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MIDFREQUENCY DYSFUNCTION IN LISTENERS HAVING HIGH-FREQUENCY SENSORINEURAL HEARING LOSS

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Two-tone unmasking, psychophysical tuning curves and pure-tone masking patterns were measured at 500 and 1000 Hz in 17 listeners having high-frequency sensorineural hearing loss due to noise exposure. Results were compared to similar data obtained from 20 normal-hearing young adults. In addition, measures of word-recognition ability were obtained in quiet and in noise for both groups. The primary findings were as follows: (a) 29% (n = 5) of the hearing-impaired subjects exhibited abnormal results on at least one of the psychoacoustic tasks investigated; (b) the observed abnormalities were reliable; and (c) there appeared to be a relation between the presence of midfrequency dysfunction and degree of difficulty on word-recognition tasks. These results and their implications are discussed.

It has been estimated recently that as many as 10 million American workers suffer some degree of communication handicap as a direct consequence of occupational noise exposure (Snow, 1976). When one considers the number of recreational and other nonoccupational noise sources to which an individual may be exposed, moreover, it is soon realized that 10 million is probably a conservative estimate of the number of Americans suffering from noise-related hearing impairment (Eldred, 1976; Schori, 1979). Hence, exposure to occupational and nonoccupational noise poses a serious problem to a significant portion of the American population.

Much research on the effects of noise on hearing has been conducted in the past few decades in an effort to understand better the nature of noise-induced hearing loss. A significant portion of this research has been devoted to the study of noise-induced temporary threshold shift (TTS) and to retrospective field studies of permanent threshold shift (PTS) in man. A major conclusion of both lines of research has been that hearing sensitivity for high frequencies (> 2000 Hz) is much more susceptible to damage than it is for low frequencies following exposures to broadband noise. This basic conclusion is so well accepted that it has been incorporated into the derivation of various damage-risk criteria (e.g., Kryter, 1970; Kryter, Ward, Miller, & Eldredge, 1966).

Recent research, however, questions the validity of this very basic premise. In particular, the sensitivity of simple pure-tone threshold measurements to the functional integrity of the hearing mechanism has been challenged. More specifically, it has been suggested that pure-tone thresholds for frequencies below 2–3 kHz may not provide an accurate reflection of the functional status of the region of the inner ear associated with these frequencies. An implication of this research is that noise-exposed persons exhibiting the classic high-frequency hearing loss on the pure-tone audiogram may, in fact, have significant auditory functional deficits and underlying lesions in regions of normal pure-tone sensitivity. That is, the pure-tone audiogram may often convey an impression of normal low-frequency and midfrequency hearing in noise-exposed listeners when significant pathology is actually present in this same frequency region. Additional evidence indicates that this pathology, moreover, may contribute to the communicative disability of the individual.

Before describing the specific procedures utilized in this investigation, a review of the data supporting the existence of midfrequency dysfunction is provided. The reader should bear in mind that although these studies suggest the presence of cochlear pathology undetected by pure tones, there are many more studies which indicate that the pure-tone audiogram provides an accurate picture of underlying cochlear pathology. Nonetheless, evidence supporting the possibility of undetected midfrequency dysfunction in noise-exposed persons is extensive. It can be divided into three basic areas: (a) histological research with laboratory animals and man; (b) studies of TTS in man; and (c) investigations of subtle midfrequency dysfunction in noise-exposed listeners having PTS.

Histological Research

Several studies of noise-induced hearing loss (PTS) in laboratory animals have been performed in which both histological status of the inner ear and pure-tone audiograms were obtained from the same animals. Several of these studies indicate that pure-tone sensitivity measures underestimate cochlear damage, especially in the low frequency regions (Dolan, Bredberg, Ades, & Neff, 1971; Eldredge, Mills, & Bohne, 1973; Henderson, Hamernik, & Sitler, 1974; Miller, Eldredge, & Bredberg, cited in Bredberg & Hunter-Duvar, 1975). Of particular importance is a study of Bredberg (1968) in which data

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were gathered from noise-exposed humans. In this study, it was demonstrated that individuals may have as much as 50% of the outer hair cells missing in the region of the cochlea associated with a frequency of 250 Hz and still only exhibit a 5-15-dB hearing loss. By comparison, a similar loss of outer hair cells in the high-frequency region of the cochlea resulted in a 65-75-dB hearing loss at 8000 Hz. Thus, equivalent amounts of cochlear damage are not reflected in equivalent degrees of hearing loss, with low-frequency hearing loss tending to underestimate existing damage.

However, there are an equivalent number of studies employing laboratory animals that have observed a good correspondence between pure-tone sensitivity and histology (e.g., Lipscomb, Axelsson, Vertes, Roettger, & Carroll, 1977). Bredberg and Hunter-Duvar (1975) suggested that a decisive answer regarding the correlation between pure-tone hearing thresholds and underlying histological damage will require use of (a) more accurate and reliable methods of hearing assessment in animals; (b) a more detailed histological analysis of the cochlea; and (c) an appropriate group of control animals. Nonetheless, existing histological data from laboratory animals and humans are currently sufficient to warrant concern about the sensitivity of pure-tone thresholds to cochlear pathology, especially for low frequencies.

TTS Studies

A number of investigations of TTS conducted in the past few years have suggested that temporary changes in pure-tone thresholds may not be a sensitive measure of the reversible dysfunction incurred by short-term exposures to moderately intense sound. Balthazor, Cooper, and Feth (1976), for instance, documented the insensitivity of threshold measurements to reversible injury of the hearing mechanism. These investigators measured psychophysical tuning curves (Zwicker, 1974) in normal hearers using the pulsation-threshold technique (Houtgast, 1974). Tuning curves are believed to provide a measure of the frequency selectivity of the auditory system (Zwicker, 1974). First, Balthazor et al. (1976) observed that tuning curves became broader following a noise exposure producing measurable TTS. Broader or "detuned" tuning curves are characteristic of cochlear pathology (Evans, 1975; Leshowitz & Lindstrom, 1977; Wightman, McGee, & Kramer, 1977; Zwicker & Schorn, 1978). Although TTS recovered in the expected amount of time, the tuning curves remained broad for a much longer period. Thus, even though threshold measurements had indicated complete recovery of function, measures of frequency selectivity were still indicative of cochlear dysfunction.

Feth, Oesterle, and Kidd (1979) and Feth, Burns, Kidd, and Mason (1980) confirmed and extended these early findings. Psychophysical tuning curves and pure-tone thresholds again were measured pre- and postexposure. Some exposure conditions were selected to produce little or no ($\leq$ 3 dB) TTS. In these cases, a detuning of the tuning curves was apparent following exposure despite a lack of significant threshold shift. Once again, broadened tuning curves were observed for periods far beyond the time required for recovery of threshold shift.

Two recent studies of frequency selectivity prior to and following exposure to noise support the findings of Balthazor et al. (1976), Feth et al. (1979), and Feth et al. (1980) obtained with similar measures (McFadden & Pasanen, 1979; Mills, 1982). Both of these investigations reported a detuning of tuning curves for frequencies at which postexposure hearing sensitivity appears to be unaffected. That is, both studies report the presence of a positive sign of cochlear pathology (detuning) despite pure-tone sensitivity indicating normal auditory function. Furthermore, both investigations indicated that long periods were required for recovery of normal tuning.

Humes and Schwartz (1977) also concluded that TTS was not an accurate indicator of dysfunction, especially for low frequencies. In their study, pure-tone thresholds and aural overload thresholds (Humes, 1978, 1980) were measured prior to and following 3-minute exposures to broadband noise at overall levels of 50, 60, 70, 90, and 110 dB SPL. The basic finding of this study was that aural overload thresholds at low frequencies (500 Hz) had shifted by as much as 8 dB ($\bar{x}$ of 4 subjects) for exposure conditions that produced no TTS at 500 or 1000 Hz. The shift was in a direction that was consistent with the presence of cochlear dysfunction. Humes and Schwartz (1977) suggested that shifts in pure-tone threshold may not be an adequate indicator of hearing dysfunction.

Bienvenue, Michael, and Violon-Singer (1976) came to a similar conclusion after they studied the effects of exposures to loud sound on pure-tone threshold and the intensity difference limen. Thresholds at 1000 Hz and difference limens for intensity at 1000 Hz were measured in nine normal ears prior to and following a 15-minute exposure to a 105-dB SPL pure tone at a frequency of 750 Hz. These researchers observed that although TTS recovered in 1 hour, it required more than 4 hours for the difference limens for intensity to return to normal preexposure values.

In a subsequent study, Bienvenue, Violon-Singer, and Michael (1977) obtained pure-tone thresholds and intensity difference limens at 4000 Hz in 57 normal ears following a 15-minute exposure to pink noise at an overall level of 100 dB SPL. Following exposure, 22 of the 57 listeners showed no measurable TTS_2. However, these same subjects showed abnormal intensity difference limens at the same frequency. Bienvenue et al. (1976) and Bienvenue et al. (1977) concluded that the measurement of pure-tone threshold was not a sufficiently sensitive index of hearing dysfunction.

To summarize, the above review of recent investigations of the sensitivity of TTS to reversible changes in the functional integrity of the auditory system suggests that threshold measurements may be inadequate indicators of subtle change in function. This lack of sensitivity was most often apparent for low frequencies or frequencies below the exposure stimulus. This conclusion is based on investigations employing a variety of suprathreshold psychoacoustic tests including tuning curves, aural overload thresholds, and intensity difference limens. The next section provides further evidence of the insensitivity of pure-tone threshold measurements to midfrequency dysfunction in listeners having noise-induced high-frequency hearing loss.

Results from Studies of Noise-Exposed Listeners

Komovic (1973) was one of the first to demonstrate the presence of subtle midfrequency dysfunction in a sample of noise-exposed listeners having high-frequency sensorineural hearing loss. Komovic reported abnormal auditory adaptation, as measured with the threshold tone decay test (Carhart, 1957), and reduced temporal integration at 2000 Hz despite normal hearing sensitivity at this frequency.

Others have utilized additional suprathreshold auditory tests to confirm the findings of Komovic (1973). Nelson (1979) and Nelson and Turner (1980), for instance, reported recently that psychophysical tuning curves obtained from some listeners having high-frequency sensorineural hearing impairments due to noise exposure displayed abnormally broad tuning in regions of normal hearing sensitivity. In addition, Turner and Nelson (1982) have observed abnormal performance on a suprathreshold psychoacoustic task by some noise-exposed listeners having abrupt high-frequency hearing loss even though the measurements were obtained from regions of normal pure-tone sensitivity. More specifically, these investigators measured poorer frequency discrimination ability at 300, 1200, and 3000 Hz in many noise-exposed listeners for stimuli presented at a level of 80 dB SPL. Control experiments utilizing normal hearers with high-frequency hearing thresholds elevated to a comparable level by masking failed to reveal abnormal performance for midfrequency signals (Nelson & Stanton, 1982).

The results of the studies by Komovic (1973), Nelson (1979), Nelson and Turner (1980), and Turner and Nelson (1982) support the conclusion advanced in the investigations of TTS reviewed previously. Specifically, normal pure-tone sensitivity, especially in the low and mid frequencies, does not imply normal function of the hearing mechanism in this same frequency region in at least some listeners.

Additional studies have sought to extend these findings by examining the effect that such midfrequency dysfunction has on the communication difficulties experienced by noise-exposed listeners. Findlay (1976), for example, measured auditory adaptation (using Békésy audiometry) in two groups of 16 subjects having normal pure-tone thresholds through 2000 Hz. One group, however, had an abrupt high-frequency (≥ 3000 Hz) sensorineural hearing loss due to noise exposure. Between-group differences were observed in auditory adaptation at 2000 Hz; adaptation was greater in 12 of the 16 noise-exposed individuals than in normal ears. Thus, a positive sign of cochlear dysfunction was observed in the region of normal hearing sensitivity. Between-group differences were also observed in word-recognition scores obtained in quiet and noise backgrounds. It was suggested by Findlay (1976) that such subtle midfrequency dysfunction might be responsible for the exceptional communication difficulty experienced by noise-exposed listeners in a noise background.

Findlay and Dennenberg (1977) tested this hypothesis directly. These investigators examined the ability of normal hearers and listeners having high-frequency noise-induced sensorineural hearing loss to perceive low-pass filtered speech materials (cut-off frequency = 1800 Hz) in a background of competing noise. They reasoned that if cochlear pathology, undetected by pure-tone thresholds at and below 2000 Hz, were responsible for the reduced word-recognition scores in noise obtained from impaired ears, one would expect the two groups of subjects to show significant differences in word recognition for the low-pass filtered condition. That is, the hearing-impaired subjects would be expected to exhibit a greater breakdown in performance than the normal hearers. Contrary to this expectation, the results reported by Findlay and Dennenberg (1977) indicated that the noise-exposed group performed better than the normal hearers when listening to filtered word lists presented in noise.

It was unclear, however, whether subtle midfrequency dysfunction was confirmed in the noise-exposed subjects of Findlay and Dennenberg (1977). Rather, they appear to have assumed its existence in all noise-exposed listeners including their particular subjects. Because of these and other limitations, Humes, Schwartz, and Bess (1979) performed two experiments very similar to the studies of Findlay (1976) and Findlay and Dennenberg (1977). Humes et al. (1979), however, utilized the aural overload test to assess the presence of midfrequency dysfunction. Two groups of subjects, one normal-hearing and one noise-exposed, were examined. In the first experiment, elevated overload thresholds at 500, 1000, and 2000 Hz were observed in noise-exposed subjects having normal hearing sensitivity in this same frequency region. Elevated overload thresholds are often a sign of cochlear pathology (Humes, 1978). When the same two groups of subjects listened to unfiltered and low-pass filtered monosyllables in quiet and in noise, moreover, the noise-exposed listeners performed significantly more poorly.

Leshowitz (1977) provides data which substantiate the findings of Humes et al. (1979). He measured pure-tone masking patterns for a 1000-Hz masker and masked speech-reception thresholds in eight normal-hearing young adults and seven individuals with noise-induced hearing loss. Excessive upward spread of masking was observed in the noise-exposed listeners despite the presence of normal hearing thresholds at 1000 and 2000 Hz. Thus, this study also suggests the inadequacy of pure-tone thresholds as an indicator of the functional status of the hearing mechanism. Furthermore, Leshowitz observed that the greater the upward spread of masking, the more difficulty the noise-exposed individual had in understanding speech. He concluded, from these and other data on 40 high-frequency impaired listeners (7 of whom were noise-exposed), that "hearing handicaps are often subtle . . . and are undetectable using standard audiological techniques."

Tyler, Fernandes, and Wood (1980, 1982) have measured several psychoacoustic phenomena in listeners having noise-induced hearing loss. The phenomena investigated included critical ratios, masking patterns, psychophysical tuning curves, and temporal integration. Data presented in both studies indicate that some hearing-impaired subjects with high-frequency sensorineural hearing loss yield abnormal psychoacoustic data in their region of normal hearing (in this case, 500 Hz). Although not the primary objective of either investigation, the data in the studies by Tyler et al. indicated that midfrequency dysfunction at 500 Hz was not strongly correlated with performance on speech-recognition tasks.

To recapitulate, there is sufficient evidence to suggest that noise-exposed listeners having typical noise-induced high-frequency sensorineural hearing loss may also have additional midfrequency dysfunction that goes undetected by pure-tone audiometry. In addition, some recent investigations have suggested that a relationship may exist between subtle midfrequency dysfunction and difficulty in understanding speech in noise backgrounds. It is uncertain, however, how universal this phenomenon is in noise-exposed listeners. The present study sought to confirm this recent work in a larger sample of noise-exposed persons.

Specifically, the objectives of this study were: (a) to search for subtle midfrequency dysfunction in a larger sample ($N = 17$) of noise-exposed listeners using a larger number of suprathreshold psychoacoustic tests to explore midfrequency dysfunction and (b) to examine the relationship between the presence and extent of midfrequency hearing impairment and difficulty in perceiving speech in quiet and noise backgrounds.

METHOD

Subjects

Two groups, representing a total of 37 persons, comprised the subject samples. The control group, 20 normal-hearing subjects, was selected according to the following criteria:

1. air- and bone-conduction pure-tone thresholds at octave frequencies from 250 through 4000 Hz $\leq$ 10 dB HL (ANSI, 1969) in both ears (air-bone gap < 10 dB)
2. air-conduction pure-tone thresholds $\leq$ 10 dB HL at 6000 and 8000 Hz
3. tympanograms of normal shape, amplitude, and peak-pressure bilaterally
4. presence of an acoustic reflex bilaterally upon contralateral presentation of a 1000 Hz pure tone at 100 dB HL
5. negative otologic history, including a negative history of occupational noise exposure.

The experimental group, 17 subjects, was comprised of individuals having an otologic diagnosis of noise-induced hearing loss. The audiologic criteria for selection of this subject sample were as follows:

1. air- and bone-conduction pure-tone thresholds at octave intervals from 250 through 2000 Hz $\leq$ 15 dB HL (ANSI, 1969) in the test ear
2. tympanograms of normal shape, amplitude, and peak-pressure point
3. presence of an acoustic reflex upon contralateral presentation of a 1000 Hz pure tone at 100 dB HL
4. history of prolonged occupational or recreational noise exposure
5. age $\leq$ 55 years.

The amount of high-frequency hearing loss varied from mild-to-moderate to profound with the mean audiogram reflecting approximately a 50-dB hearing loss from 3000 to 8000 Hz.

The normal-hearing subjects were aged 22–30 years ($\bar{x}$ = 24.6 years:months) while the hearing-impaired subjects were aged 22–53 years ($\bar{x}$ = 31.2 yrs.). Approximately 12 hours were required for each subject to complete the study. All subjects were paid for their participation.

Apparatus

Stimuli were generated by three pure-tone oscillators (Krohn-Hite Model 4100), gated by electronic rise/fall gates (Coulbourn Instruments Model S84-04), attenuated by a combination of manual (Hewlett-Packard Model 350D) and programmable attenuators (Coulbourn Instruments Model S85-05), mixed via custom-made active mixers, amplified (Crown Model D-75), and transduced via a TDH-49 earphone mounted in a circumaural cushion (Grason-Stadler 001). All sound pressure levels were calibrated acoustically with a standard 9A 6-cm^3 coupler. A laboratory minicomputer (DEC PDP-11/03) was used to control the gating and attenuation of signals, the activation of lights on the response box, the collection of responses, and the calculation of thresholds. All testing was conducted in sound-treated suites meeting established guidelines for ambient noise levels (ANSI S3.1-1977).

Procedures

Several psychoacoustic phenomena were studied in the present investigation. These included (a) pure-tone masking patterns; (b) psychophysical tuning curves (e.g., Zwicker, 1974); and (c) two-tone unmasking (Shannon, 1976). Two frequency regions, 500 and 1000 Hz, were examined in detail. The frequencies examined were well within the region of apparent normal hearing. The three psychoacoustic phenomena were measured with the same psychophysical procedure. In particular, a forward-masking 2AFC adaptive technique designed to estimate 70.7% correct signal detections was utilized. The following data were collected from each subject:

1. pure-tone masking patterns:
   (a) masker frequencies (f_m) = .5 and 1.0 kHz
   (b) signal frequencies (f_s) = .5, .7, .9, 1.0, 1.1, 1.3, 1.5, 1.9, 2.4f_m
   (c) masker levels (L_m) = 60, 85 dB SPL
   (d) signal level (L_s) under experimental control-adjusted to level corresponding to 70.7% correct on psychometric function relating signal level to percent correct detections (Levitt, 1971).
2. psychophysical tuning curves:
   (a) f_s = .5 and 1.0 kHz
   (b) f_m = .5, .7, .8, .9, 1.0, 1.1, 1.25, 1.4f_s
   (c) L_s = 35 dB SPL (this amounted to 7–13 dB SL for individual subjects)
   (d) L_m = under experimental control—70.7% correct.
3. two-tone unmasking:
   (a) f_m = .5, 1.0 kHz
   (b) $f_s = f_m$
   (c) f_{m2} = 1.15, 1.3f_m
   (d) L_m = 60 dB SPL
   (e) L_{m2}-L_m = 10, 20, 30 dB
   (f) L_s = under experimental control—70.7% correct.

The temporal parameters selected for use in the adaptive 2AFC forward-masking technique were (a) a 350-msec warning interval followed 350 msec later by two 350-msec intervals with an interinterval duration of 350 msec; (b) masker duration of 350 msec with 10-msec linear rise/fall times; (c) signal duration of 20 msec with 10-msec linear rise/fall times; and (d) 0-msec interval between masker offset and signal onset (i.e., no temporal overlap of masker and signal). A 2-dB step-size was utilized. A single run consisted of 12 reversals in probe level, the first two of which were discarded. The mean of the 10 remaining reversals comprised a single threshold estimate (Levitt, 1971).

All measurements were made once for each stimulus condition with the exception of the first and last threshold estimate obtained for a given psychoacoustic phenomenon (e.g., masking pattern for the 500-Hz, 60-dB SPL masker). These estimates were repeated twice with the first estimate discarded as practice.

In addition to these psychoacoustic measures, three measures of speech understanding ability were obtained. These were (a) the masked speech reception threshold (Plomp, 1978); (b) the *California Consonant Test* (CCT) (Owens & Schubert, 1977) in quiet; and (c) the CCT in noise. In the masked speech reception threshold procedures, hearing loss for speech was measured under earphones using the Tillman-Olsen method (Tillman & Olsen, 1973). The "signal" was a tape-recorded version of the CID W-1 word lists. The noise masker was speech-spectrum noise presented at levels of 30, 40, 50, 60, and 70 dBA. Speech reception threshold was measured in quiet and at each noise level, with all measurements repeated twice for each subject. The order of testing progressed sequentially from quiet through the 70-dBA noise masker and back down again. From these measurements it was possible to measure hearing loss for speech in quiet (Plomp's SHL_{A+D}) and hearing loss for speech in noise (Plomp's SHL_D).

As mentioned, additional assessments of speech understanding difficulties experienced by the noise-exposed listeners were obtained with the CCT. This test has been demonstrated to be particularly suitable for use with noise-exposed listeners (Schwartz & Surr, 1979). CCT test items were presented under earphones by a female speaker via monitored live voice at a level of 50 dB SL (Schwartz & Surr, 1979). This test was also administered in a background of speech-spectrum noise at a signal-to-noise ratio of 0 dB with the signal level remaining fixed at 50 dB SL.

RESULTS AND DISCUSSION

The unmasking data obtained from the normal-hearing and hearing-impaired subjects proved not to be very informative. The mean data for the 500-Hz masker failed to show any unmasking in either group of subjects for any of the six combinations of unmasker level and unmasker frequency investigated. Table 1 illustrates the small unmasking effect observed for the 1000-Hz masker. Unmasking is evidenced by the lower masked thresholds obtained for the two-tone masker (f_m and f_{m2}) than for the single-tone masker (f_m alone). The latter masked threshold is listed as the "baseline" threshold in the extreme left column, whereas all other values in the table were obtained with the two-tone masker. Note that as a group the hearing-impaired subjects demonstrated more

TABLE 1. Means (and standard deviations) of masked thresholds in dB SPL for unmasking paradigm at 1000 Hz.

	f_m only		*f_m and f_{m2}*					
		f_{m2} =	1150 Hz			1300 Hz		
Group	Baseline *(60 dB)*	L_{m2} =	*70*	*80*	*90*	*70*	*80*	*90 dB SPL*
Normal hearers	53.3(3.9)		50.5(5.5)	49.6(5.5)	53.9(10.5)	51.6(4.5)	51.8(5.3)	51.8(6.8)
Hearing impaired	52.8(4.6)		49.6(6.3)	47.9(6.8)	47.1 (8.0)	49.0(7.6)	49.1(5.8)	50.7(6.1)

unmasking (i.e., lower masked thresholds) than the normal hearers for the same stimulus conditions, although baseline masked thresholds were essentially equivalent for both groups. The variability associated with these data, however, makes any conclusions drawn from these findings tenuous at best. Unfortunately, the condition exhibiting the largest difference between groups (f_{m2} = 1150 Hz, L_{m2} = 90 dB SPL) is also the condition manifesting the greatest variability for both groups. The standard deviations observed in the normal hearers for the unmasking paradigm were clearly the largest observed in any of the psychoacoustic phenomena for that group in this study. Mills (1982) has reported comparable variability in normal hearers.

The data obtained from the masking pattern and tuning curve paradigms, however, proved to be much more informative. These data are displayed in Figure 1 for the normal hearers and a large subgroup (n = 12) of the noise-exposed listeners. This subgroup of noise-exposed listeners represents all those impaired listeners who exhibited essentially normal performance on all of the suprathreshold psychoacoustic tasks. The mean data for the normal hearers are indicated by the solid lines while the shading reflects the 99% confidence intervals constructed around these mean values. The panels to the left provide the results for 500 Hz, while those on the right illustrate the findings for 1000 Hz. The upper panels illustrate the masking patterns for L_m = 85 dB SPL, the middle panels depict similar patterns for the lower masker level (L_m = 60 dB SPL), and the bottom panels provide the tuning curve data. The dashed lines in the middle panels illustrate the mean quiet thresholds for the normal hearers. The data for normal hearers reveal features consistent with previous data obtained for comparable stimulus conditions. The masking patterns obtained at low levels (L_m = 60 dB), for example, are fairly symmetric, with masking spreading equally well in both an upward and a downward direction, while those obtained at higher intensities (L_m = 85 dB) are asymmetric, reflecting a greater spread of masking to signal frequencies above the masker frequencies. In addition, the masking patterns are more sharply peaked at 1000 Hz than at 500 Hz, as expected when masked thresholds are plotted along an abscissa depicting relative signal frequency. The psychophysical tuning curves are also typical in that (a) the tips of the tuning curves are located at the signal frequency; (b) the high-frequency slope is steeper than the low-frequency slope; and (c) the tuning curve at 1000 Hz is more sharply tuned than that at 500 Hz.

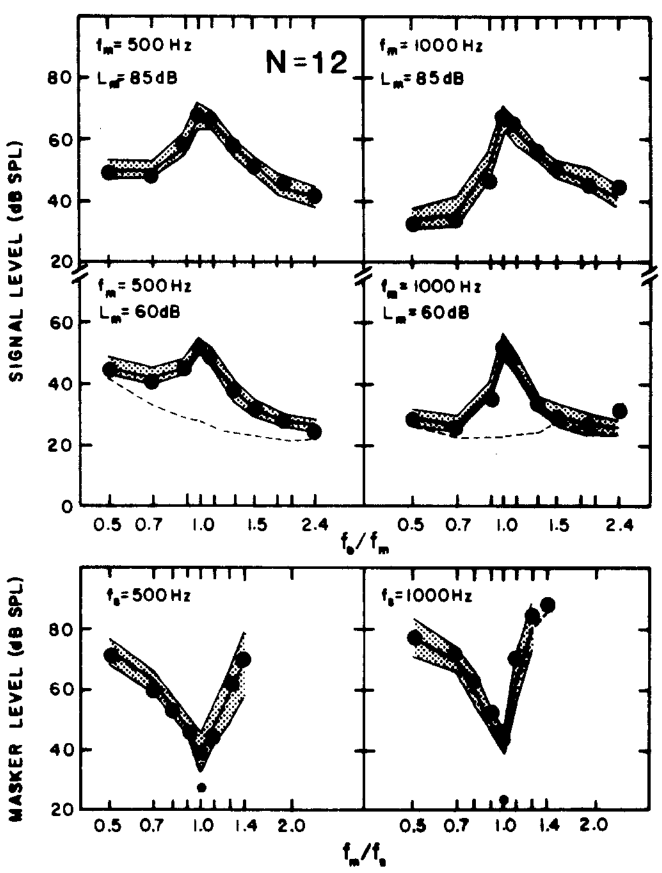

FIGURE 1. Mean masking patterns (upper four panels) and tuning curves (lower two panels) obtained from 12 of the 17 listeners having noise-induced hearing loss are depicted by the large filled circles. The solid line and surrounding shaded area depict the mean and 99% confidence interval for the 20 normal hearers. The dashed lines in the middle two panels indicate the mean threshold in quiet for the normal-hearing subjects. Small filled circles around tip of tuning curves reflect mean quiet threshold for the normal hearers. The signal was presented at 35 dB SPL.

The mean data for the subgroup of noise-exposed listeners are represented by the circles plotted in each of the six panels. This subgroup represents those hearing-impaired subjects whose individual data points fell within the 99% confidence intervals for the data from the normal hearers. In all 12 cases, fewer than two consecutive or three total data points extended beyond the confidence intervals depicted in each panel. Note that the mean data for this subgroup of listeners with noise-induced hearing loss lie within the 99% confidence intervals of the data from normal hearers in all but two cases. The standard deviations for this subgroup, moreover, were equivalent to those observed for the normal hearers. Two mean signal thresholds for the 1000-Hz, 60-dB SPL masking pattern, one at 900 Hz and the other at 2400 Hz, lie outside the established confidence intervals. Only one of these data points, however, is in a direction implying abnormal or broad masking patterns (2400 Hz), and it can be explained by the presence of a slight loss of hearing sensitivity in these subjects at 2400 Hz. That is, the slightly elevated masked threshold at 2400 Hz can be explained by a slightly elevated quiet threshold and does not reflect masking at 2400 Hz by the 60-dB, 1000-Hz masker. Thus, the data obtained at 500 and 1000 Hz from 12 of the 17 impaired ears are essentially normal.

The data obtained from the remaining five subjects, however, were clearly abnormal. Figure 2 shows data obtained from one of these subjects, RJ. Note that for this subject the criterion for abnormality is met for all four

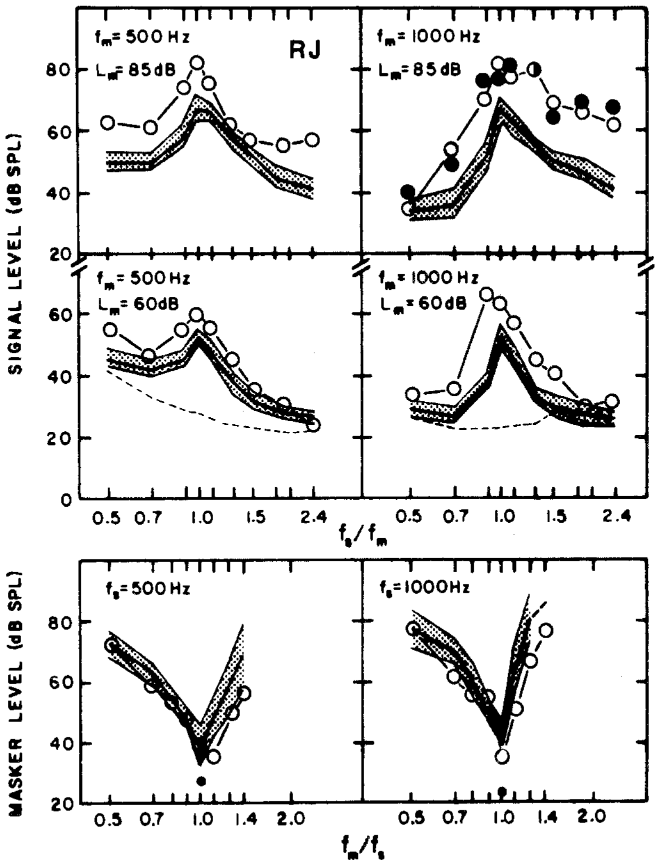

FIGURE 2. Masking patterns and tuning curves obtained from subject RJ. Shaded regions again reflect the 99% confidence intervals for the normal hearers. Open circles depict individual data points for this subject. The solid circles reflect results obtained during a replication of the masking pattern at 1000 Hz for the 85-dB SPL masker level. All quiet thresholds were within 99% confidence intervals constructed around the data from the normal hearers.

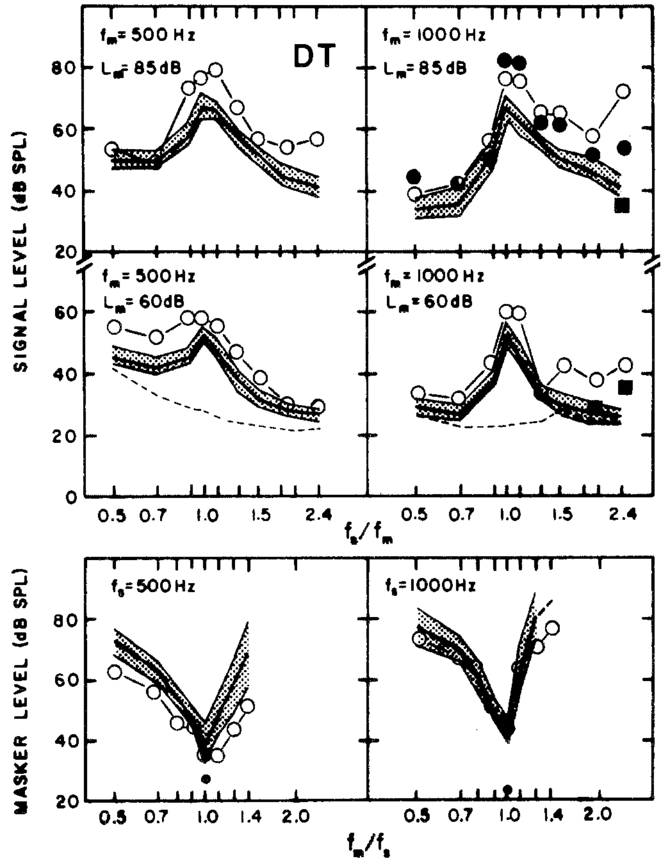

FIGURE 3. Masking patterns and tuning curves obtained from subject DT. Shaded regions again reflect the 99% confidence intervals for the normal hearers. Open circles depict individual data points for this subject. The solid circles reflect results obtained during a replication of the masking pattern at 1000 Hz for the 85-dB SPL masker level. Solid squares depict quiet thresholds that exceeded 99% confidence intervals established for data from normal hearers as well as those quiet thresholds immediately adjacent to the abnormal ones.

masking patterns and both tuning curves. The results from this subject suggest greater than normal upward and downward spread of masking at both 500 and 1000 Hz despite normal auditory thresholds over this frequency region. Hearing thresholds in quiet were all within the 99% confidence intervals of the normal hearers' data. The solid circles in the upper right panel reflect results obtained in a replication of those stimulus conditions administered several days after the completion of all other testing. The results appear to be quite reliable for this subject.

Figure 3 shows comparable individual data for another subject (DT) manifesting abnormal performance on several of the psychoacoustic tasks. The 500-Hz masking patterns and tuning curve suggest considerably greater than normal upward and downward spread of masking. The data at 1000 Hz primarily suggest pronounced upward spread of masking, especially as measured with the masking patterns. The solid squares in the upper and middle right-hand panels indicate this subject's quiet thresholds that were above the 99% confidence intervals for the normal hearers' data. At least some of the elevated masked thresholds observed for the 1000-Hz masker at L_m = 60 dB SPL can be considered simple reflections of elevated quiet thresholds. The bulk of the abnormal data points, however, cannot be explained so easily. The close correspondence of the open and solid circles in the upper right panel again suggests that the data are reliable.

The results for subject JW are shown in Figure 4. The data obtained at 500 Hz for both masking patterns, and to a lesser extent for the tuning curve, suggest excessive upward and downward spread of masking. The data at 1000 Hz are much less clear regarding abnormality. The tuning curve data, for example, are essentially normal, as are the low-frequency slopes of both masking patterns at 1000 Hz. The high-frequency slopes for the 1000-Hz masking patterns, however, are abnormal. It is clear, on the other hand, that much of this abnormality is a simple reflection of elevated quiet thresholds in that frequency region. This is reflected in the close correspondence between the solid squares and open circles.

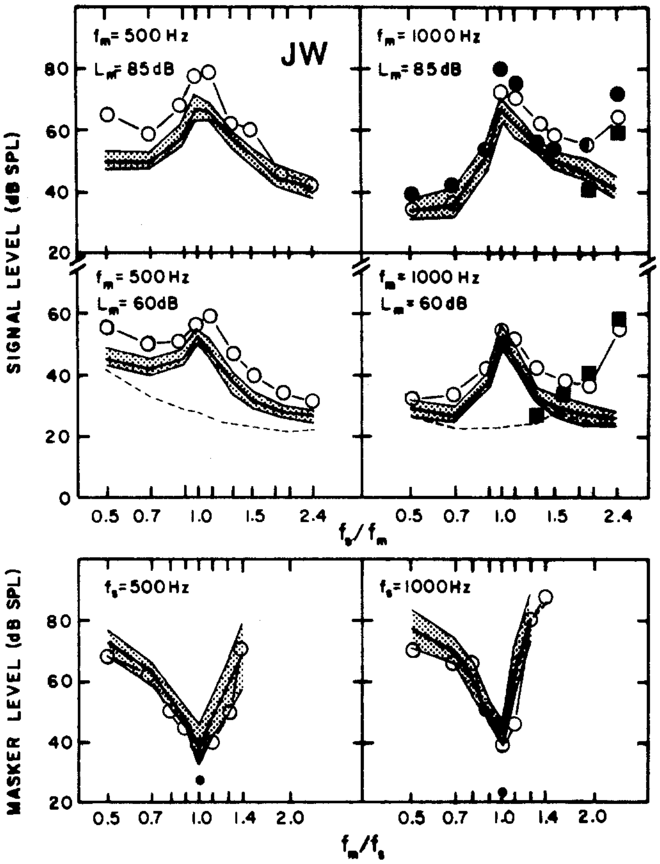

FIGURE 4. Masking patterns and tuning curves obtained from subject JW. Shaded regions again reflect the 99% confidence intervals for the normal hearers. Open circles depict individual data points for this subject. The solid circles reflect results obtained during a replication of the masking pattern at 1000 Hz for the 85-dB SPL masker level. Solid squares depict quiet thresholds that exceeded 99% confidence intervals established for data from normal hearers as well as those quiet thresholds immediately adjacent to the abnormal ones.

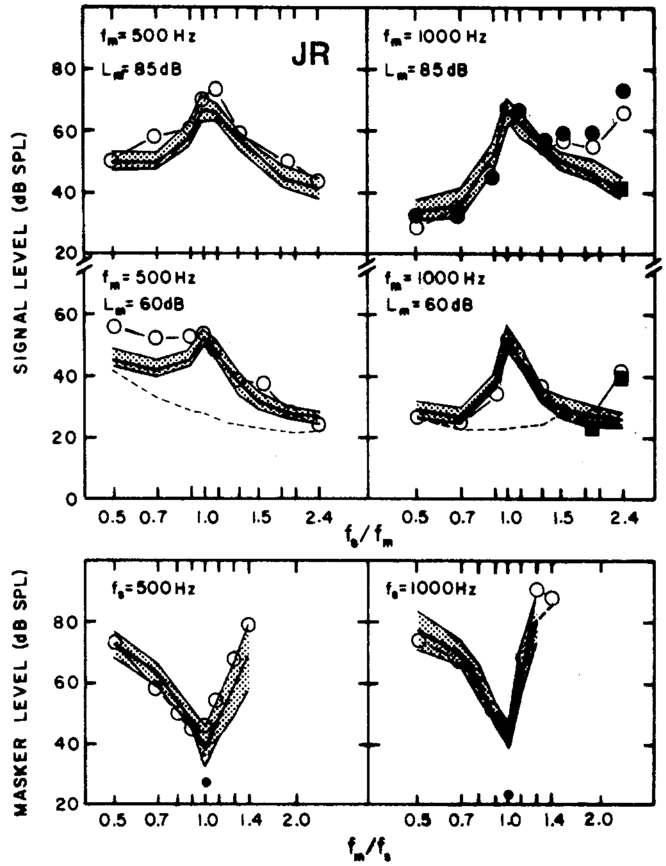

FIGURE 5. Masking patterns and tuning curves obtained from subject JR. Shaded regions again reflect the 99% confidence intervals for the normal hearers. Open circles depict individual data points for this subject. The solid circles reflect results obtained during a replication of the masking pattern at 1000 Hz for the 85-dB SPL masker level. Solid squares depict quiet thresholds that exceeded 99% confidence intervals established for data from normal hearers as well as those quiet thresholds immediately adjacent to the abnormal ones.

The data obtained from another noise-exposed subject (JR) who manifested abnormal findings are displayed in Figure 5. The data at 500 Hz suggest only slight abnormality for the masking patterns at both masker levels. The tuning curve at 500 Hz, moreover, is normal, although several data points are just within the 99% confidence interval. At 1000 Hz both the tuning curve and the lower level masking pattern are normal. The lone abnormal data point for the latter is apparently a simple reflection of the elevated quiet threshold at that frequency. The high-frequency slope of the 85-dB SPL, 1000-Hz masking pattern, on the other hand, is clearly abnormal and suggests excessive upward spread of masking for these stimulus conditions. The data in the upper right panel of Figure 5 also suggest that these results are reliable (comparison of solid and open circles) and do not appear to be governed by excessive quiet thresholds.

Finally, the data for the last subject evidencing abnormality are provided in Figure 6. The data from subject KC that meet the definition of abnormality used in this study are the results for the masking patterns obtained at 1000 Hz for both masker levels. All other data are basically normal. The abnormality apparent in the 60-dB SPL, 1000-Hz masking pattern, moreover, appears to be due primarily to the presence of elevated quiet thresholds. This does not appear to be the case, however, for the 85-dB SPL, 1000-Hz masker. The upper right panel suggests that the observed abnormality is a reliable finding. This again is manifested by the close similarity between the open and solid circles in this panel.

In summary, the results obtained with the masking pattern and tuning curve paradigms at 500 and 1000 Hz revealed abnormality in five of the 17 noise-exposed listeners of this study. That is, five of the 17 hearing-impaired subjects are considered to have midfrequency dysfunction. For the remaining 12 subjects, individual and group data were essentially normal.

The speech-reception thresholds obtained in quiet and in various levels of noise background from the normal hearers and noise-exposed listeners are shown in Figure 7. The solid circles represent the mean values obtained

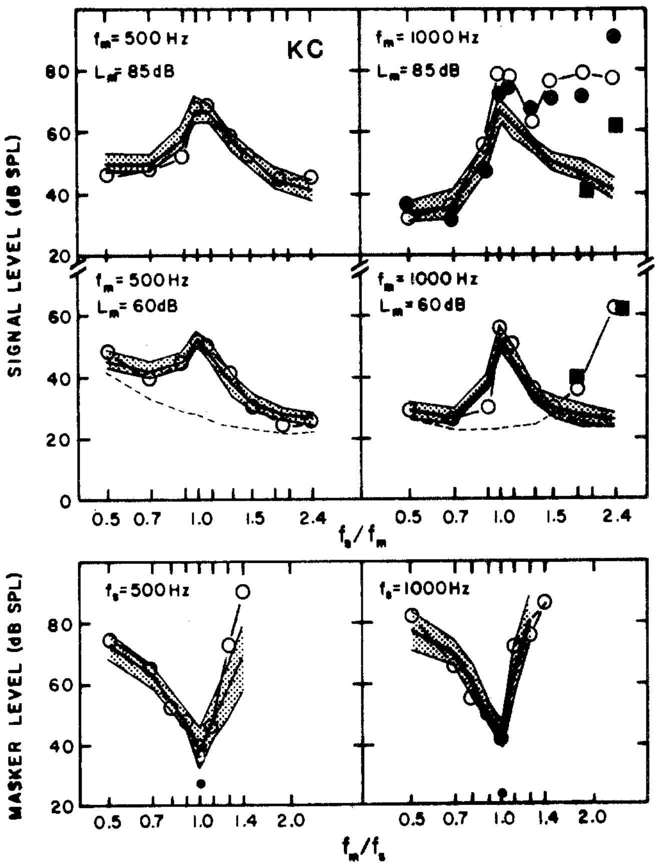

FIGURE 6. Masking patterns and tuning curves obtained from subject KC. Shaded regions again reflect the 99% confidence intervals for the normal hearers. Open circles depict individual data points for this subject. The solid circles reflect results obtained during a replication of the masking pattern at 1000 Hz for the 85-dB SPL masker level. Solid squares depict quiet thresholds that exceeded 99% confidence intervals established for data from normal hearers as well as those quiet thresholds immediately adjacent to the abnormal ones.

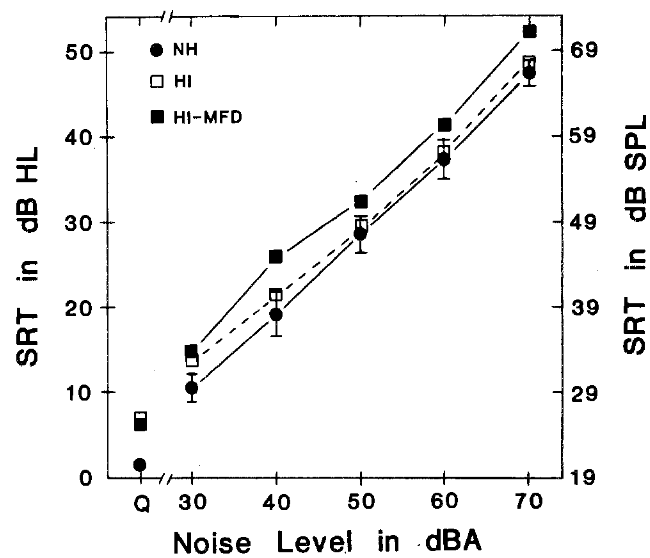

FIGURE 7. Mean speech reception thresholds obtained in quiet and in noise. Mean data for normal hearers are depicted by the solid circles while the vertical bars through these circles represent the 95% confidence interval. Squares depict mean data from the hearing-impaired subjects with the open squares representing the 12 subjects without midfrequency dysfunction (MFD) and the solid squares indicating the results from the five subjects with MFD.

from 10 normal hearers and the vertical bars running through those circles represent the corresponding 95% confidence intervals. The open squares and solid squares represent mean data from the two subgroups of hearing-impaired subjects, those without and those with apparent midfrequency dysfunction, respectively. Note that in quiet both subgroups of impaired listeners demonstrate comparable loss of hearing sensitivity for speech (6–7 dB). The same conclusion can be drawn from the data obtained at the lowest noise level (30 dBA). At higher noise levels, however, the subgroup without midfrequency dysfunction (open squares) yielded mean data not unlike those observed in the normal-hearing subjects. The subgroup of five impaired listeners with midfrequency dysfunction (solid squares), however, produced mean data significantly higher than those obtained from the normal hearers ($p < .05$). The average additional loss of hearing sensitivity for speech under noise conditions for the subgroup of hearing-impaired subjects with midfrequency dysfunction is approximately 4.7 dB relative to the performance of normal hearers. A comparable value for those impaired listeners without midfrequency dysfunction is 1.7 dB.

The results obtained on the *California Consonant Test* (CCT) are provided in Table 2. Means and standard deviations are provided for normal-hearing subjects and hearing-impaired listeners with and without midfrequency dysfunction. It is apparent that both subgroups of hearing-impaired subjects perform more poorly than normal hearers in both quiet and noise. Further, the decreased speech understanding abilities in quiet and noise are greatest for the smaller subgroup having midfrequency dysfunction. Although there was some overlap of the ranges of CCT scores obtained in quiet by the two hearing-impaired subgroups, there was no such overlap for the CCT scores obtained in noise. For the latter condition, the lowest score for any subject in the larger subgroup without midfrequency dysfunction was 30%, while the highest score among the five subjects

TABLE 2. Means ($\bar{x}$) and standard deviations (*SD*) of the scores on the *California Consonant Test* (CCT) in quiet (50 dB SL) and in noise (0 dB S:N) for the three subject groups.

Group	*n*	CCT_Q $\bar{x}$	CCT_Q *SD*	CCT_N $\bar{x}$	CCT_N *SD*
Normal hearers	10	99.8	.4	45.9	5.9
Hearing-impaired without MFD[a]	12	93.5	6.6	37.2	6.5
Hearing-impaired with MFD[a]	5	86.6	6.2	25.6	3.3

[a]*MFD* = midfrequency dysfunction.

with midfrequency dysfunction was 28% (individual scores of 28, 28, 26, 26 and 20%).

The basic findings of this investigation are twofold. First, midfrequency dysfunction of varying degrees was discovered in five of the 17 listeners having high-frequency sensorineural hearing loss due to noise exposure. This amounts to approximately 29% of the sample studied here. Second, those hearing-impaired subjects manifesting midfrequency dysfunction also appeared to exhibit poorer performance on tests of speech recognition, especially in noise, than those impaired subjects without midfrequency dysfunction.

There may be some other key factors or variables that differ between these two subgroups that might explain their different speech-recognition abilities. Differing etiology does not appear to be a possibility, in that all subjects had an otologic diagnosis of noise-induced hearing loss. Differences in hearing sensitivity do not appear to be responsible either. The mean audiograms for the two subgroups of hearing-impaired listeners are essentially equivalent, and the range of threshold values in both subgroups is similar. Finally, there were no significant differences between subgroups in the ages of the subjects. Thus, there are no immediately obvious underlying factors that might be responsible for the poor performance of the subgroup of listeners with midfrequency dysfunction other than the presence of such dysfunction.

Regarding the detection of midfrequency dysfunction in this study, several comments are in order. There is always the possibility in a study such as this that some of the "abnormal" results of the hearing-impaired subjects could be remedied with extensive training. The issue of subject training is addressed at least indirectly through the test-retest reliability of the data obtained in this study. The upper right panels in Figure 2 through Figure 6 display the results of the replication of the masking pattern obtained at 1000 Hz for the 85 dB SPL masker level. This replication of that experimental condition was administered after all other psychoacoustic data had been obtained. Thus, each subject had received 10–12 hours of practice with the 2AFC forward-masking paradigm prior to the replication of the 1000 Hz, 85 dB SPL masking pattern. As shown previously in Figure 2 through Figure 6, all subjects demonstrated good reliability. None of the five subjects with "abnormal" data points would have been reclassified as "normal" using the data from the replication. In addition, five of the 12 cases without midfrequency dysfunction were selected randomly for replication of the 1000-Hz, 85-dB SPL masking pattern. None of the replications obtained from these subjects would have resulted in reclassification as abnormal. In summary, despite the lack of rigorous training, the observed midfrequency dysfunction appears to have been detected reliably.

The criterion for abnormality established in this study for the interpretation of psychoacoustic data resulted in a fairly clear distinction between abnormal and normal test results. Those 12 hearing-impaired subjects without midfrequency dysfunction, for example, yielded normal results on all six psychoacoustic phenomena (four masking patterns and two tuning curves). Of the five impaired subjects with midfrequency dysfunction, three yielded abnormal data on all six psychoacoustic phenomena, one on three of the six phenomena, and one on only one of the six phenomena. Incidentally, the 1000-Hz, 85-dB SPL masking pattern was abnormal in all five of these subjects. It was primarily for this reason that this condition was the one selected for replication.

The data in this study suggest that cochlear pathology can go undetected by midfrequency pure-tone thresholds obtained in quiet. The mechanisms responsible for the midfrequency dysfunction observed in this and other studies (see introduction), however, are unclear. Nonetheless, it is apparent that an audiogram indicating the presence of a high-frequency sensorineural hearing loss may inappropriately imply that cochlear pathology is restricted to the high-frequency basal end of the cochlea in approximately 29% of such cases.

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