Auditory processing parallels reading abilities in adults

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A broad battery of psychoacoustic measures and standard measures of reading and spelling were applied to 102 adults. The test group included individuals with a childhood history of reading difficulties and controls with no reported reading difficulties. Reading scores were variable in both groups. Poor auditory processing abilities were recorded in poor readers; particular difficulties were posed by tasks requiring spectral distinctions, the simplest of which was pure tone frequency discrimination. In absolute terms, the greatest deficits were recorded in tasks in which stimuli were presented in brief forms and in rapid succession. Auditory processing abilities accounted for more than 50% of the reading score variance in the control group, but their correlation with reading scores was lower in the group with childhood histories of reading difficulties. The additional variability in the latter group resulted largely from the prevalence of reading-compensated poor psychoacoustic performers, whose short-term word memory was also typically poor. Taken together, these findings support a link between impaired auditory resolution and poor reading. Psychoacoustic difficulties are largely retained through adulthood and may be the source of the retained reading difficulties.

A long-standing controversy in reading research has concerned the nature of the skills required for successfully learning to read, which are deficient in the poor or failed reader. An early emphasis on underlying visual impairments has been largely superseded by a language-based model of impairment (1, 2). The latter stresses the difficulty poor readers have in developing an awareness that words can be broken into smaller sound units, called ''phonemes'' (e.g., the word ''cat'' consists of three ''elementary sounds'': /k//æ//t/). This ability is critical for mastering alphabetic systems, in which sound units (phonemes) are mapped to letters (graphemes; ref. 3). The failure in phonemic awareness tasks is typically attributed to a specific deficiency within phonology, the module in language representation engaged in processing the sounds of speech (4). This interpretation is supported by findings that children who are poor readers have difficulties in discriminating between speech sounds (5). Poor readers also have other language problems, e.g., in ordered recall of verbal materials even when presented in spoken form (6, 7).

The deficits in phonology and in verbal memory may stem from a more fundamental deficit in acoustic signal reception, at least in some poor readers. Indeed, the performance of many poor readers on some nonverbal auditory tasks is markedly impaired. For example, children who are poor readers and have problems in phonological processing also need longer time separations between two spectrally distinct stimuli for their discrimination or sequence ordering (8, 9). Poor readers also have difficulties in simpler psychoacoustic tasks requiring spectral (10) or temporal (11, 12) discrimination.

Impairments in reading are largely retained throughout life (2), as is the impaired perception of speech contrasts (13, 14). However, the extent to which the acoustic perceptual deficits are retained into adulthood remains controversial. Several studies have addressed the issues of temporal or spectral resolution (15–19) with various methods and different samples of poor

readers and found mixed results. Taken together, these studies suggest a fundamental problem in complex acoustic signal resolution in poor readers that is, at least partially, carried into adulthood. At the same time, the specific nature of any general auditory impairment and its correlation with reading ability are disputed.

The present study was designed to clarify the relationships between acoustic processing and reading ability. A set of psychoacoustic tasks measured temporal resolution, spectral resolution, and their combination within simple and more complex task and stimulus conditions. In particular, we asked which of a broad range of listening tasks poses the greatest difficulties for poorer readers and to what extent performances on those tasks account for the variance in single word and nonword reading, spelling, and reading fluency in the adult population.

Methods

The Test Population. There were 102 adult (age 16–58 years) native English speakers from the general population with widely variable reading ability, educational background (at least 10 years of formal education), and socioeconomic status who participated in this study. Recruitment of population was directed at individuals both with and without a childhood history of reading difficulties (CHRD), forming the CHRD and control groups, respectively. We advertized our study in several colleges in the Bay Area (including community colleges and Stanford University). Other participants were recruited with the help of clinicians. We asked each person who reported a CHRD to bring a friend/relative/spouse who had no reading difficulties. This policy was aimed at gathering a population balanced across reading difficulties with respect to socioeconomic background and education. The participants were administered a battery of reading and writing tests, a battery of psychoacoustic tasks, and one or two general intelligence measures during three or four 2-h test sessions.

Reading and Spelling Tests. All subjects were tested with *word attack*, accuracy of reading aloud a list of nonsense words (from *The Woodcock Reading Mastery Tests—Revised*; ref. 20); *word identification*, accuracy of reading aloud a list of real words (from ref. 20); and *spelling*, accuracy of spelling a list of words read aloud by the experimenter (from the *Wide Range Achievement Test 3*; ref. 21). Subjects were also tested with a passage comprehension test, either from the *Woodcock Reading Mastery* (20) or from the *Gray Oral Reading Tests* (22), which also measures speed and accuracy of oral reading.

Cognitive Ability Tests. These included the *Matrix Analogies Test—Expanded Form* (MAT; ref. 23) for nonverbal intelligence (*n* =

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56) and the *word memory* subtest of the *Woodcock–Johnson Tests of Cognitive Ability* (ref. 24; n = 71).

The Psychoacoustic Battery. The psychoacoustic battery administered was extremely broad, designed to cover aspects of auditory temporal and spectral resolution and their combination as well as more complex tasks and stimulus conditions intermediate toward the content and complexity of speech signals. An adaptive (asymmetric; variable step size) threshold estimation procedure based on accelerated stochastic approximation (25) was used in all measurements. A roving standard was used in all same/different discrimination tasks. All stimuli were on/off square-cosine ramped.

Task 1: tone detection. Two 250-ms visually defined intervals (screen color change) occurred in each trial; in one interval, a pure tone (250 ms long; 500, 1,000, or 2,000 Hz frequency; blocked within sessions) was presented at an adaptively varied amplitude. The subjects' two-alternative forced-choice task was to indicate which interval contained the tone.

Task 2: backward detection masking. Two 300-ms 60-dB sound pressure level (SPL) bandpass (600–1,400 Hz) noise bursts were presented in each trial, one of the two being preceded by a short (20-ms) or long (250-ms) 1-kHz tone of adaptively varying amplitude at an interstimulus interval (ISI) between 230 ms and 0 ms. The subjects' two-alternative forced-choice task was to indicate which stimulus contained the tone. Tone length and ISI were constant within each threshold estimation session.

Task 3: gap detection. Two 500-ms 70-dB SPL wide-band noise bursts were presented in each trial, one of which contained an energy gap of adaptively varied duration extending in frequency from 500 to 1,500 Hz. The subjects' two-alternative forced-choice task was to indicate which stimulus contained the energy gap.

Task 4: frequency discrimination. Two 250-ms 70-dB SPL tones in the 600–1,400 Hz frequency range separated by 800 ms were presented in each trial. In 50% of the trials the two tones had the same frequency; in the other 50%, they differed by an adaptively varied amount. The subjects' task was to indicate whether the two tones were the same or different.

Task 5: intensity discrimination. Two 250-ms tones of the same randomly selected frequency in the 600–1,400 Hz range, separated by 800 ms, were presented in each trial. In 50% of the trials, the two tones had the same amplitude; in the other 50%, they differed by an adaptively varied amount. The subjects' task was to indicate whether the two tones were the same or different.

Task 6: formant discrimination. This task was identical to the pure tone frequency discrimination task but used peak spectral energy rather than pure tones. Stimuli were constructed by passing a spectrally flat harmonic complex through a resonator.

Task 7: frequency discrimination under backward masking. Two 20-ms 70-dB SPL pure tones were presented, each with a frequency of either 900 Hz or 1,100 Hz and followed by an approximately 60-dB SPL, 300-ms bandpass (600–1,400 Hz) noise masker at an adaptively varied ISI. The subjects' task was to indicate whether the two tones were the same or different.

Task 8: tone-sequence identification. Subjects were trained to associate an 800-Hz tone with a button labeled "LOW" and a 1,200-Hz tone with a button labeled "HIGH" in a two-alternative forced-choice identification task with a single tone presented in each trial. Number of trials to criterion (10 consecutive correct responses) was measured. Two tones were then presented in each trial, separated by an adaptively varying ISI. Subjects had to label each tone in the correct order. This test was repeated with three-tone trials. The tones were 250-ms-long or 20-ms-long (blocked within sessions) 80-dB SPL. Herein, we report results for 20-ms tones only, which were more strongly correlated with reading measures.
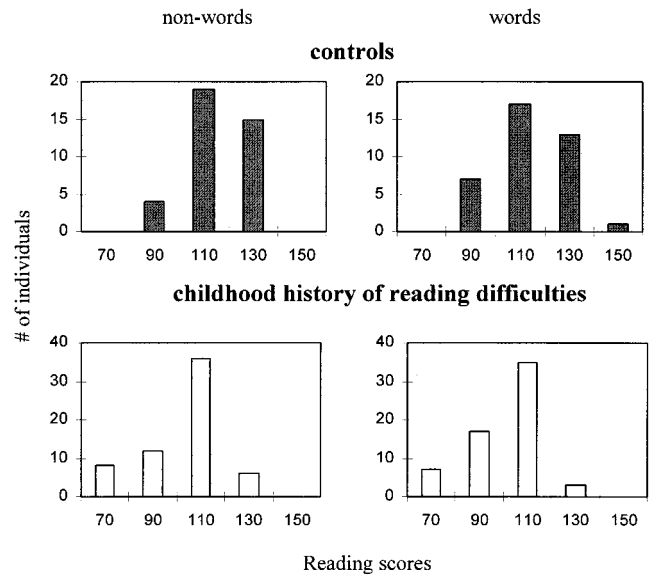

Fig. 1. Distribution of single word (*Right*) and nonword (*Left*) scores for the control group (*Upper*) and the CHRD group (*Lower*).

Task 9: interval discrimination. Two temporal intervals, each defined by the ISI between a pair of 15-ms 1-kHz tones, were presented at 80-dB SPL with an ISI of 500 ms. One of the intervals was always 100 ms and the other was longer by an adaptively varied amount. The participant's task was to identify the shorter of the two intervals.

Results

Reading Scores. Data were analyzed separately for controls (i.e., for individuals reporting no specific reading difficulty at present or in their past) and for the CHRD group (i.e., those who participated because of their self-report of CHRD). The corresponding distributions for single word and nonword reading are plotted in Fig. 1. There were no very poor readers (scores ≤70) in the control group and only a few very good readers (score >110) in the CHRD group. At the same time, there was substantial overlap between the two groups. Note that because most standard reading tests, including the ones we used, measure only accuracy, we may underestimate the reading difficulties that CHRD adults still have, often mainly expressed in reduced reading rate (2).

The various measures of reading and spelling were highly intercorrelated (Table 1). A large discrepancy between word and nonword reading or between nonword reading and spelling is rarely found. Reading is correlated with memory for orally

Table 1. Correlations (Spearman's) within reading measures

	Word-Rd	N-Word-Rd	Word-SP
N-Word-Rd			
Control	0.58**		
CHRD	0.77**		
Word-SP			
Control	0.69**	0.65**	
CHRD	0.78**	0.69**	
Word-M			
Control	0.52*	0.65**	0.58*
CHRD	0.29	0.34	0.28

Word-Rd, single-word reading; N-Word-Rd, nonword reading; Word-SP, word spelling. *, $P < 0.01$; **, $P < 0.001$.

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Table 2. Correlations (Spearman's) between psychoacoustic thresholds and reading scores

Task	Word-Rd	N-Word-Rd	Word-SP	Word-M
GAP-DET				
Control	−0.19	0.01	0.43	−0.27
CHRD	−0.05	−0.01	−0.02	−0.12
FR-DIS				
Control	−0.48*	−0.49*	−0.68**	−0.22
CHRD	−0.36*	−0.30	−0.23	−0.39
FR-BM				
Control	−0.67**	−0.54*	−0.64**	−0.35
CHRD	−0.36*	−0.25	−0.18	−0.32
2-TON-ID				
Control	−0.63**	−0.70**	−0.65**	−0.39
CHRD	−0.44**	−0.41*	−0.31	−0.48*
3-TON-ID				
Control	−0.40	−0.59**	−0.65**	−0.39
CHRD	−0.36*	−0.39*	−0.15	−0.63**
FOR-DIS				
Control	−0.58	−0.34	−0.43	−0.30
CHRD	−0.39	−0.32	−0.20	−0.31
LOU-DIS				
Control	−0.45	−0.49	−0.27	−0.38
CHRD	−0.13	−0.21	−0.23	−0.20
INT-DIS				
Control	−0.41	−0.34	−0.57*	−0.35
CHRD	−0.30	−0.34	−0.44	−0.29

Word-Rd, word reading; N-Word-Rd, nonword reading; Word-SP, word spelling; Word-M, word memory; GAP-DET, gap detection; FR-DIS, frequency discrimination; FR-BM, frequency discrimination under backward masking; 2-TON-ID, two-tone identification; 3-TON-ID, three-tone identification; FOR-DIS, formant discrimination; LOU-DIS, loudness discrimination; INT-DIS, interval discrimination. *, $P < 0.01$; **, $P < 0.001$.

presented words but not for CHRD individuals, as discussed further below. In agreement with previous results (7), reading comprehension is less correlated with short-term word memory.

Psychoacoustic Measures. The results of the auditory battery showed performances on a specific subset of tasks to be correlated with reading scores of words and nonwords (26) as well as with spelling (Table 2). These findings are consistent with the hypothesis of general and fundamental deficits in auditory perception underlying poor reading and spelling.

Tone and Gap Detection. Pure tone detection thresholds, obtained in lieu of audiometric screening at 0.5, 1.0, and 2.0 kHz, were not elevated for poor readers (except for two CHRD individuals). Tone detection in the context of an ensuing masker (task 2 above) was also measured, because children with specific language impairment (SLI), a population at risk for reading impairments (27–29), have substantial difficulty with it (30). Thresholds were first assessed with a 250-ms tone followed immediately by a 300-ms noise masker and subsequently with brief (20-ms) tones with decreasing tone-to-noise time intervals. Successful detection required fine temporal resolution and, in contrast to findings with SLI children, the minimal tone intensity to report reliably which of two noise stimuli was preceded by a tone was not significantly correlated with any reading, spelling, or intelligence measure in this adult population.

Gap detection was another task measuring temporal resolution with which poor readers had no difficulty. The minimum gap duration for reliably detecting which of two noise stimuli was discontinuous was not longer for poor readers (Fig. 2 *Right*, GAP-DET), in agreement with previous reports (16, 31). Similar findings have been interpreted as evidence against the hypothesis

that poor readers have particular difficulties in reliably processing rapid streams of signals (8). Note, however, that this task probes only the ability to detect stimulus components as distinct, and not the ability to identify or process them in any way.

Frequency Discrimination and Tone-Sequence Identification. The simplest task in which subjects' performance was correlated with reading measures was pure-tone frequency discrimination measured in a successive signal format. In this task, subjects had to classify two 250-ms-long tones 800 ms apart as "same" or "different." Successful performance does not require fine temporal resolution but does require fine resolution and short-term memory for tone frequency. Fig. 2 (FR-DIS) illustrates the correlation between single nonword reading and the just noticeable difference (JND) in frequency for the two groups. For the control group, the Pearson's reading-JND correlation was extremely high, with frequency discrimination accounting for more than 50% of the reading score variance, although Spearman's correlation, as shown in Table 2, was lower. For the CHRD group, results are more scattered because some average readers have poor frequency resolution. The opposite correspondence— fine frequency resolution and poor reading—was rare (two individuals) but sufficient to indicate that in some cases poor reading may not be related to auditory perceptual difficulties. (The performance of these two individuals was fine on all psychoacoustic measures.)

An extension toward stimulus conditions more related to speech reception involves the application of streams of signals rather than isolated stimuli. To assess the possibly degrading effects of time constraints, tasks were administered with stimuli with relatively wider frequency separations presented in rapid succession. These included tone frequency discrimination in the context of backward noise maskers (task 7) and tone sequence identification with one, two, and three tones (task 8). Performances on these tasks were also highly correlated with reading measures. Particularly high correlations, accounting for more than 50% of the total variance (Fig. 2 *Upper*, FR-BM and 2-TON-ID), were again found for the control group, whereas substantially larger variability was observed within the CHRD group (Fig. 2 *Lower*, FR-BM and 2-TON-ID).

Individuals who had difficulty with these more complex tasks typically also had difficulty with pure-tone frequency discrimination. Performances on these tasks were very highly intercorrelated (Spearman's correlation between frequency discrimination and two-tone sequencing was $r = 0.67$ and $r = 0.66$ for control and CHRD groups, respectively). However, some poor readers had difficulties with the more complex tasks despite having no significant difficulty in the long-tone frequency discrimination task. Thus, the addition of temporal constraints resulted in the emergence of a frequency resolution difficulty in some individuals with a CHRD.

To derive an estimate of reading ability based on psychoacoustic performance, we calculated the average psychoacoustic thresholds for frequency discrimination and two-tone-sequence identifications in each reading group. The results, plotted in Fig. 3, show that poorer readers in both groups are poorer performers. Poor readers (reading scores ≤90) need an average 150-Hz difference to discriminate reliably between two tones around 1,000 Hz and a separation of 250 ms between two (800 and 1,200 Hz) tones to identify them as "high" or "low." Good readers (reading scores >110) need less than 40 Hz and less than 40 ms, respectively. The performance of average readers (90 < scores < 110) largely depends on their history, with CHRD individuals performing more poorly in psychoacoustic tasks than controls with the same reading scores.

Formant Discrimination. It may be argued that pure tones are not relevant for the processing of verbal stimuli, even though the

FR-DIS   FR-BM   2-TON-ID   GAP-DET

controls

2-TON-ID

childhood history of reading difficulties
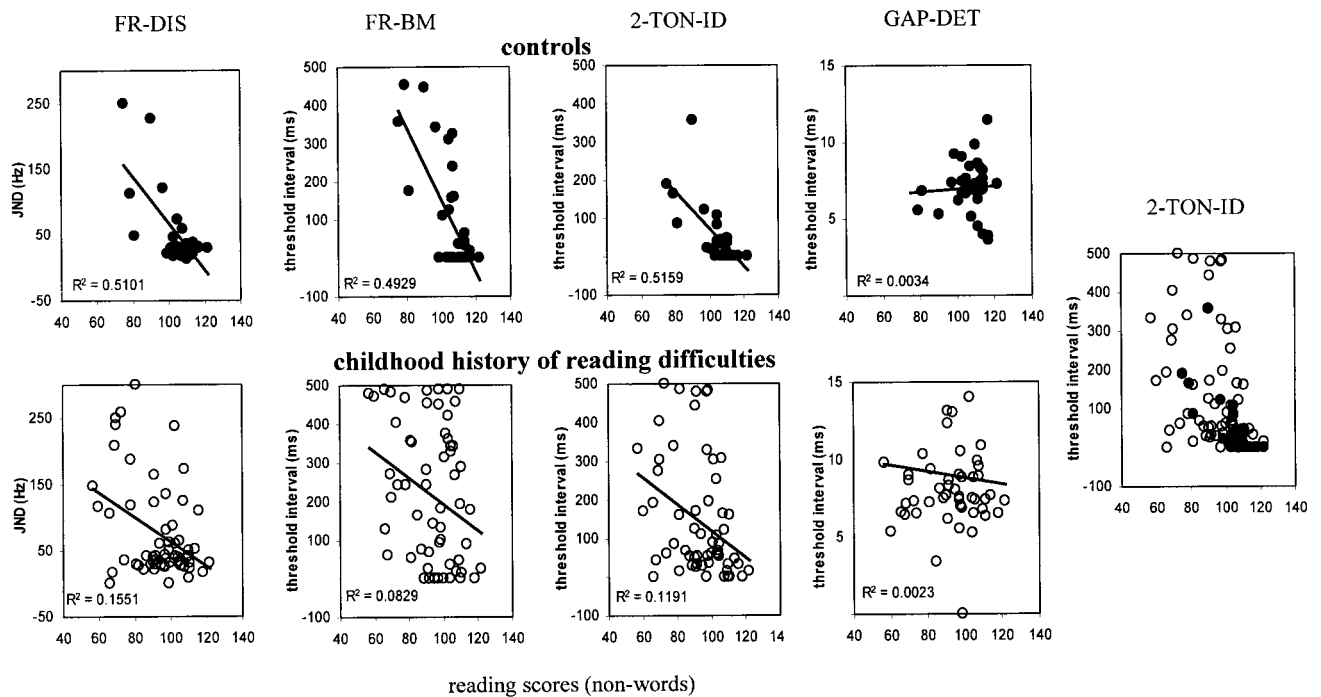
reading scores (non-words)

Fig. 2. Scatter plots showing the relationship between single nonword reading standard scores and psychoacoustic thresholds for the control group (*Upper*; filled circles) and the CHRD group (*Lower*; open circles). Data are shown for frequency discrimination (FR-DIS), frequency discrimination under backward masking (FR-BM), two-tone identification (2-TON-ID), and gap detection (GAP-DET).

latter must also pass through the peripheral auditory system and primary auditory cortex. In a step toward addressing this issue, we administered a test with intermediately complex stimuli, specifically, single formants. The formant structure of speech sounds is commonly considered to convey most of the information of the phonetic content. The ability to resolve spectral peaks is therefore directly related to speech perception. Performance on formant discrimination was highly correlated with pure tone frequency discrimination ($r = 0.69$ and 0.64 for controls and CHRD, respectively) and with reading measures (Table 2). This finding is consistent with the hypothesis that impaired phonemic awareness stems from impaired discrimination between basic speech elements.

Intensity and Interval Discriminations. Successful performance in all tasks described above with which poor readers had difficulties but not in tasks with which poor readers performed fine relies on short term memory for spectral distinctions. To investigate which of the two—memory or spectral distinction—is particularly impaired in poor readers, tasks involving other dimensions were added.

The first task was intensity discrimination, which was identical to the frequency discrimination task except that tones differed in intensity rather than in frequency. Successful performance therefore required short-term memory for intensity. Performance on this task was not correlated with reading measures (Table 2), either for controls or for the CHRD group.

In another task, we measured the ability of listeners to discriminate between the durations of intervals around 100 ms. Some poor readers from both groups had difficulties with this task, but for both groups, performance was less correlated with reading than were the spectral measures. Although difficulties in this task may stem from factors other than spectral resolution (32), almost no additional reading score variance was accounted

for, because individuals who have difficulties in this task also had difficulties in spectral tasks.

Psychoacoustic Performance and Verbal Memory. Auditory processing and reading were less correlated in the CHRD group, but the correlation between auditory processing and memory for orally presented words was not lower in this group (Table 2). Particularly high was the memory correlation with three-tone-sequence identification, the task with the heaviest short-term memory load, illustrated in Fig. 4 (note, however, the exception in the control group—an average reader with fine word memory and poor psychoacoustic performance, indicating that the latter is not necessary for good verbal memory). The lower correlation with nonword reading is manifested by the increased scatter in Fig. 4 *Right*. To illustrate this point, data for two individuals are marked by $\times$ in the scatter plots. Their reading scores are average, but both their acoustic and verbal memory were poor. Thus, although poor verbal memory is typically correlated with poor reading (Table 1, controls), compensated individuals still have poor verbal memory, perhaps because their auditory processing abilities remain impaired.

Cognitive Abilities. Poor performance in tasks requiring spectral discrimination may characterize generally poor achievers rather than specifically poor readers. Indeed, a consistent if puzzling finding in the literature has been that adult nonverbal intelligence is correlated with frequency discrimination with (33) and without (34, 35) temporal constraints.

To disentangle reading from intelligence-related psychoacoustic performance, 56 of the participants were administered the MAT of nonverbal intelligence. Only those who scored above 90 were included for this comparison. From those, two MAT-relative groups were defined, one of relatively good readers (with nonword reading score at least five points above MAT score; $n = 18$) and another of relatively poor readers (with the
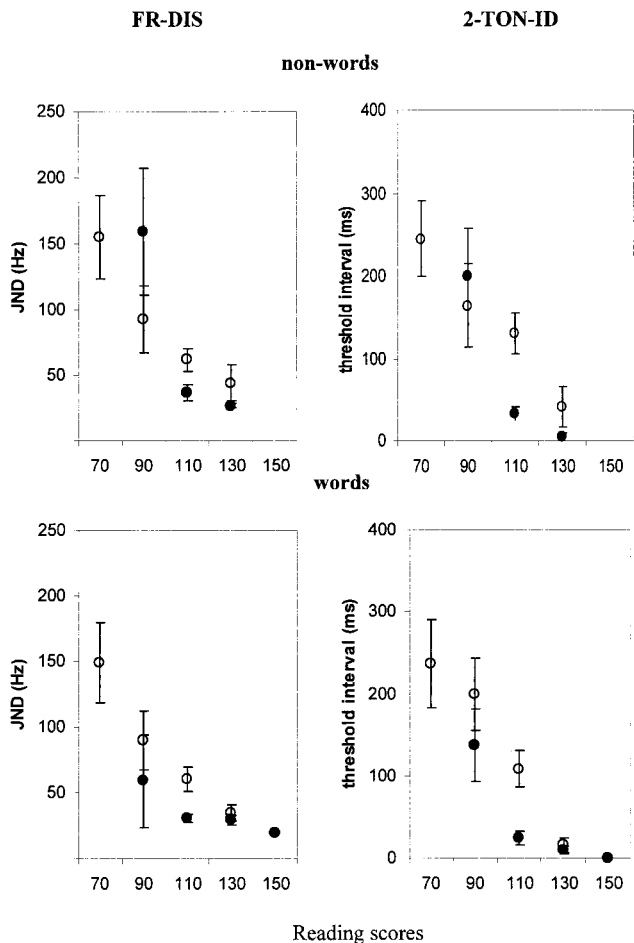
FR-DIS

2-TON-ID

non-words

words

Reading scores

Fig. 3. Average thresholds for the control group (filled circles) and the CHRD group (open circles) in frequency discrimination (FR-DIS, *Left*) and two-tone-sequence identification (2-TON-ID, *Right*) grouped by single word (*Lower*) and nonword (*Upper*) reading scores according to the bins shown in the distributions of Fig. 1. Bars denote standard errors.

reverse pattern; $n = 18$). This division was motivated by classical definitions of dyslexia (1, 2) relying on the discrepancy between general cognitive abilities and reading ability. The discrepancies are illustrated in Fig. 5 *Upper*: relatively good readers have better reading scores but lower MAT scores than poor readers. Fig. 5
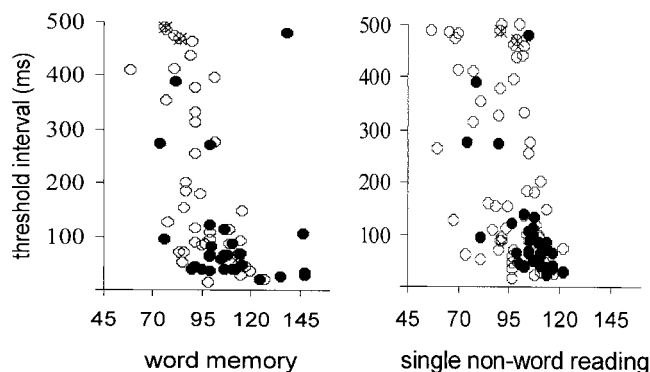

Fig. 4. Three-tone identification versus word memory (*Left*) and versus single non-word reading (*Right*) for the control group (filled circles) and the CHRD group (open circles).
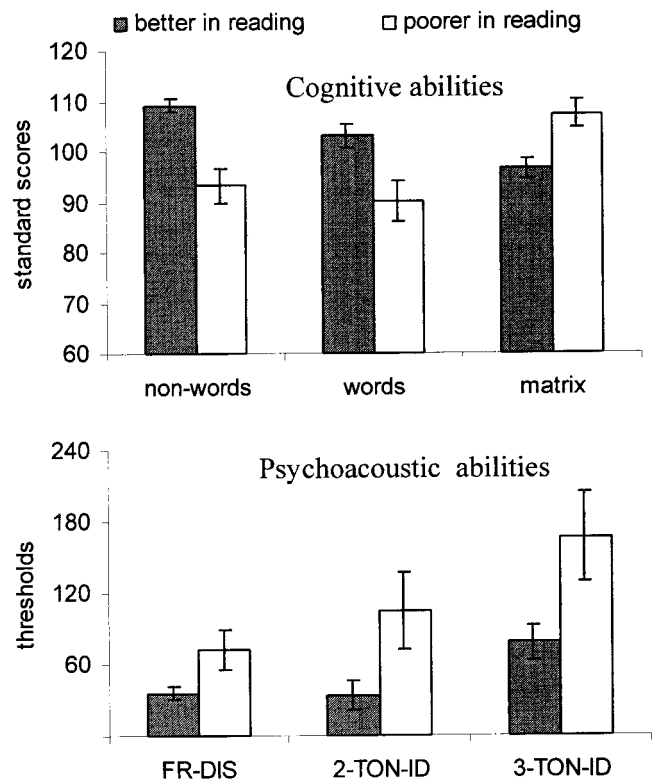

Fig. 5. (*Upper*) Single nonword and word reading and nonverbal intelligence scores for the good reader and poor reader groups (see text). (*Lower*) Mean thresholds for these groups with frequency discrimination (FR-DIS), two-tone sequencing (2-TON-ID), and three-tone sequencing (3-TON-ID). Several criteria for defining the two groups all yielded similar results.

Lower shows the significantly poorer performance of poor readers in frequency discrimination, and in two- and three-tone-sequence identification (interestingly, performance in frequency discrimination under backward masking did not differ between these two groups) compared with the performance of better readers with lower MAT scores (good readers).

Moreover, in linear regression analysis, psychoacoustic performance (pure tone frequency, formant discrimination, and tone sequencing) accounted for significant unique variance in word (12%) and nonword (26%) reading scores after factoring out the contribution of MAT (40% and 34%, respectively); three-tone sequencing alone accounted for 9% and 23%, respectively, entered after MAT. In contrast, once psychoacoustic thresholds were entered in the equation first (accounting for 44% and 58% of the total variance in word and nonword reading, respectively), MAT accounted for little additional variance (significant 8% and nonsignificant 2%, respectively; 8% and 1% after three-tone sequencing alone).

Therefore, impaired acoustic processing is directly related to reading impairment and cannot be accounted for by general cognitive difficulties. As expected, this direct relation is stronger for nonword reading than for word reading.

Discussion

The performance of adult poor readers was found impaired in specific simple auditory tasks, mainly involving spectral discriminations, even without temporal constraints. Adding such constraints, particularly when explicit categorization was required, introduced further difficulties for poor readers. Performance in intensity discrimination, with the same task structure, was not impaired, indicating that the source of difficulty was not, in

general, auditory short-term memory. In linking pure tone spectral difficulties to speech perception, performance on formant discrimination was highly correlated with both reading and pure tone frequency discrimination.

Psychoacoustic impairments were correlated with reading impairments. The estimated reading level based on psychoacoustic performance and the reliability of the estimate depend on individual reading history and specific efforts (e.g., corrective teaching). Correlations were remarkably high for individuals who never sensed reading difficulties and never received corrective teaching, in most cases, because they were good readers— but in some cases, even though they were not (Fig. 2 *Upper*). Among individuals who experienced reading difficulties in school, psychoacoustic performance was more variable. Almost all individuals who were still poor readers performed poorly in psychoacoustic tasks. Very good readers are scarce in this group. Individuals with intermediate scores had variable results. The most prominent observation was the tendency for reading scores to be higher than psychoacoustic resolution would predict, when compared with controls.

By assuming a functional relation between auditory processing and reading, both the high correlation found for controls and the lower one found for CHRD individuals can be explained. The first is obvious. The latter would be expected for individuals who, acknowledging their difficulties, focused on improving their reading abilities. Reading accuracy was consequently variably compensated, but the underlying impairments were not removed. Therefore, it is not surprising that their reading difficulties were eliminated only partially. Indeed, auditory skills, including verbal ones, remained impaired. Individuals who compensated for reading accuracy often have poor short-term memory for orally presented words (36), which is correlated with

their psychoacoustic performance (Fig. 4), as is expected because of their unresolved auditory difficulties.

A recent intervention method for SLI children (37–39) includes training basic acoustic processing. The success of this procedure in boosting language skills supports the assumption of causal relations between acoustic processing and language skills. Several previous studies point to the similarities between SLI and reading impairment (e.g., refs. 5 and 40), and our findings are consistent with these observations. The task that was the most reliable indicator of reading level was two-tone sequence identification, a task introduced in the context of SLI (41) and subsequently applied for reading difficulties (8). The finding that basic perceptual training has been beneficial for SLI children suggests that it should also be useful for ameliorating reading difficulties. Thus, given that dramatic learning effects with perceptual tasks have been measured for adults (42–44), if impaired acoustic discrimination, retained through adulthood, hinders reading acquisition, such perceptual training may be useful even for adult poor readers.

In summary, we propose that for the adult good reader, fine representation of spectral and temporal details of acoustic features facilitates the encoding of acoustic patterns into phonological representations. The translation from phonological codes into orthographic script (and vice versa) is thus performed automatically with no effort. For the poorer reader, however, the salience of representation of phonological parts of speech is degraded by an abnormal representation of inputs in the acoustic stream.

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