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The relationship between speech and nonspeech auditory processing in children with dyslexia

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Abstract

Although there is good evidence that some dyslexic children show at least small deficits in speech perceptual tasks, it is not yet clear the extent to which this results from a general auditory, as opposed to a specifically linguistic/phonological problem. Here we have investigated the extent to which performance in backward and forward masking can explain identification and discrimination ability for speech sounds in which the crucial acoustic contrast (the second formant transition) is followed ("ba" vs. "da") or preceded ("ab" vs. "ad") by a vowel. More specifically, we expect children with elevated thresholds in backward masking to be relatively more impaired for tasks involving "ba" and "da" than for tasks involving "ab" and "ad". In order to determine whether poor performance with speech sounds reflects a general deficit for perceiving formant transitions, we also constructed nonspeech analogues of the speech syllables — the contrastive second formant presented in isolation.

Two groups of 8 children matched for age (mean of 13 years) and nonverbal intelligence were selected to be well separated in terms of their performance in reading and spelling. All underwent the same set of auditory tasks: 1) forward, backward and simultaneous masking with a short (20 ms) 1-kHz probe tone in a broadband and notched noise; 2) identification as "b" or "d" of synthetic "ba"-"da" and "ab"-"ad" continua; 3) same/different discrimination of pairs of stimuli drawn from the endpoints of the two speech continua (*e.g.*, "ba-da", "da-ba", "da-da", "ba-ba"), as well as their nonspeech analogues.

There were no differences between dyslexic and control children in forward and simultaneous masking, but thresholds for backward masking in a broadband noise were elevated for the dyslexics as a group. Overall speech identification and discrimination performance was superior for the controls (barely so for identification), but did not differ otherwise for the two speech contrasts (one of which should be influenced by backward masking, and one by forward). Thus, although dyslexics show a clear group deficit in backward masking, this has no simple relationship to the perception of crucial acoustic features in speech. Furthermore, the deficit for the nonspeech analogues was much less marked than for the speech sounds, with ¾ of the dyslexic listeners performing equivalently to controls. Either there is a linguistic/phonological component to the speech perception deficit, or there is an important effect of acoustic complexity.

Introduction

Dyslexia is commonly described as a disorder manifested by difficulties in learning to read and spell, despite adequate intelligence and conventional instruction. It is often diagnosed on the basis of a discrepancy between measures of reading ability and other cognitive skills, and is said to occur in 4-7% of children (Snowling, 1998).

Explanations for dyslexia fall into two main categories. One popular idea ascribes dyslexia to an underlying deficit concerning the representation, storage and processing of information about speech sounds (typically referred to as *phonological processing*

— Snowling, 1998). A deficit in phonological processing is reflected in poor performance in tasks like: reading nonwords (which requires knowledge of letter-to-sound mappings); repeating back nonsense words presented auditorily; judging whether words rhyme; breaking up words into their component sounds or syllables. In this view the core deficit is seen to be *linguistic*, as it applies specifically to an aspect of language processing.

Other explanations of dyslexia stress more fundamental sensory/perceptual difficulties in vision and/or audition. Theories based on deficits in visual processing have, at least so far, been applied solely to dyslexia, but auditory deficits have been posited to underlie a much wider variety of language disorders. The auditory deficit view goes back at least to the early 60’s. In a groundbreaking paper, Efron (1963) attributed the language difficulties of brain-damaged patients with acquired aphasia to impairments of rapid auditory processing, as measured in a temporal order judgement task. Efron’s approach has been advanced most diligently and consistently by Tallal and her colleagues, primarily in studies of children with Specific Language Impairment (SLI), but also in dyslexia (*e.g.*, Tallal, 1980; Tallal & Piercy, 1973; Tallal & Piercy, 1974). Like dyslexia, SLI is defined by a reasonably specific deficit in language-related abilities, in the presence of relatively intact non-linguistic cognitive abilities.

Variants of these approaches do not, of course, necessarily contradict each other. There is at least some weak evidence that deficits in visual processing are correlated with deficits in auditory processing[1] (Witton *et al.*, 1998). Also, it is easy to imagine that impaired auditory processing could affect developing receptive abilities for the dynamic acoustic patterns of speech, leading to impaired phonological processing and hence to problems in reading. Our concern here is in assessing the strong claim that auditory processing problems are the underlying core deficit in dyslexia, by examining one part of the hypothesised sequence that leads from general auditory deficit to a reading problem — in particular, the detailed relationship between the particular nonspeech auditory deficits found and resulting impairments in the perception of particular phonemic contrasts.

There has been surprisingly little investigation of this crucial issue. Tallal and Piercy’s (1973; 1974) early work on SLI children attributed poor performance in differentiating synthetic /bɑ/ from /dɑ/ to the brief duration of the formant transitions which signalled the contrast. This was linked to impaired identification of short complex tones differing only in fundamental frequency when rapidly presented. Reed (1989) applied a similar set of tests to dyslexic children and also concluded that “… a deficit in processing rapidly presented information could account …” for the deficits displayed by the dyslexics.

More recently, Mody *et al.* (1997), in an unusually insightful paper, have pointed out that the nonspeech stimuli used in these earlier studies are inappropriate as controls for the speech contrasts. They compared performance of good and poor readers in discriminating a synthetic /bɑ/-/dɑ/ contrast, as well as a nonspeech analogue which

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[1] Witton *et al.* (1998) studied 17 adult dyslexics and 18 controls in auditory detection of frequency modulation and visual detection of coherent motion. The correlation between these two abilities was significant and high for the dyslexic group only (≈0.7). However, this correlation is strongly dependent on 4 of the dyslexics with motion detection thresholds considerably higher than the rest of the group (excising them leaves a non-significant correlation of ≈0.3).

consisted of sine waves whose frequencies tracked the second and third formant frequencies of the speech sounds. If the auditory deficit in poor readers really *was* due to a deficit in processing rapidly presented information, we should expect similar levels of performance with the two contrasts. Strikingly, a group of poor readers selected to have poor performance with the speech sounds were unimpaired relative to controls for the nonspeech analogues. Mody *et al.* thus argued that the selective deficit for the speech sounds reflected ‘a speech-specific, not a general auditory, deficit’. In this view, the deficits of the poor readers reported by Tallal (1980) and Reed (1989) for short tones differing in fundamental frequency reflect a different underlying cause than the deficit in distinguishing the difference between /bɑ/ and /dɑ/.

Mody *et al.’s* study has been criticised for, among other things, using children who were not poor enough readers to be classed as ‘dyslexic’ (Denenberg, 1999). Although much can be disputed about this point (Can a strict binary criterion be set for dyslexia? Do we expect the auditory abilities of moderately-impaired readers to be *qualitatively* different from those with more severe impairments), one aim of our study was to investigate this issue in a population of children with considerably more severe reading difficulties than those used by Mody *et al*. We also decided to use a different nonspeech analogue — the second formant alone (but a very similar /bɑ/-/dɑ/ contrast). Just as for the sine wave analogues used by Mody *et al.*, any dyslexics with impaired discrimination of /bɑ/-/dɑ/ should also be impaired for the isolated second formant, if the basis of the speech perceptual deficit arises from a general problem in perceiving formant transitions. Isolated formants are yet more similar to real speech than sine wave speech, and it would also strengthen the claims of Mody *et al.* if the same result were found with a nonspeech analogue that was reasonably different in detailed acoustic form.

We also wanted to go beyond Mody *et al.*’s investigations on this issue. They demonstrated that a deficit in speech-perceptual performance could not be accounted for by performance with a particular nonspeech analogue. We wanted to work the question the other way round — could a nonspeech deficit in dyslexics be used to predict performance in speech contrasts? As Mody *et al.* point out, it is hard to predict any particular difficulty in speech perception on the basis of an inability to discriminate two short rapidly-presented complex tones of vastly different fundamental frequency, not least because there is no speech contrast based on such an acoustic distinction.

We therefore chose to investigate non-simultaneous masking because it seemed that we *could* make differential predictions for speech-perceptual performance on the basis of performance in these tasks. Tallal and Stark (1981) speculated that the auditory deficits evidenced by SLI children could be the result of abnormal degrees of forward and backward masking, but it fell to Wright *et al.* (1997) to explicitly test this hypothesis. Thresholds for short probe tones when masked by a bandpass noise were compared for eight children with SLI, and age-matched controls, under conditions of forward, backward and simultaneous masking. Differences in forward and simultaneous masking were small, but there was no overlap in performance between the two groups in backward masking. Here the difference in the mean thresholds between the two groups was more than 40 dB. Wright *et al.* also reported that 5 of 12 people with reading difficulties had abnormally large thresholds in backward masking.

What implications might an abnormal degree of backward masking have for speech perceptual performance? Wright *et al.* suggest that such a deficit in backward masking would be expected to "… degrade the perception of the brief acoustic elements of speech …", and is consistent with the notion that "…children with reading difficulties are particularly poor at discriminating words that differ only in their first sound." Here then, is a possible response to Mody *et al.*'s criticism that performance in discriminating two rapidly presented short tones cannot be directly related to the ability to perceive formant transitions. Both would clearly be affected by abnormal degrees of backward masking. The second occurring tone in a rapid pair could mask the first, and the following vowel could mask the formant transitions in /bɑ/ and /dɑ/.

Note the interesting asymmetry in Wright *et al.*'s results, in that forward masking was essentially normal whereas backward masking was excessive. If a connection could be made between performance in non-simultaneous masking tasks and speech identification and discrimination, we might expect differences in performance with speech contrasts that are syllable initial, as opposed to those that are syllable final. More specifically, we ask if children with elevated thresholds in backward masking are more impaired in tasks involving /bɑ/ and /dɑ/ (whose contrastive formant transitions might be backward masked by the following vowel) than those involving /ɑb/ and /ɑd/ (whose contrastive formant transitions might be forward masked by the preceding vowel).

There are other surprises to be found in Wright *et al.* It seems at least plausible that backward masking abilities could be associated with language disorders, since it has long been surmised that backward masking relies much more heavily on central auditory processing than forward or simultaneous masking (for example, normal adults exhibit very little forward, but significant backward, masking with maskers contralateral to the probe — Elliott, 1961; Elliott, 1971). But Wright *et al.* also reported that control children showed a significantly greater difference in thresholds for a broadband and notched noise in simultaneous masking than did the SLI children. This is perplexing because this difference in thresholds is presumed to reflect the operation of a frequency selective mechanism in the cochlea, at the very periphery of the auditory system (Rosen & Stock, 1992). To complicate matters further, this index of frequency selectivity did not differ significantly between the two groups under conditions of forward masking, even though the same peripheral frequency analysis is meant to underlie it. We therefore also investigated masking performance with notched, as well as broadband, noises.

The aims of our study were thus manifold, and are summarised here:

1) To investigate backward, forward and simultaneous masking in dyslexic and control children, with a particular view to the possibility of deficits in backward masking.
2) To investigate the effect of a spectral notch on the masking performance of dyslexic and control children.
3) To investigate the identification and discrimination abilities of dyslexic and control children on two speech contrasts, one of which may be expected to be influenced by backward masking (/bɑ/-/dɑ/) and one by forward masking (/ɑb/-/ɑd/).

4) To determine if differences in backward and forward masking would lead to differences in the identification and discrimination of sounds in which the contrastive acoustic features would be expected to be differentially affected by backward and forward masking.
5) To compare the discrimination abilities of dyslexic and control children for acoustic contrasts based on formant transitions in speech sounds, and for the same transitions in nonspeech analogues.
6) To relate all measures of auditory abilities to performance on a number of assessments of phonological abilities.

Method

Subjects

All participants were required to be monolingual, native speakers of English aged between 11 and 14 years with no obvious problems of speech production. They were also required to have no history of neurological or emotional problems (other than those that might arise directly from reading problems in the dyslexic group).

IQ, as determined by the Wechsler Intelligence Scales for Children (3rd Edition, UK — WISC-III), was required to be at least average (> 90). Four subtests (two verbal and two performance) were administered to the children so as to obtain a composite cognitive ability score. The *Performance* subtests, which tap visual and general cognitive skills, were Picture Completion and Block Design. The *Verbal* subtests, which tap language and verbal reasoning skills, were Similarities and Vocabulary.

The dyslexic children were recruited through dyslexia teaching centres, clinics, special units of secondary state schools, and support groups. Their reading and spelling abilities were required to be at least one standard deviation below the mean for their age, as determined by their performance on the British Ability Scales II Reading and Spelling subtests.[2] All the members of the experimental group showed a reading and spelling delay of at least 18 months.

Seventeen dyslexic children were assessed for possible inclusion in the study, of which nine had to be excluded. Four had IQ scores below 80, and 5 obtained standard reading scores that were too high (> 95), although their spelling scores were below 85. This left 8 children (7 right-handed and one left-handed) whose characteristics can be found in Table 1.

The control group consisted of 8 normal readers of the same age who were likely to have the same degree of maturity as the experimental children in terms of auditory perceptual development. These children were recruited through word-of-mouth and advertisements at University College London. A special effort was made to recruit children from non-academic staff members. Selection was based on the criteria specified above, with the exception of reading and spelling standard scores which had to be at least average (≥ 100). Eleven controls were fully evaluated but 8 selected for

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[2] An exception to this rule was made for one subject who showed the best reading and spelling performance within the dyslexic group (D2). The standard scores were 85 (i.e. one standard deviation below the mean) for reading and 89 for spelling, the latter corresponding to a spelling delay of 18 months.

optimal matches in age and performance IQ. There were 5 boys and 3 girls, aged between 11:6 and 14:8 years. Six were right-handed and two left-handed. All showed above average reading and spelling with reading ages ranging between 14:3 and 18+ years, and spelling ages between 14:9 and 18+ years. IQ ranged between 114.4 and 136.8.

As Table 1 shows, the two groups were well separated in terms of reading and spelling performance. The difference between the groups in the mean IQ scores is clearly attributable to the fact that the controls had on average higher verbal IQ scores than the dyslexics, as indicated in Table 1. The two groups, however, were well matched in terms of non-verbal intelligence, as shown by their mean scaled scores in the performance IQ subtests.[3]

Child (Sex)	***Age***	***Reading age (y:m)***	***Spelling age (y:m)***	***V- IQ***	***P- IQ***	***Full IQ***	***Nonword Accuracy***	***Spooner-isms***
D1 (M)	11:11	7:04	7:01	10.5	12.5	110	88	90
D2 (F)	12:03	9:09	10:09	11.0	13.5	114	93	100
D3 (F)	12:11	8:09	9:03	11.5	15.0	121	89	88
D4 (M)	13:03	8:09	8:09	11.5	13.0	114	80	94
D5 (M)	11:07	7:01	7:10	8.0	13.5	105	87	89
D6 (M)	14:03	7:01	7:07	10.0	11.0	103	77	79
D7 (M)	13:07	7:01	7:10	10.5	12.0	108	84	83
D8 (F)	14:01	10:09	9:03	10.0	11.5	105	78	89
Mean of dyslexics	13:0 (0:11)	8:03 (1:05)	8:06 (1:01)	10.4 (1.1)	12.8 (1.3)	110 (6.1)	85 (5.7)	89 (6.4)
Mean of controls	13:0 (1:4)	15:11 (1:01)	16:08 (1:04)	14.4 (2.2)	12.8 (1.7)	123 (8.5)	112 (11.9)	113 (13.5)

Table 1. *Individual and group characteristics, including standardised IQ and phonological test scores. Scaled scores are given for Verbal (V-IQ) and Performance IQ (P-IQ). Standard scores are reported for the phonological tests (Nonword Accuracy and Spoonerisms) and Full IQ. Standard deviations are given in parentheses.*

Phonological Awareness Test Materials and Administration

Two tests from the Phonological Assessment Battery (PhAB), developed by Frederickson *et al.* (1997), were used. The *Spoonerisms Test* investigates the perception and manipulation of sounds in words, while the *Nonword Reading Test* examines the ability to decode regular words (*i.e.*, those whose pronunciation follows the general rules of grapheme-to-phoneme conversion in English).

The *Spoonerisms Test* is designed to assess whether children can segment single syllable words and then synthesise the segments to provide new words or word combinations. All presentation of stimuli is oral, and the child is allowed three

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[3] Given that a short form of the WISC-III was used, the individual subtest scores could not be converted into standard scores. Therefore, the mean scaled score of the performance and verbal subtests is reported. The scaled score corresponds to the raw score obtained for each subtest, after taking into account the child's age. A scaled score which is above 10 indicates an above average performance on the particular subtest (range: 1-19).

minutes to respond. In Part I the child is asked to replace the first sound of a word with a new sound (*e.g.*, “cot” with a /g/ makes “got”). Note that *sounds*, and not letter names, are specified. In Part II (true Spoonerisms) the child is asked to exchange the initial sounds of two words (*e.g.*, “sad cat” makes “cad sat”).

The Nonword Reading Test is designed to assess the decoding of letter strings. As already mentioned, when children read phonetically regular real words, they may draw on their knowledge of letter-sound relationships to decode the word, and/or they may draw on their sight vocabulary to recognise the word. The latter strategy, based on visual processing, cannot be used when reading non-words. In this test the child is asked to read aloud regular nonsense words, consisting of either one (*e.g.*, “tib”) or two syllables (*e.g.*, “haplut”).

The child was introduced to each task prior to its administration by means of practice items, for which feedback was given. No feedback was given for the test items, but the children were praised for their efforts.

Stimulus Construction for Auditory Tests of Identification and Discrimination

All stimuli used in these tests were generated using the Klatt (1980) synthesiser in cascade mode with a 1-ms update interval. The synthesiser sampling rate of 20 kHz was resampled to 22.05 kHz, one of the output digitisation rates available on the sound card used for testing.

For the *Identification Tests***,** two 8-step continua were synthesised, one for the /bɑ/-/dɑ/ and one for the /ɑb/-/ɑd/ contrast. All speech stimuli consisted of six formants. The values of the first three formants at the endpoints of the /bɑ/-/dɑ/ continuum were based on those specified by Mody *et al.* (1997), but with lengthened transitions because this seemed to lead to better percepts for the /ɑb/-/ɑd/ pair. Steady-state formant frequencies were 750, 1200, 2350, 3250, 3700 and 4990 Hz with bandwidths of 90, 90, 130, 200, 200 and 500 Hz respectively. The first formant (F1) transition was identical for all stimuli, beginning at 200 Hz and reaching 750 Hz after 35 ms. The second formant (F2) began at 825 Hz for /bɑ/ and at 1500 Hz for /dɑ/, reaching its steady-state value after 50 ms. The six intermediate stimuli had their second formant transitions beginning at frequencies equally logarithmically spaced between those of /bɑ/ and /dɑ/. The relatively small F3 transition used by Mody *et al.* (1997) was eliminated, as this did not seem to degrade the contrast. All higher formants were static and identical for all the stimuli in the continuum. Bursts were not included. Thus the crucial acoustic distinction was carried only by the F2 transition and was similar for the speech and the nonspeech conditions (details on the latter are given below). The /ɑb/-/ɑd/ continuum was created from the /bɑ/-/dɑ/ continuum by manipulating the stimulus parameters such that the F1 and F2 transitions occurred at the end of the syllable, but were of identical magnitude and duration.

For all syllables the fundamental frequency began at 125 Hz, stayed constant for 60 ms, fell logarithmically to 100 Hz during a 130-ms period, and then stayed constant to the end of the syllable. The voicing source was turned off 235 ms into the signal and allowed to decay naturally so as to avoid transients. The total duration of each signal was 250 ms.

For the *Discrimination Tests*, the stimuli were presented in pairs. Each of the test conditions used a different pair of stimuli (*e.g.*, the endpoint stimuli of the /bɑ/-/dɑ/ continuum). Pairs of stimuli were presented equally often in one of the 4 possible stimulus orderings (*e.g.*, /bɑ/-/dɑ/, /dɑ/-/bɑ/, /bɑ/-/bɑ/, /dɑ/-/dɑ/). In addition, the stimuli were digitally edited to have inter-stimulus intervals of 0, 10, 50, 100 or 400 ms, for a total of 20 different stimuli per condition. The stimuli used in the 5 different test conditions were:

- The endpoint stimuli of the /bɑ/-/dɑ/ and /ɑb/-/ɑd/ continua.
- Nonspeech control stimuli for the two speech sound pairs, consisting of the F2 transition alone. Isolated F2 stimuli were obtained simply by outputting from the synthesiser the waveforms from the F2 resonator on their own (a straightforward option in the Klatt synthesiser). In order to make these sounds as un-speech-like as possible, they were synthesised on a monotone fundamental frequency of 112 Hz (see **Figure 1**).
- Steady-state vowel stimuli. These were based on the stop-vowel syllables used, with identical durations, fundamental frequency contours and formant bandwidths. One of the vowel sounds used the steady-state formant frequencies of the stop-vowel syllables, which simply remained constant for the whole duration of the stimulus (750, 1200, 2350, 3250, 3700 and 4990 Hz), thus being perceived as /ɑ/ (“ah”) The other vowel was created by shifting the F1 downwards by a factor of 0.8 and the F2 upwards by a factor of 1/0.8=1.25, leading to a percept of /ʌ/ (“uh”).

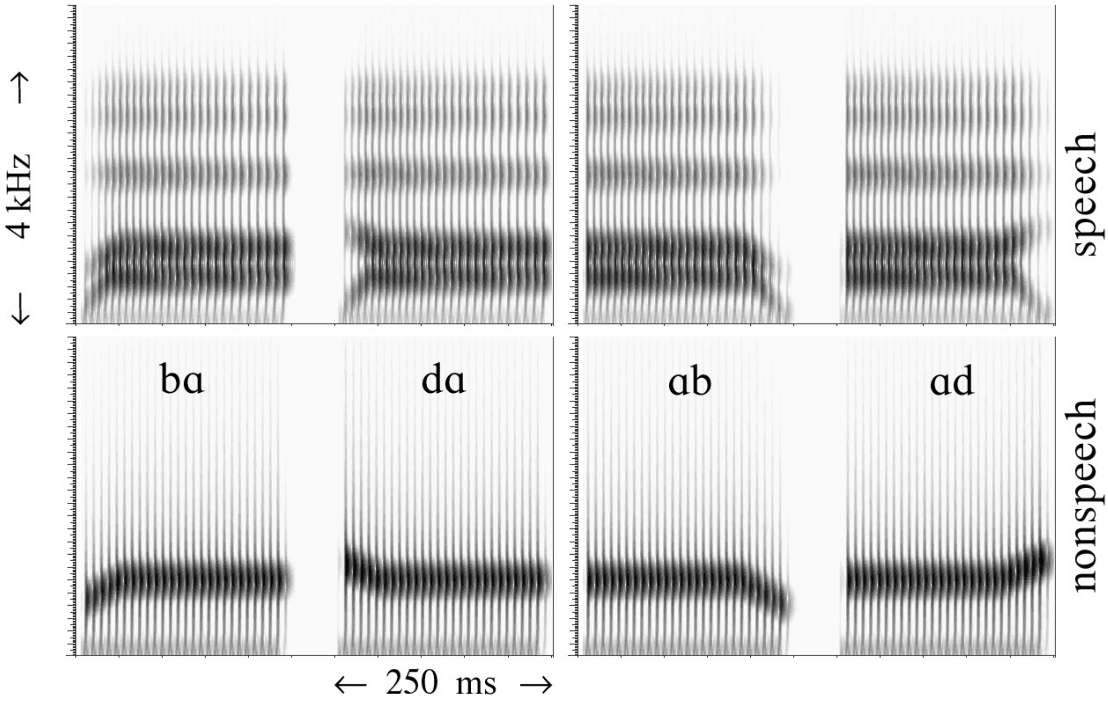

Figure 1. *Spectrograms of the stimuli with formant transitions used in the discrimination experiments. The four speech sounds were also the endpoints of the two continua used in the identification experiments.*

Procedure for the Auditory Tests of Identification and Discrimination

All aspects of stimulus presentation and response collection were controlled by a computer. Stimuli were presented binaurally for the identification and discrimination tasks over Sennheiser HD475 headphones at comfortable levels (about 80 dB SPL).

Subjects were first introduced to the tasks by means of a demonstration. For the identification tests, this consisted of randomised presentations of the endpoint stimuli from each continuum through the loudspeaker. Two squares labelled “BA” and “DA” (or “AB” and “AD”) appeared on the computer at each presentation and the listeners were trained to click with the mouse button on the appropriate icon. For the discrimination tests, listeners were presented with identical (*e.g.*, /bɑ/-/bɑ/, /dɑ/-/dɑ/) and different (*e.g.*, /bɑ/-/dɑ/, /dɑ/-/bɑ/) pairs of stimuli, separated by the longest inter-stimulus interval (400 ms). They were instructed to click on a picture of two green circles on the computer screen if they thought that the sounds presented were the same, and on a picture of a yellow circle and a red triangle, if they thought they were different.

To try to assure that each child understood the nature of the task and how to perform it, criterion tests preceded the administration of the experimental trials in both identification and discrimination tests. In order to pass the criterion, 12 correct responses out of 16 consecutive trials were required in a maximum of 40 randomised presentations. For the identification test, the endpoints of the speech continua were used. For the discrimination test, identical and different pairs of stimuli from each test series were presented, separated by 400 ms. Feedback was given after each trial in the form of a “happy” face on the computer screen for correct responses and a “sad” face for incorrect ones. Children went on to perform in the test session even if they failed to reach criterion after 40 trials, as long as they reached criterion with the initial steady-state vowel sounds.

After reaching criterion performance, the experimental trials were administered to each subject. The identification tests consisted of 8 presentations of each stimulus in a continuum in random order, giving a total of 64 for each series. The discrimination tests consisted of 8 presentations of each stimulus pair (two of each type for identical and different pairs) at each inter-stimulus interval (0, 10, 50, 100, 400 ms) in random order. This gave a total of 40 trials for each subtest. Feedback was provided during the discrimination, but not the identification tests.

Measurements of Auditory Masked Thresholds

The masking tasks were modelled closely on those described by Wright *et al.* 1997, with identical stimuli and some minor differences in the adaptive tracking procedure. Again, all aspects of stimulus presentation and response collection were controlled by a computer. Stimuli were presented monaurally in the right ear over Sennheiser HD475 headphones.

Masked thresholds were measured using a two-interval two-alternative forced-choice task. A maximum likelihood adaptive procedure was used to track 90% correct. On each trial, two 300-ms bursts of masking noise were presented with a 340-ms inter-stimulus interval. Along with one of the noise bursts occurred the 1-kHz sinusoidal probe tone. The listener indicated which of the noise bursts was associated with the probe by pressing one of two buttons on a response box. Feedback was given by lighting the correct button. Masking noises were either bandpass (0.6-1.4 kHz) or notched (0.4-0.8 kHz and 1.2-1.6 kHz) at a spectrum level of 40 dB. The probe was 20 ms long. The probe tone could occur either simultaneously with the masking noise (200 ms after masker onset — *simultaneous* masking), with its onset 20 ms prior to the start of the masker (*backward* masking), or with its onset at the offset of the masking noise *(forward* masking). In the last two conditions there was no overlap between the probe and the masker (*non-simultaneous* masking). All stimuli were gated on and off with 10-ms cosine-squared envelopes.

The listeners were first acquainted with the experimental situation by being tested with the probe alone (*i.e.*, without the masker). This provided training for the experimental tasks to follow and also established the listener's threshold for the tone. Following this, at least two measurements were obtained for each type of noise (bandpass and notched). Measured thresholds were accepted as long as the two of them for the same condition were within 6 dB. When this criterion was not met, a further two thresholds were run, until two were within 6 dB.

The adaptive tracking technique is somewhat sensitive to lack of attention, especially during the beginning of the task. In order to minimise this effect, results from a particular session were excised if: a) there was an error on the 1st or 2nd trial, and a final threshold 6 dB higher than any others in the set, or; b) only one error was made during a session, and the final threshold was 6 dB higher than any others in the set. However, thresholds were only excised if there were more than 2 thresholds available in a particular condition. Results were then summarised by calculating the median threshold for *all* the thresholds taken, in order to minimise the effect of outliers. Each median consisted of 2-6 individual thresholds, with about 8% of thresholds excised for the reasons given above (27 of 337). The proportion of thresholds excised was very similar for the two groups.

Overall Procedure

Testing took place in two sessions. In a first session of approximately one hour duration, the language tests (reading, spelling and phonological ability) and the IQ tests were administered to the children at their homes. After the initial screening, qualified listeners met with the experimenter for the second (listening) session which took place in a laboratory sound-treated room. All listeners were required to pass a bilateral hearing screening for octave frequencies between 250 and 8000 Hz at 20 dB HL.

Auditory testing was conducted individually, divided into two parts which were separated by an interval of at least 30 minutes. Each part lasted approximately 45 minutes to an hour. The first part consisted of the masking tasks, which began with the measurement of the absolute threshold for the 1-kHz probe tone. The order of the masking conditions (simultaneous, backward, forward) was randomised, with the noise type presented in a fixed counterbalanced order (bandpass, notched, notched, bandpass).

The second part of the session began with the discrimination tests. The vowel condition was always presented first, followed by the nonspeech and speech conditions. Within the latter two, the order of the subtests (/bɑ/-/dɑ/ and /ɑb/-/ɑd/) was randomised. The nonspeech condition was presented before the speech so as to minimise the possibility that the listeners would hear these nonspeech analogues as speech. None of the listeners questioned, in fact, reported hearing speech sounds during this testing. Finally, the identification tests were administered, again with the order of the subtests randomised.

Results

Phonological Awareness Tests

The dyslexics, as anticipated, were much poorer as a group than the controls on Nonword Reading (with no overlap in the scores) and on Spoonerisms (with one dyslexic falling within the full range of the controls). High and significant correlations ($r \geq 0.83$) were obtained among all combinations of the phonological tests, and the standardised reading and spelling tests. None of these correlated significantly with performance IQ.

Auditory Tests of Identification and Discrimination

Criterion Training. All children reached the training criterion for identification within a maximum of 15 trials. In the discrimination tests, all children reached criterion for the vowel condition with at most one error. However, two dyslexic children failed to reach criterion in the /bɑ/-/dɑ/ nonspeech condition. These children (listeners D6 and D7) also required the largest number of trials to reach criterion on the rest of the discrimination tests (summed over the other four conditions). Logistic regressions were used to test for a group difference in each of the 5 conditions separately. Controls performed significantly better than the dyslexics for two conditions only — /bɑ/-/dɑ/ nonspeech and /ɑb/-/ɑd/ speech ($p<0.005$ in both cases). Excluding the two dyslexic children with the worst performance resulted in superior training to criterion for the dyslexic group for /bɑ/-/dɑ/ nonspeech, although this difference did not quite reach statistical significance ($p=0.053$). Performance was still statistically better for the controls for /ɑb/-/ɑd/ speech, but barely so ($p=0.044$).

Identification Tests. The mean identification functions obtained by each listener group and for each consonant position (/bɑ/-/dɑ/ and /ɑb/-/ɑd/) are presented in Figure 2. There was quite a bit of variability in both groups of listeners, but the figures show that the dyslexics had, on average, a slightly shallower identification function.

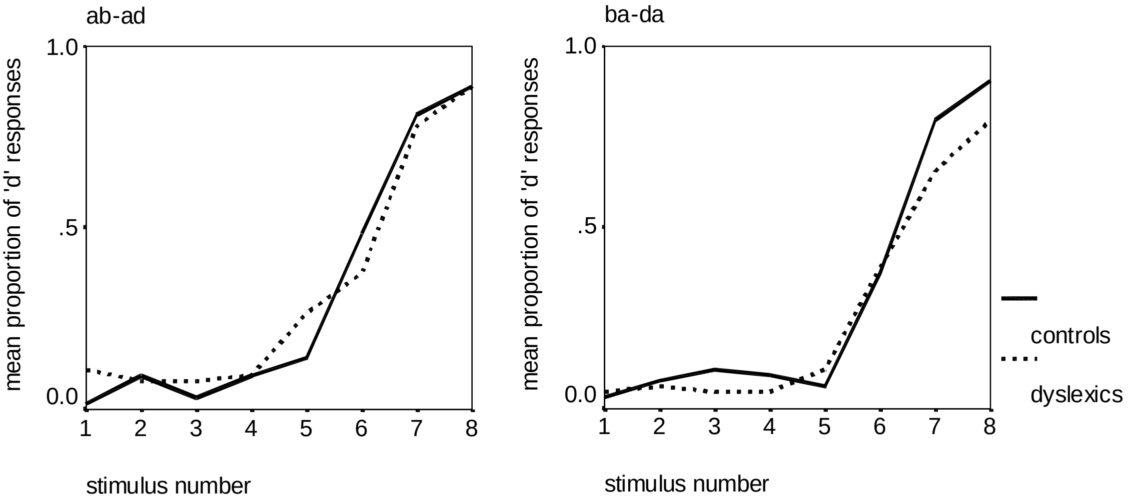

Figure 2. *Mean identification functions for the speech continua for each of the two experimental groups.*

Summary statistics for each individual listener were obtained by logistic regression on the individual identification functions to obtain an estimate of the slope and phoneme boundary[4]. All /ɑb/ slopes were statistically different from a flat function (*i.e.*, there was at least some evidence of categorisation across the continuum), but for /bɑ/, two listeners had slopes that were not different from 0 (one control and one dyslexic, D6).

Boxplots of the slopes and phoneme boundaries as a function of consonantal position and listener group can be seen in Figure 3. Repeated measures ANOVAs showed no significant differences between groups (dyslexic vs. control) or consonant position (initial vs. final), nor any interaction, on the slope or phoneme boundary values.

We also investigated the use of another measure of identification accuracy, performance on the two endpoint stimuli of the continua. This was calculated by simply adding together the number of ‘b’ responses to stimulus 1 and the number of ‘d’ responses to stimulus 8. A logistic regression showed no effect of consonant position but that the controls were significantly more accurate than the dyslexics ($p \approx 0.03$), with no interaction term. Even so, many of the dyslexic listeners performed perfectly or near perfectly (a score of 15 or 16 of 16 was obtained in 12 of 16 sessions for the controls, and 9 of 16 for the dyslexics).

To summarise, the dyslexics do appear, as a group, to be slightly impaired overall in consonant identification compared to the controls, although many are performing well within the normal range. No effect of consonant position (initial vs. final) was ever found.

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[4] For two of the control listeners in both conditions, it was not possible to estimate a slope directly from the data because the identification functions were too steep. We estimated limits on slopes by assuming that twice the number of trials were run on stimuli adjacent to the transition point, and that one 'error' was made on those 16 trials. Slopes obtained ranged from 3.4 to 4.7. A somewhat arbitrary decision was made to set these slopes to 3.6, also because the maximum slope for the rest of the functions was 3.4.

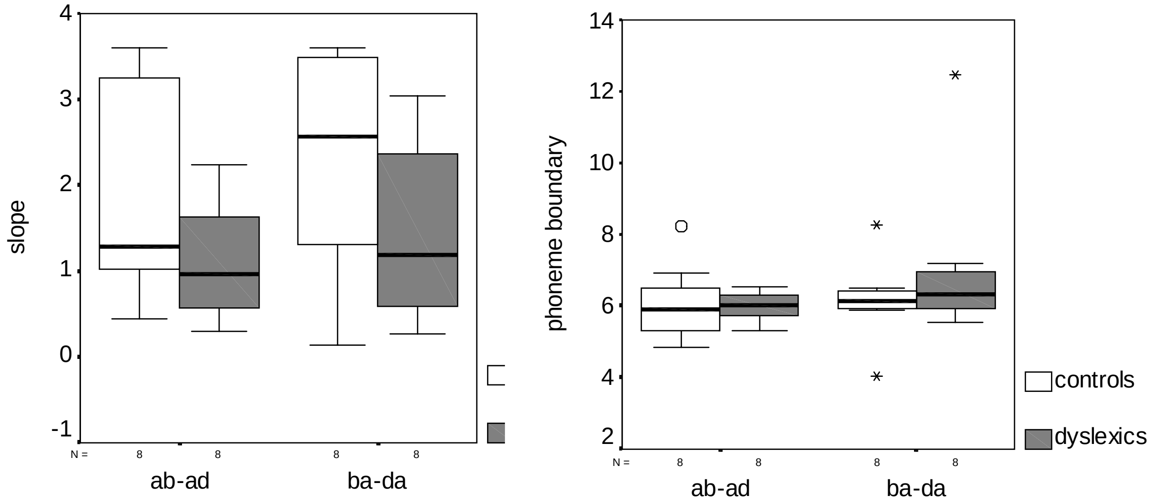

Figure 3. *Boxplots of the summary parameters used to describe consonantal identification functions, shown separately for syllable-initial and syllable-final positions, and for the two listener groups. The box indicates the inter-quartile range of values obtained, with the median indicated by the solid horizontal line. The range of measurements is shown by the whiskers except for points more than 1.5 (indicated by 'o') or 3 box lengths ('*') from the upper or lower edge of the box.*

Discrimination Tests. The role of inter-stimulus interval (ISI) was first examined using a logistic regression with number correct (of 8) as the response variable, and 3 possible explanatory variables. ISI was treated as a continuous variable, with listener and condition as categorical factors. An adequate model required the main effects of listener and condition, as well as their interaction, but neither the main effect of ISI, nor any of its interactions were statistically significant. Therefore we only discuss overall performance in these tasks, calculated by summing for each listener, the total number of correct response across ISIs (Figure 4).

A complex pattern of interactions between listener group and conditions is revealed. Both groups showed almost perfect performance on the vowel stimuli (on average 39.75 out of 40 trials correct). There are large listener group differences for the speech sounds, but smaller ones for the nonspeech analogues.

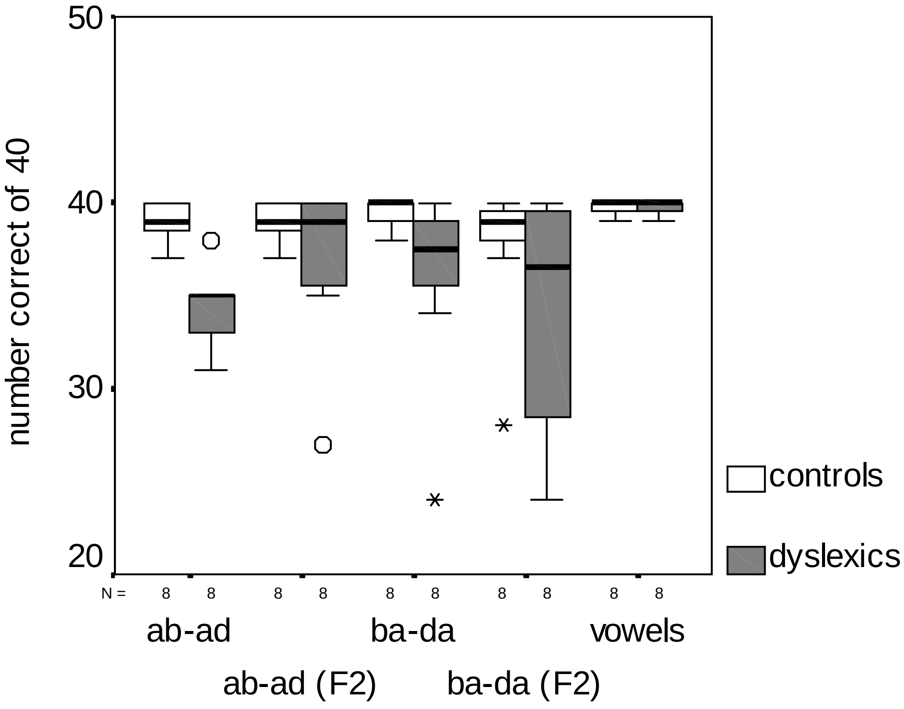

Figure 4. *Boxplots of the total number correct (of 40) in the discrimination tasks, as a function of condition and listener group. Chance performance would lead to 20 correct.*

We began by using logistic regression to test for differences between dyslexics and controls for each of the 5 conditions separately. Only for the vowel contrast was there no significant difference, all other differences reaching a significance level of at least p=0.003. However, as is clear in the boxplots, the difference between the dyslexics and controls is considerably more consistent for the speech than for the nonspeech sounds. It is also not clear if the significant differences between the groups result from the small number of very poor performances in the dyslexic group.

To explore these issues further, we excluded the vowel condition from further analyses, and ran a 2x2x2 logistic regression with the factors of listener group, speech/nonspeech, and position (initial/final). Both the third-order interaction, and the second-order interaction between group and position were non-significant, but all other effects were ($p \leq 0.02$). Thus, the contrast is easier in initial position for the speech sounds, but more difficult when nonspeech (speech/nonspeech x position). More pertinent to the matter at hand, dyslexics are relatively less impaired on the nonspeech contrast (group x speech/nonspeech interaction). Although extreme care must be taken in discussing main effects in the presence of such interactions, only one of the three main effects had an estimated value more than twice the size of its estimated error, that of listener group. Here it is clear that, overall, the dyslexics perform more poorly than the controls.

As the effect of position (initial vs. final) has no strong main effect, we focused on the difference between performance in discriminating formant transitions in speech and nonspeech contexts by summing the number correct across the two positions for the transitions (Figure 5). Separate logistic regressions examining differences in listener group performance show highly significant differences between the two groups for both speech and nonspeech sounds (p<0.0001). However, A 2x2 logistic regression of this data using speech/nonspeech and listener group as factors showed, as expected, a highly significant interaction. This, of course, merely re-states the finding above that dyslexic listeners were less impaired for the nonspeech than for the speech sounds, even if they appear to be impaired on both sets of sounds. The saturated model, however, still fit the data very poorly, with a generalized Pearson chi-squared statistic that is more than 6 times larger than the 28 degrees of freedom remaining.

We therefore calculated modified Pearson residuals and Cook’s distances (Francis *et al.*, 1993) . Unusually large values of Cook’s distance indicate data points that have an undue influence on the fitted model whereas large residuals indicate, of course, data points that would be considered outliers. Four of the 32 data points had very large Cook’s distances (at least 50% bigger than the next largest value); these were also the four lowest scores in the set, as well as the data points that led to the 4 largest residuals. Three listeners accounted for these results, dyslexic listeners D6 (2 scores) and D7, and one control listener. In order to avoid a possible distortion of results by selective elimination of certain scores only, all the results from these three listeners were excised, and the analyses re-done. The boxplots on the right-hand side of Figure 5 shows that the separation of the two listener groups for the speech sounds remains robust, but that there is now a great deal of overlap between the scores obtained by the two groups for the nonspeech sounds. Logistic regression of the two conditions separately confirms the visual impression — only the speech contrast shows a significant difference between the two listener groups (p<0.0001). This results also holds if only the two dyslexic listeners are excluded from the analysis (the outlying control listener did especially poorly for nonspeech).

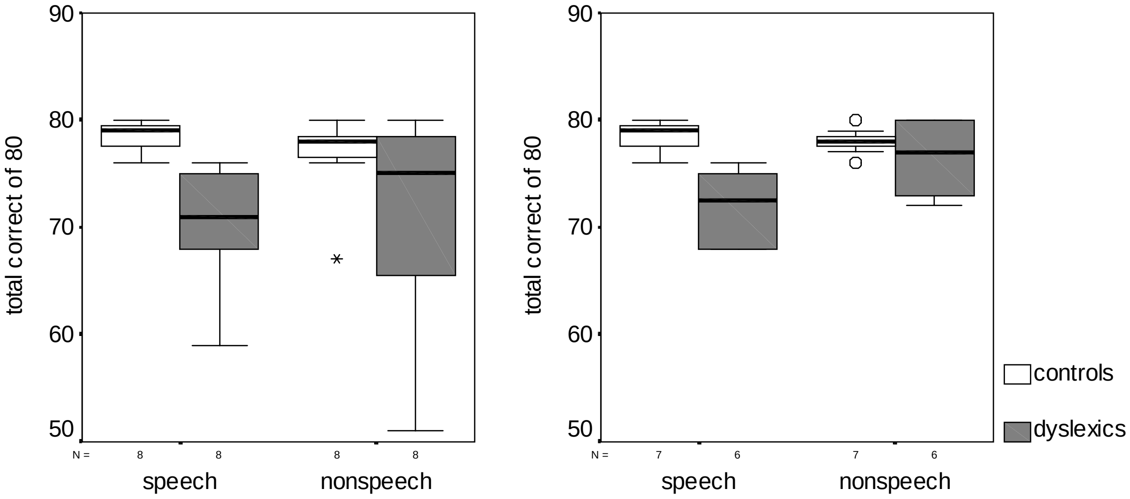

Figure 5. *Boxplots of the total number correct (in 80 trials) for the discrimination of a formant transition in nonspeech and speech contexts. The plots on the left include all the data, whereas that on the right excludes data from three listeners with outlying results (two dyslexics and one control).*

There are thus two main results from the discrimination data. The position of the formant transition, whether sound-initial or sound-final has no consistent effect on its discriminability. Secondly, the majority of the dyslexic listeners (3/4 of the group here) appear to show no deficit in discriminating formant transitions in a nonspeech condition consisting of a single formant, while still showing consistent deficits for the same acoustic contrast in a multiple formant speech sound.

Masking

Boxplots of the masking results can be found in Figure 6 and Figure 7. Mann-Whitney U Tests and t-tests (taking into account the possibility of unequal variances in the two groups) were both used to test for differences between dyslexics and controls for each combination of masking condition and notch width. Only for backward masking with the bandpass noise did the two groups differ ($p<0.005$), with equivalent performance in all other conditions ($p>0.14$). In fact, for the bandpass noise, only one control child had a higher threshold than any of the dyslexics.

Figure 8 shows the difference between the thresholds in the bandpass and notched conditions for simultaneous and forward masking, an index of peripheral frequency selectivity. No differences were found between the two groups here, unlike the reduced degree of selectivity measured in simultaneous masking reported by Wright *et al.* (1997) for SLI children.

The groups did vary, however, for the difference in the two thresholds in backward masking ($p\leq0.013$). Backward masked thresholds dropped significantly (by about 16 dB, on average) for the dyslexics when a spectral notch was put in to the masking noise. This means that they were able to use the difference in frequency spectrum between the probe and the masker to improve their performance. Thresholds for the controls only dropped by a small amount (about 4 dB), but they experienced relatively little backward masking in any case.

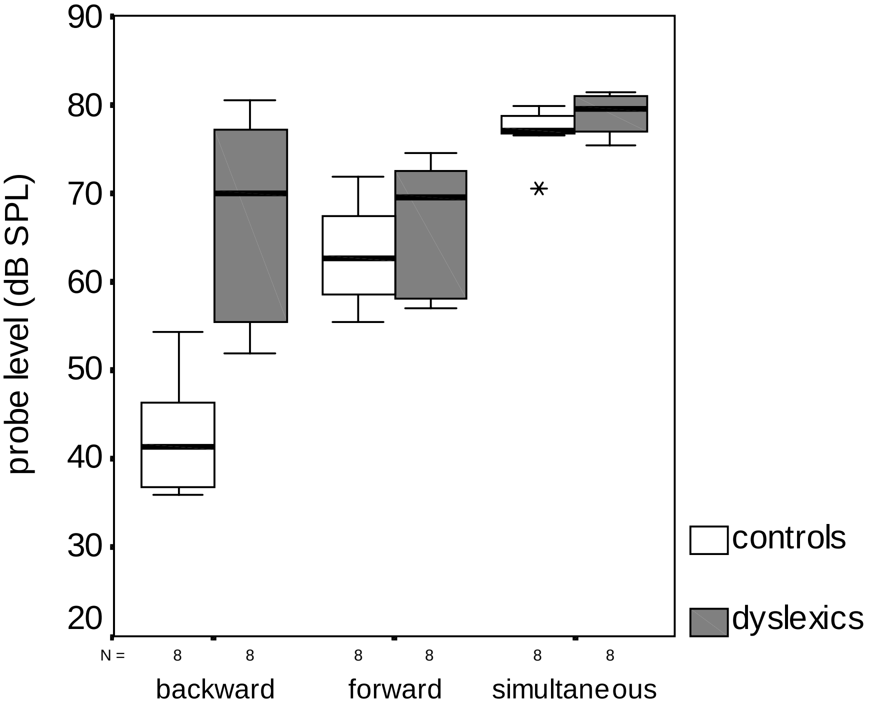

***Figure 6.** Boxplots of the masking results obtained with a bandpass noise.*

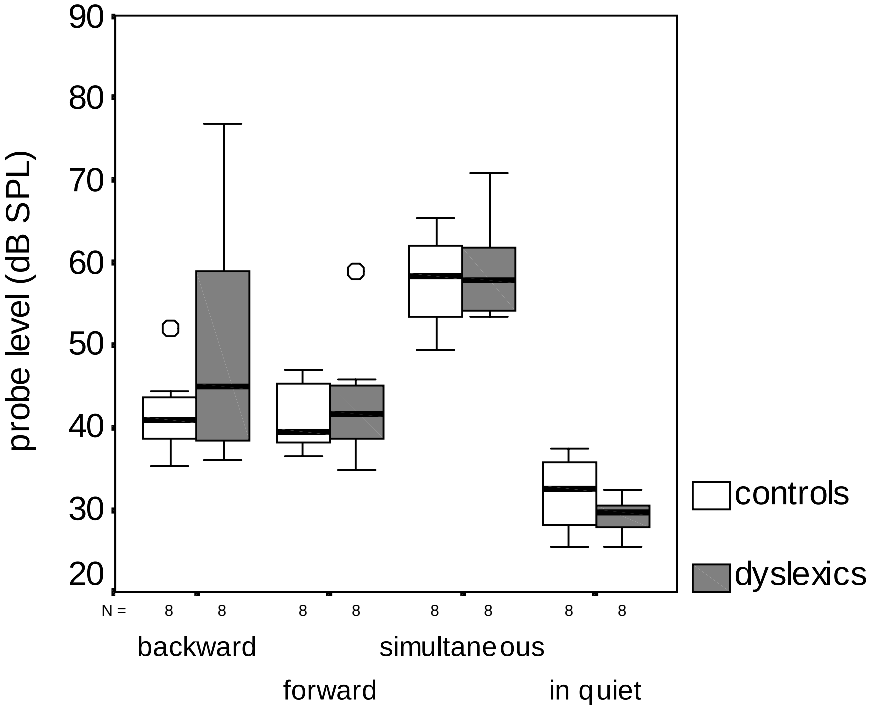

***Figure 7.** Boxplots of the masking results obtained in three conditions with a notched noise, and in quiet.*

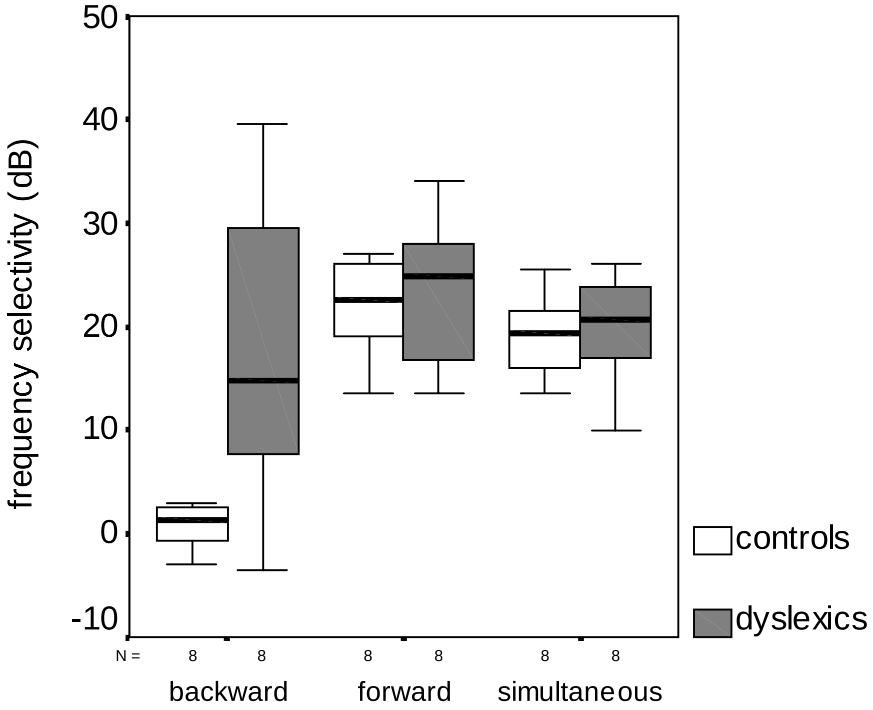

Figure 8. *Boxplots of the difference between the thresholds obtained in a bandpass and a notched noise.*

Discussion

Masking

As regards differences between dyslexics and controls, the results of the masking experiments are reasonably clear cut. The dyslexic children had significantly higher thresholds, as a group, in backward masking for the bandpass noise than did the controls. Statistically this was the only condition on which the two groups differed. Importantly, there were no differences in frequency selectivity, an ability which is understood to arise primarily from processing in the auditory periphery.

The fact that a deficit appears under one particular condition, but not in other very similar ones, lends strong support to the notion that the auditory deficit exhibited here is *genuinely* auditory, and not a more general problem in, say, attention. On the other hand, it is likely that such general abilities still play some role in determining thresholds, as evidenced by the large degree of inter-correlation among the 6 masked thresholds. Of 15 correlations, 9 were significant in one-tailed tests at the 0.05 level when less than one significant result would be expected (0.05 x 15 = 0.75). It also is possible that there is a complex interaction of task difficulty and the influence of general skills like sustained attention. For example, although simultaneous and backward masking *seem* to have the same task demands, it is clear that backward masking taps central auditory processing skills to a greater extent. So, we might expect level of attention to influence performance in backward masking much more than it does in simultaneous masking. More work is necessary to test this possibility. Informal observations suggest to us that fatigue leads to a much greater variability in backward than simultaneous masking, but no controlled studies of this are available.

Regardless of the explanation, however, group differences in backward masking are clearly evident. It is impossible to say, though, on the basis of this study alone, whether all dyslexic children can be said to be impaired in this task — primarily because of the small number of children tested. There may also be a problem in terms of the extent to which the control group is representative of the general population, since our control listeners were volunteers, recruited primarily through university staff members. Although we made some effort to recruit children from as broad an ability range as possible, the only way we can be assured of this is by looking at larger groups who are recruited less selectively. It is thus interesting to compare the results obtained here with those obtained in two other studies of backward masking which used teenage control listeners (Figure 9). The largest study recruited listeners at a state-funded secondary school which does not select for ability, so those results are likely to be the most generally representative. In fact, the medians from all three studies were very similar, although there is more variability in the largest study. By amalgamating them, our best estimate for the mean backward-masked threshold in a teenage population is 49 dB SPL (s.d.= 12.2 dB). Using these estimates, 3 of the 8 dyslexics have a normal backward-masked threshold (under the stringent criterion of being within one standard deviation of the mean), while 5 of the 8 are within the worst 8% of controls.

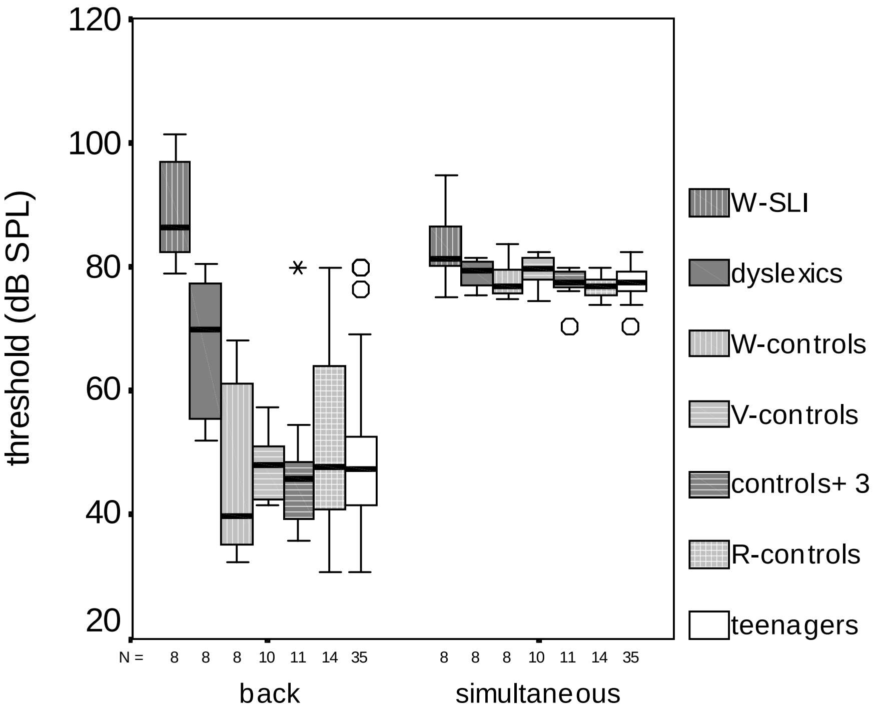

Figure 9. *Boxplots of thresholds obtained in backward and simultaneous masking with a bandpass noise in four different studies.* **W-SLI** *and* **W-controls** *are the SLI group and their controls from Wright et al. (1997);* **dyslexics** *are from the present study;* **V-controls** *were aged 12-16, from Vance et al. (1999);* **controls+3** *are the controls from the present study plus three further controls who were tested, but dropped from the main study to obtain the best age and performance IQ match;* **R-controls** *are from Rosen et al. (in press);* **teenagers** *are simply the aggregate of the results from the last three mentioned studies.*

The issue of recruiting of appropriate controls has come to the fore recently in a study by Bishop *et al.* (1999) who found no differences in backward masking between language-impaired children and age-matched controls who were of a similar age to those used by Wright *et al.* (1997). Interestingly, the crucial discrepancy between these two studies was *not* in the results from language-impaired children, but in the controls. Wright *et al.*'s controls had considerably lower thresholds than those obtained by the controls in Bishop *et al.*, even though the masker level in the latter was 10 dB less intense. In fact the median threshold of Wright *et al.*'s controls is better than that obtained by the three control groups in Figure 9 who were, on average, at least 5 years older. Buss *et al.* (1999) have recently shown large improvements in backward masked thresholds (nearly 4 dB/year) for children aged 5-11, so we might expect the thresholds for 8-year olds to be some 18 dB higher than those found for 13-year olds (assuming for convenience little change in threshold after this age), or nearly 70 dB. In fact, such a result has recently been reported in a group of 24 control children aged 7-10 recruited at a primary school (Rosen *et al.*, in press). It therefore appears that Wright *et al*. have seriously underestimated the typical backward masked threshold of 8-year olds. This is not to say that there might still not be a difference, on average, between the thresholds obtained from control and SLI children of that age, but it seems unlikely that the two groups will no longer overlap on this measure.

Identification of speech sounds

There were few differences between groups on the speech identification tasks, although some evidence of a slight deficit in performance for the dyslexics. More importantly, there was no effect of syllable position (initial vs. final). Differences in susceptibility to backward and forward masking had no relationship to the ability to identify speech sounds that would be expected to be differentially affected by backward and forward masking. The slope of the identification functions for /bɑ/-/dɑ/ did not correlate with backward-masked thresholds (in fact they uninterpretably correlated with forward-masked thresholds in a bandpass noise), and the slopes of the identification functions for /ɑb/-/ɑd/ did not correlate with forward-masked thresholds. Neither did similar relationships hold when considering performance solely on the endpoints of the continuum, a measure which, unlike the slopes, did distinguish the dyslexics from the controls on average.

Discrimination of speech and analogous nonspeech contrasts

Continuing the theme of the relationship between the asymmetry of forward and backward masking, we examined correlations between (but not among) the 4 discrimination and 6 masking tasks using a Bonferroni-corrected significance level of p=0.002 (0.05/24) in one-tailed tests. The only significant correlation was between backward masked thresholds in a bandpass noise and discrimination of the /ɑb/-/ɑd/ speech contrast (r= -0.75, p<0.001), although the correlation of the same backward masked thresholds with discrimination of the /bɑ/-/dɑ/ speech contrast was nearly as strong (r= -0.64, p=0.004). Forward masking correlated with none of the discrimination tasks. Inspection of the scatterplots of these significant relationships indicates that the correlations arise from differences *between* dyslexics and controls, rather than a relationship within the groups. For example, since dyslexics have higher thresholds in backward masking and worse performance for speech discrimination as a group, we expect correlations between these two variables. In short, just as we found for speech identification, the asymmetry in performance between backward and forward masking was not reflected in the ability to discriminate formant transitions that varied in position, either for nonspeech analogues or speech.

It thus seems more sensible to think of formant transition discrimination as an ability distinct from those involved in backward and forward masking. Whether this ability independently varies in speech and nonspeech contexts (another version of the Mody *et al.* view, after all), is less certain. The pattern of correlations among the 4 discrimination tasks (excluding the vowels) is not very clear on this point. Of the 6 correlations, all were positive, with 3 significant at the 0.005 level (Bonferroni-corrected level of 0.008), but with no simple relationships. The nonspeech /ɑb/-/ɑd/ contrast correlated not only with nonspeech /bɑ/-/dɑ/ (suggesting related abilities for nonspeech sounds) but also even more highly with the speech /bɑ/-/dɑ/ contrast (suggesting a general ability for perceiving formant transitions). The nonspeech /bɑ/-/dɑ/ contrast also correlated with speech /bɑ/-/dɑ/ (suggesting related abilities for sound-initial formant transitions).

The difference between processing for speech and nonspeech is much more evident, of course, in overall performance for speech and nonspeech analogues. Across the entire set of listeners, it is clear that that the deficit in dyslexics for formant transitions in a speech syllable is much more consistent than for the same formant transition presented on its own in a nonspeech context. It is also interesting to note that, although the changes are small, median performance in the control group is slightly better for speech for nonspeech sounds, whereas in the dyslexics the opposite pattern holds.

What deficit remains for the nonspeech contrasts appears to result from two of the dyslexic listeners who performed much worse for the nonspeech contrasts than all the others (the lowest 3 scores for the dyslexics were 51, 59 and 73 correct of 80). Excluding the two listeners leaves us with a finding essentially the same as that reported by Mody *et al.* — the deficit that dyslexic listeners demonstrate for perceiving a speech contrast based on formant transitions is not expressed for nonspeech analogues of that contrast. Thus, there appears to be no general auditory problem in perceiving rapid spectral changes.

We part company with Mody *et al.* when it comes to further interpretation of this finding. They conclude that “deficits in speech perception are domain specific and phonological rather than general and auditory in origin”. Although this is one reasonable interpretation, there is at least one other. As Figure 1 so clearly shows, the nonspeech analogues used here (and by Mody *et al*.) are acoustically much simpler than the speech contrasts. So it is at least possible that the auditory deficit in dyslexia is general, but confined to stimuli that are more complex than the nonspeech analogues used here. Perhaps, for example, perception of second-formant transitions is only disturbed in the presence of a first formant. Only further work will be able to clarify this issue, but it may be quite difficult to construct nonspeech analogues of speech stimuli that are of sufficient acoustic complexity, but that are still not perceived as speech.

Although it is clear that a phonological explanation of deficits in speech perception completely refutes the notion of a general auditory deficit, an explanation invoking acoustic complexity might not also sit very well with exponents of the auditory view.

In particular, strong support of the general auditory view is seen to arise through the success of a computer-based, primarily auditory, training program for language disorders (Merzenich *et al.*, 1996; Tallal *et al.*, 1996). An important part of this scheme relies on training with highly simplified sounds (frequency-modulated sinusoids) meant to represent formant transitions (Merzenich *et al.*, 1996). If the majority of language-disordered children have no deficit for simplified sounds, why train with them?

Relationships among auditory, phonological and psychometric tests

Generally speaking, our experimental design is not well suited to clarify the inter-relationship of various measures with the tests of literacy. Because we selected the experimental groups to be non-overlapping in terms of reading and spelling achievement, any auditory measure which differs significantly between the dyslexics and controls will almost certainly be correlated with measures of literacy. And indeed, backward masking performance in a bandpass noise correlates highly with both measures of phonological processing and with reading and spelling ($0.87 \geq |r| \geq 0.65$, $p \leq 0.004$), as does aggregate performance for discriminating speech sounds ($0.81 \geq |r| \geq 0.73$, $p \leq 0.001$). All these correlations would still be significant after Bonferroni correction. Aggregate discrimination performance for nonspeech sounds correlates much less strongly with the measures of literacy and phonological processing — although all are positive, uncorrected significance levels are in the range $0.12 \leq p \leq 0.02$, so none would survive Bonferroni correction (the smallest, and far from significant, correlation is with Nonword Reading). This observation supports the notion that perceiving formant transitions *per se* is at best weakly related to reading ability, although perceiving formant transitions in a speech context is strongly related.

Of important interest would be any significant correlations *within* groups, but the small number of listeners makes statistical significance hard to achieve. Also, the effect of outliers become even more important. One listener, D6, performed very poorly overall, and in fact was the worst performing subject in backward masking in a bandpass noise, discrimination of speech and nonspeech sounds, spelling, real word reading and nonword reading. In some of these tasks he performed considerably worse than all other subjects. In future studies it may be advantageous to sample more continuously along the dimension of reading ability by, for example, assessing all students in mixed ability classes at a particular school.

Finally, as it has sometimes been noted that nonverbal IQ can influence performance in various auditory tasks (*e.g.*, Bishop *et al.*, 1999) we note that performance IQ did not correlate significantly with any of the auditory, phonological or literacy measures.

Final remarks

One of the most consistent findings concerning dyslexia is that auditory processing deficits are far from universal, typically affecting 25-35% of dyslexics. This study is no different, although it does appear that a somewhat higher proportion of the group exhibit some deficit. Still, three dyslexics of 8 (D1, D2 and D8) performed normally both in backward masking and for discrimination of the nonspeech contrast.

Due to findings like these, it has long been clear that an auditory deficit is not a *necessary* condition for dyslexia. As Bishop *et al.* (1999) has recently pointed out, less attention has been paid to the question of *sufficiency* — here, the extent to which normal readers exhibit impaired auditory processing. As it turned out, none of the normal readers in the main study had an elevated threshold for backward masking in a bandpass noise. But it is interesting to note that one of the 3 controls eliminated for matching purposes *did* have a very high threshold in that condition (readily seen in Figure 9 at 80 dB SPL), yet exhibited perfectly normal reading and spelling. In fact, her scores for nonword reading were the highest obtained. So it is clear that an auditory deficit is neither necessary *nor* sufficient to cause dyslexia.

This, of course, does not mean that a general auditory deficit could not be a contributing factor for dyslexia in a subset of children. If genuine auditory deficits are present, it is difficult to see how these could *not* have an impact on speech perception, and the development of phonological skills. One difficulty, as we noted in the introduction, is that there is no convincing account of exactly *how* the auditory deficit affects speech perception. Tallal and her colleagues have stressed rapid temporal aspects of acoustic signals, but there is good evidence that not all such contrasts are impaired (in particular, gap detection — McAnally & Stein, 1996; Schulte-Korne *et al.*, 1998), nor is the deficit restricted to such contrasts (Adlard & Hazan, 1998; Nittrouer, 1999; Reed, 1989;Tallal & Stark, 1981; Talcott *et al.*, 1999). Mody *et al.*'s study and this one cast doubt that any deficit for formant transitions in speech sounds arises from a problem in processing spectral transitions, *per se*.

Secondly, if auditory processing indeed does play a major role in dyslexia, it needs to be made clear what other factors allow one child with an auditory deficit to read normally, while another child with normal auditory processing develops dyslexia. There is, of course, a long history of theorising about different subtypes of dyslexia, but these ideas have, so far, shed little light about the variability in auditory processing. One interesting study on this topic compared dyslexics with and without accompanying language delay, and found disordered auditory processing only in the presence of language delay (Heath *et al.*, 1999). Significantly, even in the group with language delay, a substantial proportion of the children had no measurable auditory deficit. Unfortunately, we did not measure general aspects of language skill here, but it may be very useful for future studies to include such measures.

There is, of course, the alternative view put forward by Mody *et al.*, that the core deficit in dyslexia has a linguistic/phonological basis. In this view, any nonspeech auditory deficits are seen to be unrelated to the speech perceptual one. Clearly this is a matter for further empirical investigation. We believe this viewpoint only remains viable because of the surprisingly few nonspeech abilities that have been shown to be impaired in dyslexics in more than one study. If one also requires evidence of a normal performance on a related task, or with some manipulation of stimulus parameters (to exclude the possibility of a general deficit in attention, for example) there are perhaps only three auditory skills that this is true for: identification and discrimination of short tones differing in fundamental frequency when presented at short inter-stimulus intervals (Heath *et al.*, 1999; Reed, 1989; Tallal, 1980); backward masking (Wright *et al.*, 1997; this study); detection of frequency modulation (Talcott *et al.*, 1999; Witton *et al.*, 1998). For none of these has a clear relationship with speech perception been shown.

If a sufficient number of different auditory skills were shown to be associated with dyslexia, and which were consistent within subjects, it would be harder to maintain the Mody *et al.* view that they were unrelated to the dyslexia. On the other hand, we should not dismiss the possibility out of hand that some or all of the auditory deficits reported *do* stand completely separate from normal speech perceptual processing. It is hard to square the enormous deficit claimed, say, for backward masking with the usually minor perturbations seen to speech perceptual skills in children with language disorders. Until a unified framework convincingly relates deficits found in nonspeech to those in speech in a predictive and specific manner, the phonological explanation of dyslexia will not lose its advocates.

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