Amplitude modulation thresholds in chinchillas with high-frequency hearing loss

Donald Henderson, Richard Salvi, Gary Pavek, and Roger Hamernik
Callier Center for Communication Disorders, University of Texas at Dallas, 1966 Inwood Road, Dallas, Texas 75235

(Received 22 June 1983; accepted for publication 3 January 1984)

Estimates of auditory temporal resolution were obtained from normal chinchillas using sinusoidally amplitude modulated noise. Afterwards, the animals were exposed to noise whose bandwidth was progressively increased toward the low frequencies in octave steps. The first exposure was to an octave band of noise centered at 8 kHz. Three additional octave bands of noise were subsequently added to the original exposure in order to progressively increase the extent of the high-frequency hearing loss. The first exposure produced a temporary hearing loss of 50 to 60 dB near 8 kHz and elevated the amplitude modulation thresholds primarily at intermediate (128 Hz) modulation frequencies. Successive noise exposures extended the temporary hearing loss toward lower frequencies, but there was little further deterioration in the amplitude modulation function until the last exposure when the hearing loss spread to 1 kHz. The degradation in the amplitude modulation function observed after the last exposure, however, was due to a reduction in the sensation level of the test signal rather than to a decrease in the hearing bandwidth. The results of this study suggest that the high-frequency regions of the cochlea may be important for temporal resolution.

PACS numbers: 43.66.Gf, 43.66.Sr, 43.66.Mk [FLW]

INTRODUCTION

A listener's ability to segregate or resolve the rapid amplitude fluctuations in a complex acoustic waveform is one measure of temporal resolution. Normal hearing listeners show a remarkable ability to extract information regarding the envelope of a signal and can detect amplitude fluctuations as short as 2–3 ms (Green, 1973; Plomp, 1964). In recent years, there has been a growing awareness that temporal resolution may be compromised in hearing-impaired listeners, however, there are limited data concerning the overall nature of the temporal deficits and their relationship to other measures of hearing performance.

Much of the temporal resolution data that are available from hearing-impaired listeners are based on the detection of brief, silent intervals (gaps) embedded in noise. In general, listeners with sensorineural hearing loss exhibit abnormally long gap thresholds indicative of a breakdown in temporal resolution (Boothroyd, 1973; Cudahy, 1977; Irwin *et al.*, 1981), however, the specific changes depend on a variety of factors. For example, elderly subjects tend to have longer gap thresholds than young adults even when matched for the degree of hearing loss (Church and Cudahy, 1978). The magnitude of the hearing loss appears to be an important variable. When data from normal and hearing-impaired listeners are compared at the same sensation level (SL), gap thresholds begin to deteriorate only after the hearing loss exceeds approximately 30 dB (Giraudi-Perry *et al.*, 1982). The configuration of the hearing loss can also have an effect on measures of temporal acuity obtained from different spectral regions. A high-frequency or sloping high-frequency hearing loss appears to produce a greater increase in gap thresholds obtained at the low frequencies than those obtained at the high frequencies (Cudahy, 1977; Fitzgibbons and Wightman, 1982). In fact, low-frequency gap thresholds may be longer than normal even though the low-frequency pure-tone thresholds are within normal limits.

Although gap detection studies indicate that the minimum integration time is prolonged in impaired ears, this measure provides a somewhat limited description of the deficits in temporal resolution. Another method, which appears to provide a comprehensive measure of temporal acuity, involves measuring the modulation threshold for sinusoidally amplitude modulated wideband noise. When the modulation thresholds are determined over a range of modulation frequencies, a function is obtained which describes the system's sensitivity to different modulation rates. The modulation thresholds of humans are found to be lowest and nearly constant for modulation frequencies below approximately 30 Hz. As the modulation frequency is increased, the sensitivity declines at the rate of 3–6 dB/oct out to 1 kHz after which it remains constant (Dubrovski and Tumarkina, 1967; Zwicker and Feldkelter, 1967; Rodenburg, 1977; Viemeister, 1977, 1979). The amplitude modulation function of another mammal, the chinchilla, is similar to the human function except that the modulation thresholds of the chinchilla are slightly poorer than those of humans at low frequencies but somewhat better at high frequencies.

Since the amplitude modulation function provides a relatively comprehensive description of temporal resolution, it is of interest to determine how the function is altered by various patterns of hearing loss. The purpose of this study was to determine how high-frequency hearing loss influences the shape of the amplitude modulation function. The extent of the high-frequency loss was systematically manipulated by exposing subjects to a band of high-intensity noise and then sequentially lowering the low-pass cutoff of the noise. Because of ethical constraints, the study was carried out on the chinchilla. The auditory capabilities of the chinchilla are similar to those of humans; its amplitude modulation thresholds have been measured (Salvi *et al.*, 1982a) and much is known about its response to noise.

I. METHOD

A. Subjects

Three chinchillas were used as subjects. Prior to training, the animals were anesthetized with sodium pentobarbital (50 mg/kg) and were made monaural by surgical destruction of the left cochlea (Salvi *et al.*, 1978). Each of the animals had normal pure-tone thresholds (Miller, 1970; Balkeslee *et al.*, 1978).

B. Apparatus

Testing was conducted in a soundproof booth (IAC-400) lined with sound-absorbing foam. Most of the control and stimulus generating equipment has been described previously (Blakeslee *et al.*, 1978; Salvi *et al.*, 1978; Salvi *et al.*, 1982a). The amplitude modulated signals were generated with a voltage-controlled amplifier (Aries, AR316). White noise (Grason-Stadler, 455C) was fed to one input of the voltage-controlled amplifier while a sinusoidal signal (Wavetek 186), summed with a dc voltage, was led to the second input. The amplitude of the sinusoidal component was varied independently of the dc component to control the depth of modulation. The sinusoidal signal was gated on for 2 s at the positive zero crossing. The output of the voltage controlled amplifier was then led through an attenuator, filter (Allison 2B), power amplifier, impedance matching transformer, and a loudspeaker. The amplitude modulated noise was low-passed filtered at 20 kHz and presented at a sound pressure level (SPL) of 53 dB (*re*:0.0002 dynes/cm^2).

C. Behavioral testing

The behavioral tests were based on a shock avoidance conditioning procedure (Blakeslee *et al.*, 1978) and the psychophysical method employed was a threshold tracking procedure (Clark *et al.*, 1974) which increased the rate of data collection and minimized the time needed for testing during the exposures. The tracking procedure was previously used to obtain pure-tone, noise, and gap thresholds; the thresholds and false alarm rates obtained with this method were similar to those reported previously with the method of limits (Giraudi-Perry *et al.*, 1982).

The animals were tested on three measures: pure-tone thresholds (500 ms on, 500 ms off, 5 ms rise–fall time), thresholds for noise bursts (500 ms on, 500 ms off, 5 ms rise–fall time), and thresholds for detecting the modulation of the noise carrier. Pure-tone thresholds were measured at octave steps from 0.25 to 16 kHz. The thresholds for tones and noise bursts were tracked until there were four to six reversals and mild shock was given up to the first miss of each run. The mean pre-exposure thresholds for the tones and noise are based on 30 threshold crossings obtained over five test sessions. Catch trials were presented during each session in order to assess the animal's false alarm rate.

Amplitude modulation thresholds were measured at 12 modulation frequencies spaced at octave intervals between 2 and 4028 Hz. Modulation depth (M) is equal to $(A_{\max} - A_{\min})/(A_{\max} + A_{\min})$ where A is the signal amplitude. The modulation thresholds in this study were expressed in terms of 20 log (M). Modulation thresholds were measured using noise low-pass filtered at 20 kHz and having a SPL of 53 dB. The modulation depth was varied in steps of 1 to 2 dB. Each modulation threshold represents the mean of 12 crossings per point measured over two test sessions.

D. Noise exposure

The exposures were conducted in a reverberant room using a noise generator (Grason-Stadler 455C), octave-band filter (Allison 2B), power amplifier, and speaker. The animals were confined in a 12 × 20 × 15-cm wire cage during the exposure and given free access to food and water. Acoustic measurements were made with a half-inch condenser microphone at 12 locations within the cage and found to vary by less than 5 dB for the four exposure conditions. The chinchillas were exposed to four different bands of noise over a period of four weeks. The series of noise exposures were chosen to produce a high-frequency loss that spread to lower frequencies with each ensuing week. During the first week, the animals were exposed to an octave band of noise centered at 8 kHz and having an SPL of 90 dB. During the second week, a second octave band of noise centered at 4 kHz and having an SPL of 86 dB was added to the original noise exposure. Another octave band of noise centered at 2 kHz and having an SPL of 90 dB was added in the third week. Finally, in the fourth week, an octave band of noise centered at 1 kHz and having an SPL of 90 dB was added.

The animals were removed from the noise each day for approximately 1 h to accomplish the testing. The pure-tone thresholds (six threshold crossings per session) were remeasured at 16 and 40 h after the start of each exposure so that the animals would be in a relatively stable state of asymptotic threshold shift (ATS) (Carder and Miller, 1972). The amplitude modulation thresholds (six threshold crossings per session) were measured during the next four days. On the following day, the noise-burst thresholds were measured (six threshold crossings). The false alarm rate during testing was generally less than 10%.

II. RESULTS

The hearing loss of each of the three animals was very similar across each of the noise exposures. The mean threshold shifts for each condition are plotted in Fig. 1. Table I contains the means and standard deviations for each condition. Exposure to the octave band of noise centered at 8 kHz produced a small hearing loss beginning at 4 kHz which rapidly increased to an average loss of approximately 57 dB at 8 and 16 kHz. With the successive addition of the three lower octave bands of noise, there was a progressive decrease in the low-frequency boundary of the hearing loss. It is interesting to note that the addition of low-frequency energy pro-

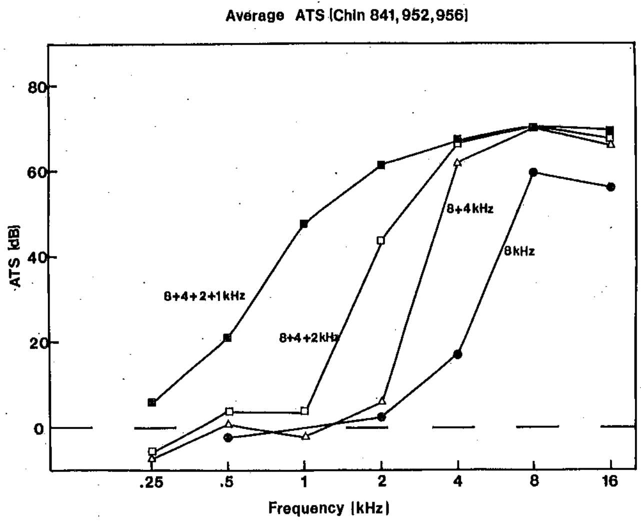

FIG. 1. The average ($N = 3$) level of asymptotic threshold shift (ATS) is plotted as a function of frequency for the four noise exposures.

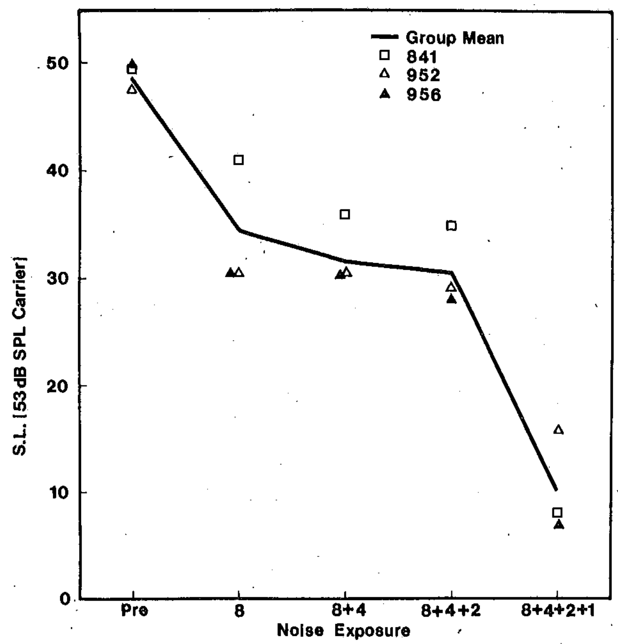

FIG. 2. The individual data and mean ($N = 3$) sensation level (SL) of the noise carrier are shown for the pre-exposure and the four noise exposure conditions.

duces only a slight increase in the high-frequency hearing loss.

The noise exposures not only changed the hearing bandwidth, but it also influenced the sensation level (SL) of the noise carrier used in the amplitude modulation paradigm. Figure 2 shows the SL of noise carrier before and during each of the four exposure conditions. Prior to exposure, the 53 dB SPL noise carrier was at a SL of approximately 49 dB. The exposure centered at 8 kHz reduced the SL from 49 dB to roughly 34 dB; the next two exposures reduced the SL to 32 and 31 dB, respectively. Finally, the four octave bands centered at 1, 2, 4, and 8 kHz reduced the SL to about 10 dB SL.

Figure 3 shows the average pre- and post-exposure amplitude modulation functions. The pre-exposure modulation thresholds varied by less than 3 dB across subjects and the amplitude modulation function is in general agreement with previous results reported for the chinchilla (Salvi *et al.*, 1982a). The mean amplitude modulation functions obtained after the four noise exposures are also shown; the variability around the mean was generally less than 3–4 dB across subjects. Table II shows the means and standard deviations of the modulation threshold shifts following each of the exposures. Exposure to the octave-band noise centered at 8 kHz had little effect on the modulation thresholds obtained at the highest and lowest frequencies, however, there was a consistent increase in the modulation thresholds obtained at intermediate frequencies, particularly near 128 Hz. These changes in the amplitude modulation function are associated with an average reduction in the SL of the carrier of about 14 dB; however, as shown in Fig. 2, the carrier signal is still 30 dB above threshold for all the animals. The next two exposures consisting of the bands centered at 4 and 8 kHz and the bands centered at 2, 4, and 8 kHz increased the extent of the hearing loss, but had little effect on the SL of the carrier and did not alter the amplitude modulation function beyond the effects seen with the first exposure. The final exposure consisting of the bands centered at 1, 2, 4, and 8 kHz produced a marked reduction in the modulation thresholds across the

TABLE I. Threshold shift means and standard deviations.

Exposure center frequency		Test frequency in kHz 0.25	0.5	1.0	2.0	4.0	8.0	16.0
8.0	X		−2.6		2.1	16.0	59.2	55.4
	SD		4.1		5.7	7.5	8.7	6.6
4.0	X	−7.1	0.1	−2.3	5.4	47.4	69.6	65.4
	SD	4.6	10.8	7.5	3.7	1.4	5.2	3.1
2.0	X	−6.4	3.5	3.7	43.1	66.0	70.2	67.1
	SD	7.0	5.2	3.7	8.3	4.2	4.4	1.9
1.0	X	5.9	20.4	47.1	60.7	66.4	69.2	68.8
	SD	3.8	6.3	11.1	3.2	1.1	1.5	1.8

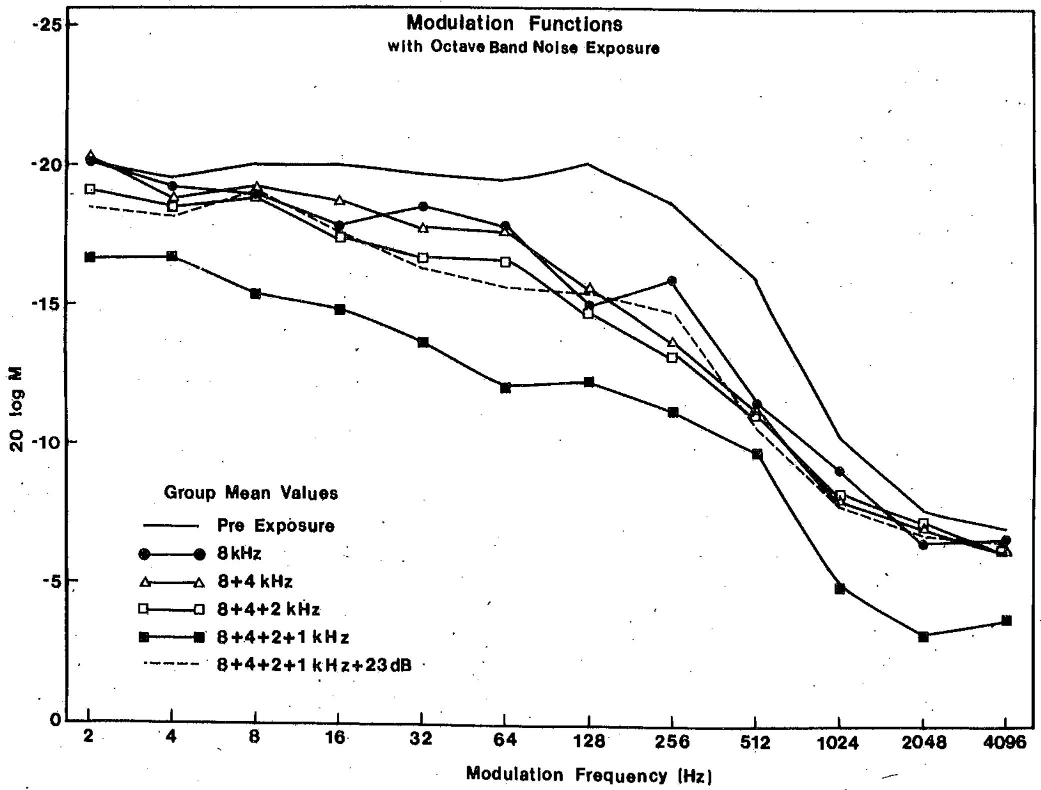

FIG. 3. The mean ($N = 3$) amplitude modulation thresholds are plotted as a function of the modulation frequency for the pre- and post-exposure conditions. All of the data were collected with the level of the carrier set at 53 dB SPL; data for the last exposure were also collected at 76 dB SPL (i.e., + 23 dB).

whole range of modulation frequencies. The greatest differences between the pre- and post-exposure amplitude modulation functions were again seen at modulation frequencies near 128 Hz. It is important to note that the chinchillas were now listening to an amplitude modulated carrier signal that had dropped from approximately 48 dB SL to 10 dB SL (see Fig. 3).

It was reasoned that the changes in the amplitude modulation function seen with the last exposure could simply be due to the difficulties associated with listening to a low-level carrier rather than to the high-frequency hearing loss *per se*. To test this idea, the level of the carrier was raised 23 dB and the amplitude modulation function was remeasured. As shown in Fig. 3, increasing the level of the carrier restored the amplitude modulation function to a level comparable to that seen with the first three exposures.

Since the SL of the carrier had a pronounced effect, one might argue that the changes observed after exposure to the band of noise centered at 8 kHz might also be related to a decrease in the SL of the carrier (Fig. 2). In order to evaluate this hypothesis, the animals were removed from the noise and allowed to recover for six months before retesting. During the recovery period, one animal died of unknown causes and the experiment was repeated using only two animals.

TABLE II. Modulation threshold shift means and standard deviations.

	Exposure CF									
	8		8 + 4		8 + 4 + 2		8 + 4 + 2 + 1		8 + 4 + 2 + 1 + 23 dB	
Hz	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
2	0.1	0.7	0.7	1.0	1.2	0.7	3.5	1.7	1.6	0.7
4	0.2	2.9	0.3	1.5	0.9	1.4	2.7	1.4	1.3	0.8
8	1.1	1.7	0.5	1.4	1.3	0.8	4.6	2.4	1.1	2.0
16	2.2	0.9	1.4	1.8	2.6	0.7	5.2	1.1	2.4	1.5
32	1.1	1.9	2.5	1.2	2.9	0.4	6.1	2.3	3.3	0.6
64	1.6	1.2	2.0	0.2	3.1	1.2	3.1	1.2	7.4	1.3
128	5.0	1.0	4.6	0.8	5.1	0.3	7.7	2.6	4.6	0.7
256	2.7	1.2	4.5	0.2	5.4	0.6	7.4	1.1	3.9	0.2
512	4.4	2.6	4.4	1.1	4.8	0.6	6.2	2.0	5.3	0.4
1024	1.3	2.3	2.9	0.6	2.2	0.2	4.8	0.2	2.7	0.4
2048	1.2	0.2	1.1	0.8	0.5	1.0	4.8	0.2	1.0	0.2
4096	0.3	1.1	0.9	0.4	0.7	0.2	3.2	0.6	0.5	0.9

Both of the animals had developed a slight (less than 15 dB) permanent hearing loss from the initial exposures. As shown in Fig. 4, the pre-exposure amplitude modulation function was similar in shape to that obtained earlier (Fig. 3), however, the modulation thresholds below 64 Hz were slightly better than those measured prior to the first exposure. The reason for this improvement in the low-frequency modulation thresholds is unclear, however, one possibility is that there could be a slight practice effect occurring over the course of the experiment.

Exposure to the octave-band noise centered at 8 kHz produced essentially the same pattern of results as the first exposure, i.e., a high-frequency hearing loss, a change in the SL of the carrier of about 15 dB, and an elevation in the modulation thresholds, particularly those in the mid-frequency range (Figs. 3 and 4). The modulation sensitivity at very low frequencies was reduced slightly more than that seen previously in Fig. 3; this minor difference could be due to differences in the pre-exposure thresholds noted above. To determine if the changes in the modulation thresholds were the result of a reduction in the SL of the test signal, the level of the noise carrier was increased by 15 dB and the amplitude modulation function was remeasured. As shown in Fig. 4, increasing the level of the carrier from 53 to 68 dB SPL (i.e., from 33 to 48 dB SL) failed to restore the amplitude modulation function to pre-exposure values.

III. DISCUSSION

The changes in the amplitude modulation function that occurred with the high-frequency hearing loss were probably due to both a reduction in the SL of the noise carrier and a reduction in the effective hearing bandwidth. The degradation of the amplitude modulation function that accompanied the hearing loss at 8 kHz and above was not related to the SL of the noise carrier (Fig. 4); thus the elevation of the modulation thresholds must be due to the high-frequency hearing loss. These results, plus other measures of temporal acuity obtained on hearing-impaired listeners, indicate that the high-frequency region of the cochlea may play an important role in temporal resolution (Cudahy, 1977; Fitzgibbons and Wightman, 1982; Fitzgibbons, 1983).

There was little deterioration in the modulation thresholds as the hearing loss progressed from 4 to 1 kHz. However, when the hearing loss spread below 1 kHz there was a further decline in the amplitude modulation function of 2 to 3 dB. This drop in temporal resolution was related to a decrease in the SL of the carrier rather than to a reduction in hearing bandwidth, since increasing the level of the carrier restored the modulation function to its previous level. The overall decline in the amplitude modulation function that occurred with the last exposure also resembles the effects seen in normal listeners when the carrier signal is presented at low intensities (Viemeister, 1979).

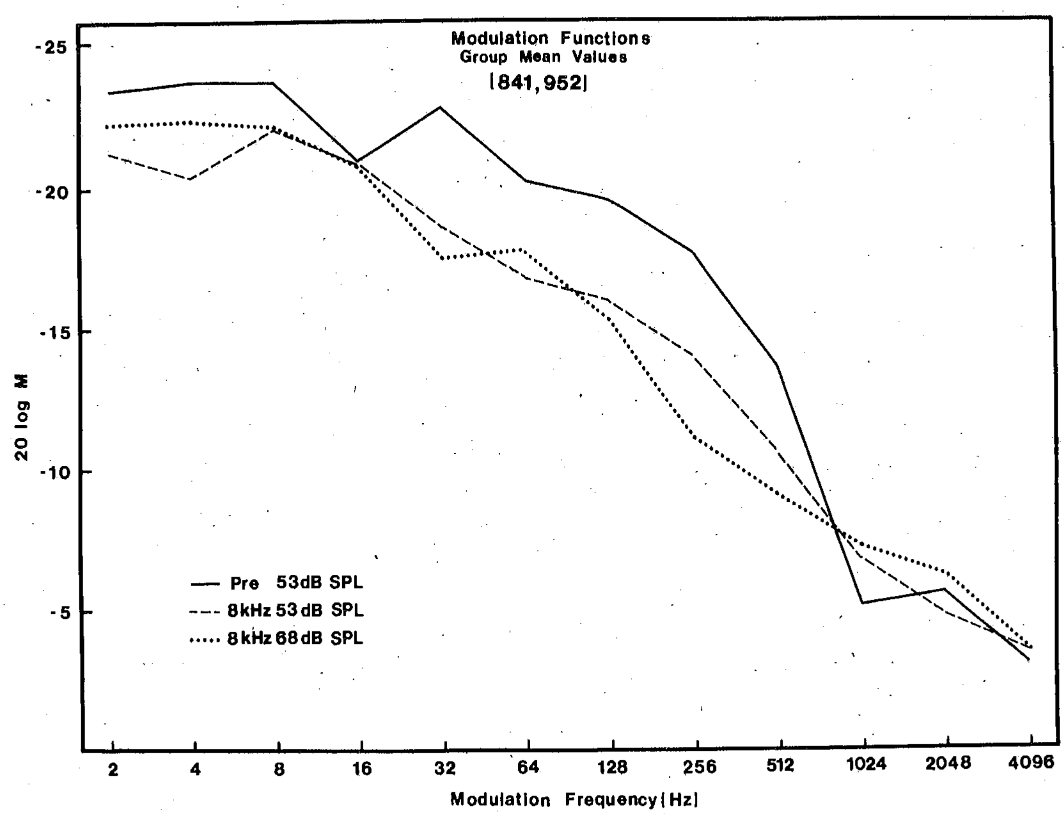

FIG. 4. The mean ($N = 2$) amplitude modulation thresholds are plotted as a function of the modulation frequency. The pre-exposure modulation function was collected at a SPL of 53 dB. The post-exposure modulation functions were collected at a SPL of 53 and 68 dB SPL and the asymptotic threshold shift (ATS) was produced by an octave band of noise centered at 8 kHz.

The specific changes that occurred in the amplitude modulation function following exposure to the band of noise centered at 8 kHz are of some interest since detection of the signal may be based on two different cues: the individual peaks and valleys of the stimulus waveform and the long-term average power of the signal. With the high-frequency hearing loss, the greatest changes in the modulation thresholds occurred near 128 Hz whereas the effects were negligible at the lowest and highest modulation frequencies. One interpretation of these results is that the high-frequency hearing loss attenuates the fluctuations in the stimulus envelope at a faster than normal rate as modulation frequency increases. This would explain why the amplitude modulation function rolls off at a faster than normal rate up to 256 Hz. However, at higher modulation frequencies, the observer may no longer be able to resolve the individual peaks and valleys in the stimulus waveform and instead may gradually switch his detection criterion to one based on the increment in the long-term average power of the signal during the modulation interval (Viemeister, 1979). Presumably, high-frequency hearing loss does not significantly alter the detection of the dc level shift and thus the modulation functions for normal and hearing-impaired ears converge at very high modulation frequencies.

An important issue relevant to studies of temporal resolution is the extent of involvement of the sharply tuned auditory filters that have been observed psychophysically (Fletcher, 1940; Patterson, 1976) and physiologically (Khanna and Leonard, 1982; Sellick *et al.*, 1982; Kiang *et al.*, 1965; Salvi *et al.*, 1982b). The auditory filter bandwidths are known to systematically increase with the center frequency of the filter. By analogy with a linear filter, one would expect an increase in auditory filter bandwidth to result in greater damping, a faster response time, and better temporal resolution. Support for this view comes from several studies which show a decrease in temporal gap thresholds as stimulus test frequency is increased (Cudahy, 1977; Fitzgibbons, 1983; Shailer and Moore, 1983). Likewise, there is an increase in the cutoff frequency (or decrease in the time constant) of the amplitude modulation transfer function as the center frequency of the noise carrier is increased (Rodenburg, 1977; Viemeister, 1979). In the context of the present study, the high-frequency hearing loss effectively reduced the center frequency of noise carrier which in turn forced the listener to detect the amplitude fluctuations through progressively narrower filters. Accordingly, one would have predicted a systematic decrease in the cutoff frequency of the modulation function, however, the only significant change in the cutoff frequency occurred after the 8-kHz exposure (excluding the effects due to SL).

The peripheral filter model, likewise, failed to account for the breakdown in temporal resolution observed in an earlier study on hearing-impaired chinchillas (Giraudi *et al.*, 1982). Gap detection thresholds were found to be prolonged at a time when the tuning curves of auditory nerve fibers were much broader than normal and when there appeared to be less "ringing" in the neural response (Salvi *et al.*, 1980). Thus, the peripheral filter model does not seem to accurately account for the data from hearing-impaired subjects. It appears, then, that there may be other neural factors located more centrally that limit temporal acuity.

ACKNOWLEDGMENTS

This research was supported in part by grants from NIH (1-R01-NS1676) and NIOSH (1-R01-OH-00364). The authors wish to thank E. Rockwood, K. Rockwood, O. Caraway, and L. Sipes for their generous donation of chinchillas.

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