Patterns of deficit in auditory temporal processing among dyslexic adults

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We characterized temporal psychoacoustic performance in a group of adult dyslexics with excellent cognitive abilities. These individuals performed adequately on a two-tone frequency discrimination task when inter-stimulus intervals were long (≥ 1 s or more). However, their performance gradually deteriorated as interval duration was shortened (0.7–0.1s). Dyslexics with similar reading abilities, but with average cognitive abilities, performed poorly at all intervals. These findings show that, though both

groups suffer from non-phonological deficits in auditory discrimination, the nature of their deficits differs. Dyslexics with excellent cognitive abilities seem to have slow, yet adequate, stimulus identification and comparison mechanisms. The fundamental impairment of the other dyslexic group is difficult to determine because their performance was poor across all intervals. *NeuroReport* 15:627–631 © 2004 Lippincott Williams & Wilkins.

Key words: Auditory processing; Dyslexia; Frequency discrimination; Inter-stimulus interval; Sluggish attention; Temporal processing

INTRODUCTION

Developmental dyslexia is a specific reading disability affecting 5–10% of the population, in which proficient reading skills are not acquired despite sufficient cognitive abilities and education. Although it is commonly accepted that the majority of dyslexics have impaired phonological awareness [1], dyslexia is a heterogeneous disorder. Dyslexic individuals vary in types of reading errors, presence of other developmental disorders (e.g. language delay [2]) and the extent of perceptual difficulties [3]. Perceptual deficits in dyslexia have been found on both visual [4] and auditory [5–7] tasks. The relationship between perceptual deficits and subtypes of dyslexia is still an open question.

A prominent perceptual theory proposes that dyslexics suffer from a fundamental deficit in processing rapidly presented brief signals. This theory is based on Tallal's [8] finding that reading-disabled children had a difficulty in judging the temporal order of complex tones when separated by short intervals. Since this difficulty was highly correlated with decoding ability (reading non-words), Tallal suggested that impaired acoustic processing leads to inadequate perception of brief phonemes, which degrades phonological awareness and impedes reading acquisition. According to this theory, dyslexics should have difficulties in auditory processing whenever stimuli appear in fast succession, but not when presentation rate is slower or stimuli are longer. There is substantial evidence for dyslexics' impaired performance with brief stimuli (see [6,9] for reviews); however deficits with longer stimuli were also reported [5–7,9]. For example, in frequency discrimina-

tion tasks, using a variety of procedures, significantly higher thresholds were found in disabled compared with age-matched normal readers [4,5,7,10]. Ahissar *et al.* [5] measured two-tone frequency discrimination with both temporal order judgments of brief tones and intervals, and same/different judgments of longer tones and intervals. Under both procedures frequency discrimination was impaired among disabled readers and thresholds were similarly correlated with decoding abilities.

Frequency discrimination findings vary extensively. Although many studies found poorer performance in dyslexics than in normal readers [4,7,10], others did not [11]. Two inter-study differences may underlie this variance. First, studies vary in the experimental design used, such as tone duration, inter-stimulus interval (ISI) and behavioral paradigm, which could affect dyslexics' relative difficulties. Second, studies vary in their recruitment procedure, which affects the heterogeneity of the dyslexic group and potentially their perceptual discrimination abilities.

Although dyslexics form a highly heterogeneous population, the relevant subtyping to groups differing in their etiology of reading deficits is still debated. One classification to subtypes is based on patterns of reading and spelling difficulties. However, it is difficult to divide dyslexics to those with and without phonetic deficits, since most have both [1]. Another classification is based on co-morbidity of reading difficulties with other learning disorders, such as an oral language delay [12]. Indeed, several studies suggested that temporal processing deficits are found only among dyslexics with concomitant language disorders [12]. These

classifications are not independent of general cognitive abilities, since dyslexics with language difficulties and also had lower cognitive scores (e.g. verbal IQ of dyslexics with oral language delay was 88.3 [12], lower than that of other subtypes). Consistent with associating lower cognitive abilities with poorer perceptual performance, Banai and Ahissar [13] found that a subgroup of adult dyslexics characterized by poor frequency discrimination (measured with an ISI of ~ 1 s) also scored poorly on a standard cognitive test (Raven's Matrices [14]). This subgroup had particularly poor working memory, probably underlying their more pervasive learning disability. Taken together, these studies suggest that cognitive-based divisions concur with different patterns of performance on simple psychophysical tasks. Differences in psychophysical performance may reflect differences in the etiologies underlying reading deficits of dyslexic individuals with different cognitive abilities.

In the present study, we compared the psychoacoustic performance of dyslexics with excellent cognitive abilities to that of controls with similar cognitive abilities and of dyslexics with similar reading skills and average cognitive abilities. Based on previous findings [13], we expected that at long ISIs (~ 1 s) dyslexics with average cognitive abilities would perform poorly, while dyslexics with excellent cognitive abilities would perform similarly to controls. The novelty of the current study was in examining whether these dyslexic groups were affected differently by decreasing the interval available for stimulus identification. We dissociated time interval from level of difficulty by measuring frequency discrimination thresholds for several ISIs separately. Thus, in each assessment, frequency difference (rather than time interval) was the adaptive measure while ISI was fixed.

MATERIALS AND METHODS

Participants: Fifty-eight adult native Hebrew speakers participated in this study, 34 dyslexic (20 females and 14 males, age 21.5 ± 3.0 years) and 24 normal readers (16 females and 8 males, age 21.4 ± 3.6 years). Dyslexics were recruited through advertisements at the university and by referrals from clinicians. All had a documented history of reading disability and current non-word reading score (a composite z-score of reading rate and accuracy) ≥ 1 s.d. below the control group's average. Thus, the poorest reader among controls and the best reader among dyslexics had the same non-word reading score (i.e. almost no-overlap between reading abilities). Controls were matched to dyslexic participants on age and education, and none had a history of reading difficulties. All participants had scaled scores of ≥ 8 on both Similarities and Block Design subtests of WAIS-III [15], Hebrew version; they had normal hearing level in the range of frequencies tested, gave informed consent and were paid for participation.

Cognitive, reading-related and attention tests: We administered three subtests of WAIS-III [15]: Similarities (verbal reasoning), Block Design (non-verbal visual spatial reasoning) and Digit Span (verbal span and working memory); and Raven's Matrices reasoning test [14]. Rate and accuracy of phonological decoding were assessed with single non-words written with diacritics (shallow orthography). Read-

ing rate was also assessed for an academic level passage written without diacritics (deep orthography, for a description of Hebrew orthography see [4]). Other tests included: single word reading, spelling, speed of naming letters and numbers (RAN [16]; 30 dyslexic, 22 control) and phonological awareness (Spoonerism task). For a description of these tests see [4,17]. Visual attention was assessed using CPT-II ([18]; 24 dyslexic, 11 control), which indicates confidence in an ADHD classification.

Cognitive-based groups: All participants were high-school graduates with average or above cognitive abilities, as assessed by Similarities and Block Design subtests of WAIS-III (Table 1). However, in Raven's Matrices test dyslexics scored significantly worse than controls (mean $\pm$ s.d. 52.1 ± 5.5 vs 56.3 ± 2.6 correct out of 60; two-tailed t -test, $t(49.9)=3.9$, $p<0.01$). This test seems to pose specific difficulties for some dyslexics, perhaps because it implicitly requires adequate verbal working memory (Banai and Ahissar, submitted). Since performance on Raven's Matrices is a good predictor of academic achievements [14], we used a stringent performance criterion in this test to form groups differing in cognitive abilities. Individuals with above average performance (9 errors) were classified as excellent whereas others were classified as average (since only their performance on WAIS-III subtests was at least average). This criterion divided our participants to three groups: 24 C-excellent (C, control), 20 D-excellent (D, dyslexic) and 14 D-average. The C-excellent and D-excellent groups were carefully matched for general cognitive abilities, whereas D-average and D-excellent were matched for reading abilities (Table 1). We could not find a cognitive match for D-average participants (also among the additional 50 controls tested on Raven's Matrices, of whom only two had more than 9 errors), probably because their particularly poor verbal working memory (see Digit Span in Table 1) impedes their performance.

Stimuli and experimental design: Participants performed a 2-tone frequency discrimination task, indicating which interval contained the higher tone in a 2-alternative temporal forced choice paradigm. Two 50 ms (including

Table 1. Cognitive and reading abilities (mean $\pm$ s.d.).

	C-excellent	D-excellent	D-average
Age (years)	21.4 ± 3.6	22.8 ± 2.6	$19.6 \pm 2.7^*$
Cognitive tests:			
Block design (scaled score)	12.8 ± 2.8	12.8 ± 2.9	$10.8 \pm 2.1^*$
Similarities (scaled score)	13.8 ± 2.3	13.7 ± 1.9	12.7 ± 2.8
Digit span (scaled score)	10.4 ± 2.5	9.0 ± 2.2	$6.6 \pm 2.0^{**}$
Raven (no. errors)	3.7 ± 2.6	4.4 ± 1.8	$13.0 \pm 5.1^{**}$
Reading-related tests:			
Non-word (% correct)	$89.5 \pm 6.6^{**}$	60.4 ± 17.5	55.0 ± 13.6
Word (% correct)	$98.5 \pm 2.1^{**}$	85.3 ± 9.5	83.4 ± 9.5
Passage reading (words/min)	$130 \pm 17.6^{**}$	89 ± 23.7	81 ± 21.5
Spelling (% correct)	$98.9 \pm 3.5^{**}$	81.9 ± 15.9	$66.7 \pm 25.9^*$
RAN-letters (letters/s)	$2.5 \pm 0.4^*$	2.2 ± 0.5	1.9 ± 0.3
RAN-numbers (numbers/s)	$2.9 \pm 0.4^*$	2.5 ± 0.5	$2.1 \pm 0.4^*$
Spoonerism (% correct)	$92.5 \pm 7.7^{**}$	71.0 ± 24.4	61.8 ± 24.9
ADHD confidence index (%)	$30.9 \pm 16.5^{**}$	46.2 ± 11.7	43.7 ± 18.5

Significant differences (two-tailed t -test) between: D-excellent and C-excellent, D-excellent and D-average, are noted respectively on C-excellent and D-average columns. $^*p<0.05$. $^{**}p<0.01$.

5 ms rise and fall times, cosine-squared) 70 dB SPL pure tones were presented in each trial: a fixed 1 kHz reference tone and a test tone, which changed in a 2 down/1 up staircase manner. The test frequency changed adaptively from 1.4 kHz, using an initial step size of 30 Hz, reduced to 5 Hz after three reversals. An assessment was terminated when either 13 reversals or 70 trials elapsed. Discrimination threshold, Just Noticeable Difference (JND, as a percentage of reference frequency), was determined as the arithmetic mean of the last seven reversals. Negative visual feedback was given for each incorrect response.

Frequency discrimination was assessed for each ISI separately, in blocks, in the following order: 1, 1, 0.7, 0.5, 0.2, 0.1 s; 15 min break; 1, 2 s. In each block, a 10-trial training stage preceded data collection during which test frequency changed adaptively from 1.6 kHz, with an initial step size of 35 Hz. Testing began if $\geq 8/10$ trials were correct. Otherwise, an additional 10-trial training commenced until criterion was attained. Most participants reached the criterion score in the 1st training set.

Apparatus: Frequency discrimination was measured in a sound-attenuating chamber, using a TDT System II (Tucker-Davis Technologies) signal generator. Auditory stimuli were presented diotically through Sennheiser HD-265 linear headphones and participants responded using a response box (TDT System II).

RESULTS

Frequency discrimination: Average frequency discrimination thresholds at a range of ISIs (0.1–2 s) are shown in Fig. 1a for D-excellent, C-excellent and D-average groups. Previous studies typically measured dyslexics' JNDs with intermediate-long intervals (~ 1 s), either finding [5] or not finding [11] deficits. We now replicated these findings for 1 and 2 s ISIs, but in different dyslexic groups. D-excellent's JNDs for 1 and 2 s ISIs (respectively, $3.8 \pm 1.0\%$ and $3.4 \pm 0.7\%$) were similar to those of C-excellent (respectively, $2.2 \pm 0.5\%$ and $2.1 \pm 0.5\%$), and significantly lower than those of D-average (respectively, $16.6 \pm 4.8\%$, $t(14.1) = -2.6$, $p < 0.05$; and $15.4 \pm 5.2\%$, $t(13.5) = -2.3$, $p < 0.05$), consistent with previous findings by Banai and Ahissar [13].

As ISI was shortened (from 1 to 0.1 s), however, the thresholds of the D-excellent group gradually increased. A repeated-measures 2-way ANOVA between D-excellent and C-excellent showed significant main effects of group ($F(1,38) = 14.9$, $p < 0.01$), ISI ($F(5,190) = 7.4$, $p < 0.01$) and an interaction between group and ISI ($F(5,190) = 4.4$, $p < 0.01$). A repeated-measures 2-way ANOVA between the D-excellent and D-average groups showed similar significant main effects of group ($F(1,29) = 5.1$, $p < 0.05$) and an interaction between group and ISI ($F(5,145) = 2.9$, $p = 0.016$). As shown in Fig. 1a, at the longest ISI (2 s) D-excellent performed as good as C-excellent, whereas at the shortest ISI (0.1 s) D-excellent were as poor as D-average.

The inter-group differences are also evident at the single subject level. Figure 1b shows the (log) ratio between JNDs at the intermediate (1 s) and the shortest (0.1 s) ISI for each individual in the C-excellent (left), D-excellent (middle) and D-average (right) groups. Almost half of the D-excellent individuals had log ratios > 0.5 compared to only one participant in the C-excellent group and none in the D-average group. The mean (log) ratio of the D-excellent group (0.53 ± 0.54) was significantly higher than that of C-excellent (0.03 ± 0.32 ; $t(27.1) = -3.6$, $p < 0.001$) and of D-average (0.06 ± 0.34 ; $t(32) = -3.6$, $p = 0.001$).

Frequency discrimination, cognitive and reading-related abilities: Frequency discrimination among D-excellent individuals greatly depended on ISI. We thus asked which of their thresholds, if any, was correlated with reading measures. Analyzing their Spearman correlation matrix, we found that JNDs at 0.7 s ISI (the longest ISI for which a significant inter-group difference was found; see Fig. 1a) were significantly correlated with scores in several tests. Particularly high was the correlation with Digit Span ($r_s = 0.73$, $p < 0.01$; Fig. 2a). A significant correlation was also found with passage ($r_s = 0.54$, $p = 0.015$; Fig. 2b), word and non-word reading rates ($r_s = 0.59$, $p < 0.01$ and $r_s = 0.54$, $p < 0.05$, respectively). Rate related characterizations were consistently more highly correlated with frequency JNDs than accuracy parameters. Similarly, accuracy in the phonological awareness task was not significantly correlated with thresholds at 0.7 s ISI ($r_s = 0.32$), whereas the duration required to complete this task was significantly correlated with JNDs at this interval ($r_s = 0.76$; $p < 0.01$).

Fig. 1. (a) Frequency discrimination thresholds as a function of ISI. Mean JNDs ($\pm$ s.e.m.) are shown for C-excellent (empty squares), D-excellent (filled circles) and D-average (empty circles) groups. (b) Individual (log) ratios between JNDs at intermediate (1 s) and short (0.1 s) ISIs. Log ratios of 0 indicate that JNDs are the same in both ISIs. Positive log ratios indicate that JNDs are higher (poorer) at the short ISI.

Fig. 2. Spearman correlations for D-excellent between frequency JNDs (0.7s ISI) and (a) Digit Span, (b) passage reading rate. Higher ranks denote lower JNDs, longer spans and faster reading.

To summarize, D-excellent participants with higher JNDs at intermediate ISIs (0.5–0.7s) also had poorer verbal memory and slower reading rates. In contrast, accuracy in performing the phonological awareness task was not correlated with JNDs measured at any of these intervals.

DISCUSSION

Dyslexics with excellent cognitive abilities could adequately compare the frequency of two sequentially presented brief tones, but only when the interval between these tones was sufficiently long (>1 s). A deficit in comparing two stimuli given a short interval was observed in about half of the dyslexic participants in this group. Dyslexics with average cognitive abilities had difficulties in such comparisons across all ISIs tested (0.1–2 s).

Relationship with previous findings: Our findings are consistent both with studies that found impaired frequency discrimination in dyslexics compared to age-matched controls [4,5,7,10] and with studies that did not find such impairments [11]. We found that the presence or absence of discrimination difficulties depend on both the ISI between subsequent stimuli and the cognitive profile of the dyslexic individuals assessed.

In our study, both dyslexic groups had high JNDs at intervals <1 s. Previous studies found elevated frequency JNDs for a similar range of interval durations (from 0.2 s to 1 s). Even the original findings of temporal order deficits in dyslexia were for intervals up to 0.3–0.5 s [8]. Hill *et al.* [11], however, found no deficit even though they used relatively short intervals (<1 s). However, since their design included longer stimuli (≥ 0.25 s), which increase the interval from stimulus onset, and their participants' cognitive measures were similar to those of our D-excellent group, their results are consistent with ours. An additional difference, which may be relevant, lies in the behavioral protocol. In our study participants had to assess the direction of change, judging which tone was higher, whereas other studies required only repetition identification [10]. Identifying direction of change may involve higher processing levels [19], which are perhaps not challenged in repetition detection tasks.

Longer attentional dwell time or elevated backward masking? The difficulty experienced by D-excellent indi-

viduals when required to identify and compare two tones separated by short ISIs, resembled previous reports of abnormal auditory and visual performance in dyslexia with short ISIs [9]. For example, adult dyslexics experience a segregation of alternating high-low tones to two parallel streams (pitch streaming) at longer ISIs than normal readers [9]. One interpretation that could account for the deficit underlying the difficulties the D-excellent group experiences with short ISIs was proposed by Hari and Renvall [9]. They suggested that dyslexics suffer from sluggish shifting of auditory attention between frequency channels (sluggish attentional shift hypothesis). This interpretation is consistent with our finding that the performance of D-excellent improved with long ISIs. It does not, however, account for the deficit of the D-average group, which was not amended by increasing ISI.

An alternative bottom-up interpretation, which also predicts poor performance with brief intervals and improved performance with longer intervals, is increased susceptibility to inter-stimulus masking. For example, a recent mismatch negativity (MMN) study reported elevated masking in dyslexic adults when tones were presented with ~ 10 ms ISIs [20]. In our study, D-excellent participants experienced difficulties at intervals as long as 500–700 ms. Thus, while dyslexics may have elevated backward masking effects at time scales of tens of milliseconds, such effects were not assessed in our study and do not seem to explain our findings. When MMN was assessed for a frequency oddball with ISIs in the range of several hundred milliseconds, results were mixed (compare [21] with [22,23]). Taken together, the deficit of the D-excellent group seems to be consistent with the sluggish attentional shift interpretation.

The relevance to reading disability: JNDs for intermediate ISIs were highly correlated with several reading-related measures among D-excellent. Particularly high correlations were found for measures of verbal memory and for reading rate. These correlations suggest that perhaps D-excellent have longer time constants for shifting processing mechanisms from one stimulus to the other, whether presentation is visual (written text) or auditory (digit span). An interesting prediction of this hypothesis is that with longer ISIs the verbal memory ability of the D-excellent group would not be impaired.

Determining the relation between dyslexics' attentional shifting deficit and their phonological deficit is difficult. On the one hand, accuracy in the phonological awareness test was not correlated with any discrimination threshold. This suggests independent sources for these deficits, consistent with the double deficit hypothesis [24] that points to two independent core deficits in dyslexia. One, underlying impaired phonological awareness and affecting mainly accuracy of decoding, and the other related to retrieval (or encoding) rate, affecting naming and reading speed. According to this hypothesis, sluggish attention tapped by this study underlies dyslexics' slower rates in many tasks but not their specific phonological deficit. Alternatively, the slower shifts of attention in the D-excellent group may also impede their within-stimulus segmentation, consequently contributing to their core phonological deficit. According to this interpretation, the reason we did not find correlations with accuracy scores is that these very competent individuals trade accuracy for time. Thus, a better parameter to tap D-excellent's phonological deficits may be the duration it took them to perform the phonological awareness task, which was indeed highly correlated with frequency JNDs.

CONCLUSION

Dyslexics with excellent cognitive abilities performed 2-tone frequency discrimination poorly when given short ISIs. This deficit may stem from slower attentional shifts from one incoming stimulus to another, which perhaps also underlie their slower reading rate and somewhat poorer memory span. Though dyslexics with average cognitive abilities also had poor frequency discrimination at short intervals, their discrimination was not improved by increasing ISI. Thus, slower attentional mechanisms cannot explain the deficit of this dyslexic group.

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