Gap detection in hearing-impaired chinchillas[a)]

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Auditory temporal resolution is known to deteriorate with sensorineural hearing loss; however, there is considerable intersubject variability in human studies. The purpose of the present study was to obtain measures of temporal resolution in the chinchilla as the degree of noise-induced hearing loss was systematically varied. Gap-detection thresholds, a measure of temporal resolution, were evaluated at four levels of noise-induced asymptotic threshold shift (ATS). Gap thresholds were normal when the pure-tone thresholds were elevated approximately 15 dB. With a hearing loss of approximately 30 dB, the gap thresholds were longer than normal if compared at the same sound pressure level, but within normal limits if compared at the same sensation level. When the hearing loss exceeded 40 dB, gap thresholds were longer than normal both in terms of sound pressure level and sensation level. These results show that there is an orderly breakdown in temporal resolution as the degree of noise-induced ATS increases. The results are related to neural data and models of temporal resolution.

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INTRODUCTION

Temporal integration and temporal resolution are two important aspects of auditory temporal processing. At threshold, normal-hearing listeners integrate acoustic power for durations as great as 100–300 ms (Garner and Miller, 1947; Zwislocki, 1960; Henderson, 1969; Green, 1973). Integration is slightly less for high- than for low-frequency stimuli (Watson and Gengel, 1969). Temporal resolution, on the other hand, refers to the minimum time required to segregate or resolve acoustic events. The "minimum integration time" (Green, 1973) for normal-hearing listeners is on the order of 1–3 ms (Plomp, 1964; Green, 1973; Penner, 1975; Smiarowski and Carhart, 1975; Viemeister, 1977) with shorter times being required for high- than for low-frequency stimuli (Cudahy, 1977; Fitzgibbons and Wightman, 1982).

In recent years, there has been a growing awareness that auditory temporal processing is compromised in hearing-impaired listeners. It is now well known that listeners with a hearing loss of cochlear origin exhibit a shortened time constant for temporal summation (Harris *et al.*, 1952; Wright, 1968; Henderson, 1969; Gengel and Watson, 1971). Wright (1968) has interpreted the reduction in temporal integration as a reflection of rapid neural adaptation at the cochlea. Based on Wright's (1968) assumption, it follows that the sensation resulting from the stimulus would be expected to decay more rapidly for subjects with cochlear impairment than for normals. A rapid decay of sensation (Plomp, 1964) would also lead one to expect an improvement in temporal resolution with cochlear impairment. However, this interpretation depends on an unproven relationship between temporal integration and temporal resolution.

Listeners with sensorineural hearing loss also exhibit wider critical band and psychophysical tuning curves (de Boer, 1961; Wightman *et al.*, 1977). By analogy with physical filters, one might expect wider internal filters to have faster response times and lead to an improvement in temporal resolution.

Several psychophysical techniques have been used to assess temporal resolution in hearing-impaired listeners; however, the results have been varied. For example, Jesteadt *et al.* (1976) used Huffman sequences to study the temporal resolving capabilities of listeners with sensorineural hearing losses. The temporal acuity of hearing-impaired listeners was better for the ear or frequency exhibiting the greater hearing loss. Unfortunately, their results are difficult to compare with normal listeners because of practice effects.

Perhaps the most popular technique for assessing temporal resolution in hearing-impaired listeners is gap detection. In one of the earliest reports, Boothroyd (1973) found that subjects with profound bilateral sensorineural hearing losses had much larger gap-detection thresholds (poorer resolution) than normal-hearing subjects. Because Boothroyd's subjects were profoundly impaired, there is some question regarding the generality of the results. More recently, Fitzgibbons and Wightman (1982) used narrow-band signals to examine gap-detection performance in subjects with flat, moderate sensorineural hearing losses. Their hearing-impaired listeners did not perform as well as the normal-hearing subjects for any of the frequency regions tested, even when both subject groups were tested at the same sensation level (SL). However, their findings were collected at a single intensity; thus it is unclear how temporal resolution varies with stimulus level or the degree of hearing loss.

A close examination of the individual gap-detection thresholds of hearing-impaired subjects reveals substantial intersubject variability; in fact, some hearing-impaired listeners fall within normal limits (Boothroyd, 1973; Cudahy,

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1977; Fitzgibbons and Wightman, 1982). Recent data obtained by Church and Cudahy (1978) suggest that age may be an important source of variability. When subjects were matched for both age and high-frequency hearing loss, the elderly subjects had larger gap-detection thresholds than young adults. Surprisingly, there were no significant differences between subjects on the basis of hearing loss.

At present, the evidence related to gap detection and temporal resolution of hearing-impaired listeners is incomplete. While most investigations indicate that temporal resolution deteriorates in listeners with sensorineural hearing loss (Boothroyd, 1973; Cudahy, 1977; Fitzgibbons and Wightman, 1982), others have found normal temporal resolution (Harbert *et al.*, 1968; Jesteadt *et al.*, 1976; Church and Cudahy, 1978). The reason for these discrepancies is not yet known, but could be the result of factors which are difficult to control in human studies (e.g., age effects, degree and extent of hearing loss, or etiology). Furthermore, gap-detection thresholds have not been measured over a wide range of intensities in the impaired ear. Finally, all previous studies of gap detection have dealt with permanent hearing loss; no data is yet available on gap detection in listeners with a transient hearing loss.

The purpose of the present study was twofold: First, to measure gap-detection thresholds in the same subject with different degrees of hearing loss; second, to measure gap thresholds following a noise exposure which primarily results in a temporary threshold shift; such results would fill a void in the existing literature. The hearing loss was induced by long-duration exposure to noise that resulted in an asymptotic threshold shift (ATS) (Carder and Miller, 1971). The degree of ATS was systematically increased by raising the level of the noise. Because of ethical considerations, the investigation was implemented with the chinchilla; its audiogram and gap-detection thresholds are comparable to those of man (Miller, 1970; Blakeslee *et al.*, 1978; Giraudi *et al.*, 1980) and much is known about the effects of noise on its auditory system (e.g., Carder and Miller, 1971, 1972; Salvi *et al.*, 1978).

I. METHODS

The overall protocol for this experiment was as follows. Pre-exposure thresholds for tone bursts, noise bursts, and gaps embedded in noise were assessed for each subject. Then each chinchilla was exposed to noise at four successively higher intensities ranging from 75 to 100 dB SPL. Testing commenced after an animal had been in the noise for two days. The animals were removed from the noise once a day for testing. The test period was approximately 30–40 min and was sufficiently short to preclude any significant recovery of sensitivity (Carder and Miller, 1971). Pure-tone thresholds were measured over the first four days of the exposure to ensure that the threshold shifts had reached asymptote. Then the noise bursts were measured followed by measurement of the gap thresholds. A total of 8–11 days were required to complete the testing at each level of exposure.

A. Subjects

Five adult chinchillas (300–500g) served as subjects. All animals had been made monaural by surgical destruction of the left cochlea (Miller, 1970) under sodium pentobarbital anesthesia (50 mg/kg, intraperitoneal).

B. Apparatus

Equipment for controlling the test stimuli have been described previously (Salvi *et al.*, 1978; Giraudi *et al.*, 1980). Behavioral testing was conducted in a single-walled soundproof booth lined with sound absorbing foam.

The noise exposure was conducted in a reverberant room using a noise generator, graphic spectrum equalizer, power amplifier, and speaker. The octave band of noise (OBN) had a center frequency (CF) of 500 Hz (Fig. 1). Each subject was sequentially exposed to noise levels of 75, 85, 95, and 100 dB SPL (Carder and Miller, 1971, 1972). The exposure duration was 8 to 11 days at each level. During the course of the exposure, each animal was confined in a 12×20×15 cm wire cage and given free access to food and water.

C. Procedure

The animals were trained and tested first to detect tone bursts, then to detect noise bursts, and finally to detect gaps embedded in continuous noise using a shock-avoidance conditioning procedure (see Blakeslee *et al.*, 1978; Salvi *et al.*, 1978; and Giraudi *et al.*, 1980 for details). The pre-exposure measurements were collected over approximately 3–4 weeks. Noise-burst thresholds were assessed with a tracking procedure in order to estimate the sensation level of the noise in the gap detection paradigm (Clark *et al.*, 1974). A stimulus trial consisted of six noise bursts (500 ms on, 500 ms off, rise–fall 10 μs, 0.1–10 kHz bandwidth). A response on bursts one or two was considered a HIT and resulted in avoidance of the shock, termination of the noise bursts, and presentation of a 10-s safety light. If the animal failed to respond before the onset of the third noise burst, the trial was scored as a MISS and pulsed electric shock (0.5–1.0 mA) was turned on until

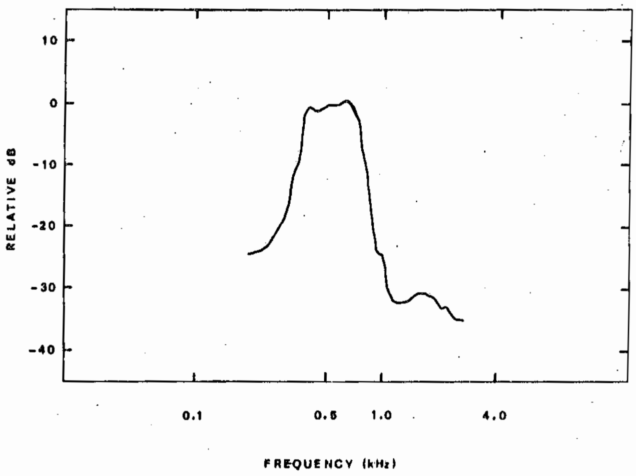

FIG. 1. Frequency spectra (bandwidth 40 Hz) for the octave-band noise with a center frequency of 500 Hz.

the animal responded or the trial terminated. After each HIT, the intensity level was decreased 10 dB and after each MISS the level was increased 10 dB until three reversals had occurred. At that point, the intensity step size was decreased to 5 dB. Testing continued until four additional reversals had occurred. The midpoint between each consecutive reversal obtained with the 5 dB step size was taken as a threshold and 20 measures were averaged to obtain an estimate of the noise-burst threshold. Catch trials (10%) were placed in each test run to monitor the false alarm rate ($<5\%$). Pure-tone thresholds (500 ms on, 500 ms off, 5 ms rise–fall time) were also determined at octave intervals from 0.25 to 16.0 kHz using the modified tracking procedure described above.

The gap-detection training procedures have been described previously (see Giraudi *et al.*, 1980 for details). The noise signal for the gap-detection task remained on continuously except during a trial when six silent intervals were presented every 750 ms. The following gap durations (ΔT) were used for measuring gap thresholds before and during ATS: 100, 75, 50, 30, 25, 20, 15, 10, 9, 8, 7, 6, 5, 4, 3, 2, 1.5, 1, and 0.75 ms. The noise was filtered after switching the signal off and on and the long-time spectrum of the noise was essentially unaltered by the gaps. Gap thresholds were determined by a tracking procedure analogous to that used for tone and noise burst. A response between gaps one through two was scored as a HIT, while responses between three through six were scored as a MISS. The gap size was initially varied two steps at a time until three reversals occurred. Then, the gap size was varied one step at a time and the midpoints of the last four reversals were used as threshold estimates. A total of 20 threshold estimates were taken at each intensity level. Pre-exposure gap-detection thresholds were measured using intensities from 20 to 70 dB SPL in 10 dB intervals. During ATS, gap thresholds were assessed only at intensities where the noise stimulus was equal to or greater than 15 dB sensation level (SL). Because of the limited output of the acoustic system, fewer levels were tested during ATS than in the pre-exposure condition. At the end of the exposure, the animals were returned to the animal colony and allowed to recover for 30 days. Then their pure-tone thresholds were remeasured over one to two weeks to assess the amount of permanent threshold shift.

II. RESULTS

A. Pure-tone and noise-burst threshold shifts

The pre-exposure thresholds and the intrasubject variability for all five chinchillas were similar to those reported by Miller (1970) and Blakeslee *et al.* (1978). The pure-tone threshold shifts at ATS for the four noise exposure conditions are presented in Fig. 2. An important point to note is that the low-frequency noise exposure produced a relatively flat hearing loss. Furthermore, the hearing loss showed an orderly increase with increasing noise level. The amount of ATS was approximately 15, 30, 45, and 50 dB for exposure levels of 75, 85, 95, and 100 dB SPL, respectively. The pattern and magnitude of threshold shift for the four levels are similar to those reported in earlier studies of ATS using essentially the same noise and exposure levels (Carder and Miller, 1971, 1972; Salvi *et al.*, 1979).

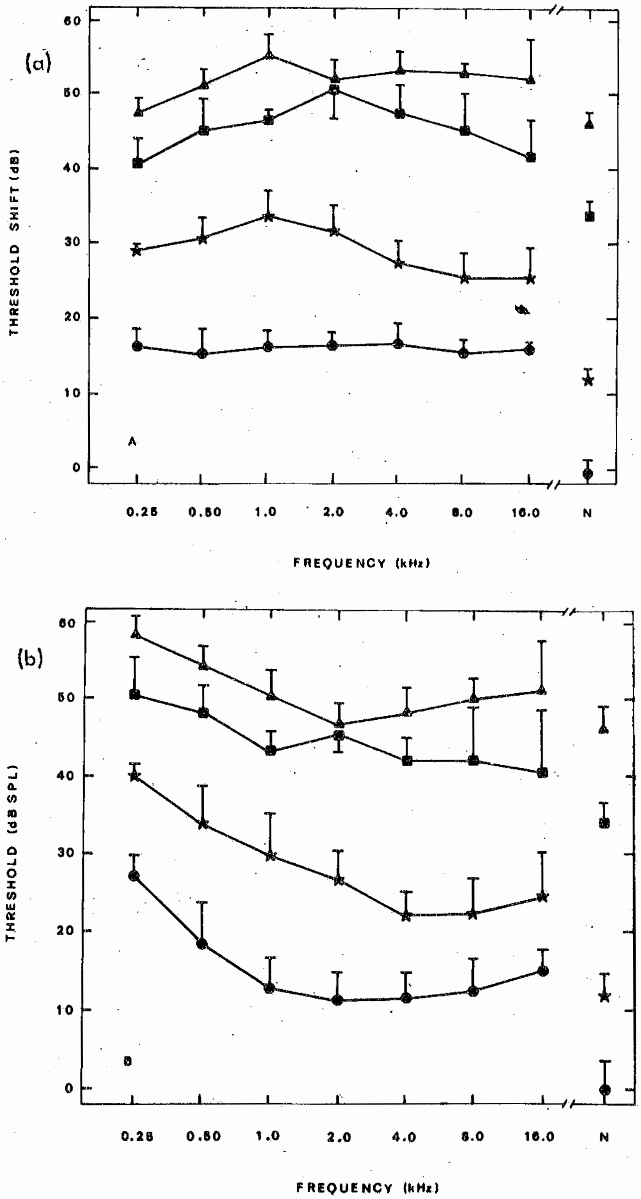

FIG. 2. Mean value of asymptotic threshold shift (panel A) and mean threshold in dB SPL (panel B) for pure tones and noise bursts (N) at the exposure levels of 75 dB (circles), 85 dB (stars), 95 dB (squares), and 100 dB SPL (triangles). Standard error of the mean indicated by (T).

The mean noise-burst threshold shifts obtained during ATS are also plotted in Fig. 2. The mean pre-exposure noise-burst threshold was approximately 0 dB SPL. At ATS, for the 75, 85, 95, and 100 dB SPL conditions, the mean noise-burst threshold shifts were 0, 12, 34, and 46 dB, respectively. It is interesting to note that the 75 dB noise caused approximately a 15 dB shift across the whole range of frequencies tested, but the thresholds for the noise bursts did not shift.

B. Gap-detection thresholds

Figures 3–6 show the pre-exposure gap-detection thresholds and those obtained during the four exposures. The upper portion of each graph depicts this comparison in terms of SPL and the bottom half in terms of the SL. Recall

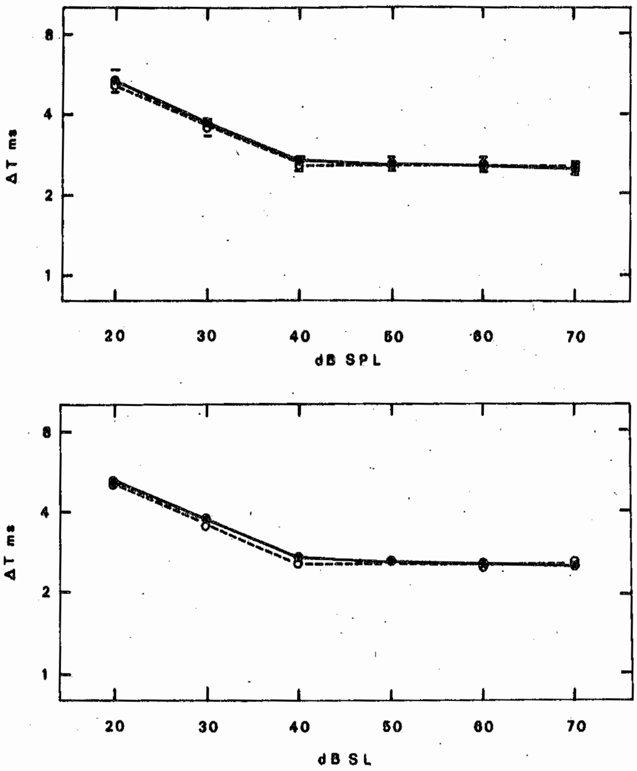

FIG. 3. Pre-exposure (filled circles) and ATS (unfilled circles) gap-detection thresholds for the 75 dB SPL noise exposure are plotted as a function of SPL (upper panel) and SL (lower panel). Lower and upper horizontal bars indicate the standard error of the mean for the pre-exposure and ATS condition, respectively.

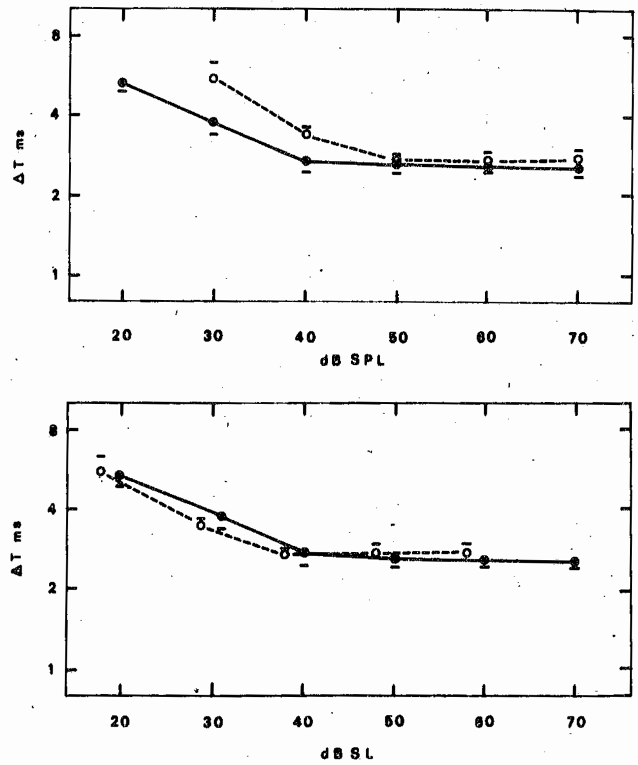

FIG. 4. Comparison of pre-exposure and ATS gap-detection thresholds for the 85 dB SPL noise exposure. The symbols are the same as in Fig. 3.

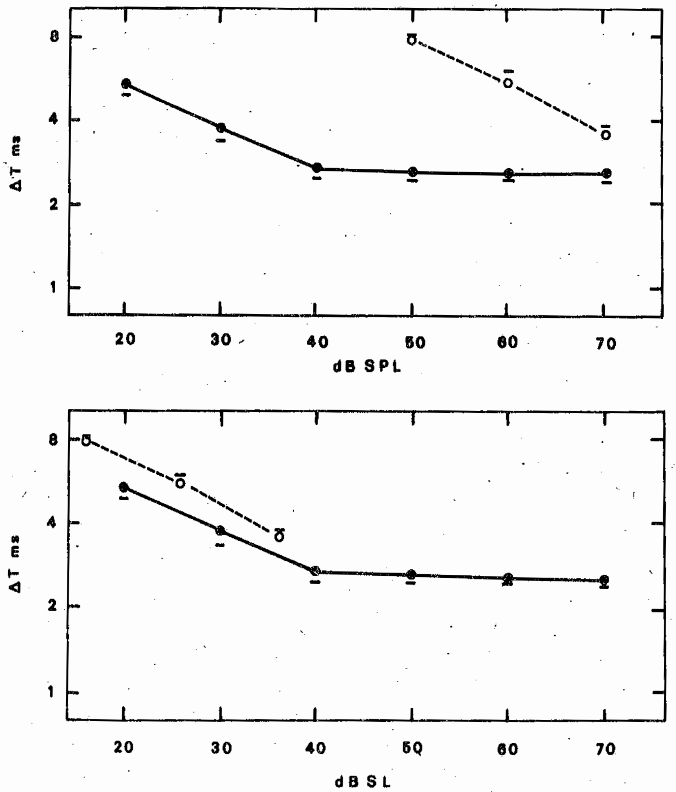

FIG. 5. Comparison of pre-exposure and ATS gap-detection thresholds for the 95 dB SPL noise exposure. The symbols are the same as in Fig. 3.

that the average pre-exposure threshold for the noise burst was 0 dB SL; thus a 60 dB SPL noise used for the pre-exposure gap thresholds was on the average 60 dB SL. The same approach was used to relate the post-exposure gap thresh-

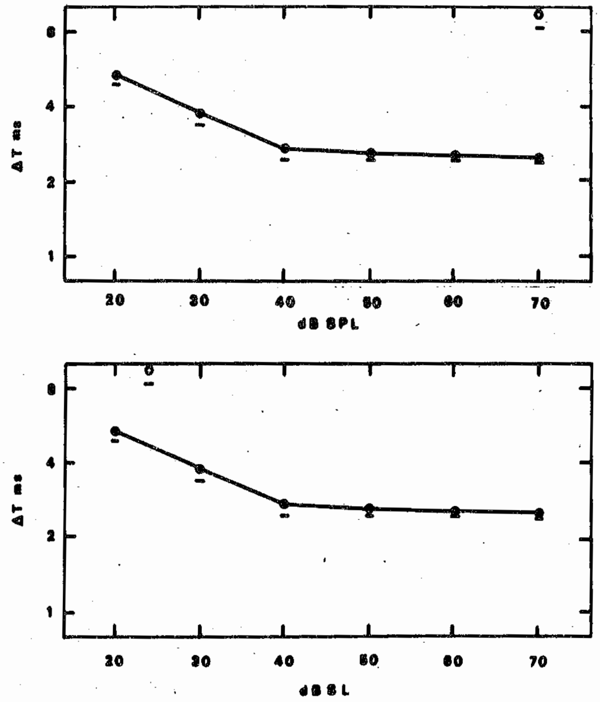

FIG. 6. Comparison of pre-exposure and ATS gap-detection thresholds for the 100 dB SPL noise exposure. The symbols are the same as in Fig. 3.

olds to the SL of the noise. The solid line in each figure shows the pre-exposure detection threshold as a function of stimulus intensity. Gap-detection thresholds are longer at lower intensities and decline to a minimum value of approximately 3 ms at 40 dB SPL. These results are consistent with previous studies of gap detection in both chinchilla (Giraudi *et al.*, 1980) and man (Plomp, 1964). The trend for increasing thresholds with decreasing stimulus levels (20–30 dB SPL) was statistically significant (F test, $p < 0.05$).

The gap-detection thresholds changed systematically with exposure level and hearing loss. The 75 dB SPL exposure produced approximately a 15 dB pure-tone threshold shift between 0.25 and 16 kHz without having a measurable effect on the noise-burst or gap-detection thresholds (Fig. 3). The 85 dB SPL exposure produced a flat loss of 25 to 35 dB. Note that gap-detection thresholds were only measured at levels equal to or greater than 15 dB SL. Gap thresholds were larger than the pre-exposure thresholds only at 30 and 40 dB SPL (Newman–Keuls test, $p < 0.05$) (Fig. 4, top). The increase in the gap thresholds was probably related to a change in the threshold of the noise because there were no significant differences between the two functions when the comparison was made in terms of SL (Fig. 4, bottom). When the noise level was increased to 95 dB SPL, pure-tone thresholds were elevated between 40 and 50 dB. At stimulus levels of 50, 60, and 70 dB SPL (Fig. 5 top), gap thresholds were significantly larger than normal (F test, $p < 0.01$). This may reflect more than a simple change in threshold since the gap-detection thresholds during ATS are still abnormally long when the functions are compared in terms of sensation level (F test, $p < 0.01$) (Fig. 5, bottom). The 100 dB exposure produced a 48 to 55 dB threshold shift. Due to the output limitations of the test equipment, gap-detection thresholds could only be measured at 70 dB SPL. The gap-detection threshold was larger than normal, both in terms of SPL and SL (F test, $p < 0.01$).

During ATS, the variability of the gap detection measures was similar to pre-exposure values, whether compared at a similar SL or SPL. The only exception occurred during ATS for the 100 dB SPL noise; here, the variability of the gap-detection thresholds (mean standard errror: 1.4 ms) was considerably greater than the pre-exposure data (mean standard error: 0.11 to 0.41 ms). However, the intersubject variability was less than that found in similar human studies.

Finally, the pure-tone and noise-burst thresholds were remeasured approximately 30 days post-exposure. The permanent threshold shifts did not exceed 13 dB at any frequency and the average loss in sensitivity was only about 8 dB. Thus the effects of the noise exposure (particularly at 75 and 85 dB SPL) can be considered primarily temporary in nature based on the behavioral data. However, some loss of hair cells is to be expected with this type of exposure (Bohne, 1976).

III. DISCUSSION

A. Threshold shifts

The hearing loss resulting from the low-frequency band of noise was relatively flat; consequently, the noise-burst threshold shifts were expected to be similar to the average pure-tone loss. Instead, noise-burst thresholds were shifted in a more complicated manner. The 75 dB SPL exposure produced a pure-tone threshold shift of approximately 15 dB, but no elevation in the noise-burst threshold. However, with increased levels of exposure, the noise-burst thresholds increased as rapidly or faster than the pure-tone thresholds. The 100 dB SPL condition produced an average pure-tone threshold shift of 52 dB while the noise-burst threshold was elevated 46 dB.

Langenbeck (1951) also found threshold shift for noise bursts to be smaller than those for pure tones in cochlear-impaired listeners. He hypothesized that this effect was due to a widening of the critical band (de Boer, 1961; Scharf, 1970). It is known that the threshold of a complex signal depends on whether the energy falls within or outside the critical band (Gassler, 1954). Furthermore, since the power through the critical band increases with bandwidth for a wideband noise but remains constant for a pure tone, more noise energy is available to the ear when the critical band widens as a result of injury to the cochlea. This increase in energy may partially compensate for the loss in sensitivity. Langenbeck's critical band explanation is consistent with broadened psychophysical and neural tuning curves observed during ATS (Mills, 1980; Salvi *et al.*, 1980); unfortunately, direct measurements of the critical band were not made in this study.

Alternatively, the difference between the threshold shifts for tones and noise might be due to the low resolution audiogram, i.e., the thresholds for some of the frequencies lying between the octave intervals may have shifted to a lesser degree than those at the test frequencies. Presumably, the threshold shifts for noise would be less than for tones since the threshold for noise would be mediated by the most sensitive and less impaired frequencies.

B. Temporal resolution and hearing loss

The results of the present study indicate that temporal resolution deteriorates with noise-induced ATS; however, the relationship is not a simple one. Mild pure-tone threshold shifts (approximately 15 dB) have no apparent effect on gap-detection thresholds (Cudahy and Church, 1978). Threshold shifts on the order of 30 dB cause an increase in gap-detection thresholds for signals of the same SPL; however, the deterioration in temporal resolution can be eliminated if the gap signals are presented at similar SL's. A more serious breakdown in temporal resolution occurs when the pure-tone threshold shifts exceed 40 dB (Boothroyd, 1973; Fitzgibbons and Wightman, 1982). Gap-detection thresholds of hearing-impaired listeners are larger than those of normal-hearing subjects even when compared at similar SL's. Although Fig. 5 (bottom) shows that the thresholds for gap detection are larger than normal, the data also indicate that the gap-detection thresholds continue to decrease with increasing signal level. Consequently, it may be possible to force the gap-detection thresholds back down to the "minimum duration" by using higher stimulus levels. Unfortunately, this could not be tested due to the limited output of our acoustic system.

C. Temporal resolution and temporal summation

The results of this study and studies of temporal summation during ATS (Mills *et al.*, 1970) show that the process of temporal summation and temporal resolution do not covary. Temporal summation deteriorates with small amounts of ATS (Mills *et al.*, 1970) while temporal resolution is not compromised until the hearing loss is approximately 30 dB or greater. Also, if the limits of gap detection are governed by the decay of sensation as suggested earlier (Plomp, 1964; Wright, 1968), then one would predict that when temporal summation deteriorates, temporal resolution should actually improve. The present results unequivocably show the opposite.

D. Model of temporal processing

Duifhuis (1973) conceptualized temporal processing in terms of a dual-stage filter model: one filter element residing in the cochlea and having a short time constant (<10 ms) and another located at the VIII-nerve or above and possessing a long time constant (>75 ms) to reflect neural adaptation. The psychophysical results from the present study and earlier VIII-nerve data on ATS (Salvi *et al.*, 1979, 1980) provide information relevant to models of temporal processing. During ATS, the tuning curves of single VIII-nerve fibers become extremely broad (Salvi *et al.*, 1980). If these auditory filters behave like physical filters, then the wider bandwidths should lead to faster response times and greater damping.

Salvi *et al.*, 1976 found no change in the latency of single VIII-nerve fibers or the whole-nerve action potential as a result of ATS (Salvi *et al.*, 1979). Also, the timing of the neural discharges to click stimuli appeared to be normal except for the fact that there seemed to be less "ringing" (greater damping) in the PST histogram. The phase-locking properties of auditory nerve fibers in response to pure tones have also been examined in animals with a sensorineural loss induced with aminoglycosides; unfortunately, the results conflict. Harrison and Evans (1979) found no change in phase locking among units whose thresholds were elevated 30–50 dB, while Woolf *et al.* (1980) noted a reduction in phase locking in the auditory nerve. The psychophysical data on the other hand clearly show that temporal resolution deteriorates when TTS is greater than 30–40 dB. Thus an important issue which now needs to be resolved is whether the breakdown in temporal resolution results from a deterioration in neural timing at the auditory periphery or whether it occurs proximal to the VIII-nerve.

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