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Auditory Processing Deficits in Reading Disabled Adults

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ABSTRACT

The nature of the auditory processing deficit of disabled readers is still an unresolved issue. The quest for a fundamental, nonlinguistic, perceptual impairment has been dominated by the hypothesis that the difficulty lies in processing sequences of stimuli at presentation rates of tens of milliseconds. The present study examined this hypothesis using tasks that require processing of a wide range of stimulus time constants. About a third of the sampled population of disabled readers (classified as "poor auditory processors") had difficulties in most of the tasks tested: detection of frequency differences, detection of tones in narrowband noise, detection of amplitude modulation, detection of the direction of sound sources moving in virtual space, and perception of the lateralized position of tones based on their interaural phase differences. Nevertheless, across-channel integration was intact in these poor auditory processors since comodulation masking release was not reduced. Furthermore, phase locking was presumably intact since binaural masking level differences were normal. In a further examination of temporal processing, participants were asked to discriminate two tones at various intervals where the frequency difference was ten times each individual's frequency just noticeable difference (JND). Under these conditions, poor auditory processors showed no specific difficulty at brief intervals, contrary to predictions under a fast temporal processing deficit assumption. The complementary subgroup of disabled readers who were not poor auditory processors showed some difficulty in this condition when compared with their direct controls. However, they had no difficulty on auditory tasks such as amplitude modulation detection, which presumably taps processing of similar time scales. These two subgroups of disabled readers had similar reading performance but those with a generally poor auditory performance scored lower on some cognitive tests. Taken together, these results suggest that a large portion of disabled readers suffer from diverse difficulties in auditory processing. No parsimonious explanation based on current models of low-level auditory processing can account simultaneously for all these results, though increased within-channel noise is consistent with the majority of the deficits found in the subgroup of poorer auditory processors.

Keywords: reading disabled, temporal processing, auditory, psychoacoustics

INTRODUCTION

Some 5% of all children experience unexpected difficulty in reading acquisition when compared with their peers that it is not a result of overall lower intelligence or lack of learning opportunity (DSM-IV, American Psychiatric Association 1994). For many, reading and spelling difficulties persist into adulthood (Pennington et al. 1990). Over the last few

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decades, it has become increasingly clear that the difficulties experienced by poor readers are not limited to the linguistic domain but extend into nonverbal visual and auditory sensory processing.

Early evidence for a perceptual deficit was provided by Tallal (1980), who demonstrated that reading disabled children require interstimulus intervals (ISIs) longer than 400 ms to discriminate or sequence two tones of different frequencies, while control children performed near ceiling. These results have been corroborated by other psychophysical (Reed 1989; Ahissar et al. 2000) and physiological (Nagarajan et al. 1999) studies on children and adults. These findings, together with evidence from the visual domain (e.g., Livingstone et al. 1991; Ridder et al. 1997; Cornellisen et al. 1998; Witton et al. 1998), led to the formulation of the ''temporal processing deficit hypothesis'' which postulates that reading impaired children have pansensory difficulty in processing rapid sequential stimuli (Tallal et al. 1993). The proposed deficit is in the time scale of tens of milliseconds. This is the time scale relevant for the perception of speech formant transitions, i.e., the brief changes in spectral energy distribution crucial for differentiating between phonemes. The temporal processing deficit hypothesis has two parts: (1) disabled readers, or a subgroup thereof, have a specific deficit in processing phoneme-rate stimuli, and (2) this deficit is ultimately the cause of their reading disabilities. Both parts of this hypothesis are discussed vigorously in the literature. Considering first the second part of the hypothesis, although the causal chain leading from perceptual deficits to reading disability is unclear, it is possible that impaired acoustic processing constrains proper speech perception and, as a result, phoneme representations may be impaired. Learning to read involves associating phonemes with graphemes (letters), so flawed phoneme representations may impede reading acquisition (Tallal 1980). In support of this hypothesis, it has been shown that phonemic awareness is necessary for reading acquisition (Bradley and Bryant 1983). However, there is some evidence against a direct causal link between nonlinguistic acoustic processing and speech perception (Mody et al. 1997).

The main goal of this article is to evaluate the first part of the temporal processing deficit hypothesis, i.e., the nature of the perceptual auditory deficits related to reading disabilities. There have been many attempts to pinpoint the locus of this perceptual deficit. A variety of auditory tasks designed to tap temporal processing in the time scale hypothesized to underlie speech perception have been used. Some tasks, such as amplitude modulation (AM) detection (McAnally and Stein 1997; Menell et al. 1999), processing of changing auditory patterns (McGivern et al. 1991; Schulte–Körne et al. 1999b; Kujala et al. 2000), and stream segregation (Helenius et al. 1999), revealed behavioral and physiological deficits in the performance of disabled readers. Others tasks, such as gap detection (McAnally and Stein 1996; Schulte–Körne et al. 1998a, 1999a; Ahissar et al. 2000) and forward masking (Rosen and Manganari 2001), failed to reveal intergroup differences. However, the results on most tasks have been inconclusive or seemingly contradictory (e.g., backward masking, Rosen and Manganari 2001 vs. Ahissar et al. 2000; binaural unmasking, McAnally and Stein 1996 vs. Hill et al. 1999; even the results for the two-tone sequencing task at variable ISIs have been challenged, Nittrouer 1999). On the other hand, frequency discrimination tasks with no obvious temporal constraint also posed difficulties for disabled readers (McAnally and Stein 1996; De Weirdt 1988; Hari et al. 1999; Cacace et al. 2000; Ahissar et al. 2000; Baldeweg et al. 1999; but see Watson 1992; Watson and Miller 1993; Hill et al. 1999; Schulte–Körne et al. 1998b, 1999a).

Even though most of the above-cited studies have purportedly measured rapid temporal processing, no consensus is apparent. There may be several reasons for the discrepancy across results. The different tasks may tap different mechanisms, some of which are impaired. The different criteria for participant selection across studies make it difficult to compare the results obtained, even on similar tasks. In addition, the behavioral methodologies vary, which makes cross-study comparison even more difficult.

To resolve these issues, we used a large and diverse battery of psychoacoustic tasks designed to probe auditory processing at widely varying time constants, from hundreds of microseconds to several seconds. In addition, tasks were chosen to allow us to compare processing within and across frequency channels in order to better characterize the affected mechanism(s). The purpose of this work was therefore not to study the relationship between psychoacoustic deficits and reading disabilities, but rather to generate a full psychoacoustic profile of reading disabled (RD) individuals and compare it with the predictions of the fast temporal processing deficit hypothesis. Whether a nonlinguistic deficit (or deficits) plays a functional role in reading difficulty is beyond the scope of this article.

Our RD population consisted of adults whose main complaint during their studies was a severe and persistent reading difficulty. They all either had finished or were completing high school requirements or better. Nevertheless, our population was heterogeneous in the sense that some needed a special support system in order to complete high school requirements whereas others managed within regular institutional frameworks.

One concern is that since our population was composed entirely of native Hebrew speakers, our RD test population may not be comparable to RDs in other languages. The Hebrew script is unique in the sense that it uses both shallow and deep orthography. Reading is taught using pointed script which is phonetically unambiguous (a shallow orthography), and the points (or diacritics) are quickly dropped in favor of unpointed script which includes consonantal information but only partial vowel information (deep orthography). Most reading beyond the first two or three years of primary school employs unpointed script. However, when testing reading, only reading in context can be performed using unpointed script, and single word (and, of course, nonword) reading requires pointed script to be unambiguous. Recent research suggests that while the depth of the orthography might influence reading performance, the neurocognitive basis of reading disability is universal and does not depend on the orthography (Paulesu et al. 2001). Based on this we expect our test population to have psychophysical performance comparable to that observed in native English speakers.

METHODS

Participants

Our participants were 23 (8 male and 15 female) adults (mean age 22.3 ± 4.1 years) with reading difficulties and 27 (8 male and 19 female) controls (mean age 21.8 ± 4.5 years) with no history of reading problems, matched for age and education level. All participants were native Hebrew speakers, and all had normal hearing thresholds in the range of frequencies used in our experiments (0.5, 1, and 2 kHz). Informed consent to take part in the experiment was obtained from all participants.

Participant selection criteria. Selection could not be performed on the basis of standard reading scores as no standardized reading tests exist in Hebrew. Participants were referred to us by educators (mainly for ages 17–20) or clinicians on the basis of psychoeducational diagnoses of reading disability or by self-report (students who read ads on the university campus) of a history of reading difficulties. We also required that all participants have current nonword reading scores at least one standard deviation below the control group average. All participants performed within the normal range in the Hebrew version Similarities subtest of WAIS III (Wechsler 1997). Performance on other subtests was not a basis for participant exclusion. Our control sample was recruited by asking the RD participants to refer to us a normal-reading friend or spouse in the sample age range.

Apparatus

The experimental setup consisted of a PC controlling Tucker-Davis Technologies System II hardware (Tucker-Davis Technologies, Gainesville, FL). Stimuli were generated digitally with a sampling period of 20 μs (50,000 Hz) and presented through headphones (Sennheiser HDA 200, Sennheiser, Old Lyme, CT) in a double-walled sound-attenuating chamber. Responses were collected via a custom-made response box and colored lights were used to demarcate stimulus presentation and to provide feedback. Stimulus presentation and response collection were entirely under computer control, using custom software developed specifically for this purpose.

Behavioral paradigms

To measure psychoacoustic performance, we used both the yes–no method with a maximum-likelihood algorithm and a two-alternative forced choice (2AFC) paradigm.

In the yes–no method, a single stimulus interval was presented. Listeners indicated target stimulus detection by pressing the appropriate key on the response box ("yes" for target present or stimuli "same"; "no" for target absent or stimuli "different"). After each trial, a psychometric curve was fitted to the accumulated data and the next experimental parameter value was estimated at the 66% point of this curve (a maximum-likelihood procedure, Green 1993; Saberi and Green 1997). Each trial had a 20% probability of being a "catch trial" (target stimulus not present), resulting in 4–5 catch trials per threshold assessment. "Yes" or "different" responses in these trials were considered as false alarms. Each threshold assessment began with a target parameter value that made the stimulus clearly recognizable as the target or discriminable in the case of same–different.

We employed the yes–no method in two tasks (frequency just noticeable difference and binaural unmasking) because our pilot studies indicated that we could get valid, repeatable threshold estimations on these tasks using this method. It has the advantage of being significantly quicker than other psychophysical methods, an important factor since we wanted to study a large number of psychoacoustic tasks.

In the 2AFC method, two intervals were presented in each trial and listeners indicated which interval contained the target stimulus by pressing the appropriate key on the response box ("1" or "2"). The adaptive (test) parameter changed in a 2-down/1-up staircase manner (Levitt 1971). The staircase always began with an initial parameter value that made the difference between the two intervals clearly audible. An initially large step size was reduced after three reversals, and the assessment was terminated after a total of 11 reversals.

In both methods, each threshold assessment was performed only once unless no reliable threshold estimation could be obtained (i.e., test parameter values did not converge to a threshold value). When using the yes–no procedure (with a maximum-likelihood algorithm), an assessment was repeated when there were 2 false positives in 4 catch trials (a single false positive in a threshold assessment was not, by itself, considered as a reason to repeat the assessment). A repeated failure to achieve a reliable threshold resulted in the assessment being labeled a "missed threshold."

Threshold estimation

In both the yes–no method and 2AFC, thresholds were determined by fitting a logistic psychometric function of the form

$$\alpha + \frac{100 - \alpha}{1 + e^{-\kappa(x-\mu)}}$$

where μ is the midpoint of the psychometric function (taken to be the threshold estimation), κ is the slope of the function, and α is the lower asymptote, to the individual decisions of the participants (coded as 0 or 1) from all trials in an assessment. We did not pool decisions, even when the same level was presented more than once. The upper asymptote was always set at 100, μ and κ were free variables fitted independently, and α was a third free variable in the yes–no procedure but was set at 0.5 in the 2AFC procedure.

Since the procedure used for threshold estimation is sensitive to the initial values of the parameters, each fit was inspected and multiple initial points were tested. Additionally, in order to ensure that our threshold estimates were unbiased and of low variance in the conditions of the experiments, we performed an extensive set of simulations. These simulations showed that our procedure gave essentially unbiased estimates of the threshold as long as false alarm rates in the yes–no procedure were lower than 10–20%. The slopes of the psychometric functions were badly estimated (they were often far too large), but this did not increase either the bias or the variance in the estimates of the thresholds. Thus, it was necessary to estimate the false alarm levels of the participants. It is impossible to estimate the probability of false alarms from single tracks because of the expected small number of failures in catch trials. Therefore, we accumulated the statistics of catch trials across all tracks of each participant. The resulting false alarm rate was low (about 10% in both controls and RD). To justify this procedure, we verified that across individual tracks the actual occurrence of failures in catch trials was consistent with a binomial distribution with probability 0.1 and the number of catch trails that actually occurred in that track. For only one participant (out of the 50 who took part in the study) did the frequency of observed false alarms in individual tracks differ from the expected binomial distribution. Thus, the procedure we used is valid for estimating thresholds.

Reading, language, and cognitive tests

We tested all participants' reading and spelling skills using a wide battery of tests similar to those used for English readers, as well as other tests aimed at assessing participants' general cognitive performance on nonlinguistic tasks. The following reading and cognitive tests were administered during several sessions prior to the session in which psychoacoustic testing was conducted:

Nonword reading (NW-*read*): Speed and accuracy of reading aloud a list of nonsense words.

Real word reading (RW-*read*): Speed and accuracy of reading aloud a list of real words.

Oral reading rate (PASS-*read*): Speed of reading aloud an academic level passage.

Spelling (SPELL): Spelling accuracy of a list of words read aloud by the experimenter.

Orthographic discrimination (ORTH): Accuracy of orthographic word recognition in a word-pseudohomophone discrimination task.

Spoonerism (SPOON): Accuracy in swapping the first phoneme of the first word in an orally presented word pair with the first phoneme of the second word. This task was used to assess phonemic awareness.

Seashore Rhythm Test (SEASHORE): Accuracy in discriminating two auditory rhythmic patterns. This is a subtest of the Halstead–Reitan neurological assessment battery (Halstead 1947) which is used to assess auditory attention (originally part of the "Seashore Test of Musical Talents," Seashore 1939).

Subtests of the Wechsler Adult Intelligence Scales (WAIS-III): Standard scores in the following subtests of the WAIS-III (Wechsler 1997): Digit Symbol – Coding, Similarities, Block Design, and Digit Span.

Psychoacoustic Tests

Just noticeable difference (JND) for frequency. Two 75-ms (5-ms rise–fall time) 70-dB sound pressure level (SPL) tones separated by 500 ms were presented on each trial. In about 20% of the trials the two tones had the same frequency (1200 Hz); in the remainder the nonreference tone was lower by an adaptively varied amount. Listeners had to indicate whether the two tones were the same or different (a variant of the yes–no method). The frequency difference in each trial was selected according to a maximum-likelihood procedure. Each experimental assessment consisted of 30 trials. No feedback was given. The first threshold assessment was always obtained for diotic presentation of the stimuli. In the second and third assessments, stimuli were presented monotically (to the left and right ears in separate assessments), with the order of ear presentation counterbalanced across listeners.

Lateralization of tones along the horizontal axis. Perception of the lateral position of gated 500-Hz, 70-dB SPL tones presented with interaural phase differences (IPDs) was determined. In each trial a 500-ms (10-ms rise–fall time) tone was presented with an interaural phase difference ranging from −157° to +180° sampled at 22.5° intervals. Each phase difference was presented 5 times in random order. No adjustment was made to the hearing level difference between the ears. Listeners had to indicate the subjective lateral position of the tone by pressing a button on a scale of −4 to +4, with −4 being the extreme left and +4 the extreme right. All participants received a short training session to familiarize themselves with the stimulus range. No feedback was provided.

Binaural unmasking. Thresholds for detection of a 500-Hz tone were measured in the presence of simultaneous broadband noise. Both noise and signal tone could be presented either diotically (no phase difference between the ears; N_0 and S_0, respectively) or in antiphase (N_π and S_π respectively), yielding the following experimental conditions: (1) N_0S_0, (2) N_0S_π, and (3) $N_\pi S_0$. The binaural masking level difference (BMLD) is typically defined as the difference in threshold between condition (1) and each of the other two conditions. The noise was presented for 600 ms (noise spectrum level 30 dB SPL in a 1-Hz bandwidth, 10-ms rise–fall time) and the 130-ms tone started 470 ms after noise onset. Tone level was varied adaptively according to a maximum-likelihood procedure. Catch trials contained only the broadband noise. Each experimental assessment consisted of 22 trials. Listeners had to indicate whether or not a tone was present in the noise (yes–no method). Feedback was provided for both correct and incorrect responses.

Amplitude modulation (AM) detection. The threshold depth of modulation required to discriminate 500-ms bursts (10-ms rise–fall times) of unmodulated broadband (white) noise from amplitude-modulated noise was determined adaptively using a 2AFC paradigm. The noise spectrum level was roved within a range of ±10 dB on each presentation with a median spectrum level of 35 dB SPL in order to ensure that level would not be a valid cue for detection of the interval containing the modulated noise. Threshold modulation depths were estimated for modulation frequencies of 4, 10, 100, and 500 Hz. A plot of the threshold modulation depth as a function of modulation frequency yields the temporal modulation transfer function (TMTF).

Comodulation masking release (CMR). Thresholds for detection of a 1-kHz tone were assessed under the following masking conditions: (1) unmodulated on-frequency band (NB-unmod): a noise band 50-Hz wide (40-dB SPL noise spectrum level) centered on tone frequency; (2) modulated on-frequency band (NB-mod): the same noise band modulated at 10 Hz; (3) modulated on-frequency band with comodulated flankers (WB-mod): the same on-frequency band modulated at 10 Hz with comodulated wideband flanking noise bands added outside the critical band (the noise was 1.8-kHz wide, centered on tone frequency, with a 130-Hz spectral notch around the center frequency). The reduction in detection thresholds due to modulation of the on-frequency band is known as the modulated–unmodulated difference (MUD). The further reduction when comodulated wideband noise is added to the modulated on-frequency band is known as the comodulation masking release (CMR). Conditions (2) and (3) were tested for each ear to get the CMR. Condition (1) was then tested only for the ear in which the CMR was higher. Two 1000-ms (10-ms rise–fall time) intervals separated by 500 ms were presented on each trial, one containing only the masker and the other containing the masker and the signal tone. The masker lasted throughout the interval and the 400-ms tone (10-ms rise–fall time) started 600 ms into the interval. Tone level was varied adaptively. Participants had to indicate which interval contained the tone (2AFC), with feedback provided for both correct and incorrect responses.

Auditory motion direction discrimination. The minimal angle required for detection of sound source movement direction (minimum audible movement angle, MAMA) was assessed using a 2AFC adaptive procedure. In each trial, two sounds were presented: one simulating rightward motion and the other leftward motion. Both motions were along a spherical, horizontal trajectory. Following Jacobson et al. (2001), the stimuli were created by filtering white noise through a position-dependent head-related impulse response (HRIR) function calculated from a set of measured HRIRs (Audis catalog of human HRTFs, © HEAD acoustics GmbH, 1998) and were generated digitally with a sampling period of 22.7 μs. The

TABLE 1

Results of the reading, language, and cognitive tests (means and standard deviations) for control and RD participants

Variable (units)[a]	*Control Mean (SD)*	*RD Mean (SD)*	*t-test p value*
NW-*read* (*z*-score[b])	0.0 (1.1)	−5.5 (2.7)	< 0.001
RW-*read* (*z*-score[b])	0.0 (1.0)	−6.4 (4.1)	< 0.001
PASS-*read* (words/min)	131 (13)	91 (18)	< 0.001
SPELL (errors/24)	0.3 (1.2)	4.8 (5.1)	< 0.001
ORTH (errors/69)	0.1 (0.6)	2.7 (4.2)	< 0.01
SPOON (errors/20)	1.8 (2.0)	7.7 (5.5)	< 0.001
SEASHORE (errors/30)	2.7 (1.9)	4.1 (2.7)	0.039
WAIS-III subtests: (scaled scores)			
Digit Symbol – Coding	11.0 (3.0)	8.7 (2.2)	< 0.01
Digit Span	10.3 (3.2)	7.8 (2.2)	< 0.01
Similarities	13.6 (2.1)	12.8 (2.6)	0.24
Block Design	12.4 (3.4)	10.9 (3.7)	0.16

[a] Abbreviations: NW-*read,* nonword reading; RW-*read,* real word reading; PASS-*read,* oral passage reading rate; SPELL, spelling; ORTH, orthographic word-pseudohomophone discrimination; SPOON, spoonerism; SEASHORE, Seashore Rhythm test; WAIS-III, Wechsler Adult Intelligence Scales (III).

[b] *z*-score: averaged *z*-scores of the reading rate and accuracy scores in relation to the control group averages (which are, by definitiom, 0.0).

starting angle of each stimulus was chosen at random in the range of ±20° from the vertical meridian at a resolution of 10°. Two conditions were tested: (1) stimuli move at a constant angular velocity of 45°/s with duration varied adaptively and (2) stimuli move for a fixed duration of 300 ms with angular velocity varied adaptively. Listeners were asked to indicate in which of the two intervals (first or second) the stimulus moved to the right. Feedback was provided for both correct and incorrect responses.

Frequency discrimination at variable interstimulus interval. Two 75-ms (5-ms rise–fall time) 70-dB SPL tones were presented in each trial, separated by a varying ISI. The ISI ranged in logarithmic step values between 4 and 2048 ms, presented in random order. The two tone frequencies used in this experiment were 1200 Hz and 1200 Hz minus 10 times each individual participant's frequency JND (average over ear conditions, as assessed previously), except in the following cases: (1) A 1000-Hz difference was used for listeners whose mean frequency JND was higher than 100 Hz (2 RDs) or for whom no reliable threshold could be measured in two or more of the ear conditions (1 control and 2 RDs). (2) When listeners failed to discriminate between the two tones presented separately prior to the beginning of the task, the frequency difference was increased until the tones were clearly distinguishable (2 controls and 2 RDs). Each two-tone combination (high–high, low–low, high–low, or low–high) was sampled 3 times for each ISI. Listeners had to indicate whether the two tones were the same or different. No feedback was provided. Left ear and right ear were tested separately, with order of presentation counterbalanced across participants.

RESULTS

Reading, language, and Cognitive Tests

Results of reading and cognitive tests for the RD and control participants are shown in Table 1. The RD group was impaired in all measures of reading and spelling, both in accuracy and in speed. Their scores on the spoonerism task (SPOON), assessing phonological awareness, were also significantly lower than the controls'. Errors on the Seashore Rhythm Test (SEASHORE) were also significantly higher for the RD group. This test has been shown to differentiate reading impaired and learning disabled children from age-matched unimpaired controls (McGivern et al. 1991). The RD group was also significantly impaired on the Digit Span and Digit Symbol – Coding subtests of the WAIS-III but not on the Block Design and Similarities subtests. This pattern of results is similar to the one previously reported for English-speaking RD adults (Gottardo et al. 1997; Hanley 1997; Snowling et al. 1997).

Psychoacoustic tests

Just noticeable difference (JND) for frequency. A summary of the results for the frequency JND test is shown in Table 2. The RD group's JND thresholds and false alarm rates were consistently higher, but these differences failed to reach significance for any of the ear conditions. The lack of a significant difference in thresholds is because participants with "missed thresholds" were not included in threshold averaging. Since a significantly higher proportion of the RD listeners had "missed threshold," the RD group average threshold is an underestimate of their difficulty

TABLE 2

Frequency JNDs, false alarm rates, and proportion of "missed thresholds" for control (C) and reading disabled (RD) participants for diotic and monotic stimulus presentation[a]

	Diotic		*Left ear*		*Right ear*		*Average*	
	C	*RD*	*C*	*RD*	*C*	*RD*	*C*	*RD*
Frequency JND (%)[b]	2.0	2.9	2.1	3.2	2.2	3.7	2.1	3.7
(SD)	(1.4)	(2.6)	(1.2)	(2.8)	(1.2)	(4.1)	(1.2)	(4.1)
Two-tailed *t*-test	$p = 0.197$		$p = 0.126$		$p = 0.120$		$p = 0.096$	
False alarm rate (%)	13.6	20.1	11.1	13.5	11.2	11.5	11.9	15.7
(SD)	(14.7)	(22.8)	(15.8)	(16.6)	(16.1)	(15.9)	(10.9)	(14.5)
Two-tailed *t*-test	$p = 0.259$		$p = 0.944$		$p = 0.599$		$p = 0.310$	
"Missed" thresholds (%)	11.1	26.1	7.4	8.7	3.7	21.7	7.4	18.8
χ^2-test	$p = 0.138$		$p = 0.404$		$p = 0.048$		$p = 0.016$	

[a] The average over the ear conditions is shown in the last column. The "missed thresholds" in this case the proportion over of all assessments.

[b] The mean thresholds were computed based on only reliable thresholds. "Missed thresholds" were excluded from this analysis.

with this task. This is emphasized in the distribution of participant thresholds, shown in Figure 1, where participants who failed to achieve a threshold are included in the right column.

Subgroups according to frequency JND. One reason for the lack of significance in the intergroup difference between controls and RDs is the high variability in thresholds within the RD group. In particular, comparisons between whole group averages downplay the difficulties of a large subgroup of the RD group in this task. Therefore, we chose the frequency JND task somewhat arbitrarily (choosing one of a range of other tasks would have yielded similar results) as a marker for potentially poor and average acoustic processors for subsequent subdivision among both controls and RDs. We used the following procedure: We defined a high-JND RD subgroup as those participants whose mean JND (averaged over ear conditions) was ≥ 2.5% or for whom we could not obtain a reliable threshold in more than one listening condition. We divided the control group according to the same criterion. Consequently, the RD group was composed of 11 high-JND and 12 low-JND participants, and the control group was composed of 9 high-JND and 18 low-JND participants.

Lateralization of tones along the horizontal axis. As seen in Figure 2, the high-JND RD subgroup was significantly different from all other subgroups in their performance of this task. The two control and the low-JND RD subgroups' curves show the expected pattern of responses. From −90° to +90° the perceived azimuth of the tone is related monotonically to the IPD. Beyond ±90°, the auditory images become increasingly ambiguous, often appearing at more than one position (usually on the opposite sides of the head). The high-JND RD subgroup's curve is flattened and shifted upward (toward the right), lying almost entirely right of the midline. A three-way ANOVA for reading group (control vs. RD) × JND subgroup (low- vs. high-JND) × IPD revealed a marginally significant main effect of reading group and highly significant main effects of both JND subgroup and IPD [reading group: $F(1,720) = 3.43$, $p = 0.065$; JND subgroup: $F(1,720) = 19.3$, $p < 0.001$; IPD: $F(15,720) = 33.3$, $p\ \ 0.001$]. There was no significant interaction between reading group and JND subgroup [$F(1,720) = 0.56$; $p = 0.45$]. However, since both reading group and JND subgroup had a significant interaction with the IPD [reading group × IPD: $F(15,720) = 2.31$, $p = 0.003$; JND subgroup × IPD: $F(15,720) = 1.74$, $p = 0.039$], we decided to explore these interactions by testing lateralization to the left and right separately. Therefore, we performed separate three-way ANOVAs for the left and right side. On the left side, this analysis revealed a strong reading group × JND subgroup interaction [$F(1,360) = 8.5$, $p = 0.004$]. To examine the source of this interaction, we subjected the data to a two-way ANOVA of the JND subgroups × IPD within each reading group. Both reading groups showed a main effect of JND subgroup, but it was much stronger in the RD group [control: $F(1,192) = 5.23$, $p = 0.023$; RD: $F(1,168) = 30.5$, $p < 0.001$]. Only the control group showed a main effect of IPD [control: $F(7,192) = 5.7$, $p < 0.001$ Rd: $F(7,168) = 1.88$, $p = 0.075$]. These results show that on average the differences between the lateralization judgments of the high-JND and low-JND RD subgroups were much larger than the differences between the lateralization judgments of the high-JND and low-JND controls (although these differences were also significant), confirming the impression given by visual inspection of Figure 2. On the right side, the interaction between reading group and JND subgroup was weaker but still significant [$F(1,360) = 4.2$, $p = 0.041$]. In neither reading group did the two-way ANOVA show a main effect of JND subgroup

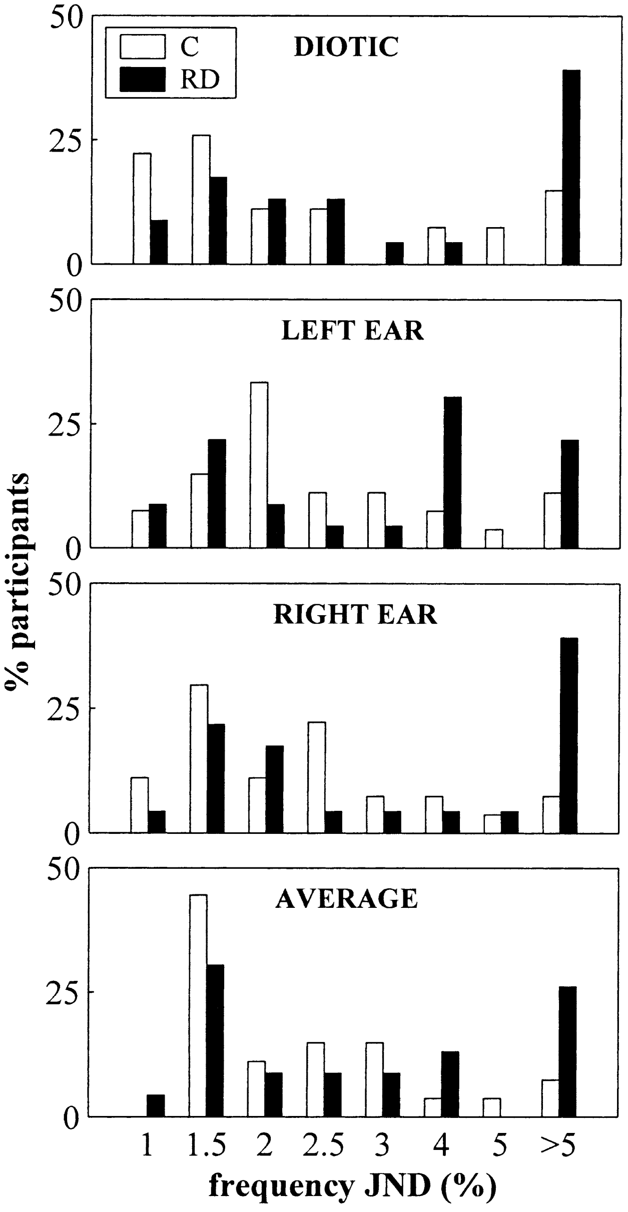

FIG. 1. Distribution of control (C, open bars) and reading disabled (RD, filled bars) participants as a function of the frequency discrimination JNDs (in percent of the reference frequency of 1200 Hz). Results are shown for the diotic, left ear and right ear conditions, and an average over all ear conditions. Participants with "missed thresholds" are included in the rightmost bars (>5%).

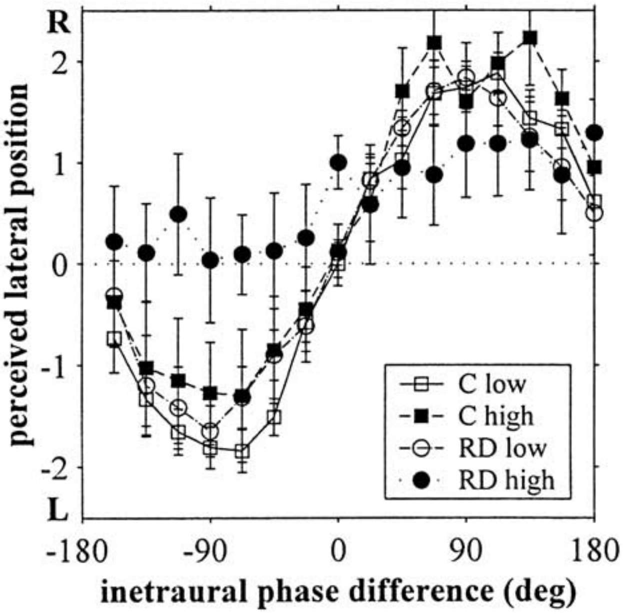

FIG. 2. Lateralization of a 500-Hz tone along the horizontal axis, plotted as the perceived lateral position (button presses) as a function of the interaural phase difference (negative values represent left ear leading and positive values right ear leading). The curves of the low-JND control group (C low, open squares) and of the low-JND RD subgroup (RD low, open circles) are symmetrical "S" shapes around the (0,0) point. The high-JND control subgroup has a similar curve that is slightly shifted toward the right, whereas the shape of the high-JND RD subgroup (RD high, filled circles) is both flattened and shifted toward the right side of the head. R = right side, L = left side. Error bars are standard errors of the means.

[control: $F(1,192) = 3.44$, $p = 0.065$; RD: $F(1,168) = 1.3$, $p = 0.26$], and only in the control group was there an effect of IPD [control: $F(7,192) = 4.7$, $p < 0.001$;RD: $F(7,168) = 0.92$, $p = 0.49$]. Thus, the differences between the judgments of the high- and low-JND subgroups were much smaller on the right side. The sign of the reading group × JND subgroup interaction was different on the two sides, since the judgments of the high-JND participants tended toward the center. This phenomenon might explain the lack of reading group × JND interaction when the full range of IPDs was considered.

Binaural unmasking. When the control and RD groups were each taken as a whole, we found no significant difference between them on any measure of performance on this task. There was no difference in detection thresholds, and the false alarm rates were comparable in the two groups (overall rate of 11.9% for the control and 11.5% for the RD group). Two control participants failed to perform the N_0S_0 and N_0S_π conditions, and three RD participants failed to perform the $N_\pi S_0$ condition. These participants were excluded from subsequent statistical analysis. We divided the two groups according to performance on the frequency JND task, as described above. Tone detection thresholds and binaural masking level differences (BMLDs) are shown in Figure 3a and b, respectively. As shown in Figure 3a, the thresholds were slightly higher for both high-JND subgroups (controls and RD) than for the low-JND subgroups, but the differences were very small (2–3 dB). A three-way ANOVA for reading group (control vs. RD) × JND subgroup (low- vs. high-JND) × condition (N_0S_0, N_0S_π, $N_\pi S_0$) showed no effect of reading group but signifi-

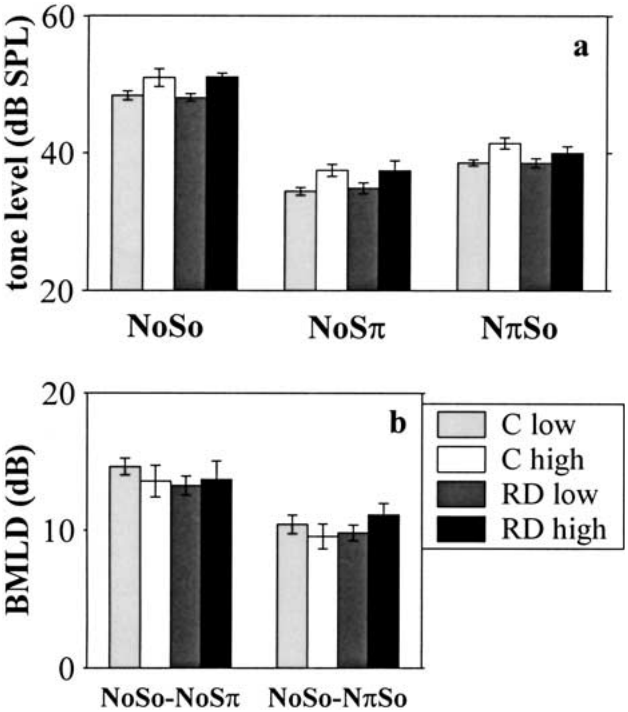

FIG. 3. **a**. Thresholds for detection of a 500-Hz tone (the signal) in different binaural conditions: diotic noise and signal (N_0S_0), diotic noise with antiphase signal (N_0S_π), and antiphase noise with diotic signal ($N_\pi S_0$). The participants with high-frequency JND from either the control or the RD experimental subgroup (C high and RD high, respectively) were slightly worse at detecting the tone in the masker in all conditions than the participants with low-frequency JND (C low and RD low). **b.** Binaural masking level differences (BMLDs) for the two antiphase conditions: N_0S_π (left side of the graph) and $N_\pi S_0$ (right side of the graph). There is no significant difference between any of the control and RD subgroup means in either condition. Error bars are standard errors of the means.

cant effects of JND subgroup and condition [reading group: $F(1,128) = 0.2$, $p = 0.66$; JND subgroup: $F(1,128) = 30.58$, $p < 0.001$; condition: $F(2,128) = 310.3$, $p < 0.001$]. None of the interaction terms was significant, signifying that BMLDs did not differ between subgroups [reading group × JND subgroup: $F(1,128) = 0.29$; $p = 0.59$; reading group × condition: $F(2,128) = 0.33$; $p = 0.72$; JND subgroup × condition: $F(2,128) = 0.2$, $p = 0.82$. Thus, while absolute detection levels were higher for both high-JND subgroups, the amount of binaural unmasking was not impaired.

Amplitude modulation detection. Figure 4 shows the temporal modulation transfer functions (TMTFs) for the high- and low-JND RD subgroups and for the controls (the high- and low-JND control groups did not perform differently, see below). Each point on the graph represents the threshold modulation depth needed to detect the AM. We performed a three-way ANOVA (reading group × JND subgroup × modulation frequency) on the AM depth threshold data. There was no main effect of reading group, but the

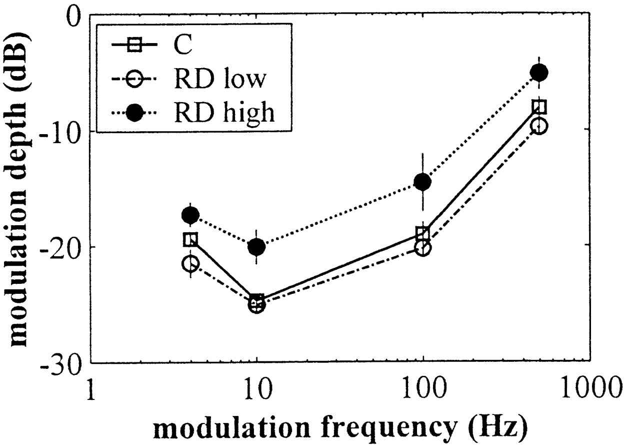

FIG. 4. Temporal modulation transfer functions (TMTFs, modulation depth at threshold as a function of the modulation frequency) for the control (C), low-JND RD (RD low), and high-JND RD (RD high) subgroups. The high-JND RD subgroup had significantly higher modulation detection thresholds than both the control group and the low-JND RD subgroup. The low-JND RD subgroup had slightly (but significantly) lower thresholds than the control group. Error bars are standard errors of the means.

main effects of both JND subgroup and modulation frequency were significant [reading group: $F(1,176) = 1.98$, $p = 0.16$; JND subgroup: $F(1,176) = 23.2$, $p < 0.001$; modulation frequency: $F(3,176) = 113.6$, $p < 0.001$]. However, the reading group × JND subgroup interaction was also significant [$F(1,176) = 8.56$, $p = 0.004$], showing that the high-JND controls and high-JND RDs performed differently with respect to this task. To establish the source of this interaction, we compared the low- and high-JND subgroups within each reading group using a two-way ANOVA. In the control group there was no main effect of JND subgroup [$F(1,92) = 1.89$, $p = 0.17$]. On the other hand, in the RD group there was a highly significant effect of JND subgroup [$F(1,84) = 28.4$, $p < 0.001$]. There was, however, no interaction between JND subgroup and modulation frequency [$F(3,84) = 0.12$, $p = 0.95$], showing that the high-JND subgroup was uniformly worse than the low-JND subgroup in detecting AM at all modulation frequencies.

Comodulation masking release (CMR). There was no difference between the high- and low-JND controls on any measure, and the entire analysis was done for the control group as a whole. There was also no significant difference between the performance in the two ears, and results were averaged over ear conditions. Detection thresholds for the various conditions in this task are shown in Figure 5a, and the CMR and MUD (modulated–unmodulated difference) are shown in Figure 5b. In this case we could not perform a three-way ANOVA with masking condition as the third factor because the threshold distributions varied between conditions, with outliers that increased

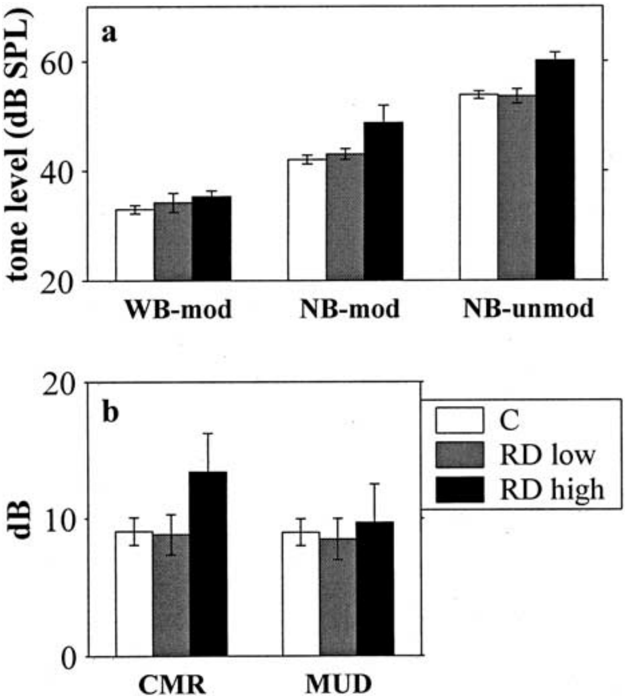

FIG. 5. **a**. Thresholds for detection of a 1-kHz tone in the three masker conditions: (1) modulated on-frequency band with comodulated wideband flankers (WB-mod), (2) modulated on-frequency band (NB-mod), and (3) unmodulated on-frequency band (NB-unmod), for the control (C), and high- and low-frequency JND reading disabled participants (RD high and RD low, respectively). Thresholds were significantly higher for the high-JND RD subgroup in both narrowband conditions (NB-mod and NB-unmod) but not in the wideband condition (WB-mod). There was no difference in thresholds between the control and low-JND RD subgroups. **b**. Mean comodulation masking release [CMR, the difference between the two modulated conditions (NB-mod and WB-mod)] and modulated–unmodulated difference [MUD, difference between the two narrowband conditions (NB-mod and NB-unmod)] for the controls and RD participants. There was no significant difference between subgroups for either measure. Error bars are standard errors of the means.

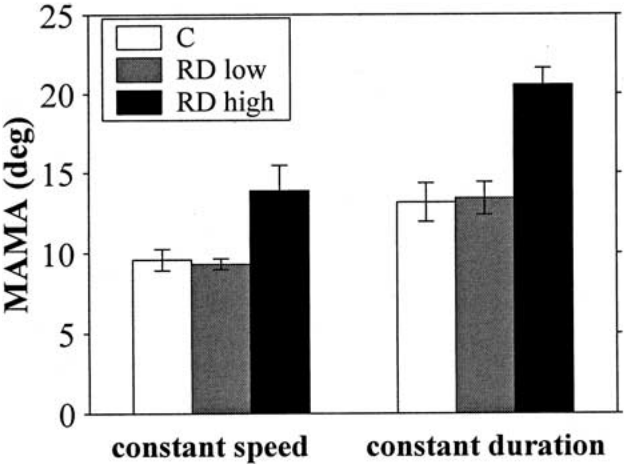

FIG. 6. Discrimination of motion direction under two conditions: (1) constant speed and variable duration, (2) constant duration and variable speed. Both thresholds are expressed in minimum audible movement angles (MAMAs). The MAMAs of the high-JND RD participants were significantly higher than those of the controls and low-JND RDs in both conditions. Error bars are standard errors of the means.

threshold variance in the modulated wideband condition. Therefore, we performed a separate two-way ANOVA (reading group × JND subgroup) for the thresholds measured in each masking condition. In the modulated wideband condition (WB-mod), there was neither a main effect of reading group nor of JND subgroup and no interaction [reading group: $F(1,44) = 1.97$, $p = 0.17$; JND subgroup: $F(1,44) = 0.06$, $p = 0.81$; reading group × JND subgroup: $F(1,44) = 0.39$, $p = 0.64$], showing that in this condition all subgroups had similar performance. In the modulated narrowband condition (NB-mod), there was a significant main effect of reading group but not JND subgroup, and the interaction was just short of significant [reading group: $F(1,44) = 5.37$, $p = 0.025$; JND subgroup: $F(1,44) = 1.84$, $p = 0.18$; reading group × JND subgroup: $F(1,44) = 3.87$, $p = 0.055$]. As seen in Figure 5, the high-JND RD subgroup performance was poorer compared with the other subgroups, but the high variance in the sample caused the interaction to be nonsignificant. In the unmodulated narrowband condition (NB-unmod), both the main effects and the interaction were significant [reading group: $F(1,44) = 6.52$, $p = 0.014$; JND subgroup: $F(1,44) = 5.52$, $p = 0.023$; reading group × JND subgroup: $F(1,44) = 8.95$, $p = 0.0045$], showing that the high-JND RD subgroup is differentially more impaired compared with the other subgroups. The true CMR did not differ between subgroups [reading group: $F(1,44) = 1.38$, $p = 0.25$; JND subgroup: $F(1,44) = 1.24$, $p = 0.27$; reading group × JND subgroup: $F(1,44) = 1.99$, $p = 0.17$], and neither did the MUD [reading group: $F(1,44) = 0.22$, $p = 0.64$; JND subgroup: $F(1,44) = 0.09$, $p = 0.77$; reading group × JND subgroup: $F(1,44) = 0.02$, $p = 0.88$]. Thus, while detection thresholds were significantly higher for the high-JND RD subgroup in the unmodulated narrowband condition, masking release was not reduced.

Auditory motion direction discrimination. Figure 6 shows the detection thresholds for motion direction (expressed as the displacement angle) of the controls and RD high- and low-JND subgroups for the constant duration and constant speed conditions (control subgroups did not significantly differ). A three-way ANOVA yielded significant main effects of reading group, JND subgroup, and condition [reading group: $F(1,90) = 8.25$, $p = 0.005$; JND subgroup: $F(1,90) = 14.65$, $p < 0.001$; condition: $F(1,90) = 16.98$, $p < 0.001$]. The only significant interaction was between reading group and JND subgroup [$F(1,90) = 6.85$, $p = 0.01$]. The source of the interaction is the poorer performance of the high-JND RD subgroup com-

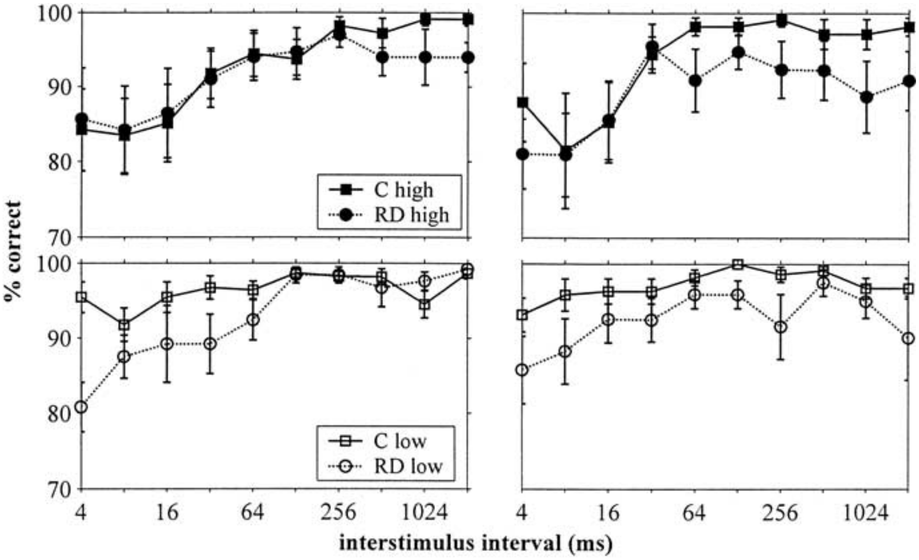

FIG. 7. Frequency discrimination at variable interstimulus intervals for monotic listening (left ear in the left panels, right ear in the right panels). The two upper panels show the performance of the high-JND control and RD subgroups (filled squares and circles, respectively), and the lower panels show the performance of the low-JND control and RD subgroups (open squares and circles, respectively). The two low-JND subgroups differed on the short ISIs (significant only in the left ear). Error bars mark indicate standard errors of the means.

pared with the other subgroups. There was no difference in performance between the two control JND subgroups [$F(1,48) = 0.67$, $p = 0.42$], but the two RD subgroups differed in both conditions [JND subgroup: $F(1,42) = 23.21$, $p < 0.001$; subgroup × condition: $F(1,42) = 0.56$, $p = 0.46$]. Thus the high-JND RD subgroup required a greater displacement to discriminate leftward from rightward motion when the adaptive parameter was either speed or duration.

Frequency discrimination at variable interstimulus intervals. This task was designed to dissociate poor performance in tone sequencing due to poor frequency discrimination from poor performance due to poor temporal processing. We thus made the frequency discrimination difficulty as similar as possible for all participants in order to focus solely on the temporal constraints. It was assumed that if temporal difficulties *per se* are the source, group differences should appear for the short ISIs but not for the long ISIs. If poor frequency discrimination is the source, then we expected to eliminate intergroup differences by this procedure.

Figure 7 shows the performance of the control and RD subgroups, high-JND at the top and low-JND at the bottom, for the left and right ear conditions. The average frequency differences used were 441 Hz for the high-JND control subgroup and 593 Hz for the high-JND RD subgroup (the difference was not significant; $p = 0.12$ on a two-tailed *t*-test) and 183 Hz for the low-JND control subgroup and 204 Hz for the low-JND RD subgroup (the difference was not significant; $p = 0.34$ on a two-tailed *t*-test).

We performed a three-way ANOVA (reading group × JND subgroup × ISI) on the data for each ear. For the left ear, there was a significant main effect of reading group but not of JND subgroup, as well as a main effect of ISI [reading group: $F(1,450) = 15.5$, $p < 0.001$; JND subgroup: $F(1,450) = 0.33$, $p = 0.57$; ISI: $F(9,450) = 6.45$, $p < 0.001$]. Only the reading group × JND subgroup interaction was significant [$F(1,450) = 8.4$, $p = 0.004$]. To look for the source of this interaction, we compared the low- and high-JND subgroups within each reading group. In the control group there was a main effect of JND subgroup and ISI as well as a strong interaction with ISI [JND subgroup: $F(1,250) = 13.7$, $p < 0.001$; ISI: $F(9,250) = 6.0$, $p < 0.001$; JND subgroup × ISI: $F(9,250) = 2.54$, $p = 0.008$]. In the RD group only the main effect of ISI was significant [JND subgroup: $F(1,200) = 1.55$, $p = 0.21$; ISI: $F(9,200) = 2.34$, $p = 0.016$; JND subgroup × ISI: $F(9,200) = 0.15$, $p > 0.99$]. This analysis shows that the interaction results from the low-JND control group performing better compared with all other subgroups.

In the right ear condition, the three-way ANOVA yielded significant main effects only of reading group and ISI [reading group: $F(1,450) = 32.8$, $p < 0.001$; JND subgroup: $F(1,450) = 1.04$, $p = 0.31$; ISI: $F(9,450) = 3.64$, $p < 0.001$] and a nonsignificant reading group × JND subgroup interaction [$F(1,450) = 3.64$, $p = 0.057$], showing that while the two groups differed, the difference in performance was unrelated to JND.

Thus, the only interaction between subgroup and ISI is the result of the low-JND control subgroup

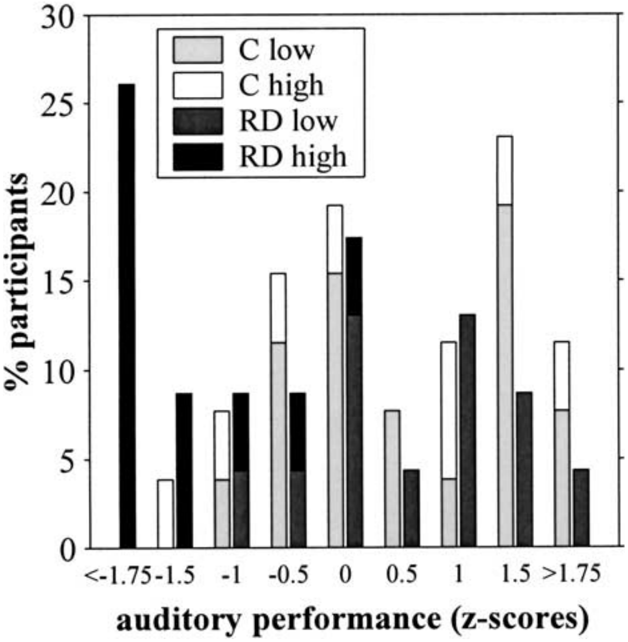

FIG. 8. Frequency histogram of the overall mean *z*-score measure of "auditory performance" for the four subgroups. The x axis indicates bin centers in units of standard deviation from the overall population mean (control and RD). The distribution of the high-JND RDs (RD high) was significantly different from all other subgroups (which did not differ from each other).

having better performance than all other subgroups for short ISIs in the left ear condition. Compared with them, the low-JND RDs were indeed poorer at short ISIs, but performed similarly to the two high-JND subgroups, both control and RD. It is also possible that this interaction arises from a ceiling effect observed in the performance of the low-JND controls at long ISIs. This result is weak for two reasons. First, it is apparent only in the comparisons between low-JND RDs and low-JND controls (some controls, those in the high-JND subgroup, had difficulties similar to the RDs at short ISIs). Second, it is significant only in the left ear condition.

Overall auditory processing

Figure 8 shows the distribution of the average of the *z*-scores of four auditory tasks for all the participants in this study (divided into the four high- and low-JND subgroups). The four tasks were (1) lateralization of a diotic 500-Hz tone with no interaural phase difference (LAT-0°, Fig. 2); (2) detection of a 10-Hz AM of broadband noise (AM-10Hz, Fig. 4); (3) detection of a 1-kHz tone within a narrow unmodulated noise band (NB-unmod, Fig. 5); and (4) motion direction detection when speed was the adaptive variable (MOT-speed, Fig. 6). These tasks were chosen out of the entire test battery because the performance of the high-JND RD subgroup on these tasks was significantly poorer than that of the other subgroups. The histogram shows that the distribution of low-JND RD participants completely overlaps the control distribution. Only three control participants (two from the high-JND subgroup and one from the low-JND subgroup) had a mean score of less than −0.75 SD from overall mean. On the other hand, the scores of about a third of all the disabled readers tested were below the −1.25 SD point, all of them from the high-JND RD subgroup.

TABLE 3

Spearman's rank correlations between the auditory measures used in calculating the auditory performance measure for the entire population[a]

	AM-10Hz	*LAT-0°*	*MOT-speed*
NB-unmod	0.575*	0.523*	0.240
AM-10Hz		0.572*	0.095
LAT-0°			0.076

[a] Abbreviations: NB-unmod: tone detection in unmodulated narrowband noise masker; AM-10Hz: detection of a 10-Hz amplitude modulation; LAT-0°. lateralization with 0° interaural phase difference; MOT-speed: motion direction detection with speed as the adaptive variable. *$p < 0.001$, otherwise not significant.

Spearman's rank correlations for thresholds in the tasks included in the measure of auditory performance are given in Table 3. Motion detection was not correlated with any other auditory measure, but scores on the other three tasks were highly intercorrelated to it.

Auditory performance and reading and cognitive measures

Table 4 shows the same reading and cognitive measures as in Table 1 but separately for the four subgroups. The *p* value for the main effects of reading group and JND subgroup in the two-way ANOVA are also reported. On all the reading and spelling measures, only the effect of reading group was significant with no difference between JND subgroups. In the spoonerism task (phonological awareness) and the Seashore Rhythm Test there was an effect of both reading group and JND subgroup. This was also true for the Digit Symbol – Coding and the Digit Span subtests of the WAIS. In the Similarities and the Block Design subtests of the WAIS there was no reading group effect but there was an effect of JND subgroup. None of the interactions between reading group and JND subgroup were significant. While reading does not appear to be related to performance on the auditory tasks, all cognitive measures of the WAIS that we administered do appear to be related to it.

Figure 9 shows a scatter plot of the oral passage reading rate (PASS-*read*) plotted against the composite measure of auditory performance for the

TABLE 4

Reading and cognitive scores (means and standard deviations) for the low- and high-JND control and RD participants[a]

Variable (units)[b]	*Control low Mean (SD)*	*Control high Mean (SD)*	*RD low Mean (SD)*	*RD high Mean (SD)*	*Reading group (p value)*	*JND subgroup (p value)*
NW-*read* (*z*-score)	0.3 (0.9)	−0.6 (1.2)	−5.4 (2.8)	−5.6 (2.8)	<0.001	0.33
RW-*read* (*z*-score)	0.2 (0.9)	−0.3 (1.2)	−6.5 (5.0)	−6.2 (3.1)	<0.001	0.90
PASS-*read* (words/min)	130 (15)	132 (10)	94 (22)	87 (13)	<0.001	0.59
SPELL (errors/24)	0.4 (1.5)	0.1 (0.3)	4.8 (4.7)	4.8 (5.8)	<0.001	0.87
ORTH (errors/69)	0.2 (0.7)	0.0 (0.0)	2.2 (3.2)	3.9 (5.1)	0.004	0.64
SPOON (errors/20)	1.2 (1.5)	2.9 (2.5)	6.0 (5.3)	9.5 (5.3)	<0.001	0.024
SEASHORE (errors/30)	2.2 (1.6)	3.6 (2.2)	2.8 (2.1)	5.5 (2.5)	0.041	0.001
WAIS-III sub-tests (scaled scores):						
Digit Symbol – Coding	11.3 (2.7)	10.1 (3.6)	9.9 (2.1)	7.4 (1.5)	0.009	0.019
Digit Span	11.1 (3.4)	8.4 (1.5)	8.6 (2.2)	6.9 (2.1)	0.017	0.010
Similarities	13.8 (2.2)	13.3 (2.0)	14.1 (1.7)	11.5 (2.8)	0.27	0.026
Block Design	13.2 (3.3)	10.3 (2.9)	13.5 (2.9)	8.1 (1.8)	0.30	<0.001

[a] The reported *p* values are for the main effects of the two-way ANOVA between reading group (control vs. RD) and JND subgroup (low- vs. high-JND). All interactions were nonsignificant.

[b] Abbreviations are the same as in Table 1.

entire population. There is a significant correlation between the reading and auditory measures (Spearman's rank correlation coefficient $r = 0.46$, $p = 0.001$). However, the pattern revealed by the scatter plot is interesting: whereas participants who did well on the auditory tasks could be either good or poor readers (i.e., either controls or members of the low-JND RD group), all participants who were consistently poor on the auditory tasks were also very slow readers. There are no good readers with very poor psychoacoustic performance.

DISCUSSION

Summary of results

About a third of our population of disabled readers had severe auditory perceptual deficits (as measured by the summary statistic, Fig. 8). These difficulties spanned a wide range of tasks covering processing time constants, from hundreds of microseconds to several seconds, and various spectral processing requirements. A subgroup of the RD population who performed poorly on frequency discrimination had on average severe difficulties in lateralizing tones using interaural time differences, detecting amplitude modulation across a broad range of modulation frequencies, and discriminating motion direction using interaural spectral energy and temporal cues. The same subgroup had elevated detection thresholds for tones in narrowband noise. In contrast, this group did not have impaired binaural unmasking, nor were they impaired in detecting tones masked by modulated wideband noise (comodulation masking release was not impaired).

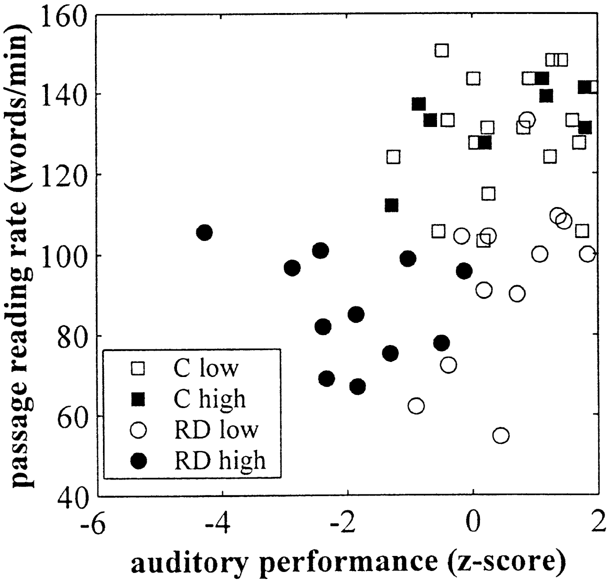

FIG. 9. Oral reading rate of a passage (PASS-*read*) plotted against the auditory performance statistic for all participants in our study. The correlation between reading and auditory performance is significant in the population, but whereas poor readers can have either good or poor auditory performance, there are no poor auditory performers who are good readers.

The complementary subgroup of RDs had slight difficulty in only one condition. Their overall psychoacoustic performance was not different from that of controls except when frequency discrimination was assessed using short ISIs. In this case, their performance on the left ear condition was impaired compared with their direct controls, although spectrally well-differentiated tones (as measured with an ISI of 500 ms) were used.

Comparison with previous findings

Difficulty in frequency discrimination is not a new finding in the reading disabled, though there is no consensus as to the extent of the deficit. Many studies have reported a large and highly significant difference in the frequency JND between disabled and normal readers (e.g., McAnally and Stein 1996; Ahissar et al. 2000). Our results are similar to those of Hill et al. (1999). Whereas frequency discrimination of disabled readers was worse overall, group differences of frequency JNDs failed to reach significance. Yet, the number of "missed thresholds" was significantly larger in the RD than in the control group. Since we could not combine these data, the average JNDs include only successful assessments and consequently the intergroup difference was underestimated. In a separate study in which the same participants were tested on a different frequency discrimination task (a "higher–lower" paradigm), frequency JNDs significantly differed between these two groups of participants (Banai et al. 1999). When listeners with "missed thresholds" in the "same–different" paradigm used here were excluded from the comparison of thresholds measured using the "higher–lower" paradigm, thresholds of the RD and control groups were no longer significantly different. A close examination showed that while control participants with "missed thresholds" did not have unusually high frequency JNDs, RD participants with "missed thresholds" had very high frequency JNDs (as measured by a "higher–lower" paradigm). Thus, the lack of a significant intergroup frequency JND difference was a consequence of our assessment procedure and cannot be ascribed to our sampled test population.

Lateralizing tones based on interaural temporal cues presented great difficulty for the subgroup of RDs with poor frequency discrimination. Lateralization in the reading disabled has not been measured systematically (though it is briefly mentioned in Hari et al. 1999, p. 2348). Given their difficulties in lateralization, we expected these listeners to have reduced binaural masking level difference (BMLD), as observed by McAnally and Stein (1996, using a 1-kHz tone). However, the group of RDs who participated in our study (including those with high-frequency JND) had normal BMLD. In fact, our results are similar to those reported by Hill et al. (1999) using a 200-Hz tone. The different results may stem from the different frequencies used (rather than populations or behavioral procedures). In this case, RDs' BMLD may be reduced only for the higher frequencies.

Disabled readers with high frequency JND were poorer in detecting tones in modulated and unmodulated narrowband noise maskers (in the CMR experiment). Higher masking thresholds in the presence of narrow noise bands have not been reported for disabled readers. While both detection thresholds were elevated, their difference, the MUD, was similar across subgroups. Detection in wideband comodulated noise was normal, leading to a somewhat (though nonsignificantly) elevated CMR.

Disabled readers with high frequency JND also had difficulties in detecting amplitude modulation within a broad range of modulation frequencies. Our results for AM are in line with data in Menell et al. (1999), who also found impaired detection thresholds in the range of 10–500 Hz. Applying an even lower modulation frequency (4 Hz), we also found deficient detection for this slower modulation rate.

Another task that has not been previously studied, in which the disabled readers with high frequency JNDs had significant difficulties, was motion direction discrimination based on binaural temporal and energy cues. Interestingly, while this same group had difficulties in both lateralization and AM detection, scores on these tasks were not correlated with motion discrimination across the entire population.

The two RD subgroups, those with and without difficulties on auditory tasks, did not differ on any reading measures. The high-JND RD subgroup had poorer cognitive performance, however. A significant correlation between frequency discrimination JNDs and cognitive abilities has also been found in normal populations (Raz et al. 1987; Watson 1991).

Frequency discrimination and fast temporal processing

As stated in the Introduction, the "temporal processing deficit" hypothesis states that disabled readers have difficulty processing rapidly presented stimuli in the time range of tens of milliseconds and that a deficit in temporal processing at this time range leads to difficulties in speech perception at the phonemic level (Tallal 1980). Our goal here was not to show how low-level psychophysical deficits, such as a fast temporal processing deficit, can cause reading disabilities. Instead, we wanted to address the first part of the hypothesis, that is, to study the profile of psychoacoustic deficits and test whether it is consistent with the temporal processing deficit hypothesis.

The only evidence we could find in favor of this hypothesis emerges for frequency discrimination with variable interstimulus intervals. This is the only task in which the subgroup of RD with good frequency discrimination showed any sign of impairment and, more specifically, an impairment specific to temporal processing in the hypothesized time scale. The low-JND RDs had a deficit in discriminating two spectrally well-differentiated tones when these were separated by short (up to about 100 ms) ISIs; this difference was significant only in the left ear listening condition and only when this subgroup was compared with their direct controls. The source of the deficit was probably temporal in this instance because the frequency difference was determined for each listener by his/her frequency JND, which avoided the potential confusion between temporal processing and frequency discrimination. The frequency difference itself was clearly perceptible to all listeners, as demonstrated by the ceiling performance at longer ISIs in the left ear condition. However, this subgroup of RD participants showed no other sign of auditory processing deficits, even in tasks designed to measure temporal resolution on the same time scale of tens of milliseconds. Thus, even if this deficit is real, it is unrelated to other classical measures of temporal processing, such as amplitude modulation detection, and therefore does not seem to reflect a problem in fast temporal processing *per se.* The deficit that was observed in the low-JND RD subgroup for the left ear condition must result from the interaction between fast processing requirements and another, as yet unspecified, feature of this specific task.

Heath et al. (1999) also found a subgroup of their RD sample deficient on a similar task (with a constant frequency step for all listeners). In their case, however, these temporal deficits were found only in the subgroup that also had concurrent language problems. None of our participants were aware of or showed any overt sign of language impairment (although we did not conduct any formal tests to assess language abilities).

On the other hand, the subgroup of RD participants who did exhibit deficits in a broad range of auditory tasks were not specifically impaired in trials having short ISIs. At short ISIs, they performed as well as their control counterparts (the high-JND control subgroup), even though the absolute frequency differences used in their case were larger.

A specific temporal processing deficit?

As shown above, within the subgroup of RD with high-frequency JND, who had a broad range of auditory processing difficulties, no particular impairment was found for short ISIs in the frequency discrimination task. Several other results are consistent with the assumption that this subgroup had no specific fast temporal processing problem.

The result of unimpaired CMR (using a 10-Hz modulation) argues against a general temporal processing deficit in the tens of milliseconds time range. There are several hypotheses regarding the mechanisms underlying CMR, but all concur that the threshold reduction results from the ability to use the information in the correlated temporal envelope of energy in different spectral regions (see review in Hirsh and Watson 1996, p. 469). Since the modulation rate used in our experiment was 10 Hz, the temporal processing required was on the order of tens of milliseconds. If it were impaired, we would expect reduced masking release in the presence of modulated wideband noise, i.e., *reduced* CMRs. Furthermore, the MUDs would be expected to be about 3 dB (the difference in energy between the modulated and unmodulated narrowband maskers). However, the actual MUDs were much higher, close to 10 dB.

Our finding that AM detection was impaired at all the tested modulation frequencies (4–500 Hz) also does not support a temporal processing deficit in a specific range of time constants. A deficit in the time range of tens of milliseconds would have caused disabled readers to be more impaired in detecting intermediate (tens of Hz) rather than slower or faster modulation rates. This finding also provides further evidence against a simple temporal explanation based on the presumed relation of AM to speech perception. Slow rates of modulation (3–4 Hz) correspond to the syllable rate of speech, and intermediate modulation rates (tens of Hz) correspond to the subsyllabic rate of AM in the speech stream (Houtgast and Steeneken 1985). Based on this, McAnally and Stein (1997) predicted that disabled readers would have normal AM detection in the lower-frequency range. However, in a subsequent study they tested only modulation frequencies of 10 Hz and above (Menell et al. 1999). Indeed, deficits were found in this entire range. Adding a test in 4-Hz AM, we found that disabled readers were as impaired in detecting 4-Hz as in detecting 10- or 500-Hz AM.

Taken together, a fast temporal processing deficit, although parsimonious, does not capture the intricate pattern of results we obtained. On the one hand, disabled readers could efficiently use temporal information in the 10–100-ms range on some tasks (having, for example, even slightly *larger* CMR than normal participants). On the other hand, on other temporal processing tasks that tested a large range of time constants (such as the AM detection task), disabled readers had uniformly deficient performance instead of a deficit restricted to the 10–100-ms range.

Nonauditory accounts

General cognitive impairment. It has been shown that in normal populations auditory psychophysical performance is associated with cognitive performance (see review in Deary and Caryl 1997). Since the subgroup of reading disabled with poor auditory performance had also scored lower on cognitive tests, one could presume that they simply fall within the lower tail of the population distribution and that their poor psychophysical performance is attributable to a more general cognitive impairment. Reed (1989) had similarly suggested that disabled readers may have general difficulties with discriminating auditory stimuli (though she did not specifically associate these with poor cognitive performance). However, the poor auditory processors in our sample do not have an encompassing difficulty in making perceptual discriminations in all standard psychophysical tasks. For example, their hearing thresholds were not higher than other disabled readers or controls. Hearing thresholds were assessed using a 2AFC method and required fine discrimination at low sound levels. A general performance deficit would predict that they would also have higher hearing thresholds. Furthermore, RD participants with great difficulty in some tasks performed other tasks as well as the control participants. There was little or no difference in their detection thresholds for tones in wideband modulated noise (in the CMR task), while in the same task they had difficulties with detecting the tones in narrowband noise.

Inattention or low motivation? Inattention or low motivation can be a possible cause of poor psychophysical performance. It was our impression that our participants were highly motivated. Most participants approached us in response to ads or recommendations from educators. All participated in an ongoing research project in which they took part in previous 3–4 sessions (each 2–2.5 hours long), and yet they continued to make themselves available for further sessions even though many found the psychophysical tasks difficult. Our participants were also well compensated financially.

To discount the possibility of inattention affecting our results, we analyzed the performance of a sample of participants (from both the control and RD groups) on stimuli that were clearly discernible (high above threshold). For each participant, the proportion of incorrect responses at the upper asymptote of the psychophysical curve was assessed over all psychophysical tasks. This analysis yielded very low proportions of such incorrect responses to "easy" trials (highly discriminable stimuli). The worst psychoacoustic performer had fewer than 10% incorrect responses on these trials, and most participants (controls and RDs alike) had 5% or less incorrect responses. Furthermore, there was no correlation between the proportion of incorrect responses and the actual psychophysical thresholds, indicating that our findings cannot be attributed to inattention.

Language-based deficit? Another alternative is that the poor acoustic processors among the disabled readers may have difficulty in rapidly applying verbal labels to the acoustic stimuli, resulting in poor psychophysical performance. This explanation is interesting since it interprets poor psychoacoustic performance as a byproduct of poor linguistic abilities. Indeed, in two-interval, two-alternative forced choice tasks, labeling the stimuli may improve performance; in contrast, in yes–no tasks, or in the lateralization task, problems in labeling are not expected to affect the results. However, the pattern of results here does not support these predictions. On the one hand, quite poor performance was found in the lateralization task. Here, participants heard one stimulus in each trial and had to press the button in the direction of the perceived sound. On the other hand, some tasks using the 2AFC paradigm did not pose difficulties for the reading disabled. For example, in the CMR task the narrowband conditions yielded a performance deficit for the high-JND RDs and the wideband condition did not. These conditions differed only in the stimuli and not in the behavioral context.

A deficit in phase locking?

Since frequencies up to about 1 kHz are reliably coded with a phase-locking mechanism in addition to the place code in the cochlea, it has been hypothesized that the reduced frequency discrimination observed in several studies is due to an impaired phase-locking mechanism in disabled readers (McAnally and Stein 1996; Baldeweg et al. 1999). Both lateralization created with IPD and binaural unmasking are thought to depend on phase locking and the calculation of binaural correlation in the brainstem. Thus, performance on both tasks should be deficient if phase locking is impaired. Lateralization by disabled readers with poor frequency discrimination was indeed severely impaired. However, binaural unmasking was not reduced in this subgroup of reading disabled. In both tasks the tone frequency was 500 Hz, so both should have been affected to the same extent by the proposed deficit in phase locking. Given this discrepancy, we conclude that impaired phase locking does not explain the pattern of deficits and nondeficits described here.

A deficit in across-channel integration?

Even though in our experiment we used a pure tone, which is a narrowband stimulus, for the lateralization task, lateralization is a wideband process that uses across-channel information when such is available (Stern et al. 1988). The same is probably true for frequency discrimination (Zwicker 1970). Binaural detection, however, is narrowband, occurring within the critical band (CB, the basic perceptual frequency channel of the auditory system). Thus, the two "wideband" processess—frequency discrimination and lateralization — are impaired in disabled readers, whereas the "narrowband" process tapped by binaural unmasking is not.

CMR also reflects across-channel integration processes, yet it was not impaired. In the wideband comodulated condition, high-JND RDs had thresholds similar to those of all other participants, suggesting they can utilize across-channel information as well as the others. This is surprising, especially in light of the lower AM detection ability, because both stimuli have wideband modulated noise and require the use of the AM information to operate. It appears that in detecting the tone embedded in suprathreshold modulated noise, high-JND RDs make better use of the available across-channel information than would be expected given their reduced thresholds in detecting AM.

Thus, we cannot conclude that there is a general deficiency in across-channel integration processes.

A deficit in within-channel processing?

Another possibility is that within- rather than across-channel processing is deficient. The simplest within-channel deficit is lower signal-to-noise ratio, caused by an increase in internal noise. The main support for this hypothesis is the significantly higher threshold for tone detection in narrowband noise (as measured in the narrowband unmodulated CMR condition, NB-unmod, Fig. 5).

This hypothesis may easily explain some other features of the results. In particular, the nonspecific elevation of AM thresholds is consistent with this view. The commonly accepted model of temporal resolution consists of four stages (see review in Viemeister and Plack 1993, pp. 121–124). According to this model, a bandpass filter (corresponding to the peripheral auditory filtering by the basilar membrane) is followed by a nonlinearity, a low-pass filter or leaky integrator, and a decision mechanism. A temporal deficit suggests either an increase in integration time ("smearing" the output of the integrator) or a reduced sensitivity to its output (a deficit further up the processing stream). However, reduced signal-to-noise ratio in the bandpass filter would result in a similar outcome since it would make the output of the integrator less reliable.

Elevated noise within the critical bands may also explain the differences in BMLD results found in different studies of binaural unmasking: BMLD is impaired at 1 kHz (McAnally and Stein 1996) but not at 200 Hz (Hill et al. 1999) and 500 Hz (this study). Since the jitter in spike times is independent of tone frequency (Joris et al. 1994), the same amount of noise would degrade phase locking at high frequencies more than at low frequencies. As a result, the computation of changes in binaural correlations, thought to underlie BMLD, would be more degraded at higher frequencies. The finding that the absolute thresholds for both N_0S_0 and N_0S_π conditions were higher than in low-JND RD and controls (although the difference, BMLD, was normal) is also consistent with the hypothesis of increased within-channel noise.

The hypothesis of higher noise levels within the critical bands predicts very broad and nonspecific auditory deficits, consistent with our general pattern of results. It is also compatible with impairments in performing tasks that require across-frequency integration. Intuitively, we would assume that a consistent pattern would apply for lateralization, motion discrimination, and tone detection in modulated wideband noise (WB-mod) since they all use across-channel integration. Our mixed pattern of results — finding difficulties in the first two but not in the latter — seems at odds with a straightforward prediction. Yet, since our understanding of the particular nature of the integration mechanisms activated in each condition is only partial, this mixed pattern does not necessarily refute the hypothesis of increased within-channel noise as the main deficit in these individuals.

Deficits at higher processing levels?

None of the hypotheses suggested above accounts for the poor performance of the high-JND RD subgroup on the frequency discrimination task at long ISIs. This is not surprising since this result reflects characteristics that are not assessed in standard psychoacoustic tasks. Typically, psychoacoustic measures are aimed at determining the limits of the system in terms of detection and resolution. In this task, however, we find that even in very undemanding conditions, the performance of these individuals is poorer than that of the controls. The source of this impairment is probably different from that responsible for the difficulties experienced by the high-JND RDs in other psychoacoustic tasks. Consistent with previously discussed data, it is obvious that the results of this task do not support a specific fast temporal processing deficit. We suggest that the poorer performance of the disabled readers on this task reflects impaired high-level processing which is not necessarily related to the "within trial" stimulus parameters (in this case, the frequency). A possible explanation relates to parameters controlling performance at time scales larger than that of the single trial. Perhaps the procedure used in this task, i.e., presenting the grossly different ISIs in random order, posed particular difficulties for this subgroup.

Does a nonlinguistic deficit play a role in reading difficulties?

Taken together, our data suggest that a nonlinguistic deficit does play a role in reading disability, because there are no good readers in our sample with consistent difficulties in acoustic processing (see Fig. 9; there are no participants in the upper-left quadrant), whereas a significant proportion of the RD population had consistent auditory difficulties. As a result, reading measures and measures of auditory performance are not independent across the population, and a significant correlation is observed between psychoacoustic performance and reading measures (Spearman's rank correlations are between 0.4 and 0.5 and are significant). On the other hand, some RDs performed essentially as well as controls on all tasks, showing that an auditory processing deficit is not a necessary condition for reading disabilities.

Conclusion

The auditory deficits of some disabled readers may not be the result of a single impaired mechanism. Rather, different tasks may probe deficits at several levels of processing. Thus, reading disability may be a cumulative result of several different processing deficits. Our results in general are not consistent with specific problems in phoneme-rate auditory processing deficits, and they show that the reading disabled form a heterogeneous population in terms of their auditory deficits. Among the reading disabled there are poor acoustic processors who show a definite pattern of deficits that seems to be of auditory origin, though not specifically due to impaired fast temporal processing, whereas other disabled readers are essentially unimpaired in any standard psychoacoustic task. Determining the functional role of these perceptual deficits in specific reading difficulties requires further studies.

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