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PAPER

Rise time and formant transition duration in the discrimination of speech sounds: the Ba–Wa distinction in developmental dyslexia

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Abstract

Across languages, children with developmental dyslexia have a specific difficulty with the neural representation of the sound structure (phonological structure) of speech. One likely cause of their difficulties with phonology is a perceptual difficulty in auditory temporal processing (Tallal, 1980). Tallal (1980) proposed that basic auditory processing of brief, rapidly successive acoustic changes is compromised in dyslexia, thereby affecting phonetic discrimination (e.g. discriminating /b/ from /d/) via impaired discrimination of formant transitions (rapid acoustic changes in frequency and intensity). However, an alternative auditory temporal hypothesis is that the basic auditory processing of the slower amplitude modulation cues in speech is compromised (Goswami et al., 2002). Here, we contrast children’s perception of a synthetic speech contrast (ba/wa) when it is based on the speed of the rate of change of frequency information (formant transition duration) versus the speed of the rate of change of amplitude modulation (rise time). We show that children with dyslexia have excellent phonetic discrimination based on formant transition duration, but poor phonetic discrimination based on envelope cues. The results explain why phonetic discrimination may be allophonic in developmental dyslexia (Serniclaes et al., 2004), and suggest new avenues for the remediation of developmental dyslexia.

Introduction

Despite widespread agreement across languages that the cognitive difficulty in developmental dyslexia lies with phonology, there is little agreement concerning the neural/sensory antecedents of the phonological deficit. Indeed, current causal theories of dyslexia encompass a variety of sensory modalities (e.g. Stein & Walsh, 1997; Tallal, 2004; Sperling, Lu, Manis & Seidenberg, 2005). For the auditory modality, Tallal and colleagues have long argued for a sensory difficulty with temporal processing. Tallal and Piercy (1973) demonstrated that children with developmental language disorders showed poor rapid auditory processing (RAP) of non-speech sounds in tasks such as temporal order judgment, and argued that a RAP deficit would affect the perception of phonemes in spoken language. Phonemes have been assumed to be the fundamental units underpinning speech-based representations (Port, 2007), and have traditionally been conceptualized as individual sound elements in words (e.g. /b/, /d/, /w/ and /l/). In terms of the acoustic basis of phonemes, there are assumed to be language-general acoustic or physical features that make up speech sounds, with particular languages grouping these features into the phonemes used by that language. Classical models of speech perception assumed that invariant acoustic features in the speech signal, such as spectral energy peaks (formants), were the auditory correlates of phonemes (e.g. Blumstein & Stevens, 1981). As formant transitions often depend on rapid acoustic changes in frequency and intensity, Tallal and colleagues argued that a RAP deficit could be causal in explaining the well-documented difficulties with phonemes shown by children with developmental dyslexia in phoneme awareness tasks.

Learning to read an alphabetic language depends in part on linking graphemes (letters or letter clusters, e.g. F, PH) to phonemes (/F/). Clearly, children who have auditory difficulties in discriminating phonemes would be at a disadvantage in acquiring the alphabetic principle. Over and above this, the RAP hypothesis depends on two assumptions. The first is that phonemes are the fundamental units of speech perception, and the second is that phonetic discrimination depends on formant transitions. The first assumption is now thought to be wrong. It has been argued persuasively that words are not stored by the brain as a linear collection of phonetic segments (Nittroser, 2006; Port, 2007).
‘universal phonetic inventory’ or inventory of elemental speech sounds upon which all languages depend. Rather, the letter-like symbolic units (phonemes) that we appear to experience perceptually when we hear words are a direct result of becoming literate. Indeed, while infants are sensitive from birth to the physical features that make up speech sounds, studies of phonological development suggest that pre-reading children can only reflect on the sound structure of words at the syllable and onset-rime level (when the syllable is divided at the vowel, linguists term the two resulting units the ‘onset’ and the ‘rime’; see Ziegler & Goswami, 2005). On this view, the development of phoneme awareness depends largely on learning an alphabet, and accordingly the difficulties with phonemes shown by children with developmental dyslexia would be a result of their difficulties in acquiring literacy, and not a cause (see Ziegler & Goswami, 2005).

The second assumption, that phoneme discrimination depends predominantly on formant changes, may also be wrong. Any sound (such as speech) can be factored mathematically into the product of a slowly varying envelope (also called amplitude modulation) and a rapidly varying fine time structure (Smith, Delgutte & Oxenham, 2002). Speech carries multiple auditory cues to phonetic identity, in both the envelope and the fine structure, but the envelope is dominant for speech intelligibility (Smith et al., 2002). Regarding formant transitions, experiments with adult listeners have shown that speech intelligibility is remarkably good even when no formant structure is present (Remez, Rubin, Pisoni & Carrell, 1981). In fact, adult listeners show high speech recognition performance with envelope information from as few as 3–4 lower frequency bands (Shannon, Zeng, Kamath, Wygonski & Ekedal, 1995). Related work suggests that speech intelligibility relies on the slower amplitude modulations in these lower frequency regions (1–16 Hz) of the speech signal (Drullman, Festen & Plomp, 1994). The critical importance of the slowly varying amplitude envelope information in speech to speech intelligibility suggests that sensitivity to these cues might be central to setting up a phonological lexicon in infancy (Goswami, 2009). Consistent with this hypothesis, deaf babies who are given cochlear implants that transmit only envelope information and discard the fine structure manage to develop good speech recognition skills, and also develop reasonable phonological awareness (James, Rajput, Brown, Sirimanna, Brinton & Goswami, 2005; Johnson & Goswami, 2009).

If amplitude envelope information is indeed central to phonological representation, then children with phonological processing difficulties such as children with developmental dyslexia would be expected to show reduced perceptual sensitivity to the shape of amplitude modulation. This is indeed the case (e.g. Goswami, Thomson, Richardson, Stainthorp, Hughes, Rosen & Scott, 2002; Richardson, Thomson, Scott & Goswami, 2004; Thomson & Goswami, 2008; Goswami, Gerson & Astruc, 2009). Discrimination of amplitude envelope onsets (rise times) by children with dyslexia is particularly compromised across languages (Muneaux, Ziegler, Truc, Thomson & Goswami, 2004; Hämäläinen, Leppänen, Torppa, Muller & Lyttinen, 2005; Hämäläinen, Salminen & Leppänen, in press; Surányi, Csépe, Richardson, Thomson, Honbolygó & Goswami, 2009). The perceptual consequences of insensitivity to rise time include difficulties in perceiving speech rhythm and stress, and poorer segmentation of the speech stream at the syllable level (Cheah, Hämäläinen, Soltesz & Goswami, 2009; Greenberg, Carvey, Hitchcock & Chang, 2003). To date, rise time difficulties have not been expected to cause difficulties in phonetic representation. Yet logically, if amplitude envelope information is critical for speech intelligibility, it must play a role in phonetic discrimination.

Here, we measured children’s discrimination of a phonetic contrast, Ba/Wa, created either by varying the rate of formant frequency change or the rate of amplitude change or rise time. We predicted that children with developmental dyslexia would show difficulties in phonetic discrimination only for the amplitude envelope stimuli (BaWa<AE>). We compared children with developmental dyslexia to typically developing children matched for either age (CA controls) or reading level (RL controls). We did not predict generalized difficulties in perceiving any temporal rate of change, tested here by the formant transition duration stimuli (BaWa<FT>).

Methods

Participants

One hundred and six children aged between 7 and 12 years participated in this study. Only children who had no additional learning difficulties (e.g. dyspraxia, ADHD, autistic spectrum disorder, specific language impairment [SLI]), a nonverbal IQ above 85, and English as the first language spoken at home were included. The absence of additional learning difficulties was based on school reports, discussion with parents, and our own testing impressions of the children. Note that in other studies we have given similar tasks to those used here to children with a diagnosis of SLI (Corriveau, Pasquini & Goswami, 2007; Corriveau & Goswami, 2009). Children with SLI who have phonological difficulties also show rise time deficits. All children received a short hearing screen using an audiometer. Sounds were presented in both the left and the right ear at a range of frequencies (250, 500, 1000, 2000, 4000, 8000 Hz), and all children were sensitive to sounds within the 20 dB HL range. Forty-six of the children (27 male; mean age 9 years 6 months) either had a statement of developmental dyslexia from their local education authority, or showed severe literacy and phonological deficits according to our own test battery. Children were referred to the study by

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teachers with responsibility for special educational needs from a number of schools. They were assessed experimentally using the British Ability Scales standardized tests of reading and spelling, and were included in the study if they scored at least 1 standard deviation below the test norm of 100. Thirty-three age-matched control children (CA control group; 16 male; mean age 9 years 6 months) and 27 reading-level matched control children (RL control group; 11 male; mean age 7 years 6 months) were recruited from the same schools as the dyslexics and received the same standardized tests. Note that the CA controls differed by 27 standard points and by 3 years in average reading age from the children with dyslexia, whereas the RL controls differed by 23 standard points. Both group differences were significant. The RL controls did not, however, differ significantly from the children with dyslexia in terms of reading age in months, even when statistical comparisons were limited to the reading-matched groups (dyslexic and RL). Participant details are shown in Table 1.

Tasks

Psychometric tests

The psychometric tests comprised the British Ability Scales (BAS) (reading and spelling; Elliott, Smith & McCulloch, 1996; note that because of measurement slip typically developing children in the UK now routinely score above the standardized mean of 100); the British Picture Vocabulary Scales (receptive vocabulary; Dunn, Dunn, Whetton & Pintillie, 1982); and four subtests of the Wechsler Intelligence Scale for Children (WISC-III): block design, picture arrangement, similarities, and vocabulary. IQ scores were prorated following the procedure adopted by Sattler (1982).

Psychoacoustic tasks

The psychoacoustic stimuli were presented binaurally through headphones at 75 dB SPL. Earphone sensitivity was calculated using a Zwislocki coupler in one ear of a KEMAR manikin (Burkhard & Sachs, 1975). Children’s responses were recorded on the computer keyboard by the experimenter. The auditory tasks used a child-friendly AXB or 2IFC ‘Dinosaur’ threshold estimation program, originally created by Dorothy Bishop (Oxford University). The original tasks were reprogrammed for this study by the third author. The amended Dinosaur program used an adaptive staircase procedure (Levitt, 1971) with a combined 2-up 1-down and 3-up 1-down procedure; after two reversals, the 2-up 1-down staircase procedure changes into 3-up 1-down. The step size halves after the fourth and sixth reversals. For the BaWa task, synthetic speech tokens were created in Sensyn with an update interval of 5 ms, giving rise to 20 tokens as described below. A test run typically terminates after eight response reversals or alternatively after the maximum possible 40 trials. The rationale for this adaptive method is rapidly to place stimuli as close to the individual threshold level of the child as possible via the 2-up 1-down trials, and then to estimate the 79.4% correct point on the psychometric function using the 3-up 1-down procedure (which is standard psychoacoustics). Four attention trials were randomly presented during each test run, using the maximum contrast of the respective stimuli in each auditory task. The threshold score achieved was calculated using the mean of the last four reversals.

BaWa task. Children were introduced to three cartoon dogs and required to identify the dog who sounded different from the other two. Two continua of 20 speech syllables 235 ms in duration were synthesized using a

Table 1 Participant details

<table>
<thead>
<tr>
<th>Group</th>
<th>Dyslexic</th>
<th>CA Controls</th>
<th>RL Controls</th>
<th>F(2, 105)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chronological age (months)</td>
<td>114.24</td>
<td>114.85</td>
<td>90.37</td>
<td>53.69***</td>
</tr>
<tr>
<td>(SD)</td>
<td>(12.35)</td>
<td>(10.28)</td>
<td>(6.18)</td>
<td></td>
</tr>
<tr>
<td>Reading age (months)</td>
<td>90.59</td>
<td>126.70</td>
<td>95.41</td>
<td></td>
</tr>
<tr>
<td>(SD)</td>
<td>(14.88)</td>
<td>(21.98)</td>
<td>(11.67)</td>
<td></td>
</tr>
<tr>
<td>WISC short-form IQ</td>
<td>105.9</td>
<td>110.76</td>
<td>106.37</td>
<td></td>
</tr>
<tr>
<td>(SD)</td>
<td>(15.10)</td>
<td>(11.74)</td>
<td>(12.16)</td>
<td></td>
</tr>
<tr>
<td>Reading standard score</td>
<td>82.80</td>
<td>109.21</td>
<td>106.33</td>
<td>73.77***</td>
</tr>
<tr>
<td>(SD)</td>
<td>(9.85)</td>
<td>(10.73)</td>
<td>(11.61)</td>
<td></td>
</tr>
<tr>
<td>Spelling standard score</td>
<td>83.50</td>
<td>105.52</td>
<td>106.33</td>
<td>65.38***</td>
</tr>
<tr>
<td>(SD)</td>
<td>(9.48)</td>
<td>(10.62)</td>
<td>(10.07)</td>
<td></td>
</tr>
<tr>
<td>BPVS standard score</td>
<td>102.72</td>
<td>107.76</td>
<td>107.26</td>
<td>2.79</td>
</tr>
<tr>
<td>(SD)</td>
<td>(12.13)</td>
<td>(8.79)</td>
<td>(9.09)</td>
<td></td>
</tr>
<tr>
<td>Phonological awareness % correct</td>
<td>56.6</td>
<td>75.3</td>
<td>60.6</td>
<td>12.94***</td>
</tr>
<tr>
<td>(SD)</td>
<td>(17)</td>
<td>(16)</td>
<td>(16)</td>
<td></td>
</tr>
<tr>
<td>Rise time discrimination threshold (max. = 40)</td>
<td>25.37</td>
<td>18.82</td>
<td>28.00</td>
<td>5.53**</td>
</tr>
<tr>
<td>(SD)</td>
<td>(11.10)</td>
<td>(12.12)</td>
<td>(10.44)</td>
<td></td>
</tr>
<tr>
<td>Rise time discrimination threshold in ms</td>
<td>193.0</td>
<td>145.2</td>
<td>212.3</td>
<td></td>
</tr>
<tr>
<td>Frequency discrimination threshold</td>
<td>24.04</td>
<td>13.55</td>
<td>25.67</td>
<td>13.12***</td>
</tr>
<tr>
<td>(SD)</td>
<td>(11.37)</td>
<td>(9.89)</td>
<td>(9.27)</td>
<td></td>
</tr>
<tr>
<td>Frequency discrimination threshold in semitones</td>
<td>1.18</td>
<td>0.64</td>
<td>1.26</td>
<td></td>
</tr>
</tbody>
</table>

a Dyslexic = CA, different from RL. b Dyslexic = RL, different from CA. c Dyslexic, RL worse than CA. *** p = .000; ** p = .005.

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Klatt Synthesiser by the second author (SenSyn, Sensi-metrics). In both (BaWaFT, BaWaAE) the Ba syllable (shortest frequency rise or shortest amplitude rise, respectively) was the standard sound presented twice in each trial. In the BaWaAE condition, the standard Ba had a 30 ms amplitude rise that was compared with a Wa (beginning with a 125 ms amplitude rise that became shorter in accordance with the adaptive staircase procedure). In the BaWaFT condition, the standard Ba had a 25 ms frequency rise that was compared with a Wa (beginning with a 120 ms frequency rise that became shorter in accordance with the adaptive staircase procedure). A change from an initial stop consonant (Ba) to an initial glide (Wa) syllable was achieved by varying either the frequency rise time of the first (F1) and second (F2) formants or by varying the amplitude rise time of the Klatt voicing parameter (AV). In the BaWaFT continuum, AV was kept constant at a 25 ms amplitude rise time. In the BaWaAE continuum, AV varied linearly from 30 ms amplitude rise (Ba) to 125 ms amplitude rise (Wa) in steps of 5 ms. F1 and F2 transitions rose from 250 Hz to 780 Hz and 650 Hz to 780 Hz, respectively, in both continua. The rate of spectral change (F1 and F2 transition rate) was held constant at 55 ms in the BaWaFT continuum and varied linearly from 25 ms frequency rise (Ba) to 120 ms frequency rise (Wa) in steps of 5 ms for the BaWaFT continuum. The end-point stimuli of each continuum are shown in Figure 1.

Rise time task. This was a rise time discrimination task with intensity roving, using a 2IFC format. Two 800 ms tones were presented on each trial, with 500 ms ISIs. The standard tone had a 15 ms linear rise time envelope, 735 ms steady state, and a 50 ms linear fall time. The other tone varied the linear rise time envelope logarithmically along a continuum, with the longest rise time being 300 ms. The intensity of the sounds varied randomly between 65 and 75 dB, so that intensity was not a cue to rise time. Children were introduced to two cartoon dinosaurs. It was explained that each dinosaur would make a sound and that the child’s task was to decide which dinosaur’s sound had a softer rising sound (longer rise time). The child then participated in five practice trials. As an integral part of the software program, feedback was given after every trial on the accuracy of performance. During the practice period this was accompanied by further verbal explanation and reinforcement by the researcher.

Frequency task. This was a frequency discrimination task delivered in an AXB format. The standard was a pure tone with a frequency of 500 Hz presented at 75 dB SPL, which had a duration of 200 ms. The maximum pitch difference between the stimuli presented in this task was 3 semitones. Children were introduced to three cartoon elephants. It was explained that each elephant would make a sound and that the child’s task was to decide which elephant’s sound was higher. Verbal as well as visual feedback was again given during the five practice trials. The software program then gave feedback on the accuracy of performance, as for the BaWa and rise time tasks.

Phonological awareness task. This task used digitized speech and measured rhyme awareness using an oddity format (e.g. kick, pick, tip; see Thomson & Goswami, 2008). Children listened to the computer ‘speaking’ three words in a semi-random order and were asked to select the word that did not rhyme with the other two words. The presentation order of the words and thus the position of the target word was counterbalanced across groups. Trials were presented in two fixed random orders. The task comprised 20 trials, and a score of 1 was given for each correct answer. Performance (% correct) by group is shown in Table 1. Scores out of 20 were used in the analyses.

Results

Discrimination data for the 106 participants were explored by group using box plots as well as measures of kurtosis and skew to check that assumptions of normality were met. Any data points lying further than three interquartile ranges from the nearer edge of the box were removed. Six outliers were identified for the BaWaFT task only (six dyslexics). As shown in the boxplots provided as Figures 2 and 3, as a group the children with dyslexia had relatively low thresholds in the BaWaFT task compared to the BaWaAE task, suggesting that this task was tapping a processing strength. Discrimination data for the basic auditory processing tasks are provided in Table 1, and for the BaWa tasks in Table 2. Regarding the BaWaFT and the BaWaAE conditions, the age-mat-
ched groups (CA and dyslexic, N = 73) were compared using a 2 × 2 (Group × Condition) repeated measures ANOVA. The interaction between Group and Condition was significant, \(F(1, 71) = 25.2, p = .000\). Post-hoc inspection of the interaction (one-way ANOVAs) showed that it arose because the children with dyslexia were significantly poorer at BaWa\AE discrimination than were the CA controls, \(F(1, 72) = 14.4, p = .000\). However, they were significantly better than were the CA controls at the BaWa\FT discrimination, \(F(1, 72) = 9.9, p = .002\) (this comparison remained significant when the Brown-Forsythe test was used to correct for unequal variance in the BaWa\FT task, \(p = .006\)). Second, the reading-level matched children (RL and dyslexic, N = 66, as one RL child had a missing score for the BaWa\AE task) were also compared using a 2 × 2 (Group × Condition) repeated measures ANOVA. The interaction between Group and Condition was again significant, \(F(1, 64) = 25.8, p = .000\). Post-hoc inspection of the interaction (one-way ANOVAs) showed that this time it arose because the children with dyslexia were significantly better at the BaWa\FT discrimination than their reading-matched controls, \(F(1, 65) = 21.4, p = .000\). Again, this comparison remained significant when the Brown-Forsythe test was used to correct for unequal variance in the BaWa\FT task, \(p = .001\). The reading-level matched groups showed equivalent discrimination thresholds for the BaWa\AE discrimination however, \(F(1, 65) = 3.4, p = .068\).

If poorer discrimination of the BaWa\AE stimuli is indeed associated with difficulties in amplitude envelope perception, then individual differences in sensitivity to amplitude envelope shape should predict performance in the BaWa task, but for the BaWa\AE stimuli only. This was investigated for the age-matched children (N = 73) using two-step fixed entry multiple regression equations controlling first for age (step 1) and then IQ (step 2). The third step was the children’s rise time discrimination threshold. Children’s thresholds for the BaWa\AE or BaWa\FT continua were the dependent variables, respectively. Results are shown in Table 3. While rise time processing explained 11% of unique variance in BaWa\AE discrimination \((p = .002)\), it explained no unique variance in BaWa\FT discrimination. In contrast,

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1 There has been some debate in the literature concerning whether it is appropriate to include younger RL-matched children in the analysis of auditory or other sensory data in studies of dyslexic children. For example, on a maturation hypothesis, the appropriate control group for the dyslexics would be the CA controls (see Ramus, White & Frith, 2006, for this argument: ‘a reading age [and therefore younger] control group could only have poorer sensorimotor performance’, p. 266). Alternatively, on a developmental hypothesis, auditory sensory processing skills might also be expected to be affected by being taught to read (see Goswami et al., 2009, for this argument). In the current paper, we adopt a conservative analysis strategy for our sensory data, comparing the children with dyslexia to their CA controls, and using only the age-matched children (dyslexics and CA controls) for the multiple regression analyses. However, as the comparison between the dyslexics and their RL controls is of theoretical interest, we also compare performance in the Ba/Wa tasks between the children with dyslexia and the younger RL controls. If all three groups are compared in one-way ANOVAs, then all Ba/Wa comparisons remain as currently reported, and the RL controls are also significantly poorer than the CA controls for the BaWa\AE stimuli, while showing equivalent performance to the CA controls for the BaWa\FT stimuli. Similarly, if the multiple regressions are run using the entire sample, all significant results remain as reported here, with age additionally contributing significant unique variance in Step 1 in the BaWa\FT analysis shown in Table 3b.
when we explored whether individual differences in sensitivity to frequency were predictive of performance in the BaWaFT task, significant unique variance was accounted for (9.6%, $p = .008$). However, frequency sensitivity was also predictive of performance in the BaWaAE task (here, frequency sensitivity accounted for 7% of unique variance, $p = .018$). Inspection of Table 3 reveals that the standardized Beta coefficient is positive for the BaWaAE task, and negative for the BaWaFT task. Therefore, while children who were more sensitive to frequency performed more successfully with the BaWaAE discrimination, having good frequency discrimination was associated with being less good at following the duration of rising frequency in the BaWaFT task. We consider explanations for this result in the Discussion.

Finally, if difficulties in perceiving phonetic contrasts on the basis of amplitude envelope cues are one cause of the phonological deficit found in developmental dyslexia, then BaWaAE but not BaWaFT should predict significant unique variance in phonological awareness. Two three-step fixed entry multiple regression equations (as above, with Ba/Wa as step 3) confirmed this prediction (Table 3).

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Unique variance ($R^2$ change) in BaWaAE (3a) and BaWaFT (3b) explained by amplitude envelope onset and frequency discrimination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step</td>
<td>Beta</td>
</tr>
<tr>
<td>3a. DV: BaWaAE</td>
<td></td>
</tr>
<tr>
<td>1. Age</td>
<td>−.289</td>
</tr>
<tr>
<td>2. IQ</td>
<td>−.211</td>
</tr>
<tr>
<td>3. Rise</td>
<td>.359</td>
</tr>
<tr>
<td>3. Frequency</td>
<td>.284</td>
</tr>
<tr>
<td>3b. DV: BaWaFT</td>
<td></td>
</tr>
<tr>
<td>1. Age</td>
<td>−.138</td>
</tr>
<tr>
<td>2. IQ</td>
<td>−.117</td>
</tr>
<tr>
<td>3. Rise</td>
<td>.006</td>
</tr>
<tr>
<td>3. Frequency</td>
<td>−.336</td>
</tr>
</tbody>
</table>

**$p < .01$; * $p < .05$. DV = dependent variable; Beta = standardized Beta coefficient; $R^2$ change = unique variance accounted for at each step of the three-step fixed entry multiple regression equations; IQ = WISC IQ short form; Rise = rise time discrimination with intensity roving; Frequency = frequency discrimination.

This study establishes for the first time a mechanism whereby perceptual insensitivity to amplitude modulation can explain the difficulties with some phonetic contrasts experienced by children with developmental dyslexia. Children with dyslexia showed excellent phonetic discrimination when formant transition duration was varied, but impaired phonetic discrimination when rise time was varied. In fact, the children with dyslexia were significantly better at making a phonetic discrimination (Ba/Wa) on the basis of formant transition duration than both age-matched children without developmental dyslexia and younger reading-level matched children. However, they showed significantly poorer phonetic discrimination than expected for their age when the change from Ba to Wa depended primarily on amplitude envelope cues. The analyses showed that they also came close to being poorer at this phonetic discrimination than the younger RL-matched children ($p = .068$). The fact that the two groups equated for

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Unique variance ($R^2$ change) in phonological awareness explained by BaWaAE and BaWaFT (4a) and by frequency and rise time discrimination (4b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step</td>
<td>Beta</td>
</tr>
<tr>
<td>4a. DV: phonological awareness</td>
<td></td>
</tr>
<tr>
<td>1. Age</td>
<td>.301</td>
</tr>
<tr>
<td>2. IQ</td>
<td>.320</td>
</tr>
<tr>
<td>3. BaWaAE</td>
<td>−.343</td>
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<tr>
<td>3. BaWaFT</td>
<td>.118</td>
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<tr>
<td>4b. DV: phonological awareness</td>
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</tr>
<tr>
<td>1. Age</td>
<td>.301</td>
</tr>
<tr>
<td>2. IQ</td>
<td>.320</td>
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<tr>
<td>3. Rise</td>
<td>−.371</td>
</tr>
<tr>
<td>4. Frequency</td>
<td>−.303</td>
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<tr>
<td>3. Frequency</td>
<td>−.361</td>
</tr>
<tr>
<td>4. Rise</td>
<td>−.316</td>
</tr>
</tbody>
</table>

**$p < .01$; * $p < .05$. DV = dependent variable; Beta = standardized Beta coefficient; $R^2$ change = unique variance accounted for at each step of the three- or four-step fixed entry multiple regression equations; IQ = WISC IQ short form; BaWaAE = discrimination in the amplitude envelope version of the BaWa task; BaWaFT = discrimination in the formant transition duration version of the BaWa task.

Discussion

This study establishes for the first time a mechanism whereby perceptual insensitivity to amplitude modulation can explain the difficulties with some phonetic contrasts experienced by children with developmental dyslexia. Children with dyslexia showed excellent phonetic discrimination when formant transition duration was varied, but impaired phonetic discrimination when rise time was varied. In fact, the children with dyslexia were significantly better at making a phonetic discrimination (Ba/Wa) on the basis of formant transition duration than both age-matched children without developmental dyslexia and younger reading-level matched children. However, they showed significantly poorer phonetic discrimination than expected for their age when the change from Ba to Wa depended primarily on amplitude envelope cues. The analyses showed that they also came close to being poorer at this phonetic discrimination than the younger RL-matched children ($p = .068$). The fact that the two groups equated for
reading level (the children with dyslexia and the RL controls) showed equivalent discrimination of Ba from Wa on the basis of rise time suggests that reading development itself may affect the sensory perception of amplitude envelope shape. However, we are still following all the children who participated in this study, and two years after the current test point the children with dyslexia were showing significantly worse discrimination of amplitude envelope rise time compared to their RL control group (mean dyslexic threshold, 1 Rise task = 17.0 (116 ms), mean RL threshold = 7.6 (43.2 ms)). This finding implies that learning to read is only one environmental factor affecting the development of auditory sensory discrimination in children.

These data support the hypothesis that the phonological difficulties characteristic of developmental dyslexia arise from difficulties in perceiving amplitude envelope structure, particularly the rate of change of amplitude envelope onsets (e.g. Goswami et al., 2002; Richardson et al., 2004; Hämäläinen et al., in press). The data do not support the theory that difficulties in perceiving formant transitions explain the phonological difficulties experienced by children with dyslexia (Tallal, 2004). The finding that the children with dyslexia were significantly more sensitive to a phonetic contrast based on formant transition duration than control children suggests that perceiving formant transition durations may be an auditory processing strength for these children (see also Abrams, Nichol, Zecker & Kraus, 2009). Given the multiple and redundant cues to phonetic contrasts in natural speech, children with a processing weakness for rise time may compensate by focusing more on cues like formant transition duration. The data may also suggest that formant transition duration is less critical for discriminating phonemes than classical theories of speech perception had assumed (Blumstein & Stevens, 1981). However, this does not mean that such cues are unimportant. Developmentally, as proposed by Nitttrouer (2006), children may focus their perceptual attention first on the acoustic consequences of the relatively slow vocal tract movements that produce amplitude envelopes. This information would then be supplemented with the other acoustic properties that are relevant to phonetic identity on the basis of linguistic experience. Children with dyslexia, who are less efficient at representing amplitude envelope information, may hence rely more on these other acoustic properties.

Consistent with this explanation, children with dyslexia can be more sensitive to allophonic variation (phonetic variation within phoneme categories) than typically developing children (Serniclaes, Van Heghe, Mousty, Carre & Sprenger-Charolles, 2004, Bogliotti, Serniclaes, Messaoud-Galusì & Sprenger-Charolles, 2008). For example, Bogliotti et al. (2008) reported that French children with dyslexia were weaker in a phoneme categorization task (to-do) based on voice onset time (VOT) than both age-matched typically developing children and younger reading-level matched children. At the same time, they showed a non-phonemic discrimination peak in VOT indicative of phonetic-level perception. This non-phonemic discrimination peak was absent in the typically developing groups. Such phonetic sensitivity may arise from enhanced sensitivity to certain auditory features, in compensation for reduced auditory sensitivity to other features (such as rise time). As Bogliotti et al. (2008) point out, phonetic-level perception would have serious consequences for establishing grapheme–phono-

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who were in general more sensitive to frequency, relied more on their previously categorized templates for Ba and Wa, this could explain the negative association with frequency discrimination. We are currently exploring this possibility with a categorical task. A second explanation could be that our frequency discrimination task measured sensitivity to absolute differences in pitch, whereas discrimination in the BaWaFT task required sensitivity to pitch change across duration. Hence conceptually, the frequency discrimination task was not related to BaWa discrimination as closely as the rise time discrimination task. We are currently exploring this possibility also.

The four-step multiple regression analyses indicated that frequency discrimination and rise time discrimination played relatively independent roles in phonological awareness. Data such as these may indicate that impaired frequency discrimination is an associate rather than a cause of some phonological difficulties (see for example Halliday & Bishop, 2006a). Indeed, Bishop and her colleagues have found that for children with mild-to-moderate sensorineural hearing loss, frequency discrimination dissociates from reading abilities (Halliday & Bishop, 2006b). Similarly, Kraus and colleagues recently reported that reading development in children is related to subcortical encoding of timing and harmonic information, but not of pitch (frequency; see Banai, Hori, Hor, Nicol, Zecker & Kraus, 2009). In our own work, we have found that children with low IQ but preserved reading skills are poorer at frequency discrimination than typically developing children with the same reading levels (Kuppen, Huss, Hosker, Mead & Goswami, in press). Hence for some low IQ children, impaired frequency discrimination skills can accompany good reading skills. In the same study, rise time discrimination was found to be equivalent in these two groups. The finding that sensitivity to rise time was age-appropriate in the low IQ children who were good readers but sensitivity to frequency was not suggests a closer relationship between rise time perception and reading development than between frequency perception and reading development.

With respect to phonological awareness, both rise time discrimination and frequency discrimination were significant predictors of individual differences in the current study. In prior studies contrasting frequency discrimination and rise time discrimination, we have found similar results. For example, Richardson et al. (2004) did not find a processing deficit for children with developmental dyslexia in a rapid frequency discrimination task (based on Tallal and Piercy’s, 1973, same-different judgment task). However, individual differences in both rapid frequency discrimination and in rise time discrimination were significantly associated with rhyme awareness. Similarly, using a different sample of children with dyslexia and different CA- and RL-matched control children, Goswami et al. (2002) reported a significant association between performance in the rapid frequency discrimination task and rhyme awareness, and also a significant association between performance in an amplitude envelope onset task and rhyme awareness. However, when multiple regression equations were used to estimate the amount of variance in reading ability contributed by the two auditory measures after controlling for rhyme awareness, only the amplitude envelope task continued to account for unique variance in reading (9%, after controlling for age, IQ, vocabulary and phonological awareness, which together accounted for 56% of variance in reading). Hence rise time discrimination appears to be associated specifically with phonological development and reading development, whereas frequency discrimination does not.

The latter conclusion is also supported by a recent meta-analysis of studies measuring performance in non-speech auditory processing tasks and associations with reading (Hämäläinen et al., in press). Hämäläinen et al. found that amplitude modulation and rise time discrimination were linked to developmental dyslexia in 100% of the studies that they reviewed, whereas frequency discrimination was linked to developmental dyslexia in 57% of studies. A more systematic analysis of the role of frequency discrimination in phonological development that takes into account task demands may help to clarify the role of individual differences in sensitivity to frequency in developmental language disorders. In particular, it may be important to dissociate the roles of rapid frequency detection vis-a-vis the perception of formant transitions, and overall frequency discrimination abilities vis-a-vis the general development of the child’s auditory system. Neuromuscular representation may be a lower-level process than the representation of amplitude envelope shape, since frequency is represented on the cochlea whereas amplitude envelope rise time is represented in the cortex (see Malone, Scott & Semple, 2007). Malone et al. (2007) recorded from cortical neurons in the awake Rhesus macaque during exposure to slow sinusoidal amplitude modulations (comparable to a continuous form of the stimuli used here) and found that cortical neurons fired to represent envelope shape. However, Malone et al. noted that changes in carrier frequency would be expected to affect these firing patterns, and until representation at the neural level is better understood, it is difficult to interpret differences between studies concerning how frequency versus rise time discrimination are related to phonological and literacy development.

In conclusion, the current study showed that making a phonetic discrimination on the basis of rise time was significantly impaired in children with developmental dyslexia in comparison to age-matched controls, whereas making a phonetic discrimination on the basis of formant transition duration was significantly enhanced in children with developmental dyslexia in comparison to age-matched controls. This suggests that, in principle, the development of phoneme awareness by children with developmental dyslexia is affected by an auditory insensitivity to amplitude envelope rise time. As accurate
processing of the amplitude envelope in the lower frequency regions is critical for speech intelligibility, a difficulty in rise time discrimination may affect the development of the child’s entire phonological system. Whereas difficulties in syllable segmentation and supra-segmental phonology are clearly predicted by a rise time deficit hypothesis (Goswami et al., 2002), the current study shows that the shape of the amplitude modulation for particular syllables also contains information important for phonetic discrimination. Therefore, a rise time deficit can also be expected to affect the development of segmental phonology, and to impair the development of phoneme-level representations as literacy is acquired.

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