



# Delayed detection of tonal targets in background noise in dyslexia

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## Abstract

Individuals with developmental dyslexia are often impaired in their ability to process certain linguistic and even basic non-linguistic auditory signals. Recent investigations report conflicting findings regarding impaired low-level binaural detection mechanisms associated with dyslexia. Binaural impairment has been hypothesized to stem from a general low-level processing disorder for temporally fine sensory stimuli. Here we use a new behavioral paradigm to address this issue. We compared the response times of dyslexic listeners and their matched controls in a tone-in-noise detection task. The tonal signals were either Huggins Pitch (HP), a stimulus requiring binaural processing to elicit a pitch percept, or a pure tone—perceptually similar but physically very different signals. The results showed no difference between the two groups specific to the processing of HP and thus no evidence for a binaural impairment in dyslexia. However, dyslexic subjects exhibited a general difficulty in extracting tonal objects from background noise, manifested by a globally delayed detection speed. © 2006 Elsevier Inc. All rights reserved.

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## 1. Introduction

Developmental dyslexia is characterized by impaired reading despite adequate intelligence and educational opportunity (Lyon, Shaywitz, & Shaywitz, 2003) and several studies suggest a genetic or neurobiological basis for this disorder (Grigorenko et al., 2001; Meng et al., 2005; Ramus, 2004; Wood & Grigorenko, 2001). The difficulties in acquiring literacy in this population have been associated with a fundamental deficit in phonological processing and phonological awareness, such as the ability to isolate and manipulate the constituent sounds of words (Bradley & Bryant, 1983; National Reading Panel, 2000; Snowling,

2000; Snowling, Goulandris, Bowlby, & Howell, 1986; Torgesen, Wagner, & Rashotte, 1994). In addition to a wide variety of phonological deficits, individuals with dyslexia are often (but not always) impaired in a range of non-linguistic auditory and visual processing tasks (Eden et al., 1996; Hari & Renvall, 2001; Stein, 2001; Witton et al., 1998; Wright, Bowen, & Zecker, 2000; see also Ramus, 2003). The relationship between these lower level sensory deficits and reading impairment is unclear and extensively debated (Eden & Zeffiro, 1998; Hari & Renvall, 2001; Ramus, 2003, 2004).

Among the wide range of auditory deficits linked with dyslexia (for reviews see Ramus, 2003; Rosen, 2003; Wright et al., 2000), several studies, motivated by the hypothesis that dyslexia may be associated with an impaired phase locking system (resulting in an inability to follow the acoustic fine structure of sounds), reported deficits in low level

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binaural processing and specifically in binaural unmasking. Binaural unmasking (Grantham, 1995), refers to the fact that a signal masked by correlated noise (identical noise signals at the two ears) can be made easier to detect by inverting the signal, or the noise, in one ear. That is, when the phase of the signal at the two ears is not the same as the masker. In natural environments, sound sources at different spatial locations result in different interaural phase configurations and binaural unmasking is thought to be one of the mechanisms that facilitate listeners' ability to detect objects in noisy environments (e.g. being able to follow a conversation in a cocktail party; Cherry, 1953). Binaural unmasking is based on the peripheral preservation of accurate timing information of the signal at each ear and on mechanisms that are sensitive to the similarity of the signals at the two ears. Cells exhibiting these properties are found in the Medial Superior Olive (MSO) of the brainstem. In animal studies, the Inferior Colliculus (IC), the projection target of the MSO, exhibits correlates of binaural unmasking (Jiang, McAlpine, & Palmer, 1997a; Jiang, McAlpine, & Palmer, 1997b; Palmer, Jiang, & McAlpine, 2000). McAnally and Stein (1996) found reduced binaural unmasking in dyslexic listeners. This has been attributed to impaired low-level (MSO/IC) binaural integration mechanisms and hypothesized to be a component of a more complex processing disorder for temporally fine sensory stimuli (Stein, 2001). Similar findings of impaired binaural facilitation of signal-from-noise extraction in dyslexia have been reported by Dougherty, Cynader, Bjornson, Edgell, and Giaschi (1998) and Edwards et al. (2004), using dichotic pitch stimuli. However other investigations (Amitay, Ahissar, & Nelken, 2002; Hill, Bailey, Griffiths, & Snowling, 1998) found no difference between control and dyslexic listeners' binaural unmasking thresholds.

The present study seeks to clarify this issue by assessing dyslexics' binaural processing abilities using a different behavioral paradigm. We compare the performance of dyslexic listeners with that of matched controls in a tone detection task. The stimuli (see Figs. 1 and 2) consist of a tonal object appearing amidst wide-band background noise. The tonal object is either a pure tone (TN) or a Huggins Pitch (HP)—perceptually similar but physically very different signals. Huggins Pitch (Cramer & Huggins, 1958) is the auditory counterpart of the well known 'random dot stereogram' (RDS) effect in vision (Julesz, 1971). An RDS is a binocularly presented pair of images with randomly distributed dots. Each image appears random when viewed individually but when displayed simultaneously, one to each eye, they evoke a coherent 3D percept. The illusion is created by presenting identical RDSs to the two eyes except that one image contains a group of dots that are slightly shifted relative to the other. The visual system fuses the shifted and non-shifted dots to create a 3D percept of an image (corresponding to the shifted dots) floating above the background (of the un-shifted dots). Similarly in audition, if a random broadband noise signal is presented to one ear, and the same random noise—but with a phase shift of  $\pi$  over a narrow frequency band—is presented to the other ear, this results in the perception of a faint tonal object with a pure tone quality (and a pitch that matches the center frequency of the phase-shifted band), embedded in noise. The input to either ear alone is just white noise, completely lacking any spectral or temporal cues to pitch. The fact that we are nevertheless able to perceive pitch when the two signals are presented dichotically implies that the HP percept is created by a mechanism that receives the inputs from the two ears, collates them, and emerges from the correspondence the percept of a tone (Fig. 1).

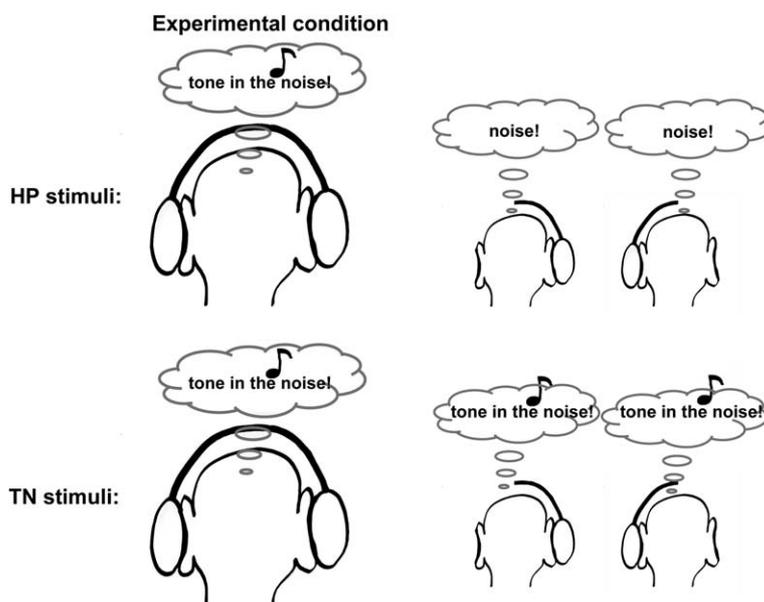


Fig. 1. Huggins Pitch (HP) and Tone-in-Noise (TN) stimuli evoke very similar percepts when listening dichotically: a faint tonal object amidst background noise. However, whereas the tone in the TN stimuli is perceptible monaurally, the tone in the HP stimuli is only audible when listening with two ears. When listening with each ear alone, HP stimuli sound like white noise.

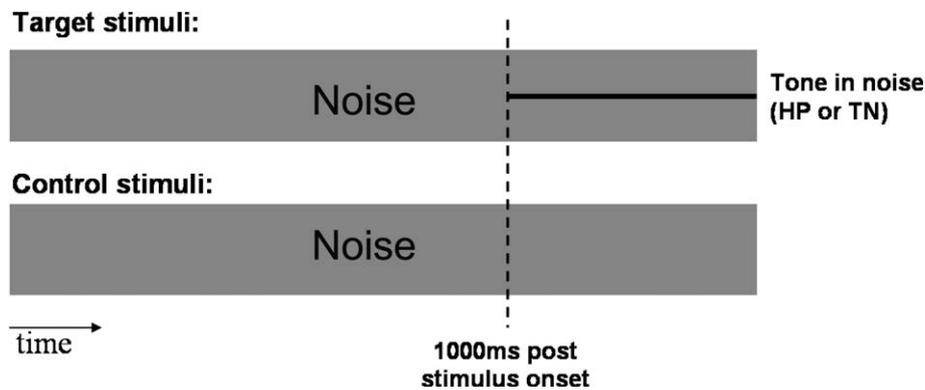


Fig. 2. Schema of the stimuli used in the current experiment. Signals consisted of 1500 ms correlated wide-band noise (dark grey) with a 500 ms faint tonal object (TN or HP; black line) appearing at 1000 ms post-onset. Control stimuli were 1500 ms long wide-band correlated noise.

Dougherty et al. (1998) and Edwards et al. (2004), using signals similar to HP, measured dyslexic listeners' perception of melodies consisting of dichotic pitch signals. In both studies they report that dyslexic listeners were impaired at processing dichotic pitches and conclude that the deficit results from impaired transmission of temporally fine neural information caused by abnormal low-level (brain stem) physiology. However, since they did not use simple tone-in-noise controls, it is unclear whether the deficit indeed originates from binaural mechanisms or is related to general difficulty in extracting objects from noise. The paradigm in the present study is more straightforward: subjects, who were not informed about the existence of different types (HP vs. TN) of tonal stimuli, performed a pitch detection task (50% of the trials) by pressing a button as soon as they heard a tone popping out of the noise (Fig. 2). Reaction times (RT) and accuracy scores were stored and analyzed. This design is based on the fact that the pitch evoked by HP is perceptually similar to that evoked by a binaurally (diotically) presented tone in noise but HP stimuli lack any structure (spectral or otherwise) that can be extracted at a low level within monaural pathways. Whereas the TN stimuli contain explicit pitch information that can be detected monaurally even at the level of the auditory nerve, the HP stimuli are indistinguishable from white noise up to the level of the MSO, where phase and timing information from the two ears are first compared.

We have previously used the same stimuli in a combined brain-imaging (with Magnetoencephalography; MEG) and psychophysical investigation (Chait, Poeppel, & Simon, 2006). In that study, we identified an auditory cortical response, at approximately 160–200 ms post-tonal onset, evoked by the appearance of a tone (HP or TN) in the noise. These responses to HP and TN appeared to result from the same cortical processing mechanism but differed in their *timing*: normal subjects responded (behaviorally and electrophysiologically) approximately 30 ms *faster* to HP stimuli than to perceptually similar TN stimuli. The latency difference is attributed to low level binaural processes (as early as the MSO) that operate differently on the two kinds of signals (see Chait et al., 2006). Specifically,

noise and TN signals recruit essentially the same cells whereas HP signals turn on neurons that are not activated by the preceding noise resulting in a faster response (see Fig. 3 in Chait et al., 2006).

These stimuli are therefore a useful tool to address the issue of dyslexics' alleged impaired binaural processing. In the extreme case, binaural impairment may result in a complete inability to hear the HP signals (as reported by Dougherty et al., 1998) while maintaining normal performance on TN signals. However our stimuli have the potential of revealing finer binaural deficits, even if HP signals are audible. A low level deficit in the dyslexic listeners should result in an altered pattern of latency differences between HP and TN stimuli, as compared to non-dyslexic controls. On the other hand, a more general deficit in noise exclusion would affect HP and TN in the same way and would result in a pattern of results where performance on both is displaced relative to that of the control group. In this way the stimuli allow us to differentiate between relatively low level impairments related to combination of fine temporal information across ears from higher level deficits such as extracting objects from noise.

The current design carries several additional benefits: most other dyslexia auditory processing studies use either multiple interval forced choice designs, requiring subjects to perform comparisons between stimuli (e.g. Amitay et al., 2002; Ben-Yehudah, Banai, & Ahissar, 2004; Hill et al., 1998; Wright et al., 1997) or designs that involve verbal labeling of the stimuli (e.g. 'left'/'right' in Dougherty et al., 1998). Our task is based on the simple detection of a signal. This delivery method avoids alternative explanations related to impaired working memory in the dyslexic population (Banai & Ahissar, 2004; Marshall, Snowling, & Bailey, 2001). Additionally, most investigations of auditory processing deficits in dyslexia are based on threshold measurement as a metric of performance (e.g. Amitay et al., 2002; Ben-Yehudah et al., 2004; Boets, Wouters, van Wieringen, & Ghesquiere, 2006; Hill et al., 1998; Montgomery, Morris, Sevcik, & Clarkson, 2005; Wright et al., 1997), whereas we assess listeners' response times. Although response time measures and threshold measurements are

correlated, they do not necessarily reveal identical information about processing (Luce, 1986). Response time measures may be more appropriate for detecting real time processing bottlenecks that may undermine reading or the processing speech sounds.

The variety of diagnostic criteria employed by different investigators often results in conflicting experimental findings. Our dyslexic sample was defined by reading deficits measured in childhood and as adults they continue to exhibit single real and non-word reading deficits, as well as weaknesses in phonemic awareness. Controls were recruited from the same longitudinal cohort. Our results show no evidence of a low level, binaural processing impairment associated with dyslexia. We find, however, that the dyslexic subjects exhibited a general difficulty, manifested by globally delayed response times, in extracting tonal objects from background noise.

## 2. Methods

### 2.1. Subjects

Seven dyslexic listeners (1 male; ages 24–27; average age 24.4) and ten controls (3 male; ages 23–26; average age 25.4) participated in the experiment. One control subject was excluded from analysis because of inability to perform the task (over 50% miss rate for both HP and TN targets). The subject profiles below refer to the 16 remaining participants.

Handedness was assessed using the laterality quotient from the Edinburgh Handedness Inventory (Oldfield, 1971). Subjects' scores ranged from +40 to +100 (out of a full range of –100 to +100) and were, therefore, classified as right handed.

### 2.2. Subject selection based on childhood testing and adult test profiles

#### 2.2.1. Childhood identification

The participants were recruited from an epidemiological longitudinal study of reading development that followed students from early elementary grades through high school (Flowers, Meyer, Lovato, Wood, & Felton, 2001; Wood, Hill, Meyer, & Flowers, 2005). A threshold for identifying dyslexic subjects in childhood was based on the normally distributed results of reading tests in a sample of 220 of those children who had complete test data in both 1st and 3rd grades. IQ was also normally distributed in this sample, demonstrating that they were representative of the general population. This step was necessary because standard scores were not available for the non-word reading subtests given- Word Attack from the Woodcock–Johnson Psycho-Educational Battery (WJ; Woodcock & Johnson, 1977) and the non-word reading portion of the Decoding Skills Test, Part II (DST; Richardson & DiBenedetto, 1985). The subjects in the current study were from two cohorts of subjects that

had been randomly selected during their 1st or 3rd grade years (for two dyslexic subjects only 1st grade scores were available). Children scoring at or below the 15th percentile (greater than one standard deviation below the mean) on either of those tests were considered dyslexic.

#### 2.2.2. Adult testing

Now adults, subjects reported in this study were those who were located following the termination of the longitudinal study. The follow-up test battery included measures in the following categories: *Phonemic awareness* was measured by the Test of Auditory Analysis Skill, adapted from Rosner (1979) and expanded to 20 items (TAAS+); and the Lindamood Auditory Conceptualization test—3rd Edition (LAC3; Lindamood & Lindamood, 2004). *Non-word reading*, was measured by the Word Attack subtest, and *real-word reading* was measured by the Letter/Word Identification subtest of the Woodcock Johnson III (WJ-III WA and WID; Woodcock, McGrew, & Mather, 2001). *Paragraph reading* accuracy was measured by the Gray Oral Reading Test, 3rd Edition, Accuracy score, (GORT3 Acc; Wiederholt & Bryant, 1992). *Reading comprehension* was measured by the Woodcock Johnson III Passage Comprehension subtest, (WJ-III PC; Woodcock et al., 2001) as well as by the Gray Oral Reading Test—3rd Edition, Comprehension score (GORT-3 Comp; Wiederholt & Bryant, 1992). *Reading fluency* was measured by the Woodcock Johnson III Reading Fluency subtest, (WJ-III RF; Woodcock et al., 2001) via sentence reading fluency. The Rapid Automatized Naming (RAN; Denckla & Rudel, 1976) was used to test fluent retrieval of highly familiar verbal labels for single letters, digits, colors, and objects. Separate RAN scores are calculated, to represent color and object naming (RANCO) and digit and letter naming (RANNL). Also included was an instrument designed to briefly measure *overall intellectual functioning*. The Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999) is a four-subtest measure consisting of two verbal and two non-verbal (performance) measures. The WASI generates a verbal intelligence quotient (VIQ) and a performance intelligence quotient (PIQ) as well as a composite, full-scale, IQ score (FSIQ), the latter being correlated with the Wechsler Adult Intelligence Scale-III FSIQ 0.92.

As adults, the dyslexic subjects, compared to controls, demonstrated significantly poorer performance on all tests of phonological processing, reading accuracy, and fluency. They all remain in the lower third of the distribution on word attack skills. Of particular interest is that they were impaired on non-word reading and also on phonemic awareness (LAC3 and TAAS+), weaknesses considered to be the defining features of dyslexia. Mean ages of the dyslexic and non-dyslexic adult groups did not differ but, as might be expected, the dyslexic group did not attain the same number of years of education as the typical readers (15.1 and 13.3 years, respectively,  $p = .02$ ). Table 1 shows score means by group.

### 2.3. Stimuli

The stimuli (Fig. 2) were identical to those used in a previous study (Chait et al., 2006, see Experiment 1). The signals were 1500 ms long, consisting of 1000 ms interaurally correlated white noise (identical noise signals at the two ears) followed by either HP or TN, as described below. Control stimuli consisted of a 1500 ms interaurally correlated noise.

We chose four center frequencies (200, 400, 600, and 1000 Hz) that span the frequency region for which HP is salient. A 1000 ms sample of ‘frozen’ noise (sampling frequency 16 kHz, bandwidth 8 kHz) was generated for each of these four conditions. The HP signals were created by introducing a constant phase shift of  $\pi$  in a particular spectral region of the noise sample delivered to the right ear, while the original sample was delivered to the left ear (Yost, Harder, & Dye, 1987). The width of the phase-shifted band was set to  $\pm 6\%$  of its center frequency (Klein & Hartmann, 1981). The corresponding TN signals were produced by adding a pure tone (with one of the above frequencies) to the same noise samples used for the HP stimuli. Generally, listeners are able to match the HP signal to the pitch evoked by a pure tone (with a frequency that corresponds to the center of the phase-shifted band) with a standard error of about 3% (Klein & Hartmann, 1981). The amplitude of the pure tone signal was separately adjusted by two listeners to match the ‘perceived tone’ loudness of the corresponding HP stimulus.

When HP is perceived, the background noise is always localized to the center of the head but the tonal object may

be reported as being at a lateral position away from the midline. It is lateralized to the left or to the right by some listeners but mostly evokes an inconsistent (ambiguous) lateralization, especially by inexperienced listeners (Yost et al., 1987; Zhang & Hartmann, 2004). Since no appreciable effects of perceived HP or TN lateralization were found in Chait et al. (2006), TN signals in the current study were not matched to the perceived lateralization of HP and were always presented with the same amplitude of pure tone to both ears (perceived in the center of the head).

The stimuli were created off-line, gated on and off using 15 ms cosine-squared ramps (with no gating in the transition at 1000 ms post-onset), and saved in 16-bit stereo WAV format at a sampling rate of 16 kHz. The signals were delivered to the subjects’ ears with Sennheiser HD580 headphones and presented at approximately 75 dB SPL, to ensure a salient pitch. HP saliency increases with increasing noise level (Durlach, 1962).

In total each subject heard 50 presentations of each of the eight pitch conditions (HP 200, 400, 600, and 1000 Hz; TN 200, 400, 600, and 1000 Hz) and 400 (50% of all) presentations of the control (no tone) stimulus. The order of presentations was randomized, with the inter-stimulus interval between 500 and 2000 ms.

### 2.4. Procedure

The experiment lasted about 1 hour. Subjects sat in a quiet, darkened room in front of a PC computer, fixated on a white cross in the middle of the computer screen, and performed a tone detection task (50% of the trials) by pressing a mouse button, with the right index finger, as soon as they heard a tone popping out of the noise. Response speed was emphasized in the instructions. Reaction times (RT) and accuracy scores were recorded. The participants were not informed about the existence of different types (HP vs. TN) of tonal stimuli. The presentation was divided into four blocks of 200 stimuli each. Between successive blocks, participants were allowed a short rest.

Before beginning the experiment proper, each listener was presented with a short (approximately 5 min) practice session in which response feedback was provided on the computer screen. The purpose of the practice session was to familiarize the participants with the requirements of the task and to point their attention to the tonal objects, which because of their faintness sometimes are not detected without directed attention. If miss rates were high (more than 20%) the practice session was repeated but in no case were more than two sessions administered. Since a major experimental hypothesis was regarding dyslexic listeners’ ability to detect HP stimuli, we chose to not present HP stimuli in the practice session (we reasoned that negative feedback in HP trials might discourage the listeners who are unable to perceive the tonal object). Instead of HP stimuli, we used noise band stimuli (BN). These signals are created using the same noise used to generate the HP stimuli but with one (narrow) band amplified. The amplified bands have the

Table 1  
Comparison of typical and affected reader performance on adult cognitive measures

Measure	Controls	Dyslexics	<i>p</i> -value
<i>Demographics</i>			
Education	15.11	13.29	.019
<i>Intellectual</i>			
WASI VIQ	107.89	92.71	.032
WASI PIQ	113.33	100.14	.036
WASI FSIQ	111.67	96.14	.009
<i>Phonemic awareness</i>			
TAAS+	18.33	13.14	.008
LAC3	104.22	81.00	.003
<i>Non-word decoding</i>			
WJ-III WA	95.89	80.14	.018
<i>Word and paragraph reading accuracy</i>			
WJ-III WID	98.33	82.29	.003
GORT-3 Acc	110.56	77.86	<.00001
<i>Reading comprehension</i>			
WJ-III PC	99.89	96.29	.441
GORT-3 Comp	103.33	98.57	.666
<i>Reading fluency</i>			
WJ-III RF	104.67	85.29	.006
GORT-3 Rate	106.1	80	.005
RANCO	109.56	85.14	.004
RANNL	106.33	88.29	.028

same bandwidth as the phase shifted region in the corresponding HP stimulus, but no interaural phase difference (i.e. they are audible monaurally). The loudness of the pitch in the BN stimuli was separately adjusted by two listeners to match the perceived loudness of the TN stimuli.

### 3. Results

#### 3.1. Control subjects

The data for the control subjects is presented in Fig. 3 (filled symbols). A repeated measures ANOVA with type (HP vs. TN) and frequency (200, 400, 600, and 1000 Hz) as factors revealed main effects of both type ( $F(1,8) = 11.56$ ,  $p = .009$ ) and frequency ( $F(3,24) = 11.94$ ,  $p < .001$ ) but no interactions. As in our previous report (Chait et al., 2006), subjects were consistently faster for HP than TN stimuli, with an average reaction time difference of approximately 30 ms. The difference at 1000 Hz was smaller than the one reported previously, possibly due to group variance.

In terms of miss rates, there was no difference between HP and TN conditions. On average, listeners missed about 6.9 targets (1.7%). The average false positive count was 19.7 targets (4.9%) with a standard deviation of 27.26.

#### 3.2. Dyslexic subjects

The data for the dyslexic subjects is presented in Fig. 3 (open symbols). A repeated measures ANOVA with type (HP vs. TN) and frequency as factors revealed main effects of type ( $F(1,6) = 8.954$ ,  $p = .024$ ), frequency ( $F(3,18) = 3.23$ ,  $p = .047$ ) and an interaction of type by frequency ( $F(3,18) = 6.543$ ,  $p = .003$ ). Subjects were consistently faster for HP than TN stimuli, with an average reaction time difference of approximately 30 ms. As in the controls' data, the difference at 1000 Hz was smaller than the one reported in (Chait et al., 2006) but this represents a small effect.

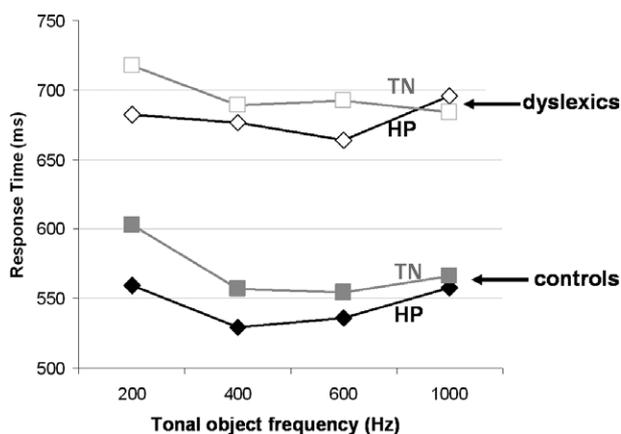


Fig. 3. Response times. HP, black lines; TN, grey lines. Controls, filled symbols; dyslexics, open symbols. Controls and dyslexics showed the same pattern of dependency on stimulus type (HP responses preceding TN responses), consistent with Chait et al. (2006). Dyslexic subjects performed similarly to controls apart from globally slower reaction times.

The results illustrate that HP was audible to our dyslexic listeners: the average number of HP misses (collapsed over frequency) was 12.71 ( $SD = 7.76$ ) out of 200 HP tokens (6.3%). There was no difference in miss rates between HP and TN conditions. On average, the dyslexic listeners missed about 18.28 targets (4.5%). The average false positive count was seven targets (1.7%) with a standard deviation of 10.64.

#### 3.3. Comparison between control and dyslexic groups

Fig. 4 shows the response times for all subjects in the control (filled circles) and dyslexic (open circles) groups. A repeated measures ANOVA for the response time data, with type (HP vs. TN) and frequency as within subject factors, and group (dyslexic vs. control) as a between-subjects factor, showed significant main effects of diagnostic group ( $F(1,14) = 17.43$ ,  $p < .001$ ), stimulus type ( $F(1,14) = 18.463$ ,  $p < .001$ ) and frequency ( $F(3,42) = 14.148$ ,  $p < .001$ ) and a stimulus type by frequency interaction ( $F(3,42) = 9.751$ ,  $p < .001$ ). Both controls and dyslexics show a pattern of results (HP responses preceding TN responses) that is consistent with those obtained in Chait et al. (2006). Notably, there was no interaction between group and stimulus type, indicating no difference between the performance of the control and dyslexic populations on these stimuli, except that dyslexic listeners' overall response times were much slower (a difference of approximately 120 ms). Importantly, there is no difference in the false positives count between the two groups ( $F(1,14) = 1.334$ ,  $p = .267$ ). In the analysis of the miss data, a repeated measures ANOVA with type (HP vs. TN) as a within subject factor and group as a between subject factor showed only a main effect of type ( $F(1,14) = 10.239$ ,  $p = .006$ ), indicating that in both groups,

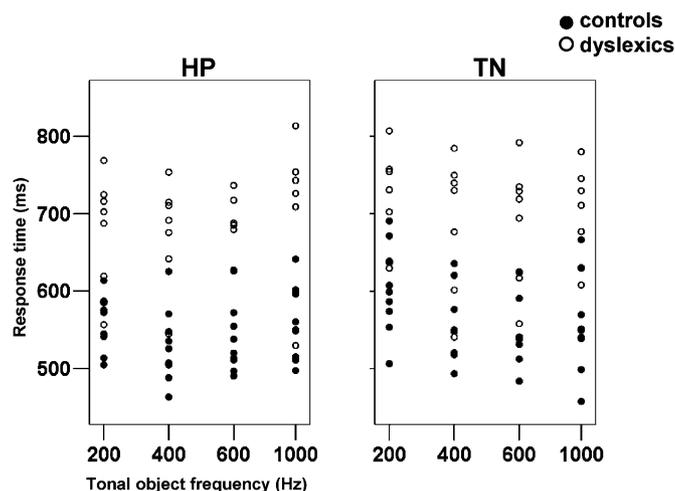


Fig. 4. Scatter plots showing response time data for HP (left panel) and TN (right panel) for all our subjects. Controls, filled circles; Dyslexics, open circles. The dyslexic and control groups show little overlap except that two of our dyslexic subjects consistently perform in the same range as the controls. This is in line with a common observation that not all dyslexics show poor performance in auditory tasks (e.g., Ramus, 2003).

HP targets were generally missed more often than TN targets, and a main effect of group ( $F(1,14)=9.15, p=.009$ ): As compared to their normal reading controls dyslexic listeners show a significantly greater miss count. There was no interaction between diagnostic group and stimulus type.

To address the concern that the dyslexics' general speed problem is due to their lower cognitive abilities (as reflected by lower IQ scores) we computed an ANOVA with mean response time (calculated for the HP and TN conditions collapsed) as a dependent measure, group (dyslexic vs. control) as a between-subjects factor and WASI FSIQ as a covariate. The results showed a main effect of group ( $F(1,13)=8.28, p=.013$ ) only. There was no main effect of IQ ( $F(1,13)=0.199, p=.663$  n.s.). The same analysis with years of education as a covariate also showed a main effect of group only.

We also compared the response variability of the two subject groups. A repeated measures ANOVA for the standard deviation data, with type (HP vs. TN) and frequency as within subject factors, and group (dyslexic vs. control) as a between-subjects factor showed only a main effect of type ( $F(1,14)=6.048, p=.028$ ) and no interactions. This effect was due to responses to HP stimuli being generally more variable than those to TN stimuli. Importantly, there was no main effect of group, suggesting that the response variability of dyslexic and control subjects did not differ.

We calculated Pearson correlations between mean response times and the scores for all tests in the test bat-

tery (see Section 2). The only tests that exhibited significant correlations with response time were the two tests of aural awareness of the sound structure of language (the only two auditory tests in our battery): TAAS+ ( $r=-.736, p=.001$ ) and LAC3 ( $r=-.743, p=.002$ ). We also found a weaker correlation with non-verbal IQ (PIQ;  $r=-.563, p=.023$ ). These results are presented in Fig. 5A–C. The two fastest dyslexic subjects (who demonstrated response times similar to controls in Fig. 4) also had higher LAC3 and TAAS+ test scores. On the other hand, non-verbal IQ (Fig. 5C) did not exhibit that predictive power. Controlling for IQ (FSIQ parameter) and years of education reduced, but did not eliminate the correlation with LAC3 and TAAS+.

To examine to what extent the correlations are due to spread between the two populations, we subtracted the means from both the response times and test scores and computed the Pearson correlation again. The correlation with PIQ was found to be non-significant under these conditions ( $r=-.3, p=.259$  n.s.), the correlation with LAC3 was approaching significance ( $r=-.48, p=.07$ ), and the correlation with TAAS+ remained significant ( $r=-.554, p=.026$ ). These results imply that response times and the TAAS+ and LAC3 test scores are indeed linked, whereas the apparent correlation with PIQ test scores is a result of the separation of the means of the two subject groups.

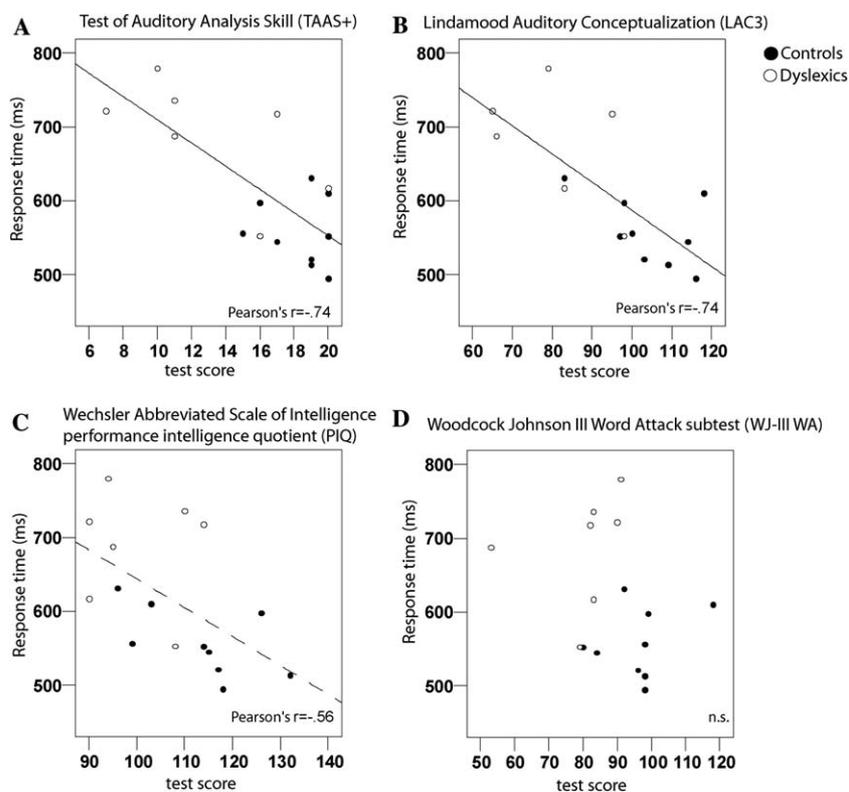


Fig. 5. Scatter plots of test scores vs. response time. Controls, filled circles; Dyslexics, open circles. Black lines are linear fits to the data ( $R^2$  values are 0.541, 0.552 and 0.316 in A, B, and C, respectively). Both auditory tests in our battery had a significant correlation with response times (A and B). There was also a correlation with the non-verbal IQ test (C), which further analysis showed to be a result of the distance between the two group means on both axes. All other common diagnostic tests for dyslexia, such as the WJ-III WA non-word reading test (D) are not correlated with the response time data.

#### 4. Discussion

Our findings clearly demonstrate that dyslexic listeners can perceive dichotic pitch. None of our subjects had difficulty in identifying the HP targets (as exhibited by low miss and false positive counts). Moreover, the fact that the latency difference between TN and HP shown by the dyslexic listeners is not different than the latency difference exhibited by the control subjects indicates that in both populations the low level binaural integration mechanisms are operating in a similar manner, and that there is no evidence for a specific binaural impairment associated with dyslexia.

Dyslexics were overall slower than controls by about 120 ms. Although we did not run a pure tone detection test in quiet (without background noise), the literature indicates that in simple reactions to pure tones, dyslexics respond as quickly as controls (e.g., Nicholson & Fawcett, 1994). Furthermore, the difference in miss-rates (but not false positive rates or response variability) between the subject groups suggest that the response time differences are not likely to be simply due to a different hearing profile, delayed motor execution or clumsiness, but are related to the processes via which the listeners detect the tonal objects in noise.

The fact that dyslexic listeners took more time than their controls to detect tonal objects in background noise appears to contradict a seemingly consistent experimental finding. Usually, there is no difference between the thresholds of dyslexics and controls in tasks involving the detection of long pure tones (similar to our TN stimuli) presented in the temporal center of a noisy background (Amitay et al., 2002; Boets et al., 2006; Hill et al., 1998; McAnally & Stein, 1996; Montgomery et al., 2005; Wright et al., 1997). Even though we did not measure thresholds in this study, the absence of difference in false positive rates and only a small difference in miss rates between the subjects groups suggest that the tonal targets (both HP and TN) were similarly detectable by the two subject groups. Thus, it is most likely that the group difference is related to the *time* needed to process stimulus changes, rather than the ability to detect them: It was the *speed* with which the tonal targets were detected that underlies the impairment in dyslexic listeners. Threshold similarities tend to be interpreted as indicating normal auditory processing. Our results suggest that important aspects may escape threshold measures (especially when the detection threshold is set to be quite high), but may be probed by reaction-time measures.

Because controls and dyslexics show a very similar pattern of dependency on stimulus type (apart from the latency difference), it is likely that the impairment resulting in increased response times is introduced at a processing stage in which TN and HP stimuli are already mapped to similar representations (i.e., above the level of the superior olive and IC, where binaural interaction occurs). Therefore, likely candidates would be thalamus or cortex.

What kinds of mechanisms could account for dyslexics' delayed responses? It may be that the deficit is specific to

the processing of signals in noise. This interpretation would be consistent with reports that reading impaired children show only subtle speech perception deficits in quiet but very significant difficulties under conditions of background noise (Ziegler, Pech-Georgel, George, Alario, & Lorenzi, 2005). Similar findings, concerning deficits in noise exclusion in developmental dyslexia, have also been reported in the visual domain (Sperling, Lu, Manis, & Seidenberg, 2005). Another possibility is that dyslexic listeners are generally slow at tracking *changes* in ongoing stimulation—their change-detection integration windows are longer than normal—and that this deficit is more evident amidst background noise. Indeed there is some evidence for a prolonged integration time in dyslexics (Hairston, Burdette, Flowers, Wood, & Wallace, 2005; Hari & Renvall, 2001; Helenius, Uutela, & Hari, 1999; Petkov, O'Connor, Benmouche, Baynes, & Sutter, 2005). For simple stimuli such as the ones used here, a prolonged integration window would cause a delay in detection. In the case of more complex signals, consisting of many consequent rapid changes such as speech, delayed change detection may cause increased interstimulus masking and result in a failure to properly perceive the sound sequence. This interpretation might also explain the apparent discrepancy between our results and those of Dougherty et al. (1998) and Edwards et al. (2004), who employed signals similar to HP but reported significant impairment in individuals with dyslexia as compared to average readers. In their study, subjects listened to dichotic pitch melodies consisting of four sequential 200 ms harmonic tone complexes. Inability to perform the task may have arisen from the longer time required by dyslexics to extract the tones from the noise and thus to follow the changes in the melody.

How does the more global deficit observed here relate to the well-known deficits in phonological information processing in dyslexia? There is considerable controversy vis-à-vis the relationship of the variety of auditory deficits and reading or phonological processing problems. One theoretical model views dyslexia as a specific phonological disorder that sometimes co-arises with a more general sensorimotor syndrome (Bretherton & Holmes, 2003; Ramus, 2004). According to this view, the reading impairments are unrelated to low-level auditory deficits (Rosen, 2003). Another theory suggests the impairments associated with dyslexia are not speech specific, but that phonological deficits arise from lower-level impairments in neural systems responsible for processing of auditory stimuli that have short duration and appear in rapid succession (Tallal, Miller, & Fitch, 1993; Tallal, 1980). Some have suggested that these auditory deficits as well as visual deficits related to rapid processing (Eden et al., 1996; Livingstone, Rosen, Drislane, & Galaburda, 1991) arise from a general defect in the magnocellular processing pathways (Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1985; Galaburda, Menard, & Rosen, 1994; Stein & Walsh, 1997; Stein, 2001) that subserves the processing of fast sensory (auditory, visual, tactile) information. *A priori*, our stimuli do not tap rapid

auditory processing, but an account in terms of increased integration time in dyslexics and a consequential slower detection of changes (that is *any* change, not necessarily only rapid changes) might be able to explain much of the rapid processing deficits dyslexics seem to exhibit (e.g. Hari & Renvall, 2001).

Hari and Renvall (see also Petkov et al., 2005) formulate their model in terms of ‘sluggish attentional shifting’ in dyslexia. This model suggests that sluggish attentional capture and prolonged attentional dwell result in an expanded ‘cognitive integration window.’ However, it is not clear that attentional mechanisms need to be invoked in explaining increased integration time. Increased integration time and delayed detection may indeed arise from quite early ‘pre-attentive’ processing mechanisms (Banai, Nicol, Zecker, & Kraus, 2005; Chait, Poeppel, de Cheveigne, & Simon, 2005).

It is noteworthy that, out of our extensive test battery, only tasks that rely on sound manipulation at a sublexical level showed a strong correlation with response times (Fig. 5). RT in our experiment did not correlate with timed tests that are generally considered to assess speed of processing such as RANCO, RANNL, GORT-rate or WJ-III. This, in addition to the fact that neither the LAC3 nor the TAAS+ are timed tests, suggests that the correlation between RT and TAAS+/LAC3 is not due to factors relating to general speed of information processing but may be associated with auditory analysis skills. For the TAAS+ test, subjects remove a sound (beginning, ending or blend) from a spoken word and say what is left. For example, say ‘bake’ without the /b/ sound (ache); say ‘blend’ without the /l/ sound (bend). The LAC3 uses colored blocks to represent sounds and subjects are asked to manipulate non-words that are presented as sequences of these blocks (e.g., change blocks representing ‘zap’ to ‘zup’ by changing the middle block to another color). The correlations between the speed with which listeners detected the tonal objects and these phonological processing tests may suggest that indeed both kinds of tasks rely on similar processing mechanisms. All other tasks in our battery involved visual stimuli and (except for performance IQ) required reading, naming, or verbal expression. For example, the WJ-III WA non-word reading test was not correlated with response time (Fig. 5) even though the dyslexic group was significantly impaired on this measure. These findings are thus consistent with previous reports of a dissociation between auditory processing and reading skills (Agnew, Dorn, & Eden, 2004). Our sample size is too small, however, to draw strong conclusions.

In a previous MEG study with typical subjects using the same stimuli and behavioral task as here (Chait et al., 2006), we identified a cortical response, at approximately 160–200 ms post-tonal onset, evoked by the appearance of a tone (HP or TN) in the noise. We hypothesized that this increase in current is generated by the neural mechanisms that are responsible for the extraction of tonal objects from background noise. Several properties of this response are

relevant to the current findings: These ‘tone onset’ responses, localized to auditory cortex, were found to activate left hemispheric mechanisms significantly more strongly than right hemisphere ones. Left temporal cortex is one of the brain regions that are most consistently reported to exhibit impaired activation in dyslexia (Eden & Zeffiro, 1998; Ramus, 2004; Shaywitz et al., 2004; Simos et al., 2002; Temple, 2002; Temple et al., 2000) and is also correlated with phonemic awareness skill (Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003). Thus, under-recruited neural substrate in the left temporal lobe may be a cortical reflection of difficulties exhibited by our dyslexic subjects.

The latency of these early MEG responses and behavioral reaction time followed similar general trends, but they were not correlated (Chait et al., 2006; Chait & Simon, in press), which suggests that the tone onset responses reflect a pre-attentive stage in processing. This conclusion is consistent with other studies where similar responses were recorded even while subjects were not paying attention to the auditory stimuli (Alain, Schuler, & McDonald, 2002; Krumbholz, Patterson, Seither-Preisler, Lammertmann, & Lütkenhöner, 2003). The pattern of early cortical response latencies vs. behavioral reaction times suggests that subjects’ response times were also influenced by a later mechanism related to deciding, based on information from the earlier sensory mechanisms, whether the target has indeed occurred (Chait et al., 2006; Chait & Simon, in press). These mechanisms are hypothesized to be the stage where the appearance of the target is brought to the subject’s attention (Carpenter, 2004). Dyslexic subjects’ delayed responses may thus have arisen either from impaired sensory (auditory cortical or sub-cortical) processing, or from impaired higher level mechanisms. An MEG study with dyslexic listeners under similar listening conditions would clarify whether the impairments observed in the current study are indeed arising from early cortical mechanisms that underlie the extraction of the tonal objects, independent of attention, or are introduced by higher level mechanisms related to attention shifting and decision making (Hari & Renvall, 2001). Abnormal early cortical processing, as opposed to higher level impairment, is expected to be manifested in increased latencies of the early ‘tone onset’ responses, reflecting a delay in the neural mechanisms responsible for the segregation of the tonal targets from the noise. Normal ‘tone onset’ responses, but delayed behavioral detection, would implicate higher level (non-sensory) mechanisms.

Most brain imaging studies of dyslexia have focused on localization of impaired brain mechanisms (Eden & Zeffiro, 1998; Eden et al., 1996; Temple, 2002) or on investigating the ‘fast temporal processing’ hypothesis with response amplitudes as the main measure of detection thresholds (Kujala, Belitz, Tervaniemi, & Naatanen, 1999, 2000; Nagarajan et al., 1999; Schulte-Körne, Deimel, Bartling, & Remschmidt, 1999). In light of the evidence provided here, that *latencies* of responses to simple auditory transients

might reveal impairments in dyslexic listeners, future studies with stimuli such as the ones used here may shed light on the exact properties of the deficits observed in the present work. Such an investigation may improve our understanding of dyslexia and, possibly, of the computations involved in phonological processing. Even if the sensory deficits are not causally related to the phonological weakness (the core of reading impairment), the investigation of auditory processing in dyslexia is valuable for hearing research: The pattern by which the system ‘breaks down’ may serve as a means to further our understanding of the computations and neural mechanisms involved in the construction of perceptual representations.

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