depend on VOT, which refers to the temporal relation between onset of "voice" (laryngeal vibrations) and release of the mouth closure (Lisker & Abramson, 1964). The first category is characterized by the onset of voice before the closure release (negative VOT, e.g., /ba/), the second category is characterized by the quasi-synchrony of voice onset relative to the release (short positive VOT, e.g., /pa/), and the third category is characterized by a delay of voice onset relative to the release (long positive VOT, e.g., /p<sup>h</sup>a/). In languages where the three VOT categories are phonemic, such as Thai, listeners exhibit two boundaries for voicing perception: a negative VOT boundary and a positive VOT boundary (Abramson & Lisker, 1970).



**Fig. 2.** Perceptual boundaries between voicing categories in infants (A), English-speaking adults (B), and French-speaking adults (C). Prelinguistic boundaries correspond to predispositions for the perception of all sound categories in the world's languages (indicated by arrows). In English, the natural boundary is activated and corresponds to a relevant phonological boundary between voiceless unaspirated stops and voiceless aspirated stops. In French, we observe a coupling between aspiration (positive VOT) and voicing (negative VOT) that generates a distinction between voiced stops and slightly aspirated voiceless stops (Serniclaes et al., 2004).

Serniclaes, 2006) (see Fig. 2C). These languages use a single distinction between negative VOT and moderately long positive VOT, and the boundary is located around 0 ms (Serniclaes, 1987).

The combination between the two predispositions—voicing (e.g., negative VOT) and aspiration (e.g., positive VOT)—is interactive in the sense that the perception of one feature depends on the perception of the other feature. Such “perceptual interdependencies” (Koffka, 1935) have been referred to by different terms in perceptual theories, with “coupling” (Hochberg, 1981) being the most appropriate in the current context because it emphasizes the functional link between a new featural entity and its primitive components. Evidence for coupling between predispositions has been collected both for voicing (Hoonhorst et al., 2006) and for consonantal place of articulation (Serniclaes, Bogliotti, & Carré, 2003; Serniclaes & Geng, in press).

#### *Origin of allophonic perception: A coupling deficit*

The existence of couplings between categorical predispositions for phonetic contrasts during the early stages of speech development suggests not only that the acquisition of language-specific distinctions proceeds by selection of prewired processes but also that they involve fairly complex combinations between predispositions. Previous data suggested that couplings between predispositions are deficient in children affected by dyslexia. The evidence was based on increased within-category discrimination by dyslexic children versus chronological age controls (Serniclaes et al., 2001) and, more specifically, on the presence of within-category discrimination peaks in the discrimination functions of children with dyslexia. When discrimination of VOT contrasts by children affected by dyslexia were compared with that of reading age controls, both groups displayed a discrimination peak around the phonemic boundary, but the dyslexic children also displayed a second discrimination peak at  $-30$  ms VOT (Serniclaes et al., 2004). This latter peak is presumably allophonic in nature because it corresponds to one of the two voicing boundaries in Thai (Lisker & Abramson, 1970), a language with three voicing categories: /d/, /t/, and /t<sup>h</sup>/ (see Fig. 2).

A child who perceives allophones rather than phonemes (e.g., /d/, /t/, and /t<sup>h</sup>/) in a language where only /d/ and /t<sup>h</sup>/ are phonemic) would have difficulty in attributing the same written symbol (e.g., “t”) to sounds belonging to different categories in his or her oral repertoire (e.g., /t/, /t<sup>h</sup>/). The mismatch between spoken categories and phonemes might lead to important problems for learning to read even in fairly transparent orthographic systems. In many languages, the establishment of grapheme–phoneme correspondences is difficult due to the lack of one-to-one, contextually invariant relationships

between phonemes and graphemes. Lack of one-to-one correspondence due to attempts to integrate allophones with a single grapheme makes a difficult learning task even harder. Allophones are neither in one-to-one correspondence with graphemes nor contextually invariant, rendering the discovery of regularities between graphemes and speech sounds highly hazardous. Computer simulations support this hypothesis by showing that the suppression of “phonological attractions” between phonetic features, conceptually similar to the “phonological couplings” defined above, has significant negative effects on the reading performance of a connectionist network (Harm & Seidenberg, 1999). This supports the contention that allophonic perception severely affects reading performances in humans.

### *The current study*

The current study aims to assess the categorical perception deficit in dyslexics in comparison with chronological age and reading level controls by collecting both discrimination and labeling data on a VOT continuum. The first objective was to replicate previous findings on categorical deficits in a single study using the same method for testing both the discrimination and labeling deficits. The second objective was to provide a further test of allophonic perception in children with dyslexia. We expected to find a higher allophonic discrimination peak in dyslexic children than in controls, and this peak should correspond to the natural negative VOT boundary ( $\sim -30$  ms). The third objective of the current study was to assess categorical deficits by comparing dyslexic children not only with chronological age controls but also with reading level controls. Because previous studies have not unambiguously pointed to the presence of a categorical perception deficit when comparing dyslexic children with reading level controls, we wanted to provide a further test of this hypothesis. The inclusion of young normal reading children matched on reading level to children with dyslexia allows one to assess whether children with dyslexia would suffer from a developmental deviance or a developmental delay in their categorical perception skill. The presence of a deficit would mean that it is partly independent of reading experience or linguistic development. The fourth objective was to assess the individual reliability of the categorical deficits and allophonic perception when compared with either chronological age or reading level controls.

## **Method**

### *Participants*

A total of 21 children in the fourth grade (10 years of age) and 10 younger children (mean age = 7.6 years) participated in our study. Children were selected using the following procedure. The parents of 75 10-year-olds received a questionnaire about participation in the current study, and we collected approximately 40 responses. From all of these responses, we selected children (a) who were monolingual French speakers and had no auditory problems and (b) who had average verbal and nonverbal IQs. Failure to fulfill either of these requirements was cause for exclusion from the study. According to a standardized reading test, *l'Alouette* (Lefavrais, 1965), the children were classified as dyslexics or average readers (chronological age controls). They were 10 dyslexics (3 girls and 7 boys, age range = 9.04–10.03 years), with a reading age at least 18 months below the expected reading age,<sup>2</sup> and 11 chronological age controls (7 girls and 4 boys, age range = 9.04–10.03 years), with a reading age above or equal to the expected lexical age.

<sup>2</sup> It should be noted that 8 children with poor reading skills were not included in the group of dyslexics because their reading level was between 17 and 6 months below the expected reading age. It should be added that the dyslexics included in the cohort were not supposed to suffer from spoken language impairment. The vocabulary level of all children integrated in the study (included that of the dyslexics) was within the normal range. Moreover, according to several pretests (see Table 1), there were no significant differences in rapid auditory naming (RAN) between dyslexics and both control groups, and there were no significant differences in phonological STM between dyslexics and reading level controls. It is important to note that the mean span of the dyslexics in the current study was fairly long (four syllables) compared with the typical performances of SLI children (Graf Estes, Evans, & Else-Quest, 2007; Newbury, Bishop, & Monaco, 2005). Taken together, these results suggest that the dyslexics included in the current cohort were not suffering from spoken language impairment.

The same procedure was used to select reading level controls. The parents of 100 children received a questionnaire regarding participation in a longitudinal study,<sup>3</sup> and we collected approximately 75 responses. Of these children, 10 (3 girls and 7 boys, age range = 6.09–8.01 years) were matched with dyslexics according to their reading scores (4 were first graders and 6 were second graders). All reading level control children had the reading level expected for their age; they presented a maximum of 1 month delay or 3 months advance in comparison with the expected lexical age.

Summary statistics of the main group characteristics are presented in Table 1. Nonverbal IQ was assessed on Raven's Standard Progressive Matrices (SPM) (Raven, 1976). Verbal IQ was assessed with the *Echelle de Vocabulaire en Images Peabody* (EVIP), a French adaptation of the Peabody Picture Vocabulary Test–Revised (Dunn, Thériault-Whalen, & Dunn, 1993), for the chronological age control and dyslexics groups, and it was assessed with the *Test de Vocabulaire Actif et Passif* (TVAP), or the Passive and Active Vocabulary Test (Deltour & Hupkens, 1980), for the reading level control group.<sup>4</sup>

In addition, we report the results obtained by each group in an assessment of their reading and reading-related skills based on the test battery EVALEC (Sprenger-Charolles, Colé, Béchennec, & Kipffer-Piquard, 2005). For reading-related skills (phonemic awareness and phonological STM), there were only pseudowords so as to avoid biases due to differences in the children's vocabulary levels. In addition, to avoid differences in the experimenter's articulation, the items were recorded beforehand and the children heard them through headphones. For these two tests, as well as for the rapid naming test, practice items were first provided and no feedback was given during the test. For the phonemic awareness test, the children were required to delete the first "sound" of 24 pseudowords: 12 with a consonant–vowel–consonant (CVC) structure and then 12 with a consonant–consonant–vowel (CCV) structure. For the CVC test, the initial consonant was either a plosive or a fricative (half of each). For the CCV test, a plosive (4 items) or a fricative (4 items) was followed by a liquid, and a plosive was either followed (2 items) or preceded (2 items) by a fricative.

For the phonological STM test, the children were required to repeat three- to six-syllable pseudowords (6 items for each length: 3 with only CV syllables and 3 with a CVC syllable). The items were presented one at a time in increasing order of length (the 6 three-syllable items first, followed by the four-, five-, and six-syllable items). The memory span measure was the number of syllables in the items of the last series for which at least four correct responses were given, and it could vary from 2 (when the child failed to correctly repeat at least 4 of the 6 three-syllable items) to 6 (when the child was able to correctly repeat at least 4 of the 6 six-syllable items).

Naming speed was assessed by a serial naming task using color (six colors presented eight times in a different order). Here 3 items had a CVC structure (*rouge* [red], *jaune* [yellow], and *vert* [green]), and 3 items had a CCV structure (*bleu* [blue], *blanc* [white], and *gris* [gray]). The items were presented on a sheet of paper. For the reading skills, children were required to read aloud two lists of words and two lists of pseudowords presented on the screen of a computer. The words of the first list were orthographically regular and were matched to the first list of pseudowords according to their orthographical complexity. The words of the second list were either short or long orthographically irregular words matched to short and long pseudowords according to their bigram frequency.

For all tasks, group differences were assessed by a repeated-measures analysis of variance (ANOVA), and contrast analyses were done to test differences between dyslexics and either chronological age controls or reading level controls. The results are presented in Table 1.

There was a significant difference in chronological age between dyslexics and reading level controls but not between dyslexics and chronological age controls. Alternatively, there was a significant

<sup>3</sup> Reading level controls were taken from an independent study in which our goal was to assess categorical perception skills in relation to reading acquisition. We followed these children for 3 years from kindergarten to second grade. For our reading level controls, we chose 10 children from this longitudinal study.

<sup>4</sup> In studies with French-speaking children, when possible (with 4- to 8-year-olds), we rely on the *Test de Vocabulaire Actif et Passif* (TVAP) (Deltour & Hupkens, 1980) to assess the level of vocabulary because this test is better designed than the *Echelle de Vocabulaire en Images Peabody* (EVIP) (Dunn, Thériault-Whalen, & Dunn, 1993). Furthermore, there were some words specific to Canadian French in the EVIP. However, the TVAP cannot be used with children older than 9 years. Therefore, we reported the results of the specific test used with the three different groups (EVIP for the dyslexics and for the chronological age controls, TVAP for the reading level controls).

**Table 1**

Chronological and lexical ages, verbal and nonverbal IQs, and reading skills for dyslexics, chronological age controls, and reading level controls

	Dyslexics (n = 10)		Chronological age controls (n = 11)		Reading level controls (n = 10) <sup>a</sup>	
	M	SD	M	SD	M	SD
<b>Chronological and lexical age</b>						
Chronological age (months)	115	7	118	3	91 <sup>***</sup>	6
Lexical age (months)	89	8	132 <sup>**</sup>	9	90	7
<b>Nonverbal and verbal IQ</b>						
Nonverbal IQ: SPM (score)	30	4	32	3	25	6
(percentile)	75	22	84	18	75	21
Verbal IQ: EVIP (standard score)	119	11	132 <sup>**</sup>	9		
Verbal IQ: TVAP (score)					51	6
<b>Phonemic awareness</b>						
Phonemic awareness CVC (scores/12)	8	4	11 <sup>*</sup>	1	11 <sup>*</sup>	1
Phonemic awareness CCV (scores/12)	7	3	10 <sup>*</sup>	2	8	3
<b>Phonological STM</b>						
	4	1	5 <sup>*</sup>	1	4	1
<b>Rapid auditory naming</b>						
RAN (color) (s)	45	17	37	7	48	17
<b>Reading</b>						
Regular words (% correct)	82	26	98 <sup>*</sup>	2	91	10
Regular pseudowords (% correct)	64	26	93 <sup>***</sup>	5	73	18
Short pseudowords (% correct)	69	22	93 <sup>***</sup>	8	88 <sup>*</sup>	16
Long pseudowords (% correct)	53	30	81 <sup>***</sup>	11	73 <sup>†</sup>	24
Short irregular words (% correct)	50	33	94 <sup>***</sup>	8	52	20
Long irregular words (% correct)	56	33	96 <sup>***</sup>	7	59	26

Note. Comparisons (dyslexics vs. chronological age controls and dyslexics vs. reading level controls) were done using contrast analysis in a repeated-measures ANOVA. SPM, Raven's Standard Progressive Matrices; EVIP, *Echelle de Vocabulaire en Images Peabody*; TVAP, *Test de Vocabulaire Actif et Passif*.

<sup>†</sup>  $p < .06$ .

<sup>\*</sup>  $p < .05$ .

<sup>\*\*</sup>  $p < .01$ .

<sup>\*\*\*</sup>  $p < .001$ .

<sup>a</sup> Data from 1 participant are missing for verbal IQ in the reading level control group.

difference in lexical age between dyslexics and chronological age controls but not between dyslexics and reading level controls.

Regarding IQ scores, there was no difference in nonverbal IQ between groups. Verbal IQ was higher in chronological age controls than in dyslexics. However, the vocabulary level of all the children in the study was within the normal range, be it assessed with EVIP (dyslexic children and chronological age controls) or with TVAP (reading level controls). For reading-related skills, the dyslexics lagged behind both control groups for the two phonemic awareness tasks, although only the CVC scores were significantly different between the two latter groups. For phonological STM, there was a significant difference only between the dyslexics and the chronological age controls. Rapid auditory naming (RAN) scores were not significantly different between groups. In addition, the reading scores of the dyslexics lagged systematically behind those of the chronological age controls. The reading scores of the dyslexics also lagged behind those of the reading level controls, but only for the reading of short and long pseudowords and not for reading of regular or irregular words.

### Procedure

#### Stimuli

Categorical perception was evaluated on a /do-to/ VOT continuum, ranging from -50 to +50 ms VOT, and developed with natural speech. We combined excerpts from three different stimuli: a French



[do] with a negative VOT, an English [do] with a +19-ms VOT, and an English [to] with a +70-ms VOT. This continuum was obtained by pasting a 50-ms negative VOT extracted from French [do] before the release of the English [do]. Then we reduced the negative VOT in 10-ms increments. After that, we progressively replaced the postrelease segment of the English [do] with positive VOT excerpts taken from the English [to] in five 10-ms increments. Stimuli were played at a comfortable level using Beyerdynamic DT290 headphones.

### Speech perception tasks

For categorical perception tasks, participants were tested individually while seated comfortably in front of a laptop monitor. They were tested with the “Percept A” and “Percept AB” programs developed by Carré.<sup>5</sup> They were first trained to relate stimuli and same–different discrimination responses to AX pairs (i.e., sequences of two stimuli, either identical or different), including the endpoints of the VOT continuum (–50 vs. +40 and –40 vs. +50 ms VOT, i.e., both pairs representing /do–to/). Participants were asked to indicate whether the pairs presented were identical or different by pressing the appropriate key on the computer. No feedback was provided. Children were allowed to continue the experiment if they reached the 75% correct discrimination threshold criterion. Then AX discrimination responses were collected. Stimuli were presented in pairs, including either two different stimuli or the same stimulus twice. Both “different” pairs (stimuli differing by 20 ms VOT in two different orders, e.g., S1S3 and S3S1, both of which represent /do–do/ syllables, or S6S8 and S8S6, which represent /do–to/ and /to–do/ syllables), and “same” pairs (e.g., S1S1 and S3S3, both of which represent /do–do/, or S6S6 and S8S8, both of which represent /to–to/) were presented in random order with equal frequency (four presentations for each pair). As in the training trial, listeners were asked to indicate whether the pairs presented were identical or different. The interstimulus interval (ISI) was 100 ms, and the intertrial interval (ITI) was 1000 ms. Finally, children were tested on their identification skills. The 11 stimuli were presented 10 times in random order, and the children needed to identify them as /do/ or /to/ by pressing the appropriate key on a computer keyboard. The total test duration was approximately 25 min (20 min for the discrimination task and 5 min for the identification task).

### Psychometric tests

Group differences were assessed by a repeated-measures ANOVA, and a contrast analysis on group in this ANOVA permitted testing differences between dyslexics and either chronological age controls or reading level controls.

### Discrimination data processing

Discrimination results were analyzed in terms of the percentage of same–different correct discrimination scores. For each stimuli pair, these scores were obtained by computing the mean percentage of “different” responses for pairs of acoustically different stimuli (e.g., 0 vs. +20 ms VOT pair, /do–to/) and “same” responses for pairs of identical stimuli (e.g., 0 vs. 0 ms VOT or +20 vs. +20 ms VOT pair, /do–do/ and /to–to/, respectively).

### Labeling data processing

Expected discrimination scores were calculated from the labeling data.<sup>6</sup> These scores are mathematically equivalent to the same–different observed discrimination scores, and they were used for comparing the labeling and discrimination data on the same scale. The slopes of the labeling functions were also used for the sake of comparing the current data with the literature (see Introduction). The slope was measured separately for each participant using logistic regression with the labeling response as the dependent variable and VOT as the independent variable. The logistic function (McCullagh & Nelder,

<sup>5</sup> “Percept” programs can be uploaded at <http://pagesperso-orange.fr/ren.carre/programme.htm>.

<sup>6</sup> With two categories (A and B), a binary discrimination choice (AX discrimination experiment), S3, S4 as stimuli and with  $P(RA/S3)$  as the proportion A responses to S3, and so forth. Predicted discrimination score = mean & {} = mean  $\{P(A/S3) \cdot P(B/S4) + P(B/S3) \cdot P(A/S4)\}$  and  $\{[P(A/S3) \cdot P(A/S3) + P(B/S3) \cdot P(B/S3) + P(A/S4) \cdot P(A/S4) + P(B/S4) \cdot P(B/S4)]/2\}$ . This formula is similar to the formulas used for comparing labeling and discrimination responses in the assessment of categorical perception (Pollack & Pisoni, 1971).

1983) is fairly simple and has been frequently used for fitting labeling curves in the studies on speech perception (e.g., Nearey, 1990), although other functions such as the cumulative normal (Finney, 1971) are also possible and the latter has also been used in speech perception studies. Eq. (1) gives the most general form of the logistic function:

$$p(\text{response}) = e^y / (e^y + 1) \quad (1)$$

where

$$y = \text{logit}(P) = \log[P/(1 - P)] = I + S * \text{VOT},$$

where  $I$  stands for the intercept and  $S$  corresponds to the slope of the labeling function. The boundary, which corresponds to  $P = 0.5$  or to  $\text{logit}(P) = 0$ , is obtained by taking  $-I/S$ .

### Analysis strategy

First, the difference in categorical perception between discrimination and labeling scores was tested in a  $\text{VOT} \times \text{Score Type}$  (discrimination vs. labeling scores)  $\times$  Group (chronological age controls vs. dyslexics vs. reading level controls) ANOVA repeated over participants. Second, because the  $\text{VOT} \times \text{Score Type} \times \text{Group}$  interaction was significant as expected, the differences between groups were tested separately on the discrimination scores and on the labeling scores with  $\text{VOT} \times \text{Group}$  ANOVAs repeated over participants. Between-group differences for the expected discrimination scores (labeling scores) were compared with those obtained for the slopes of the individual labeling functions. Differences between groups were tested separately for the dyslexics versus chronological age controls and for the dyslexics versus reading level controls.

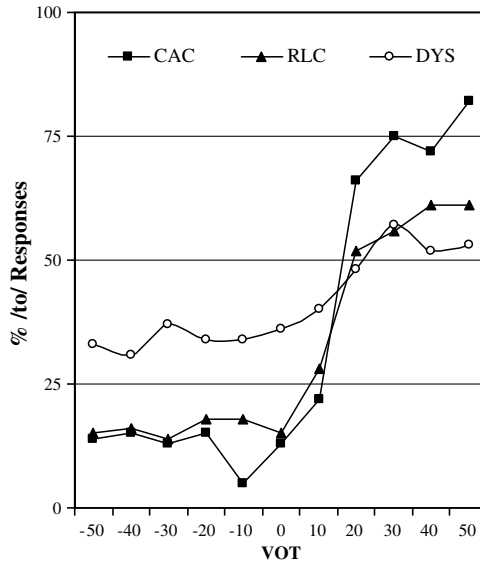
Differences in categorical perception and in allophonic perception were tested with  $\text{VOT} \times \text{Score Type} \times \text{Group}$  interaction contrasts. A phonemic peak was computed as the difference between the across-category discrimination scores (i.e., those collected for the stimulus pairs straddling the phonemic boundary) and the within-category discrimination scores (i.e., those collected for the stimulus pairs inside the two categories: either voiced or voiceless). An allophonic peak was computed as the difference between the allophonic discrimination score, presumably corresponding to the stimulus pair straddling the  $-30$ -ms VOT value, and the scores collected for the other stimulus pairs inside the voiced category. Because there were two contrasts per group comparison (dyslexics vs. chronological age controls and dyslexics vs. reading level controls), one for testing the phonemic peak and the other for testing the allophonic peak,  $p$  values for testing contrasts were Bonferroni corrected by a factor of 2 (i.e., the effective .05 probability level was set at .025). All statistical analyses, with the exception of the Bonferroni corrections, were performed with the SPSS software.

## Results

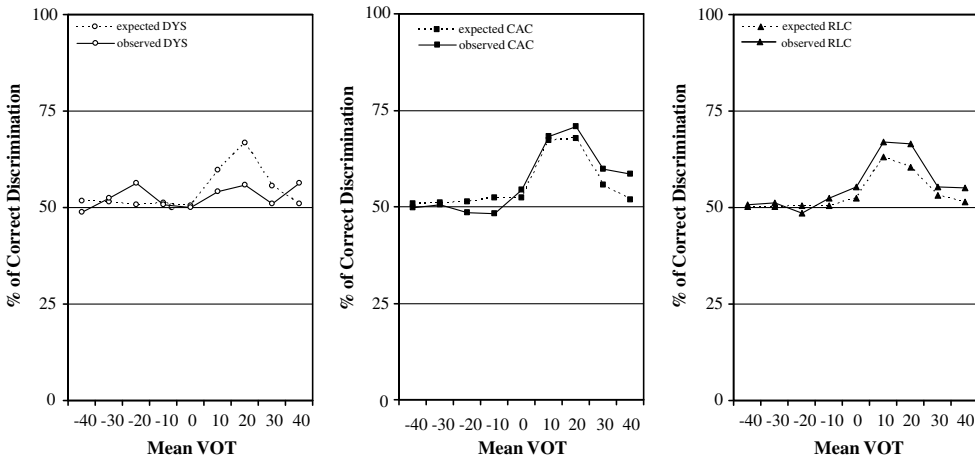
### *Categorical perception: Difference between expected and observed discrimination scores*

The labeling functions of the three groups of children are presented in Fig. 3. As can be seen, the phoneme boundary (i.e., the 50% do-to response point) is located at approximately +15 ms VOT for each group. Observed discrimination scores and those expected from labeling are presented in Figs. 4A, 4B, and 4C for the dyslexics, chronological age controls, and reading level controls, respectively. For the controls, the observed discrimination scores were close to the predicted scores, thereby showing a high level of categorical perception, whereas for children with dyslexia, the observed discrimination scores did not match the expected scores. In addition, a second discrimination peak appeared at  $-20$  ms VOT and was absent for both the chronological age controls and reading level controls. This peak was located close to the expected VOT value ( $-30$  ms [see Introduction]); therefore, it is considered as allophonic as is further commented in the Discussion.

For the comparison between dyslexics and chronological age controls, a  $\text{Score Type} \times \text{VOT} \times \text{Group}$  ANOVA indicated that the  $\text{Score Type} \times \text{VOT} \times \text{Group}$  interaction was significant,  $F(8, 152) = 2.85$ ,  $p < .05$ , Greenhouse–Geisser corrected,  $\eta^2 = .13$ . For the comparison between dyslexics and reading level controls, a  $\text{Score Type} \times \text{VOT} \times \text{Group}$  ANOVA indicated that the  $\text{Score Type} \times \text{VOT} \times \text{Group}$



**Fig. 3.** Labeling functions for dyslexics (DYS), chronological age controls (CAC), and reading level controls (RLC) (percentage of /to/ responses).



**Fig. 4.** Categorical perception in dyslexics (DYS) (A), chronological age controls (CAC) (B), and reading level controls (RLC) (C) on the /do-to/ voicing continuum (percentage of correct discrimination). Dotted lines represent expected scores, and solid lines represent observed scores.

interaction was just significant,  $F(8, 144) = 2.65, p = .05$ , Greenhouse–Geisser corrected,  $\eta^2 = .13$ . Accordingly, further analyses were conducted separately on the discrimination and labeling scores.

*Categorical perception: Discrimination peak*

For the controls (Figs. 4B and 4C), stimulus pairs straddling the phonemic boundary (i.e., the pairs centered on +10 and +20 ms VOT) were strongly discriminated, whereas discrimination scores for the

pairs inside the same category were at chance level (50%). The observed phonemic peak was fairly large, with 17 and 14% differences between across- and within-category discrimination for the chronological age controls and reading level controls, respectively (Figs. 4B and 4C). Conversely, the observed phonemic peak was quite low for the dyslexics (3% difference [Fig. 4A]), and a second discrimination peak located at  $-20$  ms VOT was present for this group.

Differences in discrimination scores were tested separately for the dyslexics versus chronological age controls and for the dyslexics versus reading level controls in two VOT  $\times$  Group ANOVAs. The VOT  $\times$  Group interaction was significant for the dyslexics versus chronological age controls,  $F(8, 152) = 4.51$ ,  $p < .001$ ,  $\eta^2 = .19$ , and was marginally significant for the dyslexics versus reading level controls,  $F(8, 144) = 2.37$ ,  $p < .05$ ,  $\eta^2 = .12$ . Examination of VOT  $\times$  Group contrasts showed that the phonemic peak difference between dyslexics and chronological age controls was significant,  $F(1, 19) = 9.55$ ,  $p < .05$ ,  $\eta^2 = .33$ , whereas the phonemic peak difference between dyslexics and reading level controls was not significant,  $F(1, 18) = 4.15$ ,  $p = .06$ ,  $\eta^2 = .19$ . Allophonic peak differences were significant for both the dyslexics versus chronological age controls and dyslexics versus reading level controls comparisons,  $F(1, 19) = 11.90$ ,  $p < .01$ ,  $\eta^2 = .39$ , and  $F(1, 19) = 19.60$ ,  $p < .001$ ,  $\eta^2 = .52$ , respectively.

### *Categorical labeling*

Examination of the expected discrimination scores in Fig. 4 indicates that fairly similar phonemic peaks were present for each group and that no secondary peak was visible for the dyslexics. Differences in labeling scores were tested separately for the dyslexics versus chronological age controls and for the dyslexics versus reading level controls in two VOT  $\times$  Group ANOVAs. The VOT  $\times$  Group interaction was not significant for either the dyslexics versus chronological age controls or dyslexics versus reading level controls comparisons, both  $F_s < 1$ . All of the interaction contrasts of interest were nonsignificant, all  $F_s < 1$ .

### *Labeling scores versus slopes*

Labeling functions are presented in Fig. 3. The slope of the function is steepest for the chronological age controls, followed by the slopes for the reading level controls and the dyslexics (in that order). However, individual slopes were highly variable within groups, and differences between groups were not significant when tested with ANOVA,  $F < 1$ ,  $\eta^2 = .02$ . Differences between groups remained nonsignificant when tested with the nonparametric Mann–Whitney  $U$  test, which was performed to take into account the effect of possible outliers (for dyslexics vs. chronological age controls:  $Z = 1.41$ ,  $p = .16$ ; for dyslexics vs. reading level controls:  $Z = 1.21$ ,  $p = .23$ ). Although nonsignificant, the differences between the slopes of the functions between groups might seem unusual given the similarities in the mean expected discrimination peaks (Fig. 4). This was due partly to the reversals in the labeling curves of 3 of the 10 dyslexic participants around the boundary region, which contributed negatively to the slope but positively to the between-category expected scores because the latter are “blind” to the direction of the changes in labeling scores. Furthermore, the floor and ceiling of the dyslexics’ labeling curve also contributed negatively to the slope but did not affect the within-category expected scores because the latter depend only on differences between labeling scores.

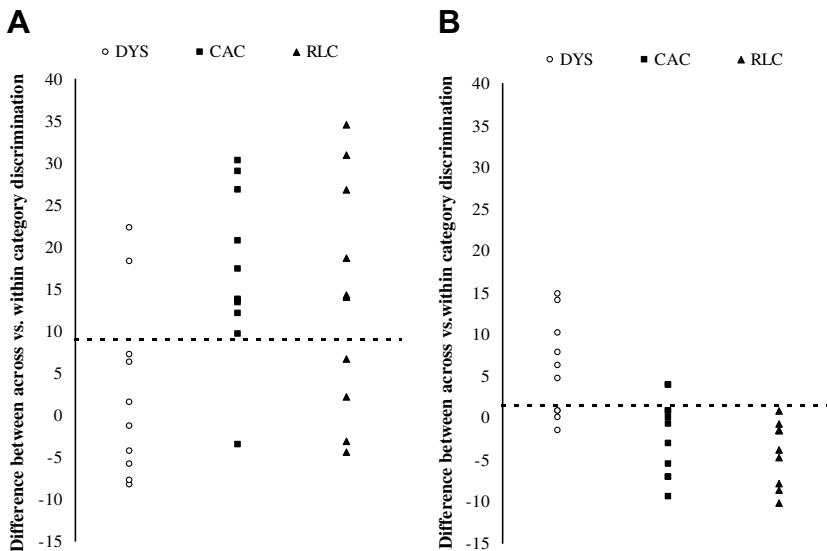
Because the groups also differed in the magnitude of the floor and ceiling values of the labeling curve (i.e., in the responses collected either below  $+10$  ms VOT or above  $+20$  ms VOT [see Fig. 3]), and given that differences in floor and ceiling values are not specifically captured by slope calculations, direct tests of the effect of group on the mean response scores in the VOT regions of interest were performed. Differences in floor values between groups were significant overall,  $F(2, 168) = 11.80$ ,  $p < .001$ ,  $\eta^2 = .12$ , and both the dyslexics versus chronological age controls and dyslexics versus reading level controls comparisons were significant,  $F(1, 168) = 21.00$ ,  $\eta^2 = 0.11$ , and  $F(1, 168) = 13.80$ ,  $\eta^2 = 0.08$ , respectively, both  $p_s = .001$ . Differences in ceiling values between groups were significant overall,  $F(2, 84) = 3.60$ ,  $p < .05$ ,  $\eta^2 = .08$ , the dyslexics versus chronological age controls

comparison was also significant,  $F(1, 84) = 6.53, p < .05, \eta^2 = .07$ , but the dyslexics versus reading level controls comparison was not significant,  $F < 1, \eta^2 = .004$ .

#### Individual reliability of categorical perception deficit

To assess the individual reliability of the categorical perception deficit, we ran a statistical discriminant analysis on the phonemic peak (see Fig. 5A for individual data). Results on individual reliability were strongly conclusive, with 81% of the individuals being correctly classified when we compared dyslexics and chronological age controls and with 70% of the individuals being correctly classified when we compared dyslexics and reading level controls. The correct classification scores were obtained after cross-validation (i.e., the “dropout” method whereby each individual score was classified according to the distributions of the other scores).

Finally, we also examined the reliability of the allophonic perception differences using the allophonic peak as an index (see Fig. 5B for individual data). The outcomes of these analyses were also strongly conclusive, although individual reliability was now better when children affected by dyslexia were compared with reading level controls rather than with chronological age controls (71% of the individuals were correctly classified when we compared the dyslexics with the chronological age controls, whereas 75% of the individuals were correctly classified when we compared the dyslexics with the reading level controls).



**Fig. 5.** (A) Individual phonemic peak values (i.e., difference between between-category discrimination score and within-category discrimination score) for three groups of participants. Dotted lines indicate classification limits obtained by a statistical discriminant analysis. Because the limit between the dyslexics (DYS) and chronological age controls (CAC) and the limit between the dyslexics and reading level controls (RLC) were fairly close (phonemic peaks of 10 and 9%, respectively), a single limit (at 9.0%) is reported on the graph. The distribution of dyslexic children and chronological age controls overlaps only slightly (81% correct classification). The overlap between the distribution of dyslexic children and reading level controls is larger (70% correct classification). (B) Individual allophonic peak values (i.e., difference between the –20-ms VOT discrimination score and the other negative and 0 VOT discrimination scores) for three groups of participants. Dotted lines indicate classification limits obtained by a statistical discriminant analysis. Because the limit between the dyslexics and chronological age controls and the limit between the dyslexics and reading level controls were fairly close (allophonic peaks of 2 and 1%, respectively), a single limit (at 1.5%) is reported on the graph. The distributions of dyslexic children and controls are fairly distinct (71% correct classification for the dyslexics vs. chronological age controls; 75% correct classification for the dyslexics vs. reading level controls).

## Discussion

### *Categorical perception deficit*

Our first aim in collecting the speech perception data presented in this study was to evaluate whether dyslexics presented a categorical perception deficit. We found such a deficit for the discrimination of speech sounds, thereby confirming the results of several previous studies (Brandt & Rosen, 1981; De Weirdt, 1988; Godfrey et al., 1981; Reed, 1989; Serniclaes et al., 2001; Werker & Tees, 1987). Although both the children affected by dyslexia and the control children exhibited a discrimination peak at the phonemic boundary, this peak was much smaller for the dyslexics. This confirms the categorical perception deficit in dyslexia. A related deficit in the labeling of speech sounds was also found. When the labeling data were tested on the same scale as the discrimination data—using “expected” discrimination scores from labeling—there were no significant differences in categorical perception between groups. Furthermore, when using a classical index of categorical labeling, the slopes of the labeling functions, we also did not find significant differences between groups. Yet the floor and ceiling of the identification curves were significantly related to the group; the floor portion of the curve (below +10 ms VOT [see Fig. 3]) was significantly higher for the dyslexics versus both control groups, and the ceiling portion of the curve (above +20 ms VOT) was significantly lower for the dyslexics versus chronological age controls.

### *Allophonic perception*

The discrimination performances of the dyslexic children were characterized not only by a reduced phonemic boundary peak but also by a nonphonemic discrimination peak. This peak was located at –20 ms VOT, close to the –30-ms peak evidenced for another group of children affected by dyslexia in a previous study (Serniclaes et al., 2004). The difference in peak location between the two studies is probably due to stimulus factors given that stimulus details might induce slight differences in the location of the allophonic peak in much the same way as they affect the location of the phonemic boundaries. Whereas the phonemic boundary is located at 0 ms for neutral consonant and vowel articulation (Medina & Serniclaes, 2005), it is, for instance, located at some +10 ms VOT in the less neutral /do–to/ context used in the current experiment. Therefore, the –20-ms VOT peak evidenced in this experiment can be safely considered as allophonic in nature and lends further support to the hypothesis that dyslexics adopt a specific mode of speech perception based on allophones rather than phonemes.

Although an allophonic peak was clearly apparent in the discrimination responses of the dyslexic children, it was completely absent from the labeling data (see the expected discrimination scores in Fig. 4). As explained above, the labeling deficit was totally absent in the current study. It is no wonder that the allophonic peak was also absent in the labeling data.

### *Comparisons between dyslexics and reading level controls*

The categorical deficits evidenced in the current study were significant for both the comparison with chronological age controls and the comparison with reading level controls. Contrary to previous studies (Boissel-Dombreval & Bouteilly, 2003; Foqué, 2004), children with dyslexia were shown to be weaker in categorical perception than younger children at the same reading level. We underline this result given that this study is the first one that reports a deficit in categorical perception in children with dyslexia in comparison with reading level controls. This suggests that the categorical perception deficit reflects a developmental deviance rather than a delay. Furthermore, reading level controls did not exhibit an allophonic peak, thereby suggesting that allophonic perception is not due simply to a delay in reading acquisition.

### *Individual reliability*

The current results showed that the reliability of the categorical perception deficit was fairly strong with fairly large correct classification scores (dyslexics vs. chronological age controls: 81%; dyslexics

vs. reading level controls: 70%). Much the same result was found by Maassen and colleagues (2001), who studied the discrimination of voicing and place of articulation continua by Dutch 9-year-olds. They found that discrimination scores allowed for correct classification of approximately 75% of the participants as dyslexics or normal readers (chronological age controls). The current study also shows that allophonic perception differences between dyslexics and controls are strongly reliable (dyslexics vs. chronological age controls: 71%; dyslexics vs. reading level controls: 75%). All of these results point to some 75% correct classification of dyslexics on the ground of categorical performances in speech perception both versus chronological age controls and versus reading level controls. In comparison, the reliability of the classical phonological deficit is approximately 80% (Ramus, Pidgeon, & Frith, 2003), and the reliability of the auditory deficit is quite a bit smaller (60% of correct classification). Thus, the reliability of the allophonic deficit is quite similar to that of the classical phonological deficit.

Although our study and that of Maassen and colleagues (2001) indicate that the categorical perception deficit is fairly reliable across individuals, the information about *individual* performance is too scarce in the literature to make strong conclusions. Therefore, it is interesting to have a look at the reliability of the difference between *groups* in categorical perception across studies (i.e., the robustness of the categorical perception deficit). Serniclaes, Bogliotti, Messaoud-Galusi, and Sprenger-Charolles (unpublished manuscript) recently reviewed studies on the differences between dyslexic children and chronological age controls in the discrimination of speech continua. The difference in categorical perception was significant in approximately 75% of the tests found in six different studies.

#### *Nature of categorical perception deficit in children with dyslexia: An allophonic mode of perception*

Our results lend further support to the hypothesis that children affected by dyslexia have a categorical deficit in speech perception and are more sensitive to allophonic contrasts than are normal-reading children, either chronological age or reading level controls. Languages display phonemic boundaries at different points on the voicing continuum. However, these different points are not determined at random. Taking foreign categorization patterns into account allows us to understand the precise location of the second peak for dyslexics. We know that Thai phonemic boundaries are located at approximately  $-30$  ms and  $+30$  ms VOT (Lisker & Abramson, 1970) (Fig. 2) and that prelinguistic children were able to discriminate three voicing categories separated by two VOT boundaries (Aslin et al., 1981; Lasky et al., 1975; Streeter, 1976). The within-category peak observed in dyslexics, which is located on the  $-20$ -ms VOT pair, corresponds approximately to one of two phonemic boundaries in languages with three VOT categories such as Thai. Of course, it is too early to parallel the possible categorization peak of Thai listeners with the one exhibited by our participants without a direct comparison. But it is already clear that dyslexics exhibit a discrimination peak close to the  $-30$ -ms Thai phonemic boundary, and this coincidence must be evoked. Furthermore, Burnham and colleagues (Burnham, 2003; Burnham, Earnshaw, & Clark, 1991) also observed that children are sensitive to both native and nonnative contrasts and that discrimination between allophonic contrasts was stronger for children with less reading experience. Finally, Serniclaes, Ventura, Morais, and Kolin-sky (2005) observed that illiterates do *not* suffer from a categorical perception deficit even though they showed less categorical *precision* than did literates. This might be the consequence of written language deprivation or impairment. Illiterates are exposed to oral language and acquire normal categorical perception, but their lack of exposure to written language leads to a labeling deficit. This means that lack of exposure to written language cannot account for the categorical perception deficit and that the latter should be considered as a cause rather than a consequence of their reading deficiency. The lack of a categorical perception deficit in reading level controls observed in the current study supports this conclusion. Although reading level controls display the same reading performances as do dyslexics, the latter display weaker categorical perception performances.

#### *Origins of allophonic perception: A coupling deficit*

Some phonemic boundaries are not included in infants' predispositions (i.e., the VOT boundary located at 0 ms in languages such as French, Spanish, and Dutch [Serniclaes, 1987]), although they do appear fairly early in the course of language development (Eilers, Gavin, & Wilson, 1979; Hoonhorst

et al., 2006). The *coupling* process suggests that a new boundary, irreducible to one of the two natural phonetic boundaries and falling right between these two boundaries, must be acquired. This process enabling such acquisition is fairly complex in that it requires a specific combination between two natural distinctions. The combination between the two predispositions is interactive in the sense that the perception of one feature depends on the perception of the other feature.

Results of the current study suggest a coupling deficit in that children with dyslexia exhibit a second discrimination peak at approximately  $-20$  ms VOT, a value close to one of the two natural VOT boundaries found in Thai listeners and prelinguistic children. The fact that children with dyslexia perceived the negative VOT boundary so easily compared with the phonemic boundary suggests that they have not developed couplings between the predispositions for perceiving voicing (e.g., negative VOT) and aspiration (e.g., positive VOT), and this is evidence of a coupling deficit. So, allophonic perception should find its origin in this coupling deficit.

But if dyslexic children fail to couple phonetic features, they should also show an allophonic peak in the positive VOT region and at a different place on the continuum from the phoneme boundary control children. Instead, they display a positive VOT peak, albeit a weaker one, at the same spot on the continuum as do the control children. This can be explained by the fact that the phonemic boundary in control children ( $\sim +15$  ms for the current do-to continuum) is close to the allophonic positive VOT boundary (at some  $+20$  or  $+30$  ms). However, another possible explanation is that the coupling deficit is not complete and that dyslexic children have partially begun to develop a phonemic VOT boundary. Future research using stimulus continua with a larger separation between allophonic and phonemic boundaries should allow the clarification of this point. Finally, allophonic perception should correspond to a developmental deviance rather than a delay because dyslexics display an enhanced sensitivity to the negative VOT boundary not only in comparison with chronological age controls but also in comparison with reading level controls. This suggests that the allophonic sensitivity evidenced in dyslexic children is not a consequence of their lower reading level. In this way, the allophonic perception deficit is similar to other phonological deficits (pseudoword reading: Rack et al., 1992; Sprenger-Charolles et al., 2000; Van Ijzendoorn & Bus, 1994; phonemic awareness: Manis et al., 1997).

#### *Allophonic perception and its implication for reading and phonological abilities*

Whereas allophonic perception has only limited consequences for oral language, it has strong repercussions for written language. Allophonic perception should not impede the categoricalness of perception, although categorical perception should be based on allophones rather than phonemes. Even though lexical access should not pose a problem for oral language processing (but would be heavier in terms of information processing), the phonological coupling deficit has straightforward implications for written language acquisition. Allophonic representations are a significant handicap for the establishment of grapheme–phoneme correspondences because they disrupt one-to-one correspondences between graphemes and phonemes. A child who perceives allophones /d/, /p/, and /p<sup>h</sup>/ instead of phonemes /b/ and /p/ will have difficulty in assigning the same graphic symbol “P” to /p/ and /p<sup>h</sup>/. It should be stressed that, due to coarticulation, allophones are commonplace for the different features and languages. Furthermore, allophonic variation is not restricted to some rare occurrences of deviant productions because phoneme categories tend to be located midway between allophonic categories and phoneme distributions spread on both sides of allophonic boundaries.

To take the example of the voiceless allophones, the mean productive VOT of /p/ in French ( $\sim +20$  ms [Serniclaes, 1987]) is fairly close to the allophonic positive VOT boundary, and individual /p/ productions are distributed roughly equally above and below this boundary. This means massive difficulty with grapheme–phoneme correspondences for an allophonic perceiver. Moreover, this difficulty will emerge even in a fairly transparent orthographic system and will be amplified with higher degrees of orthographic opacity (for a review on the effect of orthographic opacity, see Paulesu et al., 2001; Sprenger-Charolles et al., 2006; Ziegler & Goswami, 2005).

The allophonic perception hypothesis might also explain other deficits observed in dyslexia. This mode of perception could have a strong impact on phonemic awareness deficient in dyslexics because it involves the manipulation of phonemes that do not exist in their phonological decoding process. It would also contribute to the phonological STM deficit that is observed in dyslexics. The number of



decoding units is indeed higher in a system that is based on allophones rather than phonemes, thereby triggering a working memory overload. On the whole, allophonic perception offers a new conceptualization of dyslexia in terms of deficient phonological processing.

## Conclusion

The current study has confirmed the relationship between reading skills and speech perception. Using all available known criteria to assess categorical perception, we replicated the categorical perception deficit in children with dyslexia both for discrimination scores alone and for the difference between discrimination and labeling scores. There were also differences in categorical labeling between groups, but these differences were not significant. Categorical perception differences were related to the better discrimination of an allophonic distinction, lending further support to the hypothesis that dyslexics adopt a specific mode of speech perception based on allophonic rather than phonemic categories. Categorical perception differences and the related differences in allophonic perception were found not only between dyslexics and chronological age controls but also between dyslexics and reading level controls. Finally, examination of individual performances showed that both the deficit in categorical perception and the concomitant increase in allophonic sensitivity were fairly prevalent among children affected by dyslexia.

## Acknowledgment

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