# Age-Related Improvements in Auditory Temporal Resolution in Reading-Impaired Children

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Individuals with developmental dyslexia show impairments in processing that require precise timing of sensory events. Here, we show that in a test of auditory temporal acuity (a gap-detection task) children ages 6–9 years with dyslexia exhibited a significant deficit relative to age-matched controls. In contrast, this deficit was not observed in groups of older reading-impaired individuals (ages 10–11 years; 12–13 years) or in adults (ages 23–25 years). It appears, therefore, that early temporal resolution deficits in those with reading impairments may significantly ameliorate over time. However, the occurrence of an early deficit in temporal acuity may be antecedent to other language-related perceptual problems (particularly those related to phonological processing) that persist after the primary deficit has resolved. This result suggests that if remedial interventions targeted at temporal resolution deficits are to be effective, the early detection of the deficit and early application of the remedial programme is especially critical. Copyright © 2003 John Wiley & Sons, Ltd.

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## INTRODUCTION

Approximately 5% of children who are otherwise unimpaired experience a particular difficulty learning to read (developmental dyslexia) (Snowling, 1998). It has been proposed that language impairments in general, including dyslexia, are due to problems in cognitive processing specific to language (Catts, 1989; Vellutino, 1979). The inability to recall or represent basic speech sounds (phonological representations) for example, leads to later difficulties with grapheme to phoneme conversion and other verbal skills

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(Bradley and Bryant, 1983). Other researchers, however, contend that language and reading impairments are due to more fundamental difficulties in temporal processing that may be a potential diagnostic marker for language disorders (Lovegrove *et al.*, 1990; Stein, 1994; Tallal *et al.*, 1996; Wright *et al.*, 1997). Developmental impairments in reading and language have therefore been regarded as the result of a fundamental deficit in the perception and integration of rapidly changing non-verbal stimuli. Tallal (1980) was one of the first investigators to report a significant correlation between performance on a tonal-order task and a test of phonics skills (reading nonsense syllables). She found that individuals with dyslexia had difficulty in perceiving the order of tones only when the tones were separated by time intervals of less than 305 ms, and suggested that some dyslexics may suffer from a 'rate processing disorder' that impairs their ability to hear rapidly occurring acoustic changes. Temporal processing deficits in reading-disordered individuals have more recently been demonstrated in both the visual and the auditory domains (Williams and Lecluyse, 1990; Farmer and Klein, 1993, 1995; McAnally and Stein, 1996; McAnally, Castles and Stuart, 2000; Habib, 2000).

As reviewed by Habib (2000), those that support the temporal processing theory do not dispute that language impairments are due to phonological deficits. Rather, they argue that phonological problems are caused by a more basic deficiency in hearing sounds, resulting in an inability to employ grapheme to phoneme correspondence rules rapidly enough to achieve reading fluency.

A causal relationship between auditory temporal processing of non-verbal stimuli and reading competency has been questioned, however. Results from populations with specific reading problems have been inconsistent (e.g. Tallal and Stark, 1982; Watson, 1991; Watson and Miller, 1993), leading some to argue that poor auditory temporal processing ability is not a necessary underlying mechanism in dyslexia, accounting for only 25–35% of the dyslexic population (Rosen and Manganari, 2001). Stark *et al.* (1988) suggested that poor auditory temporal processing might not be related to dyslexia but rather to dysphasia, which frequently coexists with reading disability. Differences on non-verbal tasks between groups of dyslexic and control children have also been proposed to be due to a developmental or maturational lag in auditory temporal processing (Marshall *et al.*, 2001; Norrelgen *et al.*, 2001).

In order to better understand the extent to which an auditory temporal processing deficit can be regarded as a marker for dyslexia, we investigated the age-related development of auditory temporal acuity in 24 dyslexic and 50 age-matched non-impaired readers. Each group was divided into five subgroups based on age (6–7, 8–9, 10–11, 12–13 years, and adults) and a gap-detection task was employed to gauge temporal acuity. This is perhaps the most fundamental test of temporal acuity (Irwin *et al.*, 1985), and requires the subject to determine the presence or absence of a short gap in a burst of Gaussian noise. Thresholds of acuity are determined by measuring the shortest gap in the noise that can accurately be detected. All children (dyslexic, non-dyslexic) in the final sample were with average or above intelligence—an important consideration when testing hypotheses regarding temporal processing, as studies have shown significant positive correlations between intelligence and performance on a range of auditory temporal processing tasks (Raz *et al.*, 1987; Watson, 1991).

## METHOD

### Participants

Children with dyslexia ($n = 18$; 10 males, 8 females) were recruited from Reading Recovery programmes in four primary schools in Auckland, New Zealand. Teachers from these schools were also asked to recommend non-impaired readers from regular classes to act as control participants ($n = 44$; 26 males, 18 females).

Principals and instructors at the primary schools were asked to recommend potential participants on the basis of the following criteria: English as a first language, no obvious behavioural, emotional or neurological problems (according to teacher and parental report where applicable), normal receptive and expressive language, and normal or corrected-to-normal vision. The first author assessed peripheral hearing ability by using a Bruel and Kjaer automatic audiometer (model—1800). No participants had hearing loss in excess of 15 dB (with reference to ISO standards) at any of the six frequencies tested between 500 Hz and 8 kHz. The second author administered the Wechsler Intelligence Scale for Children-Revised (WISC-R Revision III, prorated vocabulary, information, picture completion, and block design subscales) to *all* children in the study.

Children were identified as dyslexic if they obtained a reading score that was at least 1 S.D. below the National norms on the Burt Reading Test-Revised (BWRT-R; New Zealand Council for Research in Education, 1981). Standardized scores on this word recognition test did not differ according to age-group, $F(3,14) = 1.68$, $p = 0.22$. The BWRT-R resembles the American Wide Range Achievement Test of reading and consists of 110 words graded in order of difficulty from simple (e.g. to, is, big, some, etc.) to difficult (e.g. autobiography, microscopical, subtlety). The BWRT-R is a consistent reading measure, with test-retest reliability coefficients ranging from 0.95 to 0.99 and internal consistency coefficients ranging from 0.96 to 0.97 (New Zealand Council for Research in Education, 1981). Presented in Table 1 are the descriptive statistics for the children with dyslexia in the final sample of 18 according to chronological age group (6&7, 8&9, 10&11, 12&13 years).

As shown in the table, reading age (determined with the BWRT-R) was at least 2 years below their chronological age. All dyslexic children had particular problems processing phonological information according to teacher report, but non-word reading was not specifically tested.

Adults with dyslexia ($n = 6$, mean age = 25.38, S.D. = 3.52; males = 3) were undergraduate students at the University of Auckland and were selected based

Table 1. Mean (standard deviation in parentheses) chronological age (CA), reading age (RA), standardized reading score, and full-scale IQ scores (Wechsler Intelligence Scale for Children-Revised) for children with developmental dyslexia according to age group (6&7, 8&9, 10&11, 12&13 years).

| | CA | RA | Reading Score | Full IQ | Sample size |
|---|---|---|---|---|---|
| Ages 6&7 | 6.05 (0.79) | 4.00 (0.82) | −2.13 (.061) | 106.50 (1.29) | 4 |
| Ages 8&9 | 8.22 (0.39) | 6.03 (0.03) | −1.84 (.169) | 106.00 (12.99) | 6 |
| Ages 10&11 | 10.55 (0.62) | 8.38 (0.48) | −1.96 (.481) | 103.25 (11.56) | 4 |
| Ages 12&13 | 12.04 (0.02) | 9.68 (0.33) | −1.69 (.333) | 95.00 (3.74) | 4 |

on recommendations by the Director of the University of Auckland Learning Assessment Centre following cognitive and neuropsychological assessment by a clinical psychologist (diagnostic data not available). Control adults ($n=6$, mean age = 28.38, S.D. = 4.14; males = 3) were recruited from the University of Auckland. IQ tests were not administered to the control adults but all had obtained a Bachelors degree.

Ethical approval was received for this study by the University of Auckland Human Ethics Committee. Parental (where applicable) and subject consent was obtained after the purpose and procedures of the study were explained.

### Stimuli and Procedure

Temporal acuity was gauged by estimating the gap-detection threshold of a brief cessation in a burst of Gaussian noise using a maximum-likelihood version of the yes/no method. The threshold was defined as the gap duration yielding 60% 'yes' responses (Green, 1993). The low centre frequency (500 Hz), and low intensity (50 dB SPL) of the octave band of Gaussian noise were selected to make the task demanding. Gap-detection thresholds are inversely related to both the centre frequency of octave bands of noise, and to their level (Irwin *et al.*, 1985). Five threshold estimates were obtained from each subject, and the median of these estimates was taken as the threshold duration.

The Gausian noise stimuli were produced with an analogue broad-band random noise generator (General Radio—model 1381) and then band-pass filtered (Krohn-Hite—model 3550) with half-power cut-offs at 353 and 707 Hz, and centre frequency of 500 Hz. The sound pressure level of the filtered noise was 50 dB. The filtered noise was then gated with an electronic switch (Tucker-Davis—model SW1) using a Hanning window with a 1-ms rise and fall. Stimulus duration was fixed at 500 ms. When required, temporal gaps were introduced into the noise using the same window characteristics. Gap durations were measured from the offset to the onset of the stimulus and, temporally, the centre of the gap coincided with the centre of the stimulus; that is, the centre of the gap occurred 250 ms after the initial onset of the stimulus. A 40-dB SPL broadband noise (Hewlett Packard—model 8904A), that was low-pass filtered by the characteristics of the earphone, was continuously present to mask any frequency side-lobes that arose as a consequence of the short-duration ramps. The stimuli were presented monaurally to the right ear of the subject via a cushioned earphone (Grason-Stadler—model TDH-49). The subject was seated in a sound-attenuating chamber (Amplaid—model E).

### Procedure

Prior to the collection of threshold measurements, subjects (tested individually) were familiarized with the sound-attenuating chamber, the headset, and the response panel. Several practice trials of the gap-detection task were conducted in which either the stimulus (500-ms Gaussian noise burst) was continuous (with no gap) or it contained a large gap (200 ms). Subjects were required to demonstrate an understanding of the task by providing correct responses to the practice trials before data collection began. Then, for each subject, the

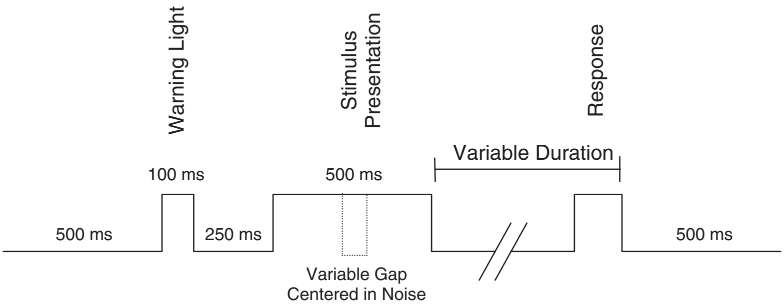

Figure 1. The sequence of events that occurred within a single trial in the auditory gap-detection task.

duration of the gap in the noise burst was systematically adjusted using the maximum likelihood procedure to find the gap-detection threshold.

An experimental session consisted of a sequence of 24 trials and each subject undertook five sessions. The number of trials employed was chosen to provide stable estimates of the gap-detection threshold on the one hand, and to provide an experimental session of sufficiently short duration to reduce the likelihood of participants becoming bored, inattentive, or fatigued. Each trial commenced with the 100-ms illumination of a 'warning' LED followed by a pause of 250 ms. (See Figure 1 for information on trial structure.) The stimulus was then presented concurrently with the illumination of an LED. Subjects were required to respond 'yes' if they heard a gap in the stimulus, or 'no' if they did not hear a gap. They took whatever time necessary to register their response on a button box. The next trial commenced after a 1000-ms pause. Trial-by-trial feedback was not provided. Subjects were provided rest and refreshments between each session, all of which were completed on a single day.

## RESULTS

The results of an age-group (5) by experimental-group (2) ANOVA, presented in Figure 2, revealed that the thresholds obtained for the five age groups were significantly different ($F(4,64)=10.4$, $p<0.001$). In addition, the thresholds for the reading- and non-reading-impaired participants were significantly different ($F(1,64)=17.0$, $p<0.001$). Of particular interest, however, was a significant interaction between age and reading group (reading vs non-reading-impaired) ($F(4,64)=3.09$, $p<0.05$). Analysis of simple effects (with *Bonferroni* adjustments) revealed that dyslexic children had significantly higher gap-detection thresholds than control subjects in the two younger age groups ($p<0.05$), but not in the three older age groups ($p>0.05$).

## DISCUSSION

Skilled reading and language acquisition draws upon the ability of the nervous system to time sensory events precisely. Theoretically then, if there is a failure in

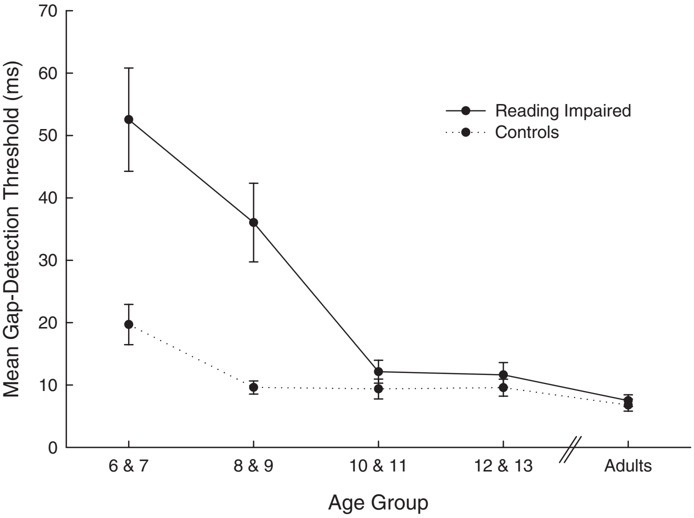

Figure 2. Mean auditory gap-detection thresholds by age-group for reading-impaired and age matched control groups (95% confidence intervals shown).

this underlying mechanism, the basic linguistic systems will function at a slower rate, and the rapidity that should develop in reading subprocesses such as phonological encoding will be impeded.

The gap-detection task, generally considered a purely temporal measure (Irwin *et al.*, 1985; Protopapas *et al.*, 2002), was employed in the present study to measure gap-detection thresholds in reading-impaired and non-impaired children and adults who were segregated into 5 age groups. Temporal acuity has been previously shown to improve significantly with age (Irwin *et al.*, 1985; Davis and McCroskey, 1980).

The findings from the present study showed that young reading-impaired children (aged 6–9 years) have significantly poorer acuity than age-matched controls (higher gap-detection thresholds). Further, this deficit was not observed in the older groups with dyslexia. That is, there was no significant difference in gap-detection thresholds between age-matched controls and the 10 and 11 year old dyslexic children, the 12 and 13 year old dyslexic children, or dyslexic adults. This suggests that there is a maturational lag in the development of temporal acuity in children with dyslexia, but that this lag is resolved by about age 10.

The possibility that the apparent improvement in temporal acuity with age (or, in the current study, differences in temporal acuity between reading groups) may be due to changes in decision criteria rather than in auditory process differences has been raised previously (Davis and McCroskey, 1980). However, as noted by Irwin *et al.* (1985), the use of a criterion-free psychophysical procedure, as in the present study, means that acuity differences can be attributed to auditory processing differences and not to systematic changes in response criterion.

Several previous studies have failed to find differences in auditory gap-detection thresholds between dyslexic adults and controls (McAnally and Stein, 1996; Protopapas *et al.*, 2002; Schulte-Korne *et al.*, 1998). The results from the adult and older child groups in the current study are in accord with this. The earlier studies did however find differences in a number of other more complex tasks that are dependent on good temporal and frequency resolution. This is consistent with proposals that individuals with language impairments have a general difficulty with sequencing and segmenting serial streams of auditory information (Bradley and Bryant, 1978; Krause *et al*., 1996) as well as quickly changing information in the visual modality (Borsting, 1996; Farmer & Klein, 1995; Lovegrove, 1993). Further, a recent study has shown that auditory FM sensitivity and visual motion sensitivity predict, respectively, phonological and orthographic ability (Talcott *et al*., 2000).

We propose here that a deficit in processing that results in higher thresholds in simple auditory gap detection, as seen in young dyslexic children in the present study, is antecedent to deficits in higher-level resolution and sequencing of spectral components in older dyslexic children and adults. The deficits in the auditory coding of spectral information are particularly related to deficits in phonological processing that have repeatedly been suggested to underlie developmental language and reading disorders. It is possible that a deficit in auditory gap detection represents a maturational lag that subsequently resolves, but that before doing so results in a deficit in phonological processing that does not.

It has been suggested that the temporal processing employed in tasks that involve phonological discrimination (judging the relative timing of the spectrally dissimilar auditory bursts composing a consonant and a subsequent vowel, for example) is fundamentally different from the sort of task employed here (Phillips *et al*., 1997; Zhang *et al*., 1990). Our within-channel gap-detection task involves a stimulus that is spectrally similar on either side of the gap. In this case, the neural correlate of gap detection may be seen as a discontinuity in the discharge of single cochlear nerve cells (Zhang *et al*., 1990). The between-channel gap-detection task, on the other hand, involves a stimulus that is spectrally dissimilar on either side of the gap. Phillips *et al*. (1997) suggest that the temporal processing in between-channel gap detection may require a 'central' representation of the stimulus. This is because, although the cochlear array as a whole contains the information for relative timing operations, the absence of lateral connections between cochlear output fibres means that the machinery for the operations must exist elsewhere.

It should be noted, that while temporal processing in a between-channel gap-detection task can only take place centrally, it is not necessary that the cause of elevated thresholds in a within-channel task is peripheral. Elevated thresholds for within-channel gap detection may be caused by either peripheral or central deficits. The link, if any, between deficits in between- and within-channel auditory tasks must be explored more fully. It should also be stressed that the small sample size in the present study makes it necessary for the findings to be replicated with larger samples in order to generalize to the general dyslexic population.

If poor performance at auditory gap detection proves to be a reliable marker of later phonological deficits and developmental dyslexia, gap detection may provide a fast, simple, and early screening tool. An estimate of the gap-detection threshold can be found in 50 trials in less than 5 min. Thus, although significant advances have been made in perceptual training for remediation of language and reading disorders (Krause *et al*., 1996; Merzenich, 1996; Tallal *et al*., 1996), earlier screening and targeting of sensory deficits may lead to the even greater success of these programmes.

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