Frequency Discrimination and Literacy Skills in Children With Mild to Moderate Sensorineural Hearing Loss

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It has been suggested that specific reading disability (SRD) may be attributable to an impaired ability to perceive spectral differences between sounds that leads to a deficit in frequency discrimination and subsequent problems with language and literacy. The objective of the present study was threefold. We aimed to (a) determine whether children with mild to moderate sensorineural hearing loss were impaired in their ability to discriminate frequency, (b) assess the extent to which any such deficits may be due to an inability to use information derived from phase locking, and (c) examine whether frequency discrimination abilities were predictive of measures of word and nonword reading and nonword repetition. Difference limens for frequency (DLFs) were obtained for 22 children with mild to moderate hearing loss (SNH group) and 22 age-matched controls (CA group) at central frequencies of 1 kHz, where phase-locking information is available, and 6 kHz, where it is not. A battery of standardized tests of language and literacy was also administered. The SNH group exhibited significantly elevated DLFs at both 1 and 6 kHz relative to controls, despite considerable variability of thresholds in both groups. Although no group differences were found for receptive and expressive vocabulary, receptive grammar, and nonword reading, the SNH group performed worse than controls on word reading and nonword repetition, even though word reading acores were age-appropriate. Frequency discrimination abilities were associated with reading and nonword repetition across groups, but these correlations largely disappeared when the two groups were analyzed separately. Together, these results provide evidence for a dissociation between impaired frequency discrimination and relatively ''spared'' language and literacy in children with mild to moderate sensorineural hearing loss. These results cast doubt on the assertion that a deficit in frequency discrimination necessarily leads to marked deficits in the development of language and literacy.

KEY WORDS: frequency discrimination, hearing loss, literacy

Specific reading disability (SRD) or developmental dyslexia affects approximately 5% of the population and is typically defined as a discrepancy between an individual's actual reading ability and that predicted on the basis of age and nonverbal intelligence. Although the cause of this condition is not yet known, one of the strongest markers of SRD is a deficit in phonological awareness, that is, the ability to analyse the sound structure of speech. Research has shown that individuals with SRD tend to experience problems on a number of phonological awareness tasks, ranging from segmenting words into

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their constituent syllables or phonemes (e.g., Manis, Seidenberg, Doi, McBridge-Chang, & Peterson, 1996) to repeating nonsense words (e.g., Snowling, Goulandris, Bowlby, & Howell, 1986). However, the underlying cause of these phonological impairments remains controversial. Some have attributed these deficits to a specific impairment in a language-based system of phonology (e.g., Liberman, 1983), but others favor a theory that sees phonological impairments as the consequence of a more general, low-level perceptual problem in auditory processing (e.g., Tallal, 2000).

Frequency Discrimination and SRD: A Causal Explanation

Although a variety of auditory processing deficits have been linked to low reading ability in both normal and reading-impaired populations, one recent view has attributed problems in reading to an impaired ability to process spectral contrasts. Such an impairment could lead to problems in perceiving crucial acoustic differences between phonemes. This idea first arose in a study by McAnally and Stein (1996), who compared the performance of a group of adults with dyslexia with that of a group of controls matched for age and nonverbal IQ on four auditory tasks: detection of a temporal gap in white noise, frequency discrimination of a sinusoid at 1 kHz, and detection of a 1-kHz tone in broadband masker when the tone was presented either diotically (0°) or in antiphase (180°, binaural unmasking) between the two ears. Thresholds for detecting both the interruption of a broadband noise and the presence of a tone in broadband noise (interaural delay 0°) were found to be normal in the dyslexic group, indicating unimpaired coding of the temporal envelope of the auditory stimulus. In contrast, the dyslexic group performed significantly worse than controls on the tests of frequency discrimination and binaural unmasking (180°).

Given that all participants had normal peripheral hearing, the question arises as to why people with SRD had problems with frequency discrimination. McAnally and Stein (1996) hypothesized that they may be impaired in their ability to extract information about the fine structure of auditory stimuli. Pitch perception for frequencies up to 5 kHz is thought to be accomplished by timing the intervals between phase-locked discharges of auditory nerve fibers (Moore & Glasberg, 1986). McAnally and Stein (1996), therefore, attributed the frequency discrimination deficits of people with dyslexia to an impairment in generating, decoding, or exploiting this phase-locking mechanism. Moreover, given the reported correlation between frequency discrimination ability and reading (both word and nonword), McAnally and Stein (1996) went on to postulate a possible causal link between deficient phase locking and the language problems associated with SRD, mediated by the reduced ability to discriminate spectral contrasts in speech.

Frequency Discrimination, Phase Locking, and SRD: The Evidence

Consistent with this theory, a number of studies have examined whether people with dyslexia exhibit poor frequency discrimination. This is not a new idea in the SRD literature, and indeed De Weirdt (1988) demonstrated that a group of "poor readers" were significantly worse than a group of "good readers" in identifying whether pairs of 130-ms sinusoids were the same or different in pitch. More recently, this evidence has been corroborated by the use of more sensitive, adaptive measures of frequency discrimination. Cacace, McFarland, Ouimet, Schrieber, and Marro (2000) compared the performance of 4 independently diagnosed remediation-resistant reading-impaired children and 4 age-matched controls on a three-alternative forced-choice oddity task. On a given trial, two of the intervals contained a 1000-Hz standard tone, and a different frequency tone, adaptively varied, was presented in the third (randomly determined) interval. The children with dyslexia required an average difference of 487.5 Hz to discriminate between tones, compared with 6.95 Hz in the control group. However, given the very small sample size used, this discrepancy cannot be considered an accurate reflection of the true population mean.

Perhaps the most striking study to date was conducted by Ahissar, Protopapas, Reid, and Merzenich (2000), who studied a total of 102 adults, half of whom had a childhood history of reading problems, on a battery of psychophysical tests. Compared with controls, the reading-impaired group had elevated difference limens for frequency (DLFs) on a task where they had to discriminate whether two 250-ms pure tones (ranging between 600 and 1400 Hz) were the same or different. While the controls required a mean difference of 40 Hz to discriminate reliably between the two tones, thresholds were closer to 150 Hz for the reading-impaired group. Furthermore, reading ability in the control group was strongly predicted by performance on the frequency discrimination task, although this relationship was less strong in the poor readers.

Aside from the studies of frequency discrimination deficits associated with SRD, other studies have examined whether deficits in phase locking are evident in this population. Dougherty, Cynader, Bjornson, Edgell, and Giaschi (1998) compared the performance of 8 children with dyslexia and 8 children with age-appropriate reading ability on a test of dichotic pitch perception. As described by Dougherty and colleagues, dichotic pitch perception is the perception of pitch from two noise sources that alone do not contain any cues to pitch. If the listener is able to exploit fine-grained auditory timing information, then shifting the start time of narrow bands of noise in one ear relative to the other should cause the interaural time-shifted frequency band to perceptually separate from the background noise, resulting in the perception of a distinct pitch. Using this method, Dougherty and colleagues found the dichotic pitch thresholds of the dyslexic group to be significantly higher than those of the controls, with 6 of the children with dyslexia showing a complete inability to extract pitch information on the basis of binaural cues alone. However, the dyslexic group were unimpaired on the task at high signal-to-noise ratios, suggesting that simple interaural time differences were not impaired in the dyslexic group. Rather, Dougherty and colleagues argued that the dyslexic group were impaired in their ability to extract the temporal microstructure of sounds from noisy contexts.

Frequency Discrimination and SRD: A Causal Explanation?

Although there is some supporting evidence for an impairment in frequency discrimination (Ahissar et al., 2000; Cacace et al., 2000), specifically in the phase-locking mechanism, in SRD (Dougherty et al., 1998; McAnally & Stein, 1996), a number of problems with this theory present themselves. First, despite a considerable number of studies reporting impaired frequency discrimination in people with dyslexia, this finding is by no means universal. Walker, Shinn, Cranford, Givens, and Holbert (2002) found that the group difference between adults with dyslexia and controls on a test of frequency discrimination at 1 kHz just failed to reach significance, owing to the high variability of scores within both the dyslexic and the control groups. Further, even studies that show a significant group effect tend to show considerable individual variation in performance, and there is often substantial overlap in scores between groups. Given this marked variation both within and between groups, it seems unlikely that poor frequency discrimination can account for the reading difficulties of all children with SRD.

Second, even if frequency discrimination were found to be impaired in children with SRD, a number of studies suggest that phase locking is unlikely to be the causal mechanism. Indeed, if poor frequency discrimination in SRD were due to a deficiency in the phase-locking mechanism, then one might predict that any differences between dyslexic and control groups would be more evident for tones at low frequencies, where phase-locking information is available, than at frequencies above 4 to 5 Hz, where it is not. Hill, Bailey, Griffiths, and Snowling (1999) used an adaptive four-interval, two-alternative forced-choice procedure to test this hypothesis by comparing frequency discrimination at 1 kHz and at 6 kHz in a group of adults with dyslexia and matched controls. The results indicated that although frequency discrimination thresholds were different for the dyslexic and control groups, this difference was not significant owing to large variations in thresholds, particularly in the dyslexic group. Those participants with dyslexia who had particularly high DLFs showed elevated thresholds at both frequencies, indicating that their poor performance could not be attributed simply to a deficit in phase locking. This finding has since been supported by evidence of both impaired frequency discrimination and spared phase locking in adults with dyslexia (e.g., Amitay, Ahissar, & Nelken, 2002; Hari, Sääskilahti, Helenius, & Uutela, 1999). For instance, although Amitay and colleagues (2002) found some evidence for impaired frequency discrimination in one third of their sample of adults with dyslexia, phase locking was presumably intact in these participants as they were unimpaired on a task of binaural masking.

Even if there is evidence for problems with phase locking and, indeed, with frequency discrimination in people with dyslexia, these problems may not be *causally* related to literacy impairments. If deficits in frequency discrimination are implicated in the etiology of SRD, language and literacy deficits should be found in any individual who is particularly poor at frequency discrimination, either because of impaired phase locking or for other reasons. Children with mild to moderate sensorineural hearing loss provide an interesting test of this prediction.

Frequency Discrimination in Mild to Moderate Sensorineural Hearing Loss

To date, little is known about the frequency discrimination abilities of children with congenital hearing loss. However, studies of adults with acquired sensorineural hearing loss generally find that some degree of impairment in the frequency discrimination of pure tones accompanies hearing loss, and this has been shown to hold across a wide range of frequencies and tone durations (Gengel, 1973; Nelson & Freyman, 1986; Tyler, Wood, & Fernandes, 1983). Reasons for this deficit are not entirely clear. In part, it may simply reflect reduced audibility of signals. Although there is evidence to suggest that frequency discrimination may be impaired at sensation levels lower than 40 dB (Wier, Jesteadt, & Green, 1977), some studies suggest that factors other than audibility may contribute to the elevated DLFs of listeners with hearing loss. Indeed, Freyman and Nelson (1991) not only found listeners with hearing loss to have elevated frequency discrimination thresholds for stimuli presented at sensation level, but also reported a relatively low correlation between DLFs and hearing thresholds. Others have shown that DLFs can be markedly different for the two ears at frequencies where the absolute thresholds are the same and, conversely, the same for ears that had different thresholds (Simon & Yund, 1993). Another possibility is that the broader width of the auditory filter in people with hearing loss may affect frequency discrimination. However, studies of adults have shown little correlation between DLFs and frequency selectivity (Moore & Peters, 1992). A third, more controversial theory, is that larger than normal DLFs associated with hearing loss may be partly attributable to the loss of neural synchrony in phase locking to auditory stimuli. Although evidence is still lacking, Wakefield and Nelson (1985) took into account the dependence of the phase-locking mechanism on sound level and put forward a model that accurately predicted DLFs in listeners with high-frequency hearing loss. Others have suggested that the central mechanisms involved in the analysis of phase-locking information may be disrupted in sensorineural hearing loss because of abnormalities in the propagation time of auditory stimuli along the basilar membrane (Loeb, White, & Merzenich, 1983; Shamma, 1985). In sum, although the mechanism is not fully understood, there is good evidence that sensorineural hearing loss does lead to impaired frequency discrimination; accordingly, one might expect to find impairments of language and literacy in children with hearing loss.

Language and Literacy in Mild to Moderate Sensorineural Hearing Loss

In contrast to the body of literature on more severe hearing loss, rather little is known about the language and literacy skills of children with mild to moderate hearing loss. Of the few studies to look at academic attainment in these children, standardized measures have not detected any major deficits (Davis, Shepherd, Stelmachowicz, & Gorga, 1981), although delays in vocabulary have been reported (Blair, Peterson, & Viehweg, 1985). More recently, a series of studies have compared the language abilities of children with mild to moderate hearing loss with those of normally hearing children who had specific language impairment (SLI; Briscoe, Bishop, & Norbury, 2001; Norbury, Bishop, & Briscoe, 2001, 2002). It was expected that the children with hearing loss would show the same pattern of language difficulties as those with SLI, but this was not confirmed. In general, the children with hearing loss performed as poorly as the SLI group on tests of phonological discrimination, phonological awareness, and nonword repetition, although the children with hearing loss were significantly better than the SLI group at repeating phonologically complex nonwords (Briscoe et al., 2001). In striking contrast to the children with SLI, most of the children with hearing loss performed as well as controls on tests of grammar; had a good memory for meaningful material, such as sentences; and performed in an entirely age-appropriate manner on tests of word and nonword reading, and of reading comprehension (Briscoe et al., 2001; Norbury et al., 2001).

Aims of the Current Study

A review of the available literature therefore suggests something of a paradox. On the one hand, hearing loss that has been linked to both marked frequency discrimination deficits and problems with phonological processing can still allow for relatively normal language and literacy skills; on the other hand, relatively mild deficits in frequency discrimination abilities are supposedly linked to quite major difficulties in reading acquisition. With these issues in mind, the present study had the following objectives:

1. First, the current study aimed to examine the frequency discrimination abilities of children with mild to moderate sensorineural hearing loss. Given that frequency discrimination performance is affected by the sensation level of the stimulus (Wier et al., 1977), the question arises as to whether stimulus levels should be adjusted to compensate for hearing loss. Arguably, efforts to equalize signal sensation levels across listeners would provide an estimate of the frequency discrimination abilities of people with hearing loss under intensities comparable to those experienced by children with normal hearing. It may be that children with hearing loss would show normal frequency discrimination skills under such conditions. However, the hypothesis that poor frequency discrimination skills may be related to language problems is dependent on the notion that auditory processing skills may have an impact on the development of language and literacy as the child is growing up. Although children with hearing loss may experience sensation levels sufficient for adequate comprehension of speech once their hearing loss has been corrected by use of a hearing aid, most of these children are not provided with hearing aids until they are approximately 4 years of age, and many do not subsequently use their aids. Moreover, the provision of a hearing aid that

simply amplifies the sound will not necessarily overcome all of the perceptual consequences associated with cochlear damage (Moore, 1997). Given that the majority of children in the current study were not identified as having a hearing loss until relatively late in life (see Participants section), it is likely that the early exposure of most of these children to sounds (both speech and non-speech) would have been at a sensation level lower than that of children with normal hearing. Consequently, we argue that the presentation of stimuli at a fixed sensation level may tend to overestimate the frequency discrimination abilities that a child with hearing loss may have had early in life. Therefore, to assess any frequency discrimination deficits that might have been experienced in the real world at a time when language and literacy were still developing, we decided not to adjust stimulus levels for the group with hearing loss in the current study.

2. Second, the current study aimed to examine whether deficits might be attributable to problems with phase locking to the auditory signal. By obtaining DLFs at 1 kHz, where phase-locking information should be available, and at 6 kHz, where it should not be, the current study aimed to investigate the extent to which any observed frequency discrimination deficits might be confined to relatively low frequency stimuli.
3. Finally, based on the hypothesis that there is a causal relationship between frequency discrimination and language development, the current study sought to investigate the relationship between frequency discrimination and a range of language abilities in children with mild to moderate hearing loss.

Method

Participants

Two samples from 6 to 13 years of age were recruited: one group of children who had sensorineural hearing loss (SNH group) and another group of children whose development was typical for their chronological age (CA) to serve as the control group (CA group). The two groups were age-matched. All children were from monolingual English-speaking backgrounds and all obtained a nonverbal IQ score z-score equivalent of at least –1.7 (corresponding approximately to the fifth percentile).

SNH group. Twenty-two children (10 boys and 12 girls) aged from 6.05 to 13.55 years (mean age = 10.47 years, SD = 1.83 years) with bilateral mild to moderate sensorineural hearing loss were included in the present study. Of the 22 participants, 12 were approached following their participation in one of two earlier projects (Briscoe et al., 2001; Halliday & Briscoe, 2002) and invited to participate in the current study. The remaining 10 participants were recruited via Peripatetic Services for children with hearing loss in five regions in South East England. For new participants, information about the study and an invitation to participate were distributed to specialist teachers for children with hearing loss, who were asked to pass them on to parents of children who (a) had a mild to moderate bilateral sensorineural hearing loss, (b) were attending mainstream school, (c) were from monolingual English-speaking backgrounds, and (d) communicated solely via the oral/aural modality. Children whose hearing loss was attributed to neurological impairment were excluded from the study.

Hearing sensitivity at 0.25, 0.5, 1, 2, 4, 6, and 8 kHz was measured using the descending Hughson-Westlake method (Carhart & Jerger, 1959) with a Digital Signal Processor audiometer and Telephonics TDH39P headphones. Two categories of hearing loss were identified in this sample on the basis of the child's pure tone average (PTA) threshold in the better ear at 0.25, 0.5, 1, 2, and 4 kHz (British Society of Audiology, 1988). *Mild hearing loss* (10 children) was defined as a PTA threshold of 20 to 40 dB HL, whereas *moderate hearing loss* (12 children) was defined as a PTA threshold of 41 to 70 dB HL. The PTA thresholds and pure tone thresholds of listeners at 1 and 6 kHz are provided in Table 1.

All but 2 of the children in the SNH group owned a hearing aid that corrected their hearing loss in at least one ear. However, of the children that owned a hearing aid, 2 were reported to be refusing to use amplification in their daily lives. In all but 4 of the cases (where hearing loss was assumed to be genetic in origin), parents reported an unknown etiology for the hearing loss, but in all cases, it was believed to be congenital. The mean age of identification was 40.5 months (range, 1.5–84 months). Although language was not a selection criterion in this study, we noted that 12 children in the SNH group had received speech and language therapy in the past, and 6 of these children were still receiving therapy.

CA control group. Twenty-two control children (10 boys and 12 girls) with no known educational difficulties or history of speech and language problems were matched to the SNH group on chronological age and gender. Controls were aged between 6.51 and 13.12 (mean age = 10.33 years, *SD* = 1.66 years). Where possible, control children were drawn at random from

Table 1. Pure tone average (PTA) thresholds (250–4000 Hz) of the ear tested, pure tone thresholds at 1 and 6 kHz, and standard scores for nonverbal intelligence, spoken language, and reading for the study groups.

	SNH group (*n* = 22)			CA group (*n* = 22)		
	M	*SD*	Range	*M*	*SD*	Range
PTA	46.36	13.61	21–67	9.82	4.14	2–16
*Pure tone threshold at 1 kHz	41.94	16.55	15–65	10.23	4.75	5–20
*Pure tone threshold at 6 kHz	43.33	18.96	10–65	9.09	8.26	−10–20
WASI Matrices	53.00	8.38	32–69	48.05	6.39	35–60
TROG-2	92.32	13.40	69–116	91.32	14.98	62–116
ROWPVT	102.82	14.87	83–136	103.68	12.05	86–137
EOWPVT	98.45	12.13	73–122	98.50	14.90	80–145
Word reading	100.91	15.43	72–136	107.95	14.53	86–141
Nonword reading	101.00	15.81	72–126	107.45	16.64	72–137
**Nonword repetition	3.33	1.83	1–6	6.05	2.16	2–9

Note. SNH group = sensorineural hearing loss group; CA group = typically developing group; WASI = Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999); TROG–2 = Test for the Reception of Grammar—2 (Bishop, 2003); ROWPVT = Receptive One Word Picture Vocabulary Test (Brownell, 2000b); EOWPVT = Expressive One Word Picture Vocabulary Test (Brownell, 2000a).

*Pure tone thresholds are reported only for those participants for whom DLFs were obtained at the relevant test frequencies. Consequently, *n* = 18 for the pure tone thresholds at 1 kHz, and *n* = 15 for the pure tone thresholds at 6 kHz.

**Because the published norms do not extend beyond 12 years, *n* = 21 for the test of nonword repetition.

the classrooms of the participants with hearing loss. For the 8 cases where this was not possible, controls were recruited from local primary and middle schools in the Oxfordshire area. In these instances, efforts were taken to match the control children to the SNH group on the basis of socioeconomic status as calculated by postcode data. None of the control participants were reported to have a history of hearing problems, and children who had experienced repeated incidents of otitis media were excluded from consideration. All control participants had PTA thresholds less than 20 dB HL (British Society of Audiology, 1988), and a maximum threshold of 25 dB HL at all audiometric frequencies.

Procedure

Testing was carried out during two sessions, each lasting approximately 1 hr; the sessions were separated by at least 24 hr. Each child was tested individually by a single experimenter in a quiet room at school or at home. The order of test sessions was counterbalanced across participants. All of the children in the SNH group who owned a hearing aid (including those who were currently refusing to use their aids in their daily lives) used amplification during the psychometric assessment, but hearing aids were removed during psychophysical testing and assessment of auditory thresholds.

Psychometric Assessment

Nonverbal ability test. Nonverbal cognitive ability was estimated using the Matrices Reasoning subtest of the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999), which is composed of 35 items graded in difficulty. The subtest measures four types of nonverbal reasoning: pattern completion, classification, analogy, and reasoning. For each item, the participant selects one of five patterned segments to complete a large patterned matrix that contains a blank segment. Scores are expressed as standard scores with a mean of 50 (*SD* = 10).

Test for Reception of Grammar—2. Grammatical abilities were assessed using a computerized version of the Test for the Reception of Grammar (TROG–2; Bishop, 2003). The test is composed of 20 blocks of four items, with each block measuring the subject's understanding of a different grammatical contrast. For each item, comprehension is assessed using a four-item multiple-choice format, where a picture depicting a spoken target sentence is contrasted with foil pictures depicting sentences that are altered in grammatical/lexical structure. The child's task is to select the picture that corresponds to the sentence that he or she has just heard. Performance is expressed as standard scores that have a mean of 100 (*SD* = 15).

Vocabulary tests. Expressive and receptive vocabulary were assessed using the Expressive subtest of the

One Word Picture Vocabulary Test (EOWPVT; Brownell, 2000a) and the Receptive subtest of the One Word Picture Vocabulary Test (ROWPVT; Brownell, 2000b). The EOWPVT and ROWPVT each contain 170 items, graded in difficulty. For the EOWPVT, each item consists of one picture, and the child's task is to name the object or group of objects depicted in the picture. Scores are expressed as standard scores with a mean of 100 (SD = 15). For each item of the ROWPVT, the child is presented with four pictures and required to select the picture that matches a word spoken by the examiner.

Word and nonword reading tests. Reading accuracy and fluency were assessed using Version A of the Test of Word Reading Efficiency (TOWRE; Torgesen, Wagner, & Rashotte, 1999), which is composed of the Sight Word Efficiency and the Phonemic Decoding Efficiency subtests. Each subtest consists of a list of eight practice items and a longer list of test items, graded in difficulty. The Sight Word Efficiency subtest contains 104 familiar regular words, and the Phonemic Decoding Efficiency subtest contains 63 orthographically legal pronounceable nonwords. After successfully reading the practice items, the child's task is to read as many words and nonwords aloud as possible in 45 s. Scores are expressed as standard scores with a mean of 100 (SD = 15).

Test of phonological skills. Phonological processing and phonological memory were assessed using the Repetition of Nonsense Words subtest from the Developmental Neuropsychological Assessment NEPSY (Korkman, Kirk, & Kemp, 1998). In this test, 13 nonword items, ranging from two to five syllables in length, are presented on audiotape at a comfortable listening level. The child's task is to repeat each nonword aloud. Scores are expressed as scaled scores with a mean of 10 (SD = 3).

Auditory Assessment

Stimuli. Two sets of stimuli were constructed to test frequency discrimination at 1 kHz and at 6 kHz. A pilot study indicated that a frequency difference of 10% of the central frequency at both 1 kHz and 6 kHz was sufficient to be easily distinguishable by 6- and 11-year-olds with normal hearing. Consequently, for the 1-kHz frequency discrimination task, 200 stimuli were constructed, at 0.5-Hz intervals between 1 and 1.1 kHz. Similarly for the 6-kHz frequency discrimination task, 200 stimuli were constructed at 3-Hz intervals between 6 and 6.6 kHz. All stimuli had a steady-state portion of 240 ms and were gated on and off by a 5-ms raised-cosine ramp. The stimuli were synthesized digitally using Tucker-Davis Technologies (TDT) System II hardware at a sampling rate of 48 kHz. The resulting waveforms were converted to voltages using a 16-bit digital-to-analog converter. Stimuli were presented monaurally via Sennheiser HD-1 headphones. For the majority of participants, stimuli were presented to the right ear. However, a number of the participants with hearing loss reported not being able to hear the stimuli via the right earpiece, and in these instances, stimuli were presented via the left ear. As a result, 4 children with hearing loss completed the 1-kHz frequency discrimination task via the left ear, and 1 completed the 6-kHz frequency discrimination task via the left ear. Stimuli were presented at an SPL of 75 dB (reference level 20 μPA). Sound pressure levels were calibrated with a Brûel and Kjær measuring amplifier (type 2610), and associated preamplifier (type 2619), microphone (type 4134), and artificial ear (type 4153).

Psychophysical procedure. A three-interval, two-alternative forced-choice more virulent parameter estimation by sequential testing procedure was used to track the frequency difference between the standard tone (1 or 6 kHz) and the higher, variable tone (Findlay, 1978). The threshold estimate was based on an adaptive run with an upper limit of 80 trials, with most runs lasting 30 to 40 trials. The threshold for each run was the mean frequency difference between the variable tone and the standard tone of the last four step-size reversals. Two runs per condition were obtained for each subject, and a third was ob-tained if one of the threshold estimates was considered to be unstable (i.e., fluctuated considerably around the threshold point after the fourth reversal).

Threshold estimates were incorporated into a computer game in which each of the auditory intervals corresponded to a visual event on a computer screen. For the auditory stimuli, each trial was comprised of three 1,000-ms stimulus intervals, separated by 500 ms of silence. Before each trial began, three animated dinosaurs appeared on the computer screen, each positioned above a different colored box that was red, white, or yellow. As the trial commenced, each cartoon figure sequentially "jumped" up and down on its box, in time with the three auditory stimulus intervals. An AXB procedure was used, whereby the middle dinosaur interval contained the standard tone (either 1 or 6 kHz) while one of the other two intervals (A or B), selected randomly, contained the target tone (again, 1 or 6 kHz) and the other contained a "higher" tone that was adaptively varied to reach threshold. Participants were instructed to select the dinosaur (red or yellow) that they believed made the same sound as the middle (white) dinosaur, either by pointing or by responding "red" or "yellow." Participants were given unlimited time in which to respond, and the initiation of each new trial was self-paced. Correct responses were reinforced by the appearance of a novel picture, which remained visible at the side of the screen as an indicator of past performance success. An upward sweeping "happy" tone accompanied the appearance of this picture. If an incorrect response was selected, a black cross appeared on the screen, and a "sad" sigh sound was presented.

Each trial could be repeated a maximum of three times upon request of the participant. This was particularly important for those trials in which participants failed to attend to the auditory stimuli. If participants were still unsure after three repetitions, they were encouraged to guess. Participants were introduced to each condition with 10 practice trials that were presented through speakers. During practice trials, stimulus parameters were set to the levels that had been deemed clearly distinguishable in a pilot study. For the 1-kHz task, the higher tone was set at 1.1 kHz, whereas the 6-kHz practice condition had a comparison tone of 6.6 kHz.

Results

Psychometric Tests

The results of the standardized tests of nonverbal and language ability indicate that both the SNH and CA groups performed at approximately age-appropriate levels for all measures except the NEPSY test of nonword repetition (see Table 1). For this test, both the CA controls and the SNH group performed well below the mean level predicted by norm data, a finding we attribute to the use of American norms and delivery of nonwords by a North American speaker. For all other tests, the range of scores for the SNH group were remarkably similar to those of the CA controls, a result that runs contrary to previous reports of wide individual variation in the language abilities of children with hearing loss (Briscoe et al., 2001). Between-group differences were assessed using a series of univariate analyses of variance (ANOVAs) and Mann–Whitney tests, with an alpha level of .05.

Despite attempts to closely match the two groups on socioeconomic status and educational background, the SNH group scored significantly higher than the CA control group on the test of nonverbal cognitive ability, $F(1, 42) = 4.87$, $p = .033$. Given the reported associations between frequency discrimination abilities and nonverbal intelligence (Deary, 1994; Raz, Willerman, & Yama, 1987; Watson, 1991), we used performance on the WASI Matrices subtest as a covariate in subsequent analyses.

Univariate ANOVAs indicated no significant differences between the SNH group and CA controls on the TROG–2, $F(1, 42) = 0.05$, $p = .817$; the ROWPVT, $F(1, 42) = 0.05$, $p = .833$; or the EOWPVT, $F(1, 42) = 0.00$, $p = .991$. Group differences remained nonsignificant on these measures once age and raw scores on Matrices had been partialled out: TROG–2, $F(1, 40) = 1.87$, $p = .179$; ROWPVT, $F(1, 40) = 1.63$, $p = .209$; EOWPVT, $F(1, 40) = .56$, $p = .457$. However, although neither the TOWRE word nor the TOWRE nonword scores yielded significant group differences—$F(1, 42) = 2.43$, $p = .126$ and $F(1, 42) = 1.74$, $p = .194$, respectively—a main effect of group emerged for word reading once age and Matrices raw scores had been covaried out, $F(1, 40) = 5.42$, $p = .025$.

Scores on the NEPSY test of repetition of nonsense words showed a strongly bimodal distribution in the CA control group. A Mann–Whitney test confirmed an overall difference between groups ($U = 81.5$, $p < .001$), driven by the poorer performance of the SNH group relative to that of controls. The effect of word length on performance was examined by calculating the percentage of syllables correctly repeated in the two-, three-, four-, and five-syllable conditions for both groups of participants. Contrary to the results of Briscoe and colleagues (2001), a Mann–Whitney test indicated that the SNH group performed worse than CA controls across all syllable levels (two syllables: $U = 92$, $p < .001$; three syllables: $U = 65.5$, $p < .001$; four syllables: $U = 106$, $p = .001$; five syllables: $U = 135.5$, $p = .011$), suggesting that impaired audition rather than reduced auditory memory might contribute to the poor nonword repetition skills in children with mild to moderate hearing loss.

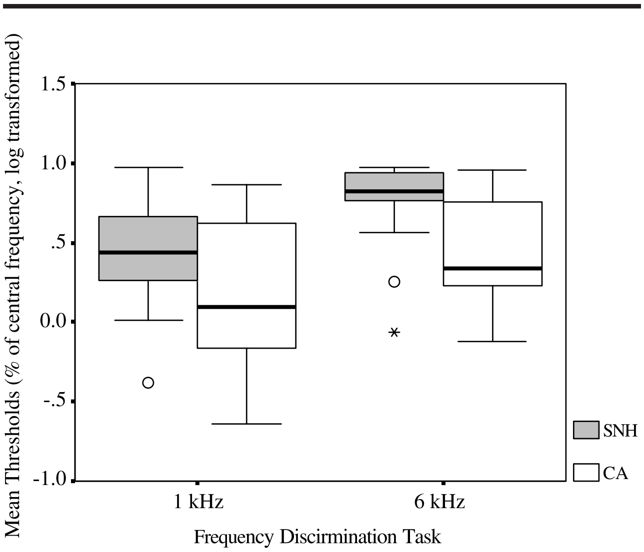
Frequency Discrimination Tests

Frequency discrimination thresholds were not obtained for those participants who had audiometric thresholds greater than 65 dB at test frequency because of concerns that they would be unable to hear the stimuli. Thus, 4 and 7 participants with hearing loss were excluded from the frequency discrimination tasks at 1 and 6 kHz, respectively. Of those 13 listeners for whom DLFs were obtained at both test frequencies, most had a relatively flat audiometric configuration, with only 4 showing a discrepancy of 20 dB or more between their PTA thresholds at 1 and 6 kHz. A Kolmogorov–Smirnov test showed that data obtained from both groups on both frequency discrimination tasks were not normally distributed. The thresholds of each run were therefore subjected to a log transformation (to base 10) in an effort to normalize the data. All subsequent analyses are based on log scores.

Preliminary analyses showed that there was no main effect of run for either of the two frequency conditions: 1 kHz, $F(1, 34) = 1.02$, $p = .319$; 6 kHz, $F(1, 27) = 0.76$, $p = .391$. Also, there were no significant interactions between run and group: 1 kHz, $F(1, 34) = 1.92$, $p = .175$; 6 kHz, $F(1, 27) = 1.09$, $p = .306$. Given that performance did not differ significantly between runs, mean thresholds across the two runs for both the frequency discrimination task at 1 kHz and that at 6 kHz were used in all subsequent analyses.

The distributions of DLFs (expressed as a logarithmic transformation of the percentage of the center frequency) for the frequency discrimination task at 1- and 6-kHz conditions for both SNH and CA groups are illustrated in Figure 1. The SNH group required an average difference of 35.28 Hz to discriminate reliably between tones at 1 kHz and an average difference of 387.68 Hz at 6 kHz. This compares to average frequency thresholds of 21.75 and 221.64 Hz, respectively, for the control group. However, there were large variations in thresholds in both the SNH and the CA groups, with a difference of 89 Hz between highest and lowest performance in the SNH group and a difference of 71 Hz in the CA group for the 1-kHz condition. Performance in the 6-kHz condition was equally variable in the SNH group (517 Hz), and the control group (498 Hz). Group differences were tested with independent samples ANOVAs, with an alpha level of 0.05. Given that different subsets of children had complete data at 1 kHz and at 6 kHz, separate univariate ANOVAs were conducted for each of the two frequency conditions. In an effort to control for possible effects of age, the age-matched controls of those children with hearing loss who were unable to perform the 1- or 6-kHz conditions were eliminated from the analyses.

Figure 1. Box plots showing log-transformed difference limens for frequency (DLFs) at 1 kHz and 6 kHz for the SNH and CA groups. The lower and upper ends of the box denote the first (Q1) and third (Q3) quartiles, respectively, and the horizontal line in the center of the box denotes the median. The whiskers extend to the smallest and largest observations within Q1 − 1.5(Q3 − Q1) and Q3 − 1.5(Q3 − Q1) of the quartiles.



Mean thresholds for the SNH group were higher than those of the CA controls for frequency discrimination at both the 1-kHz condition, $F(1, 34) = 5.09$, $p = .031$, and the 6-kHz condition, $F(1, 28) = 6.70$, p = .015 (equal variances not assumed). These main effects remained significant once the effects of age and nonverbal intelligence were controlled: at 1 kHz, $F(1, 32) = 6.48$, $p = .016$; at 6 kHz, $F(1, 26) = 5.88$, $p = .022$. A between-group comparison of standard deviations of stimulus frequency over the final four reversals indicated that the two groups did not differ in variability of performance for either the 1-kHz condition (SNH: 8.70, CA: 8.95), $F(1, 34) = .008$, $p = .931$, or the 6-kHz (SNH: 6.32, CA: 6.26), $F(1, 28) = .001$, $p = .976$, condition.

Given the poor performance of the SNH group on both the frequency discrimination tasks, the question then arises as to what may cause this impairment. As frequency discrimination abilities have been shown to be dependent on presentation level, particularly for sensation levels below 40 dB (Wier et al., 1977), one possibility is that this lack of sensitivity was perhaps the byproduct of elevated hearing thresholds in the children with hearing loss. The pure tone auditory thresholds and mean DLFs at 1 and 6 kHz of participants in the SNH group are provided in Table 2. We addressed this issue by comparing the DLFs of those members of the SNH group who had pure tone thresholds greater than or equal to 40 dB (moderate loss) to those with pure tone thresholds less than 40 dB (mild loss) at 1 and 6 kHz, respectively. At 1 kHz, DLFs did not differ significantly between those children with moderate losses at 1 kHz (35.45 Hz) and those with mild hearing loss (35.02 Hz), $F(1, 16) = 0.198$, $p = .662$. However, listeners with pure tone thresholds greater than or equal to 40 dB at 6 kHz performed significantly worse (450.23 Hz) on the 6-kHz frequency discrimination task than those with pure tone thresholds less than 40 dB (262.56 Hz), $F(1, 13) = 5.98$, $p = .029$. Nevertheless, two-tailed Pearson correlations indicated that the relationship between hearing thresholds at 1 and 6 kHz, and performance on the frequency discrimination task at 1 and 6 kHz, respectively, was low and not significant for both the moderate hearing loss group ($r = .273$, $p = .417$; $r = 0.551$, $p = .099$) and the mild hearing loss group ($r = .255$, $p = .581$; $r = .121$, $p = .847$), suggesting that factors other than signal audibility may also contribute to the poor performance of children with hearing loss on this task.

Correlates of Frequency Discrimination Abilities

When correlates of frequency discrimination were examined, data from all the control children were

Table 2. Participant characteristics (chronological age, use of hearing aid, approximate age of identification of hearing loss), pure tone auditory thresholds of the ear tested at 1 and 6 kHz, and mean frequency discrimination thresholds for the SNH group.

Participant	Age (years:months)	Use of hearing aid	Age of identification (years:months)	Auditory threshold at 1 kHz (dB)	Mean DLF at 1 kHz (Hz)	Auditory threshold at 6 kHz (dB)	Mean DLF at 6 kHz (Hz)
SNH01	11:4	Yes	2:0	20	33.61	80	____
SNH02	10:0	Yes	0:9	40	18.16	40	351.92
SNH03	11:2	Yes	1:5	65	93.28	80	____
SNH04	11:11	Refusal	6:0	15	74.17	10	400.13
SNH05	10:5	Yes	6:6	64	29.08	65	367.35
SNH06	11:7	No	5:0	30	4.18	60	568.14
SNH07	10:3	Yes	2:0	70	____	55	484.76
SNH08	8:5	Yes	1:5	70	____	65	531.11
SNH09	12:8	Yes	4:0	50	10.25	35	108.47
SNH10	11:4	Yes	2:0	50	46.09	80	____
SNH11	13:6	Yes	4:0	60	28.01	70	____
SNH12	11:1	Refusal	3:0	45	24.99	40	354.39
SNH13	11:0	Yes	Unknown	35	71.68	65	568.35
SNH14	10:5	Yes	3:6	70	____	70	____
SNH15	8:3	No	0:1.5	20	23.33	10	51.41
SNH16	9:1	Yes	1:0	60	18.10	45	218.28
SNH17	10:3	Yes	6:6	75	____	80	____
SNH18	6:5	Yes	4:0	45	72.10	45	541.35
SNH19	6:0	Yes	2:6	45	19.42	35	344.58
SNH20	10:7	Yes	7:0	25	27.11	20	408.24
SNH21	10:6	Yes	6:0	25	11.14	60	516.71
SNH22	11:11	Yes	2:0	60	30.52	80	____

combined into a single group. Given the developmental trajectory that has been proposed to exist for frequency discrimination abilities (e.g., Maxon & Hochberg, 1982), we calculated Pearson's correlation coefficients between age and DLFs at both 1 and 6 kHz. There were no significant associations between age and frequency discrimination at either 1 kHz (r = –.18, p = .281) or 6 kHz (r = –.104, p = .542). However, the absence of any effect appeared to be largely attributable to small numbers of participants in the younger age groups, and it was indeed notable that all of the children in our two youngest age-matched pairs had relatively high thresholds. Consequently, age was used as a covariate in all subsequent analyses.

To test the hypothesis that deficient frequency discrimination is related to the degree of impairment in phonological and reading skills, we computed Pearson's correlation coefficients between mean frequency discrimination at 1- and 6-kHz thresholds and performance on (a) TOWRE word reading, (b) TOWRE nonword reading, and (c) NEPSY nonword repetition, for both the SNH and CA groups (see Table 3). Because no age-appropriate norms were available for the frequency discrimination task, correlations were calculated using raw scores for the language measures.

For both the 1-kHz frequency discrimination task and the 6-KHz frequency discrimination task, there were significant partial correlations between threshold scores and scores on all three measures of word reading, nonword reading, and nonword repetition, once age and raw scores on the WASI Matrices subtest had been taken into account. However, these associations largely disappeared when the SNH and CA groups were analyzed separately. Within the SNH group, none of the correlations between frequency discrimination and reading and nonword repetition remained significant after age and nonverbal intelligence were controlled. In contrast, for the control group, significant associations remained between frequency discrimination at 1 kHz and nonword repetition (r = –.49, p = .029), and between frequency discrimination at 6 kHz and TOWRE nonword reading (r = –.63, p = .003). The correlation between frequency discrimination performance at 6 kHz and nonword repetition in the control group just failed to reach significance (r = –.44, p = .053).

Given that strong intercorrelations are reported to exist between word and nonword reading measures (Bishop & Adams, 1990), we examined whether the correlation coefficients for the control group on the TOWRE word reading task versus frequency

Table 3. Partial Pearson correlation coefficients (adjusted for age and WASI Matrices raw scores) between difference limens for frequency (DLFs) at 1 and 6 kHz, and raw scores on the tests of phonological processing and reading ability for SNH and CA groups.

			TOWRE word	TOWRE nonword	NEPSY nonword repetition
Frequency discrimination at 1 kHz	Groups combined	*r*	−.35*	−.37*	−.50**
		p	.033	.021	.001
		df	36	36	36
	SNH group	*r*	−.26	−.27	−.17
		p	.330	.315	.535
		df	14	14	14
	CA group	*r*	−.19	−.31	−.49*
		p	.410	.189	.029
		df	18	18	18
Frequency discrimination at 6 kHz	Groups combined	*r*	−.39*	−.42*	−.50**
		p	.021	.012	.002
		df	33	33	33
	SNH group	*r*	−.06	.19	−.11
		p	.844	.544	.713
		df	11	11	11
	CA group	*r*	−.41	−.63**	−.44
		p	.070	.003	.053
		df	18	18	18

Note. TOWRE = Test of Word Reading Efficiency.

*Significant at the .05 level. **Significant at the .01 level.

discrimination at 6 kHz were significantly different from those on the TOWRE nonword reading task versus frequency discrimination at 6 kHz (Guilford & Fruchter, 1973). The results indicated that the correlation coefficients of the control group for word and nonword reading versus frequency discrimination at 6 kHz were significantly different ($t(19) = 1.736$, $p < .05$).

Figure 2 shows the reported associations between word and nonword reading and nonword repetition, and log thresholds for the frequency discrimination tasks. If the hypothesis that poor frequency discrimination is causally related to poor reading and phonological processing were true, then a cluster of participants in the lower right corner, irrespective of group status, might be expected. However, these scatter plots revealed that participants with relatively high thresholds tended to be spread across both the upper and lower right-hand side. However, the contrary hypothesis, that good frequency discrimination skills might be associated with good reading and nonword repetition abilities, largely holds true. Indeed, although there was a clustering of participants in the upper left corner, indicating low discrimination thresholds and good reading/nonword repetition scores, very few participants fell into the lower left corner. Moreover, the majority of participants falling into the upper left corner were from the control group, while those falling into the lower right corner were largely from the SNH group. These scatter plots, therefore, suggest that the combined group associations between frequency discrimination and language were, in part, driven by the bimodal distribution of the two groups.

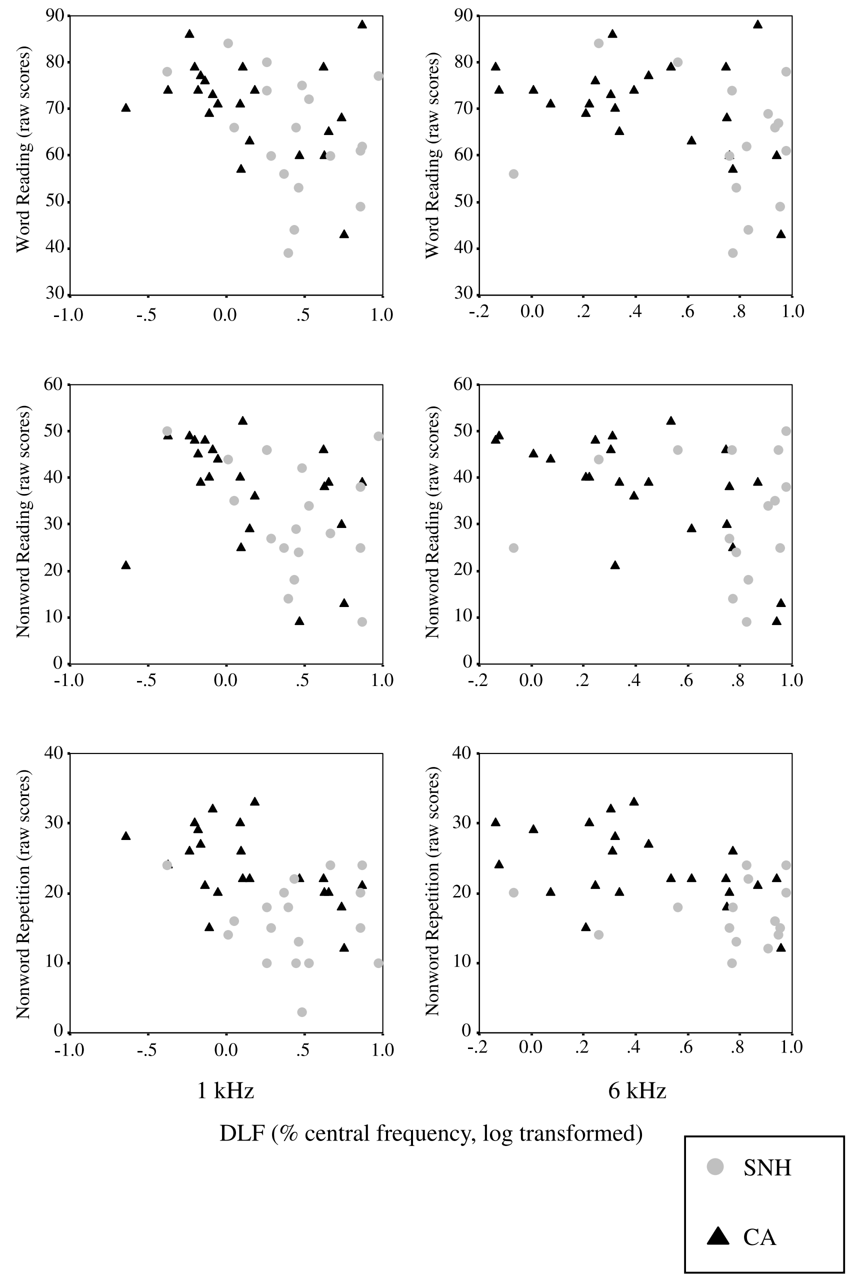
Discussion

The aims of the present study were (a) to investigate whether children with mild to moderate sensorineural hearing loss were impaired in their ability to discriminate tones of different frequencies, (b) to determine whether any impairment might be attributable to a deficit in phase locking, and (c) to consider whether frequency discrimination abilities might predict literacy and phonological skills.

Frequency Discrimination Skills in Children With Mild to Moderate SNH

The finding that children with mild to moderate sensorineural hearing loss were impaired in their

Figure 2. Scatter plots showing the relations between raw scores on the word and nonword reading, and nonword repetition tasks, and difference limens for frequency (DLFs) at 1 and 6 kHz.



ability to discriminate pure tones of different frequencies is consistent with results from adult studies (e.g., Gengel, 1973; Nelson & Freyman, 1986; Tyler, Wood, & Fernandes, 1983). However, there were substantial individual differences in frequency discrimination abilities, with quite considerable overlap in the performance of the two groups. Wide individual variation has been reported previously in relation to the frequency discrimination skills of adults with hearing loss. For instance, Glasberg and Moore (1989) found that unlike their participants with moderate unilateral hearing loss, those with bilateral loss were unimpaired on a test of frequency discrimination at 0.5, 1, and 2 kHz. Moreover, Tyler, Wood, and Fernandes (1983) showed that even some adults with hearing loss who had thresholds of 80 to 90 dB HL had entirely normal frequency discrimination abilities.

The question arises as to what may cause this massive variation in performance, especially in the control group where low-level deficits in auditory processing are unlikely to exist. One possibility is that the wide variation in performance on the frequency discrimination task was due in part to limited practice on the task. Given that frequency discrimination skills have been shown to improve with practice (e.g., Irvine, Martin, Klimkeit, & Smith, 2000), it may be that some participants in the current study took longer to master the task than others, leading to an underestimation of frequency discrimination ability in some children. Time constraints meant that the children completed, at most, three runs per condition, with most runs lasting between 30 and 40 trials. The DLFs that we obtained for control children were between 3 and 9 times greater than those reported for normally hearing adult controls at 1 and 6 kHz, respectively (Sek & Moore, 1995), and this could be due in part to the fact that psychoacoustic studies with adults typically give listeners between 10 and 20 hours of practice prior to testing, use listeners who have had prior experience on psychoacoustic tasks, and derive frequency discrimination thresholds based on the average of considerably more runs than were obtained in the current study (e.g., Sek & Moore, 1995; Wier et al., 1977). However, although limited practice may have contributed to the higher than expected DLFs observed in the current study, comparison of DLFs across testing runs gave no evidence of practice effects within the short testing period that we used. Nor was there a significant interaction between group and run for either of the two conditions; thus, the group difference could not be explained by differential practice effects.

Another possibility to consider is that nonauditory factors, such as attention or nonverbal intelligence, may have contributed to the large interindividual variability in DLFs. An examination of individual psychophysical curves did not point to any participants as particularly inattentive, but we cannot rule out the possibility that some children were simply more distractible than others, leading to elevated thresholds (cf. Allen & Wightman, 1995; Bargones, Werner, & Marean, 1995). Nevertheless, inattention does not seem to be a plausible explanation for differences between the SNH and control groups, given that the variability of threshold estimates (as indexed by standard deviations of tone frequency over the final four reversals) did not differ between the groups.

In a similar vein, we can argue that although frequency discrimination ability is associated with nonverbal IQ in adults (Deary, 1994; Raz et al., 1987; Watson, 1991), it does not provide an explanation for the group differences obtained here, where the SNH group did simultaneously better on the test of nonverbal intelligence and worse on the test of frequency discrimination.

Possible Explanations for Poor Frequency Discrimination in Children With SNH

The first possibility to consider in exploring the mechanism underlying impaired frequency discrimination in children with SNH is whether poor frequency discrimination can be totally explained in terms of the reduced audibility of stimuli for children with hearing loss, given that the majority of the SNH group in the current study performed the task at sensation levels below those experienced by controls. As reported by Wier and colleagues (1977), the frequency discrimination abilities of normally hearing listeners improve with increasing sensation level for sensation levels as high as 80 dB. The results of the current study suggest that although it is an important contributory factor, poor audibility may not be the sole explanation for the higher than expected DLFs recorded for some children with hearing loss. Although DLFs at 6 kHz were found to be elevated in those listeners with moderate hearing loss at 6 kHz relative to those with milder loss, this did not hold true at 1 kHz, where those with mild and moderate thresholds for a 1-kHz tone showed an equal degree of impairment on the frequency discrimination task. Moreover, correlations between pure tone thresholds and frequency discrimination performance were nonsignificant, indicating that there is no one-to-one relationship between frequency discrimination and hearing thresholds (see also Freyman & Nelson, 1991). These findings leave open the possibility that, aside from reduced sensation, children with mild to moderate hearing loss may also have more fundamental problems in discriminating spectral information in auditory stimuli.

If a deficient phase-locking mechanism were the sole explanation for poor frequency discrimination, then we would expect much worse performance for stimuli at 1 kHz, where phase-locking information can be used, than at 6 kHz, where phase-locking information is no longer available (Sek & Moore, 1995). In fact, we found marked impairments at both frequencies. Interpretation of the current results is further complicated by the relative lack of studies investigating the frequency discrimination abilities of people with hearing loss at frequencies above 5 kHz. Although poor frequency discrimination has been demonstrated in adults with hearing loss at central frequencies ranging from 100 to 4000 Hz (Arehart & Rosengard, 1999; Gengel, 1973; Hall & Wood, 1984; Moore & Peters, 1992; Nelson & Freyman, 1986; Simon & Yund, 1993; Tyler et al., 1983), to the authors' knowledge only one study has measured DLFs at a higher frequency (8 kHz), and the inclusion of participants with largely acquired hearing losses makes this a less than ideal comparison (Freyman & Nelson, 1991).

The findings of the current study, therefore, present two possible interpretations. First, as discussed earlier, it could be that differences in the sensation level at which stimuli were experienced by the two groups may have been responsible for the poorer performance of the SNH group on the frequency discrimination task at both low and high central frequencies. A second interpretation is suggested by the idea that two different mechanisms may be responsible for frequency discrimination in normally hearing individuals (Moore, 1997). From this perspective then, we might attribute the SNH group's deficits in frequency discrimination at 1 kHz to a deficiency in their ability to phase-lock to auditory stimuli and their deficits at 6 kHz to an impairment in their ability to use information regarding the place of maximum excitation on the basilar membrane. Although there is currently nothing to discriminate between the two interpretations, the latter view gains some support from a study showing that both phase-locking and excitation pattern mechanisms of frequency modulation detection are adversely affected in elderly listeners with sensorineural hearing loss (Moore & Skrodzka, 2002). Therefore, although the results suggest that the phase-locking mechanism may not be selectively im-paired in children with mild to moderate senso-rineural hearing loss, they do not rule out the possibility that deficient phase locking may play a role in determining frequency discrimination in this group. To distinguish these possibilities, it would be useful in future studies to compare DLFs of children with hearing loss and control children for stimuli matched for audibility.

Relationship Between Frequency Discrimination and Language/ Literacy Skills

Whatever the mechanism responsible for the frequency discrimination deficits of children with hearing loss, our data show that these impairments do not necessarily lead to problems in the development of language and literacy. Although there were moderate correlations between frequency discrimination, reading, and nonword repetition in the combined group data, the absence of significant correlations within the SNH group suggests that these associations were driven in part by the relatively poor performance of children with hearing loss on both the psychophysical and language measures compared to their age-matched controls.

One possibility to consider is that frequency discrimination deficits must fall above a certain "threshold" before they begin to affect speech processing and, consequently, phonological development. According to this interpretation, evidence for a relationship between frequency discrimination and phonology may be apparent only in an across-group analysis, where there are sufficient numbers of participants falling on either side of this critical threshold. However appealing this interpretation may be though, it has three major drawbacks. First, although their performance was significantly worse than that of the controls, the SNH group performed entirely within age-appropriate levels on tests of word and nonword reading. The children with mild to moderate hearing loss read slightly worse than might have been predicted from their nonverbal intelligence scores, but they failed to exhibit any of the marked deficits in language and literacy that are characteristic of SRD. This is particularly striking given that the SNH group in the current study exhibited higher mean thresholds at 1 kHz than the dyslexic group reported in McAnally and Stein (1996). It is likely that some of the children in the SNH group would have obtained better DLFs had we tested their discrimination at higher intensities to compensate for the hearing loss. We did not do this, because the theoretical case for a link between impaired frequency discrimination and poor literacy concerns children's ability to hear differences between speech sounds in their natural environment. Furthermore, the lack of correlation between level of hearing loss and frequency discrimination in our SNH sample indicates that many children had problems in frequency discrimination that were not explicable solely in terms of reduced audibility, yet their literacy levels were unimpaired. Second, the lack of a relationship between poor frequency discrimination and literacy level appears in our control sample, as well as in the children with hearing loss. As seen in Figure 2, those control participants who had particularly high frequency discrimination thresholds did not always show corresponding deficits in their word and nonword reading skills, which might be predicted by the threshold argument. And, third, despite the considerable variability of frequency discrimination abilities observed for controls, correlations were not found to be significant for this group between DLFs at 1 kHz and scores on the tests of word and nonword reading, nor between DLFs at 6 kHz and word reading.

Although our results do not, on the whole, support a link between poor frequency discrimination and poor literacy, frequency discrimination was associated with nonword repetition at 1 kHz, and with nonword reading and (marginally) nonword repetition at 6 kHz in controls. In this regard, the results of the current study are consistent with the findings of Ahissar and colleagues (2000), Walker and colleagues (2002), and more recently, Griffiths, Hill, Bailey, and Snowling (2003), who reported moderate correlations between frequency discrimination and a number of nonword reading measures, particularly for adult controls. We did not, however, replicate an association between frequency discrimination and word reading that has been reported both in children (Saunders, Protopapas, Cangiano, Salz, & Cerles, 1998) and in adults (Ahissar et al., 2000; Walker et al., 2002). These results, then, provide tentative evidence for a link between frequency discrimination skills and phonological abilities. However, contrary to the hypothesis that those individuals with the most severe deficits in frequency discrimination would have impaired literacy and phonological skills, we found that it is *good* frequency discrimination that is linked to *good* performance on measures of nonword reading and nonword repetition. If correlations between frequency discrimination and phonological measures are driven solely by those with good frequency discrimination, this may explain why an association between these variables was not seen in the SNH group; there may have simply been too few children with low DLFs to reveal the relationship. In a similar vein, we might attribute some of the contradictory findings in the literature to differences in participant selection, with potentially stronger associations between frequency discrimination and phonology being found in high-achieving groups.

It is less clear, however, why such a relationship may exist between frequency discrimination and phonological processing in those with good auditory processing skills. One possibility is that the performance of both the frequency discrimination task and the nonword repetition task requires auditory attention, and the successful allocation of attentional resources may in part drive the associations between good performance on both verbal and nonverbal auditory processing tasks. Poor frequency discrimination skills may result from a variety of different causes, ranging from a lack of attentional resources to physiological deficits in the auditory system. If each of these deficits disables discrimination and language abilities to a different extent, this may be expected to lead to a wider distribution of scores among those individuals with high frequency discrimination thresholds.

Conclusions

Three important conclusions arise from this study. First, much research has focused on the frequency discrimination deficits in people with problems in language or reading, with little consideration of the low-level auditory processing impairments of those with hearing loss. The current study suggests that children with mild to moderate sensorineural hearing loss may also have considerable difficulty with tasks that require them to discriminate sounds of different frequency and that these deficits are not confined to low-frequency stimuli, although the reasons for this remain uncertain. Future research is needed to examine the extent to which cochlear damage has specific effects on mechanisms of frequency analysis, over and above any effects due to reduced signal audibility. Second, the present study indicates the importance of analyzing within-group correlations when considering associations between language and psychophysical tests, especially when investigating children with auditory difficulties. Where combined group correlations were found, they were often driven by the poorer performance of the children with hearing loss on auditory, phonological, and literacy measures compared to that of controls, rather than a more general association between frequency discrimination, language, and literacy. Third, the results suggest that rather than poor frequency discrimination skills predicting poor language abilities, only the converse is true—that good performance on measures of frequency discrimination predicts good phonological processing and literacy. This finding casts doubt on the notion of a direct, causal relationship between impaired frequency discrimination and reading.

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