Article

Investigating Speech Perception in Children With Dyslexia: Is There Evidence of a Consistent Deficit in Individuals?

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Purpose: The claim that speech perception abilities are impaired in dyslexia was investigated in a group of 62 children with dyslexia and 51 average readers matched in age.
Method: To test whether there was robust evidence of speech perception deficits in children with dyslexia, speech perception in noise and quiet was measured using 8 different tasks involving the identification and discrimination of a complex and highly natural synthetic "bee"–"pea" contrast (copy synthesized from natural models) and the perception of naturally produced words.
Results: Children with dyslexia, on average, performed more poorly than did average readers in the synthetic syllables identification task in quiet and in across-category discrimination (but not when tested using an adaptive procedure). They did not differ from average readers on 2 tasks of word recognition in noise or identification of synthetic syllables in noise. For all tasks, a majority of individual children with dyslexia performed within norms. Finally, speech perception generally did not correlate with pseudoword reading or phonological processing—the core skills related to dyslexia.
Conclusions: On the tasks and speech stimuli that the authors used, most children with dyslexia did not appear to show a consistent deficit in speech perception.

Key Words: dyslexia, speech perception, noise, reading, categorical perception

Reading impairment in dyslexia is characterized by severe difficulties in phonological (letter–sound) decoding as well as in written word identification despite conventional instruction and adequate intelligence. It is widely accepted in the literature that individuals with dyslexia are impaired in the processing of phonological information that is crucial to learn to read in an alphabetic script. The origin of those phonological processing difficulties is hotly debated (Ramus et al., 2003; Ramus, White, & Frith, 2006; White et al., 2006), and a growing number of theories posit that deficits in speech processing are involved in disordered reading acquisition (Serniclaes, Van Heghe, Mousty, Carre, & Sprenger-Charolles, 2004; Ziegler, Pech-Georgel,

George, & Lorenzi, 2009). Alternatively, speech perception deficits are not seen in all individuals with dyslexia (Adlard & Hazan, 1998; Manis et al., 1997), and in a recent study that we conducted with adults with dyslexia, individuals did not perform consistently well or badly across a range of related speech perception tasks (Hazan, Messaoud-Galusi, Rosen, Nouwens, & Shakespeare, 2009). Here, we examined a key aspect of speech perceptual processing in children's phoneme categorization. We used both fixed and adaptive tasks of phoneme identification and discrimination that place varying task demands on listeners. We also investigated whether children with dyslexia are disproportionally affected by the addition of background noise in phoneme categorization and real-word identification. Finally, we attempted to relate performance on speech perception tasks to broader phonological processing skills at the group as well as the individual level.

The difficulties that individuals with dyslexia have in analyzing, memorizing, and accessing the sound structure of language are well documented. These difficulties have been shown through the use of tasks tapping phonological short-term memory and rapid lexical retrieval (McBride-Chang, 2006; Sprenger-Charolles,

Cole, & Serniclaes, 2006). In addition, a compelling body of evidence has shown that individuals with dyslexia have poor phonological awareness, as shown via tasks involving the segmentation, identification, discrimination, or blending of sublexical units (Goswami, 2003; Liberman, Shankweiler, Liberman, Fowler, & Fischer, 1977; Swan & Goswami, 1997; Windfuhr & Snowling, 2001). Individuals with dyslexia also have problems with phonological tasks that involve finding and retrieving phonological codes of known names, and common reading errors involve phonologically similar letter sounds (Liberman et al., 1977; Swan & Goswami, 1997). Such pervasive difficulties in phonological processing led several influential theorists to suggest that specific reading impairment was due to inaccurate phonological representations in the mental lexicon (Goswami, 2003; Snowling, 2000), which would lead to impaired metalinguistic processing, storage, access, or retrieval of oral speech information. Reading acquisition would be affected because grapheme–phoneme correspondences cannot be reliably established if phonological representations are inaccurate.

It has also been suggested that individuals with dyslexia show poorer speech perception abilities than do age-matched controls (Bogliotti, Serniclaes, Messaoud-Galusi, & Sprenger-Charolles, 2008; de Gelder & Vroomen, 1998; Goswami et al., 2002; Mody, Studdert-Kennedy, & Brady, 1997; Serniclaes, Sprenger-Charolles, Carre, & Demonet, 2001). Although some researchers have argued that speech perceptual deficits in dyslexia are a result of weak phonological representations (Liberman, 1983), others have suggested that problems with the processing of speech sounds may, in fact, be the cause of phonological difficulties and may be linked to atypical development of phonetic categorization early in infancy (Bogliotti et al., 2008; Serniclaes et al., 2004). According to this view, the speech perceptual deficit affecting individuals with dyslexia would be subtle and may go unnoticed in normal oral communication that provides multiple redundant and contextual cues. However, when limited acoustic information is provided or when speech is ambiguous (as in tests of categorical perception and in background noise), individuals with dyslexia would fare less well than average readers.

Godfrey, Syrdal-Lasky, Millay, and Knox (1981) first suggested that speech perception was less categorical in children with dyslexia than in age-matched average readers. Stimulus identification was less consistent and, thus, slopes of the identification were more gradual, which was interpreted as being indicative of overlapping or imprecise phoneme categories (Blomert, Mitterer, & Paffen, 2004; Hazan & Barrett, 2000). Also, discrimination in the phoneme boundary region was typically poorer in individuals with dyslexia than in average readers, suggesting that phonemic categories are more confusable.

Similar patterns were found in further studies of categorical perception with children with dyslexia (Boada & Pennington, 2006; Bogliotti et al., 2008; Brandt & Rosen, 1980; Chiappe, Chiappe, & Siegel, 2001; de Gelder & Vroomen, 1998; Mody et al., 1997; Nittrouer, 1999; Rosen & Manganari, 2001; Werker & Tees, 1987). Poor phoneme categorization would have important implications for access to abstract phonological representations, as it would make it more difficult to extract invariant phonological representation from the speech signal. This would, in turn, have an impact on word identification when limited acoustic information is available and would have even more deleterious consequences for conscious access to phonemes and for the acquisition of reading.

Some researchers have argued that the speech perception difficulties of individuals with dyslexia may also come from the fact that they perceive within-category variants as distinct units. Serniclaes et al. (2004) showed that in addition to poorer discrimination across phonemic categories, children with dyslexia showed enhanced within-category discrimination abilities relative to average readers. They concluded that phoneme inventories of children and adults with dyslexia are overcrowded, with more categories than necessary to perceive their native language. This "allophonic mode of speech perception" affects reading acquisition by inflating the number of possible spelling-to-sound correspondences.

The finding of group deficits in phoneme categorization tasks, however, is not universal, and some studies failed to find significant differences in identification between groups with dyslexia and average-reading groups in studies with children (e.g., Adlard & Hazan, 1998; Blomert et al., 2004; Joanisse, Manis, Keating, & Seidenberg, 2000; Maassen, Groenen, Crul, Assman-Hulsmans, & Gabreëls, 2001; Mody, Studdert-Kennedy, & Brady, 1997; Robertson, Joanisse, Desroches, & Ng, 2009) and adults (Ramus et al., 2003). Also, studies that presented individual data found that group data can obscure a more complex picture. Adlard and Hazan (1998) tested children with dyslexia as well as reading- and chronological-age controls and found that only 30% (4 of 13) of the children with dyslexia had poor speech perceptual abilities, whereas the remaining 70% performed within norms. A comparable proportion of poor perceivers was reported by Manis and colleagues (1997); in addition, using a more stringent criterion, McArthur, Ellis, Atkinson, and Coltheart (2008) observed that only 16% of children with dyslexia had difficulties with consonant–vowel discrimination (/ba/–/da/ continuum), and 21% of them had difficulties with vowel discrimination (/e/–/a/ continuum). These studies suggested that categorical perception deficits are less prevalent than phonological processing difficulties and might, in fact, affect only a subgroup of children with dyslexia.

Ziegler et al. (2009) argued that inconsistent findings in terms of the perceptual abilities of individuals with dyslexia may be due to the fact that most studies have presented stimuli in quiet conditions. They observed speech perception deficits in children with dyslexia for the identification of naturally produced vowel–consonant–vowel stimuli when presented in various background noise conditions but not when the same material was presented in quiet. Difficulties in processing speech in noise were also found in other studies (Boets, Ghesquiere, van Wieringen, & Wouters, 2007; Brady, Schankweiler, & Mann, 1983). Ziegler et al (2009) suggested that perceptual deficits may not be seen in quiet, as the speech signal contains much redundant acoustic cue information, but further stressing the perceptual system with additional background noise or using simplified synthesized tokens might reveal subtle deficits in perception.

In summary, studies that support a speech perceptual deficit in children and adults with dyslexia suggest that the difficulties they experience are subtle and emerge only when incoming acoustic information is limited or ambiguous. In addition to difficulties in performing operations involving oral and written phonological units, speech perceptual deficits would also compromise the access to lexical information, particularly under difficult listening conditions. Further support for a link between phonological processing and speech perception is provided by the moderate correlations reported (Manis et al., 1997; Mayo, Scobbie, Hewlett, & Waters, 2003) and also by structural equation modeling on a large sample of children indicating that the effect of speech perception on reading was mediated by its relation to phonological processing abilities (McBride-Chang, 1996).

In a recent study, we sought to address the issue of prevalence and reliability of speech perceptual deficits in adults with dyslexia who were tested on a wide range of tasks (Hazan et al., 2009). Most tasks involved the identification and discrimination of stimuli from a synthetic plosive voicing continuum ("bee"–"pea") presented in both quiet and noise. The discrimination tests were presented using both adaptive and fixed-step procedures, with the rationale that if an individual's difficulties were due to a speech perceptual deficit, this would be consistent regardless of the task procedure used. Significant group differences were found for across- and within-category discrimination when tested using a fixed-step procedure but not when using adaptive procedures. No group differences were obtained for identification, which was also tested adaptively, nor for separate tests of natural words in noise. Individuals did not show consistent poor performance across related tasks. These results were interpreted as providing weak support for a speech perception deficit in dyslexia. It was suggested that some individuals with dyslexia have speech perceptual acuity that is at the lower end of the normal range

and that is exacerbated by nonsensory factors such as attention or other task-related factors.

However, dyslexia is a developmental disorder, which implies that the profile of individuals affected is not static and changes under the influence of developmental and environmental factors (Karmiloff-Smith, 1998; Karmiloff-Smith, Scerif, & Ansari, 2003; Robertson et al., 2009). Therefore, findings of studies with adults who have dyslexia may not be generalizable to children with dyslexia. In addition, even if speech perception in children with dyslexia is atypical, it may still improve with age and be on par with that of average readers at a later stage of their language development. Therefore, it is informative to test children with dyslexia and age-matched average readers that span a large age range.

The overall goal of the present study was, therefore, to further test the speech perceptual explanation of dyslexia in childhood, during which time such deficits are less likely to have been compensated for. The children with dyslexia whom we recruited were assessed using the same range of categorical perception and speech-in-noise tasks as those used in Hazan et al. (2009). More particularly, the present study aimed at answering five research questions:

1. Is there evidence of a consistent deficit in speech perception in children with dyslexia? We hypothesized there would be support for the speech perceptual account of dyslexia if children showing such a deficit performed poorly on the discrimination of a given speech continuum (e.g., a "pea"–"bee" voicing contrast) regardless of whether this was assessed using a fixed or adaptive test procedure. Also, we expected that performance would be consistently poor or good across both tests of natural words in noise.

2. Is there evidence for better within-category discrimination in children with dyslexia than in children who are average readers? We wished to investigate claims put forward by the allophonic model of speech perception of better within-category discrimination abilities in children with dyslexia. Within-category discrimination was assessed using both fixed and adaptive test procedures.

3. Do the speech perception abilities of children with dyslexia worsen in noise? Consistent with the speech perceptual explanation of dyslexia, we hypothesized that if poor performance on identification or discrimination tasks was indicative of subtle speech perceptual impairments, then performance should be worsened by the addition of noise. To test this hypothesis, identification and discrimination tests for the "pea"–"bee" voicing contrast were carried out both in quiet and in noise. Two additional tests of natural words in noise were also presented.

4. What is the prevalence of speech perceptual deficit in dyslexic children? To assess this, we compared the proportion of children with and without dyslexia who performed below norm for each task.

5. Is there a link among speech perception abilities, phonological processing, and reading abilities? To assess this, we looked at correlations across the different kinds of tasks in the test battery.

Method
Participants

The 113 participants included in the study were between the ages of 6;6 and 13;7 (years;months). Sixty-two children had dyslexia (DYS group), and 51 children were average readers (AR group). All participants were monolingual English speakers. Children in the DYS group were recruited from specialist schools as well as from mainstream schools with a dyslexia unit. Children in the AR group were recruited primarily from the same mainstream schools as the participants in the DYS group and through personal contacts.

To be included in the study, all participants had to pass a pure-tone hearing screening test at 0.5, 1.0, 2.0, and 4.0 kHz presented at 30 dB HL. They were also required to achieve standardized scores of 85 or better for nonverbal IQ, verbal IQ, and receptive grammar tests. We measured nonverbal IQ using the block design of the Wechsler Intelligence Scale for Children—Fourth Edition (WISC–IV; Wechsler, 2004), verbal IQ using the British Picture Vocabulary Scale—Second Edition (BPVS–II; Dunn, Dunn, Whetton, & Burley, 1998), and receptive grammar using the Test for the Reception of Grammar—Electronic (TROG–E; Bishop, 2005; see Table 1). Between-groups comparisons were carried out using the Kolmogorow–Smirnov Z test because of the non-normal distribution of data and the high proportion of tied scores. Scores on the WISC–IV did not differ significantly between the DYS and AR groups ($Z = 1.198$, $p = 113$). Receptive grammar (TROG–E) and vocabulary (BPVS–II) were significantly poorer in the DYS group than in the AR group ($Z = 2.47$ and $Z = 2.44$, respectively, both ps < .01), and effect sizes were moderate (both rs = .46). This pattern of results is well documented in children with dyslexia, as reading problems have a negative impact on vocabulary and syntactic acquisition (for a review, see Vellutino et al., 2004).

In this study, children in the DYS group had to have been provided with an official diagnosis of dyslexia by a chartered educational psychologist and were excluded from the study if they were additionally diagnosed with a co-morbid disorder (e.g., specific language impairment [SLI], autism, attention-deficit/hyperactivity

Table 1. Mean (and *SD*) for the group matching measures, presented separately for the average reader and the groups with dyslexia.

Variable	AR group[a] M (SD)	DYS group[b] M (SD)
Nonverbal IQ	103 (10)	99 (10)
Verbal IQ	115 (11)	104 (11)
TROG	108 (8)	100 (8)
Age at first visit	124 (21)	132 (17)
Age at second visit	128 (23)	139 (17)

Note. Standardized scores are provided for the tests and age is expressed in months. AR = average readers; DYS = dyslexia.

[a]$n = 51$ (19 male, 32 female). [b]$n = 66$ (40 male, 22 female).

disorder [ADHD], dyspraxia). Children in the AR group were included in the study if they scored above a standard score of 100[1] on the Test of Word Reading Efficiency (TOWRE; Torgesen, Wagner, & Rashotte, 1999) and if they were free of any learning disability (reported by the school). One child declined consent, 69 volunteers were excluded because they failed to fulfill the criteria set out above, and 3 participants withdrew from the study at a later stage.

Test Battery

For a more detailed description of the experimental procedures, see Hazan et al. (2009).

Standardized Tests

Phonological awareness. We assessed phonological awareness using the Rhyme and the Spoonerism subtests of the Phonological Assessment Battery (PhAB; Frederickson, Frith, & Reason, 1997).

Phonological short-term memory. The Children's Test of Nonword Repetition (CNRep; Gathercole, Willis, Baddeley, & Emslie, 1994) was used as a measure of phonological short-term memory.

Reading. We assessed participants' reading level using the word and pseudoword reading lists from Form A of the Test of Word Reading Efficiency (TOWRE; Torgesen et al., 1999).

Experimental Tests

The synthetic continuum. The same synthesized "bee"–"pea" continuum was used in all categorical

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[1]Three AR participants had a standard score of 93, 96, and 97 when tested on the Form A of the TOWRE Reading test, but discussion with parents and teachers indicated that the students were excellent pupils and avid readers. This was confirmed in a second testing session 7 months later, when their reading scores were 100, 117, and 117, respectively, on Form B of the same test. Therefore, it was judged that they were average to good readers who might have underperformed the first time they were assessed.

perception tasks[2] so as to preclude the possibility that inconsistencies in performance across tasks could be due to stimulus differences. Stimuli were generated by copy synthesis of a natural [bi] token recorded from a female native British English speaker through use of the cascade branch of the Klatt (1980) synthesizer. The continuum was generated by delaying the onset of voicing while concurrently increasing the aspiration duration to obtain stimuli differing in voice onset time (VOT) ranging from 0 ms at the /bi/ end to 60 ms at the /pi/ end of the continuum (for a full description, see Hazan et al., 2009). In the noise conditions, a 20-speaker babble was played simultaneously with the synthetic syllables at a signal-to-noise ratio (SNR) of +6 dB. Stimuli were pretested with 5 adults and 5 children who showed a typical categorical perception pattern in both the identification and discrimination tasks—that is, a phoneme boundary located at around 22 ms VOT, as expected for an English stop voicing contrast (Lisker & Abramson, 1970) and enhanced discrimination of stimuli straddling the phoneme boundary.

Identification tasks. A one-interval, two-alternative adaptive forced-choice task was used for assessment of labeling ability. Two independent adaptive tracks were used. The two tracks, which operated under identical rules but started at opposite ends of the continuum, were designed to track 71% and 29% of "bee" responses using a two-down/one-up rule (Levitt, 1971). On any particular trial, the choice of track was made at random. The task ended after seven reversals on each track (with step sizes decreasing over the first three reversals) or a maximum of 50 trials. Catch trials (continuum endpoints) were randomly interspersed 20% of the time so that participants would not hear an uninterrupted sequence of ambiguous stimuli. The interspersed endpoints also provided a measure of response consistency throughout the task. Given that catch trials were accurately identified at the start of the task by every listener, we reasoned that a reduction in correct identifications of catch trials as the test proceeded would be a good indication of lapses in attention. The task was presented in quiet (ID-Q) and in a background of 20-talker babble at +6 dB SNR (ID-N) in two different blocks.

We used logistic regression to fit a sigmoid curve to the data for each participant. Two measures were extracted: (a) the phoneme boundary that indicates the point along the VOT continuum that is equally labeled as /b/ or /p/, and (b) the slope of the identification function that provides information on labeling consistency.

By design, the adaptive procedure concentrated responses to stimuli in the fastest changing part of the identification function, leading to more accurate estimates of the slope and phoneme boundary. The catch trials were included in the data for the calculation of slope values but were also analyzed separately along with test trials presenting endpoint stimuli and were used as a measure of the level of attention maintained through the task, as described above. This allowed us to determine whether poor and good perceivers differed in terms of their attention level throughout the task rather than in their categorization ability, per se.

Discrimination tasks. Three different discrimination tasks were presented to each participant, using the same /bi/–/pi/ continuum: two adaptive discrimination tasks and a fixed-procedure discrimination task. A three-interval, three-alternative forced-choice oddity procedure was used for all three tasks.

In the adaptive discrimination task that tested within-category discrimination, the standard stimulus for every test trial was the /pi/ endpoint of the continuum. The test started with the /bi/ endpoint as the comparison stimulus. We used a three-down/one-up adaptive procedure (Levitt, 1971) to choose the comparison stimulus. This enabled us to estimate the stimulus that could be discriminated from the standard 79.4% of the time. The test continued until seven reversals, or a maximum of 50 trials. This test was done both in quiet (AdaptWC-Q) and in the same background of babble noise as that used in the identification task (AdaptWC-N). We calculated the just-noticeable difference in VOT (jndVOT) by taking the mean of the final four reversals (i.e., when the minimum step size had been reached). A jndVOT that was less than 38 ms VOT (in quiet) indicated that the listener was able to discriminate differences within the /pi/ category. This is because the jnd was with reference to the "pea" endpoint (VOT = 60 ms) and the mean phoneme boundary was at 22 ms VOT (60 ms – 22 ms = 38 ms VOT). Not all listeners reached this level of performance.

The adaptive discrimination task that tested across-category discrimination (AdaptAC-Q) was essentially identical except that here, both the comparison and standard stimuli changed as the adaptive track proceeded so as to remain centered at 22.5 ms VOT, near the phoneme boundary. Therefore, the standard /bi/ was initially set at 0 ms VOT, and the comparison /pi/ was initially set at 45 ms VOT, resulting in jndVOTs that were always across category and could lie between 1 ms and 45 ms. For both these tasks, larger jndVOTs indicate poorer discrimination abilities.

In order to look for consistency of good or poor discrimination across related tasks, a nonadaptive discrimination task using a fixed presentation was also presented through the use of tokens from the same

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[2]Given the greater decay in memory trace in tasks relying on nonlexical items (Hulme, Newton, Cowan, Stuart, & Brown, 1999; Hulme et al., 1997), we intentionally used highly familiar words in all experimental tests to assess more directly speech perception abilities and to circumvent the detrimental effect of memory, which could obscure the interpretation of group differences.

stimulus continuum. This included a number of within-category stimulus pairs (5–20 ms, 35–50 ms, 40–60 ms, and 50–35 ms) and across-category pairs (20–35 ms and 15–35 ms), each presented 18 times in random order.[3] The proportion of correct responses was calculated over the across-category pairs (FixedAC-Q) and within-category pairs (FixedWC-Q), with chance-level performance at 33%. This task was presented in quiet only.

Identification of highly frequent words and words in context with background noise. The aim of these tasks was to assess the identification of a set of familiar and naturally uttered words with noise in the background.

Words in Noise (WiN). Twenty-five highly frequent monosyllabic words (e.g., *girl, blade*) with an objective age of acquisition of no more than 4 years were selected (De Cara & Goswami, 2002). Items were presented in random order with the same babble in the background as in other tasks, presented at a fixed level of 65 dB SPL (measured over a frequency range of 0.1–10 kHz). The SNR varied by altering the level of the word.[4] The procedure started with an SNR of 12 dB and tracked 50% correct adaptively with a one-up/one-down rule. The test ended after 10 reversals or 25 trials, with the speech reception threshold (SRT; the SNR that leads to approximately 50% correct) calculated from the mean of the reversals.

Words in Noise in Connected Speech (WiNiCS). This test was modeled after the Coordinate Response Measure (Bolia, Nelson, Ericson, & Simpson, 2000) and was modified to be particularly appropriate for children. On each trial, participants heard the carrier phrase "show the dog where the [color] [number] is" with the same babble in the background as that used in other tasks. Displayed on the computer screen was a picture of a dog and six identical digits, matching the one uttered in the target sentence and differing only in color. Participants were instructed to click on the digit in the color that they heard. All the digits from 1 to 9 were used (except the bisyllabic 7), and the six colors were black, white, pink, blue, green, and red. We used a three-up/one-down adaptive procedure to vary SNR,

tracking the threshold for a 79.4% correct level from the mean of the reversals excluding the first two. Unlike the WiN task described above, the total level of the output was fixed at 65 dB SPL. The first sentence was presented at an SNR of +20 dB, with an initial step size of 10 dB that decreased linearly to 5 dB over the first two reversals. The test ended after a total of eight reversals or after 30 trials.

Procedure

Testing took place individually in a quiet room at the child's school for all the participants except the 15 AR children who had been recruited through personal contacts; these children were tested at home. Participants were visited a first time over a week during which six testing sessions, each lasting approximately 30 min, were organized. The screening tasks were presented in Sessions 1 and 2 (hearing threshold, nonverbal IQ, phonological awareness–rhyme subtest, phonological awareness–reading subtest, TROG–E). The remaining tasks that did not involve speech perception were given in a random order over Sessions 3, 4, 5, and 6, depending on different factors such as the time allocated by a school for testing during a given session. All the speech perception tasks, apart from the WiN and the WiNiCS, were presented in a fixed order: categorical perception in quiet (ID-Q and AdaptWC-Q) and categorical perception in noise (ID-N and AdaptWC-N) were presented consecutively over two sessions taking place at least 24 hr apart. A small number of children missed a session, leading to missing data: one AR child for AdaptWC-Q, one AR child for AdaptWC-N, and two other AR children for the WiN test.

The nonadaptive (FixedAC-Q and FixedWC-Q pairs) and AdaptAC-Q tasks were presented at a second occasion, within a single session carried out between 1 month and 1 year later. At that stage, 44 AR children and 58 DYS children were present and available to take the tests. Testing had to be interrupted for one of the AR children who was not administered the AdaptAC-Q task.

Fifteen AR children who were tested at home were administered the entire assessment over two sessions: the testing order differed only in that all categorical perception tasks in quiet were played during the first session and tests in noise were presented in the second session. Sessions were discontinued if a child showed signs of tiredness. For all the tests, the instructions and test items were recorded by a native female English speaker and were played via a Sony-VAIO VGN-TX2XP computer using Sennheiser PC 150 combined stereo headset–noise canceling microphone. The experimenter provided encouragement during breaks and answered any questions.

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[3]Pre-testing of the fixed procedure among 20 university students without dyslexia indicated that the /bi/ endpoint of the continuum with 0 ms VOT was unusually discriminable from other stimuli located in the /bi/ portion of the continuum. Examination of its spectrogram indicated that the first 5 ms of transition were rising sharply, making this stimulus acoustically discriminable from the remaining /bi/ exemplars with a flatter transitions trajectory. The /bi/ stimuli with VOT of less than 5 ms were excluded, and an extra /pi/ stimulus of 65 ms VOT was created to reproduce a 60-ms VOT range similar to that used in the other discrimination tasks.

[4]Because individual lexical items are differently affected by noise, some being much more robust than others and, thus, able to be identified at lower SNRs, we performed a preliminary calibration study that allowed the determination of a "correction factor," uniquely specified for each word, to lead to similar levels of performance across words. This manipulation makes the adaptive track behave better, thus resulting in more accurate estimates of thresholds.

Results
Group Comparison

All outcome measures described are raw scores and, hence, are not standardized by age. Therefore, we typically expect to see improvements in performance with age, as children tend to improve in most tasks as they get older. Results were analyzed through the use of techniques similar to those used in Thomas et al. (2009), which ensure that potential differences between groups are not concealed by developmental trends.

Our goal was to compare children with dyslexia to age-matched average readers on all the experimental tasks while systematically accounting for the continuous effect of age. The data were analyzed using a general linear model (GLM), with the score on a particular task as the outcome variable and two predictor variables: group and age. The GLM incorporates aspects of both (a) analysis of variance (ANOVA) using categorical predictors and (b) regression using continuous predictors.

Five models were fitted to each outcome variable. The most parsimonious model was determined using an F statistic comparing models on the basis of their residual sums of squares and degrees of freedom following the method in Cook and Weisberg (Cook & Weisberg, 1999).

Model 1. This is the most general and complex model, in which the intercept and slope parameters for each group are different, indicating a significant Age × Group interaction. A model such as this means that differences between the two groups change with age.

Model 2. This is the second most complex model, in which both main effects are significant but there is no interaction. Thus, the regression lines have equal slope, but the intercepts differ. Here, developmental trends are the same in the two groups, but the groups differ overall.

Model 3. In Model 3, the slope and intercept are the same for both groups, but with a main effect of age, indicating performance improving over age but otherwise no difference between the groups.

Model 4. In this model, neither age nor its interaction with group is significant, but there is a simple main effect of group. Therefore, performance does not change with age but still differs overall between the two groups.

Model 5. Finally, in the degenerate Model 5, neither age nor group significantly predict performance.

The significance level was set at the traditional $p < .05$ level, which typically minimizes the risk of a false positive to 5% or less. Only statistically significant predictor variables ($p < .05$) are mentioned. In cases where $p > .05$, the power of the group comparison has also been provided, as support to negative results can be granted in cases where the risk of a false negative is low (Cohen, 1988). Power was calculated using G*Power (Erdfelder, Faul, & Buchner, 1996) and was computed as a function of the significance level, the sample size of each group, and the population effect size (Cohen, 1988).

Reading and phonological processing. There was a significant effect of group and age for the raw word reading scores ($p < .001$) and a significant Age × Group interaction for the pseudoword reading scores ($p < .001$), owing to the fact that AR children improved with age whereas DYS children, whose scores were poorer at all ages, performed similarly across age. The DYS group scored significantly lower than did the AR group on all phonological processing tasks: Rhyme, Spoonerisms, and Nonword Repetition (all $ps < .001$; see Table 2). The main effect of age was also significant for nonword repetition, with scores improving with age in both groups. For the Spoonerism subtask, the Group × Age interaction was significant ($p < .05$) due to AR children improving with age ($p < .001$), whereas DYS children of all ages performed below the level of the youngest AR children. As expected, the DYS participants were, therefore, impaired in their reading of words and pseudowords and in the processing of phonological information relative to AR children of the same age.

Identification of the /pi/–/bi/ continuum in quiet and in noise. Differences in identification between the DYS and AR groups were observed when comparing the slopes derived from their identification functions in quiet but not in noise. The distribution of the individual slopes was highly skewed, so that each slope was log transformed for further analysis.

We conducted an initial analysis to confirm that the presence of noise had a substantial effect on categorization performance. Two 2 × 2 mixed-design ANOVAs were conducted on the log-transformed slope of the identification functions and on the phoneme boundary (calculated when both test items and catch trials were included), with noise (quiet vs. noise) as a within-subject factor and group (DYS vs. AR) as a between-subjects factor. The two groups did not differ in phoneme boundary, with noise as the only significant factor, $F(1, 111) = 82.46$, $p < .001$. When the slopes of the identification functions were examined, the Noise × Group interaction was significant, $F(1, 111) = 9.21, p < .001$, due to a greater effect of noise on the slope of the identification functions for the AR group than for the DYS group. Given that the identification tasks presented stimuli adaptively, this lack of group differences in noise cannot be explained by a floor effect in the performance of the DYS children. For this reason, along with poorer performance in identification in quiet, we would expect DYS children to perform less well than their AR peers in noise if their speech perception skills were weaker and more prone to be disrupted by interfering noise than those of AR children.

Table 2. Summaries of performance on all tasks for the two groups of participants.

Measure	n	AR group Score M (SD)	AR group % M (SD)	n	DYS group Score M (SD)	DYS group % M (SD)	Sig[a]
Reading (standard scores)							
Words	51	108.78 (11.68)		62	84.81 (9.40)		***
Pseudowords	51	119.31 (10.81)		62	82.95 (10.68)		***
Sum	51	116.73 (11.86)		62	81.15 (11.58)		***
Phonological processing							
Phonological Awareness Rhyme	51	18.88 (1.61)		62	16.15 (2.96)		***
Phonological Awareness Spoonerism	51	15.51 (3.09)		62	10.82 (3.37)		***
Short-Term Memory (Nonword Repetition)	51	36.39 (2.64)		62	31.92 (4.74)		***
ID-Q Slope							
All items	51	0.43 (0.25)		62	0.24 (0.18)		***
Test items only	51	0.44 (0.24)		62	0.33 (0.22)		*
Items 11–49 ms VOT only	51	0.44 (0.24)		62	0.33 (0.22)		*
Proportion correct catch trials for ID-Q							
Total	51	0.98 (0.08)		62	0.93 (0.09)		ns
ID-N Slope							
All items	51	0.21 (0.22)		62	0.23 (0.25)		ns
Test items only	51	0.23 (0.23)		62	0.26 (0.25)		ns
Items 11–49 ms VOT only	51	0.26 (0.24)		61[b]	0.26 (0.25)		ns
Proportion correct catch trials for ID-N							
Total	51	0.95 (0.10)		62	0.91 (0.11)		—
AdaptAC-Q							
jndVOT	43	19.03 (11.51)		58	16.92 (9.59)		ns
Adapt WC-Q							
jndVOT	50	28.83 (7.49)		62	34.58 (7.77)		*
Adapt WC-N							
jndVOT	50	33.65 (14.19)		62	40.62 (12.71)		*
Fixed across- and within-discrimination in Quiet							
Pair 65–50 ms VOT	44		36% (11%)	58		33% (11%)	ns
Pair 60–40 ms VOT	44		39% (11%)	58		37% (10%)	ns
Pair 50–35 ms VOT	44		40% (10%)	58		34% (10%)	***
Pair 35–20 ms VOT	44		64% (15%)	58		51% (17%)	***
Pair 35–15 ms VOT	44		73% (14%)	58		61% (16%)	***
Pair 20–5 ms VOT	44		48% (16%)	58		43% (14%)	ns
Fixed WC-Q (average 65–50, 60–40, 50–35, 20–5)	44		41% (6%)	58		36% (6%)	***
Fixed AC-Q (average 35–20, 35–15)	44		68% (13%)	58		56% (15%)	***
WIN							
Threshold SNR	49	−4.11 (1.43)		62	−4.30 (1.68)		ns
WiNiCS							
Threshold SNR	51	−5.96 (2.04)		62	−6.31 (1.76)		ns

Note. For each experimental measure, the number of participants (*n*), mean scores, and standard deviation (in parentheses) are given for the two groups separately. AR = average readers group; DYS = groups with dyslexia; Sig = the extent to which the mean scores statistically differ between the average readers and the readers with dyslexia; *ns* = nonsignificant; ID-Q = identification task presented in quiet; VOT = voice onset time; ID-N = identification task presented in noise; AdaptAC-Q = adaptive task testing across category discrimination in quiet; jndVOT = just noticeable difference in VOT; AdaptWC-Q = adaptive task testing within-category discrimination in quiet; AdaptWC-N = adaptive task testing within-category discrimination in noise; FixedWC-Q = fixed presentation discrimination task: within-category stimulus pairs; FixedAC-Q = fixed presentation discrimination task: across-category stimulus pairs; WIN = Words in Noise; SNR = signal-to-noise ratio; WiNiCS = Words in Noise in Connected Speech.

[a]Significance levels provided are for the effect of group (with AR group > DYS group), except for pseudowords reading, catch trial ID-N, and AdaptWC-Q, where significance levels are for the Age × Group interaction (with scores significantly improving with age for the AR group but not for the DYS group).
[b]One participant was not presented with intermediary items 11–49 ms by the adaptive procedure because the participant's performance was so poor.

*p < .05. **p < .01. ***p < .001.

Results of the stepwise GLM analysis conducted on the slope of the identification function in quiet indicated that the effects of age and group were significant ($p = .003$ and $p < .001$, respectively; effect size $r = .47$), with no interaction. The slopes increased as a function of age and were shallower in the DYS group (see Figure 1, left panel).

Responses to endpoint stimuli (whether they are catch or test trials) are of particular interest given the strong evidence that such errors reflect inattention rather than an inability to categorize stimuli (in particular, errors were very rare at the beginning of test sessions). The vast majority of AR listeners (86%) made no errors, whereas nearly half of the DYS group made at least one error (48%). DYS participants mislabeled, on average, 5.7% of the endpoint stimuli presented, in comparison with only 1.9% of endpoint stimuli mislabeled by AR participants. In order to more fully characterize errors made to endpoint stimuli, we used a logistic regression to model endpoint errors as a function of age (in months), group (AR or DYS), and trial (1–50), as well as all of their interactions. Both age and trial were treated as continuous variables. By examining changes in deviance as predictors were eliminated from the model, we found that no interactions were significant ($p = .16$ in comparing a model with all interactions and a one model with none), but all the main effects were ($p < .001$ for all). Thus, inattention increases through a testing session, is higher for younger listeners, and is higher for DYS participants than for average readers. Figure 2 compares the original endpoint error data as a function of trial number with the prediction of the logistic regression in the two participant groups (without accounting for the effect of age). A comparison of the size of the obtained regressions' coefficients shows that being dyslexic is equivalent to a 4-year delay in attentional capabilities as compared with average readers.

Errors to endpoint stimuli are also important because it is well known that performance in the endpoint regions of the identification function can greatly influence the slope values obtained when fitting psychometric functions by logistic regression (Wichmann & Hill, 2001). This means that a shallow slope may reflect an inconsistent pattern of identification in these endpoint regions rather than be related to responses around the phoneme boundary region. Therefore, individual slopes were recalculated on the basis of test trials only (excluding catch trials). Despite an increase in slope values for the DYS group (see Table 2), the group and age effects remained significant ($p = .016$ and $p = .002$, respectively;

Figure 1. Individual scores and regression line of the slope of the identification function for ID-Q (left panel) and ID-N (right panel) for the AR (full triangles and line) and the DYS (open circles, dotted line) groups as a function of age (in months). A larger value corresponds to a steeper slope. ID-Q = identification task presented in quiet; ID-N = identification task presented in noise; AR = average readers group; DYS = group with dyslexia.
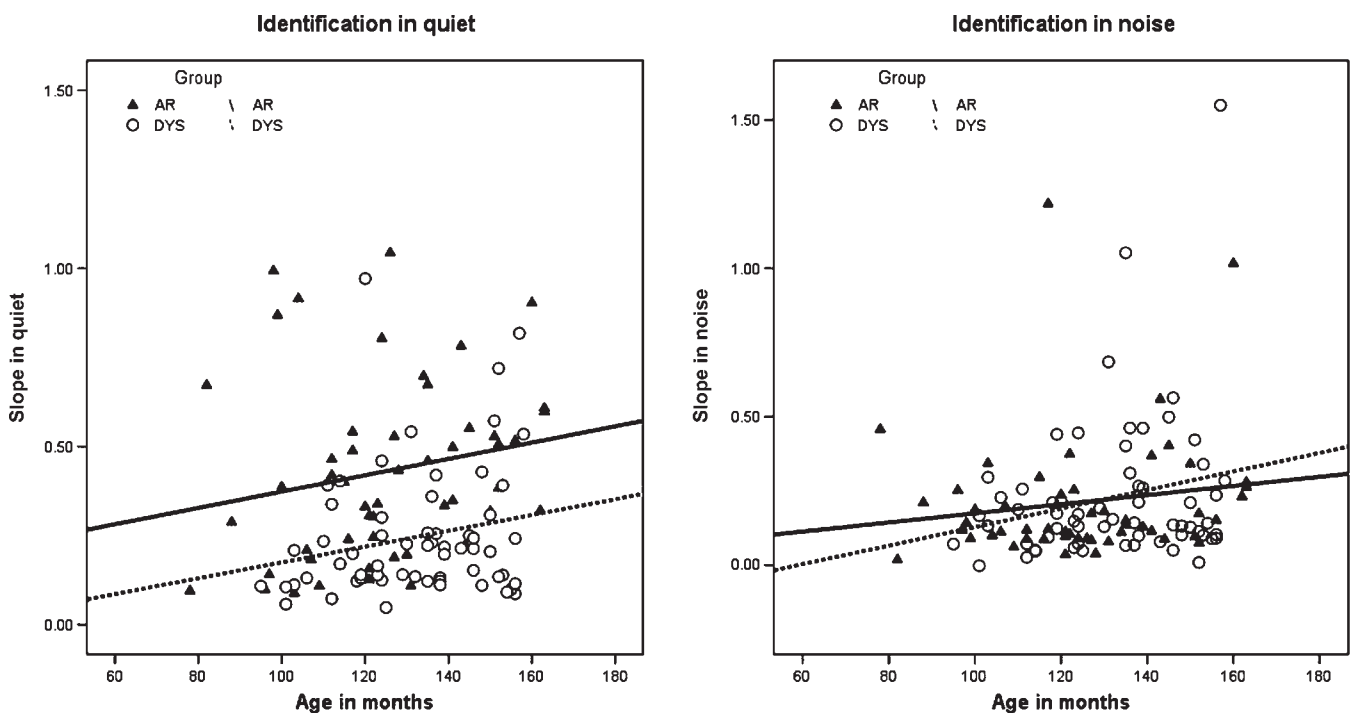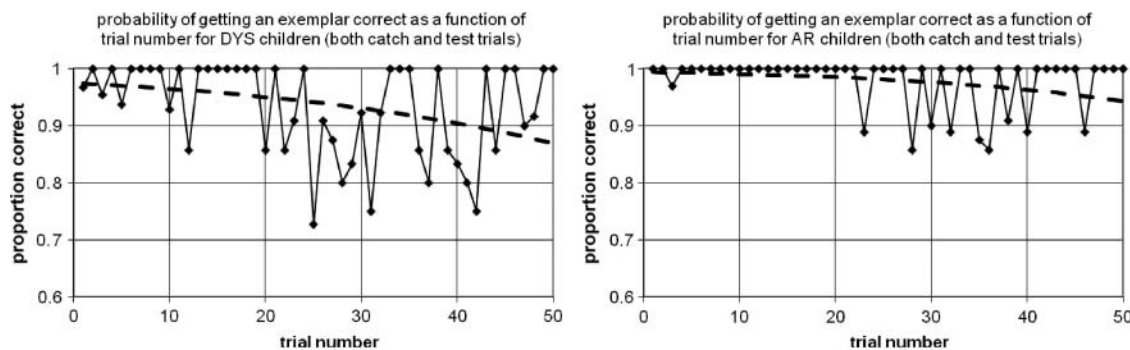
Figure 2. Proportion of times the endpoint stimuli were correctly labeled as a function of trial number shown separately for the AR and DYS children. The smooth dashed lines result from a logistic regression using trial number as a continuous predictor but not accounting for the effects of the child's age.


effect size $r = .33$). We further assessed the effect of endpoint stimuli on the slope estimate by excluding from the calculation of the slope those stimuli outside the 11- to 49-ms VOT range, corresponding to the plateaus of the identification function. Here again, the group and age effects remained significant ($p = .045$ and $p = .003$, respectively; effect size, $r = .3$). Paired t tests indicated that the mean slope that included all trials was significantly shallower than the slope excluding catch trials, $t(112) = -5.14$, $p < .001$, and the slope including midrange stimuli only, $t(112) = -5.07$ $p < .001$, whereas the latter two slope measurements did not differ. When the same analysis was run separately for each group, none of the measures differed in the AR group, whereas for the DYS group, the "all trials" slope differed from the "no catch trial" slope and the slope for mid-range stimuli only, $t(61) = -5.12$, $p < .001$, and $t(61) = -5.11$, $p < .001$, respectively. This suggests that DYS children are being less consistent in their labeling of "easy" regions of the continuum throughout the test, probably indicating lapses in attention as the test progresses, and that this is affecting the statistic used to assess the degree of categorical labeling. Of course, lapses in attention would affect responses to all steps of the continuum but can only be readily quantified for the regions of the continuum where consistent labeling is expected (i.e., the endpoint regions), as we have done here. Therefore, although it is clear that accounting for inattention in the ways described above reduces the group differences in the slope measure, it is still an open question whether any differences in slope would remain once all differences in attention were accounted for.

When slopes derived from the identification task in noise[5] were considered (see Figure 1, right panel,

and Figure 3, bottom panel), neither the effect of age nor group was significant, but the power of the group comparison was low (0.52). As can be expected, slopes were shallower in noise, and the continuum's endpoint could not be identified with 100% accuracy. Therefore, we could not assume perfect categorization at the continuum endpoints and derive children's level of attention

Figure 3. Identification functions for the "bee"–"pea" continuum for the AR group (at left) and the DYS group (at right) in quiet (top) and in noise (bottom). The circles indicate the proportion of "bee" responses along the voice onset time (VOT) continuum in ms for the data aggregated across all participants within the group. The size of each circle is proportional to the number of presentations at a given VOT. The solid lines result from a logistic regression on each set of aggregated data. Note that all endpoint stimuli were labeled correctly at least 89% of the time, even in noise.


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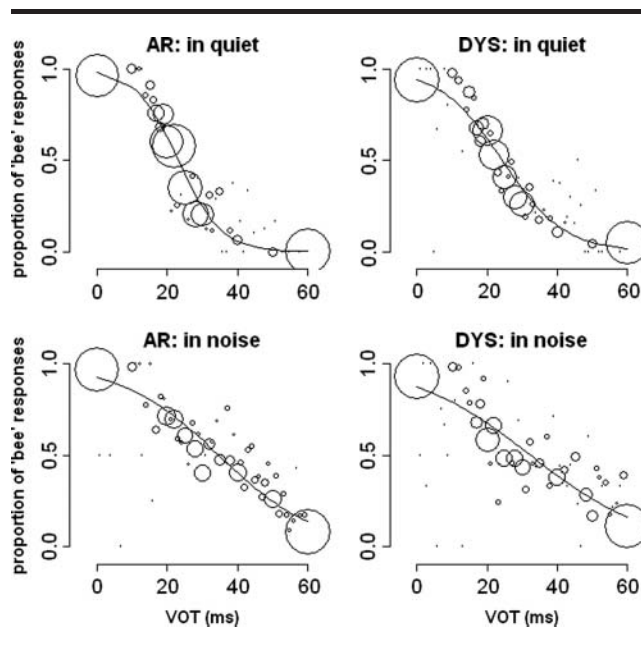
[5]For one participant with dyslexia, the slopes in noise that had a negative value were not transformable using a logarithmic scale and were instead given the lowest log-transformed slope observed in the sample.

using the catch trials. However, it should be noted that all individual slopes were different from 0, so the lack of a group effect was unlikely to be due to a floor effect (see Figure 3, bottom panel).

Across-category discrimination. We examined across-category discrimination using both adaptive (AdaptAC-Q) and fixed-step (FixedAC-Q) procedures. For AdaptAC-Q (in quiet), task scores were log-transformed because of skewed distribution. Neither group nor age significantly predicted log-transformed jndVOT, even though the power of the group comparison was high (0.82). However, when we used a fixed-step procedure (FixedAC-Q), we obtained better performance for the AR group than for the DYS group. A two-way repeated-measures ANOVA with stimulus pair as the within-subject factor and participant group as the between-subjects factor revealed that the Group × Stimulus Pair interaction was significant, $F(5, 500) = 430.64$, $p < .001$: Independent-sample t tests indicated that the across-category pairs of 20–35 ms VOT and 15–35 ms VOT were discriminated significantly better in the AR group than in the DYS group, $t(100) = 3.64$, $p < .001$, and $t(100) = 3.79$, $p < .001$, respectively. We examined age trends by calculating a mean discrimination score for the FixedAC-Q pairs for each participant (see Figure 4). Across categories, older children scored significantly better than did younger children, and AR children discriminated better than did DYS children ($p = .023$ and $p < .001$, respectively). This

Figure 4. Box plot of the proportion of correct discrimination scores for each pair of stimuli presented using the fixed procedure (FixedAC-Q and FixedWC-Q). The DYS children are represented in white boxes, and the AR children are represented in gray boxes. The horizontal line represents chance level of performance, which is set at .33 proportion correct in this task. FixedAC-Q = fixed presentation discrimination task: across-category stimulus pairs; Fixed WC-Q = fixed presentation discrimination task: within-category stimulus pairs.
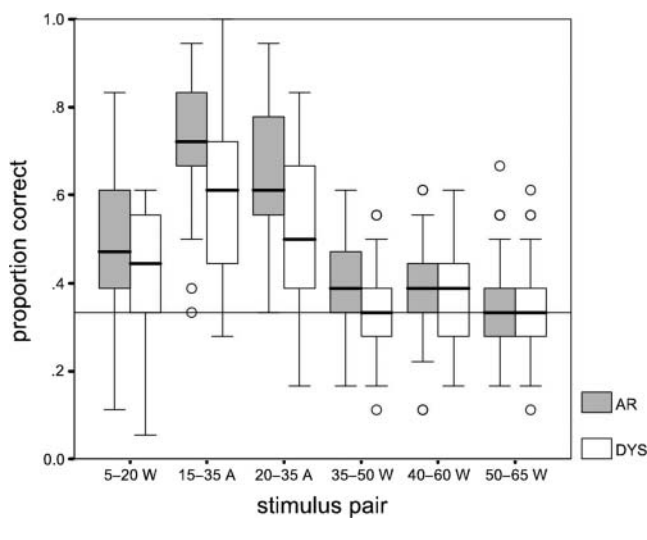
is not consistent with the results obtained using an adaptive procedure, as the effect of group was not significant in AdaptAC-Q.

Within-category discrimination. We examined within-category discrimination using both adaptive (AdaptWC-Q) and fixed-step (FixedWC-Q) procedures. For AdaptWC-Q, the Age × Group interaction was significant ($p < .05$). When the effect of age was analyzed separately for each group, it was significant for the AR group ($p < .001$) but not for the DYS group. Figure 5 indicates that the discrimination threshold for the AR group improves with age and is well within category at all ages for most individuals (< 37 ms VOT), whereas the mean discrimination threshold for the DYS group is at boundary values (see Table 2), with a smaller proportion of individuals discriminating within category. When the same adaptive task was presented in noise (AdaptWC-N), the main effects of group and age were significant ($p = .002$ and $p = .016$, respectively) due to the improvement in discrimination threshold with age and a lower threshold (better performance) in the AR group relative to the DYS group (see Figure 5). As mentioned above, a significant Group × Stimulus Pair interaction was obtained in the fixed-step procedure task: Independent-sample t tests indicated that the within-category 35–50 ms VOT pair was discriminated significantly better in the AR group than in the DYS group, $t(100) = 3.65$, $p < .001$; see Figure 4. Again, age trends were examined by calculating a mean discrimination score for FixedWC-Q pair. Better within-category discrimination scores were found for AR participants than for DYS participants ($p < .001$).

WiN and WiNiCS. For the identification of highly predictable words in isolation (WiN) and in context (WiNiCS) presented in noise, neither the effect of group nor the effect of age were significant for either of the two tasks (see Table 2). In addition, the power of the group comparison was medium to high for WiN (0.63) as well as for WiNiCS (0.69).

In summary, significant differences in performance between the AR and DYS groups were found for the identification task in quiet; for within-category discrimination in quiet, whether tested adaptively or through use of a fixed-level procedure; for the discrimination task in noise; and for across-category discrimination when assessed using a fixed-level procedure. For all of these tests, better performance was obtained for the AR group than for the DYS group, therefore countering the findings of Serniclaes et al. (2001, 2004) of better within-category discrimination in DYS children. The AR and DYS groups did not differ when across-category discrimination was evaluated adaptively or for the two tests of word perception in noise.

Prevalence of poor perceivers. Because some studies have found that only a subset of DYS children show

Figure 5. Just noticeable difference in ms VOT (jndVOT) relative to a fixed reference stimulus of 60-ms VOT for Adapt WC-Q (left panel) and Adapt WC-N (right panel) for the AR group (full triangles and line) and DYS group (open circles, dotted line) as a function of age (in months). A discrimination threshold of < 37 ms VOT (marked on the y axis by a notch) is within category.
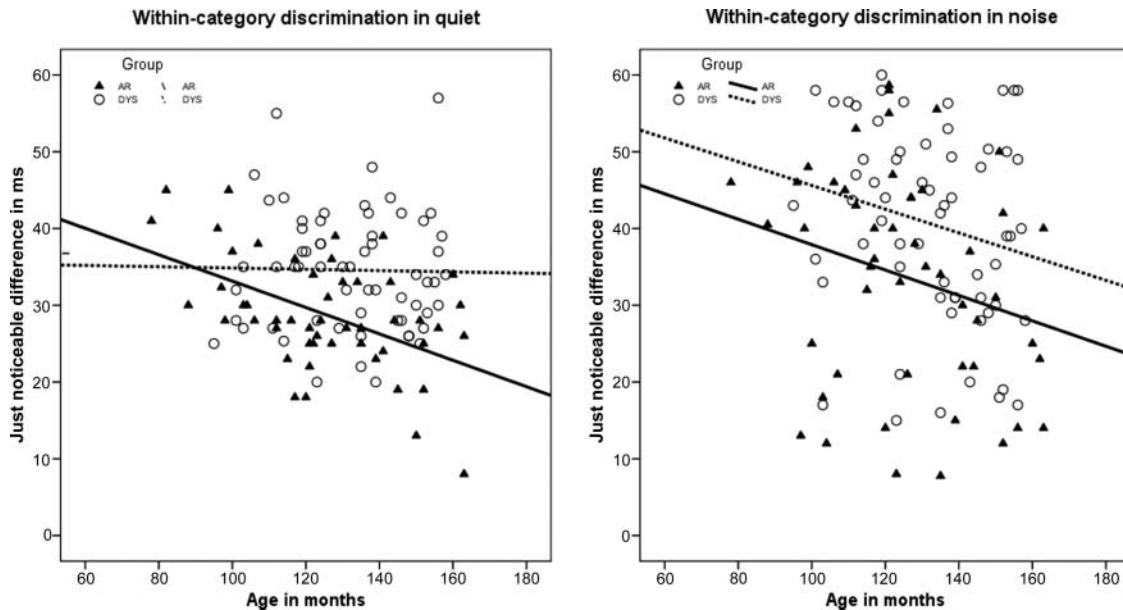
perceptual deficits (e.g., Adlard & Hazan, 1998; Manis et al., 1997; McArthur et al., 2008), it is important to look at individual performance in order to evaluate how many of the DYS children were performing below norm. Therefore, we determined the proportion of participants in each group who were performing poorly relative to age-matched peers and compared the prevalence of poor perceivers in the DYS group to that in the AR group. To do this, we calculated age-corrected z scores for each task and listener in the AR group by taking the residual of the linear fits to the AR data and then dividing by the SD of the raw residuals. Data were mostly normally distributed in the AR group, and appropriate transforms were made when necessary. This resulted in a measure of auditory performance that had no correlation with age, and an M and SD close to 0 and 1, respectively. When age was not a significant factor, we used a simple z score based only on the M and SD of the AR scores, ignoring age. The z scores for the DYS participants were calculated in the same way using values derived from the AR group.

As in Ramus et al. (2003), *poor perceivers* were defined as those who scored at least 1.65 SDs below the AR mean on each test (theoretically, below the 5th percentile). The overall proportion of poor perceivers in each group and task are presented in Table 3.

There was a relatively small difference in the proportion of poor perceivers in the DYS and AR groups, except for two tasks. More than five times as many DYS children as AR children were classified as poor perceivers

for FixedAC-Q (40% vs. 7%) and for AdaptWC-Q (32% vs. 6%). It is also notable that more than twice as many DYS children as AR children were classified as poor perceivers for ID-Q (18% vs. 8%) and for FixedWC-Q (14% vs. 5%). Nevertheless, it is noteworthy that for each of the speech perception tasks, the majority of the DYS children scored within the normal range for their age.

Table 4 provides an overview of individual performances and allows us to identify those who performed below norm on a task. As can be seen, a much higher proportion of AR children performed within norm for all tests relative to the DYS group. Therefore, a child will

Table 3. Proportion of "poor perceivers" in the AR and DYS groups (calculated over participants who took the test only).

Variable		AR group	DYS group
Discrimination in quiet	FixedAC-Q	7%	40%
	AdaptAC-Q	0%	0%
	FixedWC-Q	5%	14%
	AdaptWC-Q	6%	32%
Identification	ID-Q	8%	18%
	ID-N	6%	5%
Discrimination in noise	AdaptWC-N	6%	11%
	WiN	6%	8%
	WiNiCS	8%	2%

Note. For each task, *proportion of poor perceivers* is defined as the percentage of individuals scoring 1.65 SDs below the mean for the AR group.

Table 4. Poor and good perceivers in each task presented individually for the 51 children in the AR group and for the 62 children in the DYS group.

AR group									DYS group								
ID		Discrimination					Words in noise		ID		Discrimination					Words in noise	
ID-Q	ID-N	Adapt WC-Q	Adapt WC-N	Adapt AC-Q	Fixed AC-Q	Fixed WC-Q	WiN	WiNiCs	ID-Q	ID-N	Adapt WC-Q	Adapt WC-N	Adapt AC-Q	Fixed AC-Q	Fixed WC-Q	WiN	WiNics

(Continued on the following page)

Table 4 *Continued.* Poor and good perceivers in each task presented individually for the 51 children in the AR group and for the 62 children in the DYS group.

| | AR group | | | | | | | | | DYS group | | | | | | | |
| | ID | | Discrimination | | | | | Words in noise | | ID | | Discrimination | | | | | Words in noise | |
ID-Q	ID-N	Adapt WC-Q	Adapt WC-N	Adapt AC-Q	Fixed AC-Q	Fixed WC-Q	WiN	WiNiCs	ID-Q	ID-N	Adapt WC-Q	Adapt WC-N	Adapt AC-Q	Fixed AC-Q	Fixed WC-Q	WiN	WiNics
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Note. Each row represents a listener. Gray cells represent scores within the "below normal" range. Empty cells represent scores score within the "normal" range. The asterisk (*) represents scores that could not be collected.

be more likely to perform below norm on a task across a range of speech perception tests if he or she has dyslexia. However, in order to conclude that this is due to a deficit in speech processing abilities, poor performances would be expected across several tasks testing the same speech perceptual ability. Therefore, individual performance was also examined within each ability tested. Evidence of consistent difficulty of both groups across four perceptual abilities was considered: categorical labeling (ID-N, ID-Q), discrimination across category (AdaptAC-Q, FixedAC-Q), discrimination within category (AdaptWC-Q, FixedWC-Q), and perception of naturally produced words in noise (WiN, WiNiCS).

In categorical labeling, a child having problems identifying speech in quiet should also be expected to experience difficulties in more difficult noisy conditions. Within the AR group, four children were below norm for ID-Q, but only one of them was also below norm for ID-N. In the DYS group, 11 children were below norm in quiet, and only two of them were also below norm in noise. For the discrimination tasks, one would expect that if poor performance is linked to weak perceptual skills rather than to task-related difficulties, it should be evident as to whether an adaptive or fixed-step procedure was used. Twenty-three DYS individuals and 3 AR individuals performed below norm when across-category discrimination was tested through the use of a fixed-step procedure, but only 2 DYS individuals and none of the 3 AR individuals performed below norm in the adaptive condition. A similar trend was observed for within-category discrimination: Two DYS children and none of the AR children performed below norm in both the fixed and adaptive tasks. Finally, as WiN and WiNiCS both tested the perception of lexical items in background noise, consistent performance across both of these tasks could be expected. However, none of the 5 DYS children and 1 of the 3 children who performed below norm on WiN also performed poorly on WiNiCs.

Are Measures of Speech Perception Related to Reading, Phonological Processing, Nonverbal IQ, and/or Language?

Significant group differences in some speech perception tasks cannot, of course, be taken as direct evidence that deficits in those tasks are causal to (or caused by) a reading (or any other cognitive) deficit. Such claims would be much strengthened if correlations between those skills were significant. Therefore, we calculated correlations for all nine speech perceptual measures against the two reading scores (words and pseudowords), nonverbal IQ, the two measures of language (TROG–E

and BPVS–II) and the three measures of phonological processing (Rhyme, Spoonerisms, and CNRep). All measures were normalized for age using either published norms (TROG–E, BPVS–II, TOWRE, Nonverbal IQ) or results from the AR group. With these 72 comparisons, we would expect about four significant correlations at the .05 level simply by chance in the absence of any genuine relationships. Instead of using the exceedingly conservative Bonferroni correction, we thus reduced the significance threshold to .01 so that the expected number of significant correlations due solely to chance was less than 1. One-tailed tests were used because of our prior expectations of how these variables should be related. Rosen (2003) argued that if auditory deficits are the prime cause of dyslexia (or reading abilities, more generally), strong correlations would be expected between auditory processing and reading skills not only across the entire population but also within groups of controls and individuals with dyslexia. Therefore, correlations were calculated within groups. Only one correlation was significant in the AR group: that between Nonverbal IQ and FixedAC-Q. Because this was the only speech perception measure that correlated with Nonverbal IQ (even at the .05 level), little can be inferred from it. Quite different results were obtained in the DYS group. AdaptAC-Q was correlated with rhyme, but much more strikingly, FixedAC-Q was correlated at $p < .005$, with four of the reading-related tasks (Words, Pseudowords, Rhyme, and Spoonerisms; $r = .32–.37$). We focus only on the relationship of this speech perception measure to pseudoword reading because deficits in the latter are a central feature of dyslexia, but consideration of the other reading-related abilities leads to the same general conclusions.

Figure 6 shows the relationship between these two abilities. Regression analyses similar to the ones used above show that both group and FixedAC-Q performance were significant predictors of pseudoword reading ability, with an insignificant interaction. Therefore, the relationship between these two skills appears to be the same in children with and without dyslexia.

However, although FixedAC-Q has some predictive value, it is very weak. Group membership alone accounts for 75% of the variance in pseudoword reading, and once this is entered into the regression, FixedAC-Q accounts for only 2% more of the variance (see Rosen, 2003, for other examples of this kind of analysis). This weak predictive power of FixedAC-Q is apparent in Figure 6, which shows a very small degree of overlap between the two groups in pseudoword reading (as would be expected) but a great degree of overlap in performance for the perceptual measure (however, very low performance on this task, with $z < -2$, appears to be restricted to children with dyslexia). In other words, knowing a

Figure 6. Scatterplot showing the relationship between standardized scores in pseudoword reading and standardized scores in FixedAC-Q.
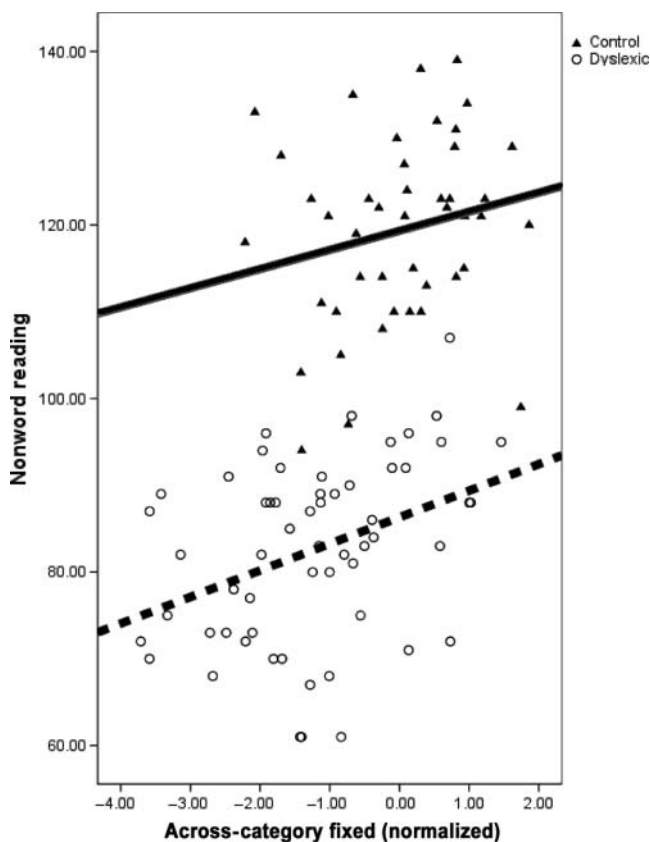
child's performance on FixedAC-Q would not allow a reliable inference about the reading ability of that child.

Discussion

The results of the present study suggest that the claim that children with dyslexia show deficits in speech perception should be tempered. Significant group differences were certainly observed in four of nine speech perception tasks, mirroring significant group effects in many previous studies. However, in order to claim that individual children show a deficit in speech perception, it is preferable to see evidence of consistent poor performance across different speech perception tasks that tap the same processing ability. Children within the DYS group who were poor performers in one task type did not show consistent weakness across similar tasks when the ability to categorize, to discriminate within and across category, and to perceive words in noise was examined. It was also the case that numerous AR children performed below norm in at least one type of task. In addition, DYS children who performed poorly in quiet only rarely performed poorly on the same task in more difficult

noisy conditions; if poor performance in quiet was due to poorly established phonological representations, one would expect the addition of noise to further stress speech processing abilities. There was also little evidence of any correlation between performance on speech perception tasks and performance on reading or phonological processing abilities, except for a moderate link between reading-related skills and the fixed across-category discrimination task in quiet.

Participants spanned a wide age range so that we could observe the effect of age on differences between DYS and AR children. Consistent with other studies (Hazan & Barrett, 2000; Parnell & Amerman, 1978), the experimental design was sufficiently powerful to signal significant improvements with age in several experimental tasks. However, no Age × Group interactions were noted for any of the experimental tasks except for the AdaptWC-Q task, where jnd's decreased with age in the AR children but not in the DYS children, who were less rather than more able to discriminate within category relative to AR children. Except for this task, developmental trends were evident in the speech perception tasks administered, and they were similar in DYS and AR children. In addition, there was no evidence that below-norm performance correlated with age in DYS participants, indicating that whenever a deficit was found, the size of it did not change with age.

Modest Evidence of Speech Perception Deficits in DYS Children

Previous evidence of speech perception deficits in DYS children had been found for categorical identification tasks, with less consistent identification in DYS children (Godfrey et al., 1981; Serniclaes et al., 2001; Werker & Tees, 1987). As in previous studies, which all derived the slope of the identification function from all of the items presented, the DYS group showed significantly shallower slopes relative to AR when stimuli were presented in quiet. However, identification slopes for the DYS group increased significantly when catch trials were excluded and further improved when only the steepest portion of the function corresponding to responses to ambiguous stimuli was fitted. A separate analysis of the interspersed catch trials indicated that DYS children more often mislabeled these clear exemplars (5.6% averaged over all trials) than did AR children (just under 2%). Although it could be argued that these errors are simply another reflection of the less robust phonological categories claimed to characterize the DYS children (e.g., as promulgated by Ziegler et al., 2009), the fact that errors in identifying clear exemplars increased significantly over the course of the task (see Figure 2) makes it more likely that these errors resulted from inattention caused by fatigue. These lapses in attention

would affect the labeling of all stimuli, of course, but they would only be clearly identifiable for "easy" regions of the continuum, where consistent labeling is expected. In short, at least part of the group differences in identification performance may result from a greater susceptibility to lapses in attention in the DYS group (Moore, Ferguson, Halliday, & Riley, 2008).

Other evidence of a speech perception deficit in DYS individuals came from poorer across-category discrimination abilities relative to age-matched controls, using paradigms involving fixed (Godfrey et al., 1981; Serniclaes et al., 2001; Werker & Tees, 1987) or adaptive modes of presentation. Poorer discrimination was observed in the DYS group for the across-category pairs in the fixed-interval task presented in quiet, which correlated with a number of reading-related skills in the group with dyslexia. However, when across-category discrimination was tested adaptively, no group difference was obtained, despite the high power of the test. Differences in performance across the fixed and adaptive tasks could be explained by a number of factors. The adaptive procedure starts by presenting clear "pea" and "bee" stimuli and progresses toward the phoneme boundary, presenting more ambiguous items, until a certain threshold of correct discrimination is reached. On the other hand, the fixed procedure presented 108 trials, which included 72 trials that were phonemically identical (i.e., within category) and 32 cross-category trials where stimuli could potentially be discriminated. The higher proportion of "difficult" stimulus pairs in the fixed procedure could have lowered some listeners' expectation to perceive a difference, whereas the consistent cross-category presentations in the adaptive procedure might have kept up their level of interest, thus leading to a more genuine reflection of their speech perception abilities. It could also be the case that the shorter adaptive procedure relied less heavily on extraneous factors such as attention than did the fixed discrimination procedure, which was twice as long. In addition, it should be noted that AR children outperformed DYS children in the discrimination of within-category differences, which does not require the processing of phonologically distinct information and relies more on general perceptual acuity. This further supports the argument that discrimination is more demanding for DYS than for AR children because of task-related factors rather than because of poor discrimination of the stimuli's phonological properties.

In this study, we were also able to assess the hypothesis that speech perception difficulties in DYS children are due to the fact that they perceive allophones rather than the phonemes of their native language (Bogliotti et al., 2008; Serniclaes et al., 2004). The allophonic theory of dyslexia claims that "phonetic features that are not relevant for native language phonology remains [sic] discriminable" (Bogliotti et al., 2008, p. 140), and

relies on evidence that DYS children show increased within-category discrimination relative to chronological-age matched AR children (Godfrey et al., 1981; Serniclaes et al., 2004; Werker & Tees, 1987). This allophonic perception is claimed to be "a consequence of a deviant perceptual development during early childhood" as evidenced by a secondary nonnative discrimination peak in DYS children but not in AR children, located at boundaries discriminated by infants. The type of evidence supporting an allophonic mode of perception is, therefore, twofold: One involves within-category variation of phonemic contrasts of a given language and is a consequence of the other, which entails within-category variations that only infants are predisposed to perceiving. Our data, along with those of others (Ramus & Szenkovits, 2008; van Beinum, Schwippert, Been, van Leeuwen, & Kuijpers, 2005), tested the first kind of evidence and failed to show any enhanced sensitivity to within-category variation in DYS children in either of the test procedures used. If anything, AR children were better able to discriminate within category than were DYS children. Nevertheless, we should be cautious about concluding that this result completely invalidates the allophonic mode of speech perception. Indeed, it could be the case that DYS children would have been more sensitive to within-category variation in the negative VOT range that infants discriminate (Lasky, Syrdal-Lasky, & Klein, 1975) rather than in the positive VOT range tested here. However, this result questions the link between the two types of evidence and whether allophonic perception can lead to difficulties in phoneme-to-grapheme correspondences if it occurs only for a very small number of phoneme contrasts.

The DYS group did not experience greater difficulty for the identification of the "pea"–"bee" stimuli in noise, which is at odds with a speech perception account of their impairment. In addition, no group differences were noticeable between DYS and AR children in other "speech-in-noise" tasks (e.g., the WiN and WiNiCS tasks) that did not rely on the presentation of the "pea"–"bee" continuum. The WiN and the WiNiCS tasks involved independent sets of highly familiar words that had an age of acquisition suitable for the present population in order to counter the effect of vocabulary knowledge. If the phonological processing difficulty of the DYS group was mediated by poor speech processing in quiet or in noise, the access to phonological representations when retrieving frequent words from the lexicon should be disrupted in noisy conditions, and this disruption should lead to higher speech reception thresholds for such words in noise. However, in neither task were the DYS children more prone to the disruptive effect of noise than AR. Snowling, Goulandris, Bowlby, and Howell (1986) also failed to observe any differential effect of noise on the identification of highly frequent words in DYS children.

Individual Results

Relative to AR, a larger proportion of DYS children experienced difficulty with at least one task of the battery of tests presented. However, among poor DYS perceivers, difficulty in one task did not reflect consistent and general difficulties in processing speech. For the large majority of DYS listeners who performed below norm, poor performance in one task was only rarely associated with similar difficulties in a different task tapping the same speech perceptual ability. Therefore, poor speech perception scores in the majority of the DYS children could be more related to difficulties with task demand. Other studies also concluded that it is unlikely that speech perception plays a significant role in reading development in children and adults (Hazan et al., 2009; Ramus & Szenkovits, 2008; Robertson et al., 2009; Watson & Kidd, 2008). Robertson and colleagues also failed to find speech perception deficits in DYS children using similar categorical perception tasks in quiet and in noise. However, DYS children who had additional SLI experienced speech perception difficulties consistent with previous findings by Joanisse et al. (2000), more particularly when noise was presented in the background. Note that our study specifically excluded children with additional SLI or ADHD, whereas not all studies used such strict selection criteria.

It is interesting to consider how our child data compare to those obtained when the same test battery was presented to a group of DYS and AR adults. Hazan et al. (2009) reported few significant group differences, with the exception of within- and across-category discrimination when tested using a fixed-level procedure. For the fixed-level procedure task, AR outperformed DYS adults, whereas no group differences were obtained when the same speech stimuli were used in adaptive tasks. However, as with the children tested in this study, a very small minority of DYS adults experienced consistent difficulties across tasks, and poor performance in quiet did not lead to poor performance in noise. Hazan et al. (2009) concluded that their data gave weak support for a speech perception deficit in dyslexia and suggested that some individuals with dyslexia have speech perceptual acuity that is at the lower end of the normal range and is exacerbated by non-sensory factors. The results obtained here with DYS and AR children are consistent with this view.

Future studies investigating perception in children with dyslexia would benefit from including a comprehensive assessment of attention abilities in order to tease apart the role of extraneous factors from that of perception. Further investigations on the role of speech perception abilities on impaired phonological development would also gain from investigating individual variability and the contribution of non-sensory factors on the performances of children who have dyslexia with co-morbid SLI.

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