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## Evoked response 'forward masking' patterns in chinchillas with temporary hearing loss

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Evoked response "forward masking" data were measured from the inferior colliculus of the chinchilla before and during a temporary threshold shift. The hearing loss was induced by a 2 kHz pure tone of 85 dB SPL presented from 5–8 days. The exposure elevated thresholds by approximately 35 dB at the mid frequencies, but had no effect on low frequency hearing. The exposure also altered the time course of the evoked response forward masking data. Time constants fitting the forward masking data increased by up to a factor of three at the frequency with the greatest loss, but remained within normal limits at the low frequencies where hearing was normal. The increase in the forward masking time constants became most noticeable once the hearing loss exceeded 25 dB. These physiological results are consistent with psychophysical forward masking data from hearing impaired listeners.

Forward masking; Evoked response; Temporary threshold shift; Inferior colliculus; Temporal resolution; Hearing loss

### Introduction

One of the most profound deficits associated with sensorineural hearing loss is the breakdown in frequency selectivity or more specifically, the broadening of psychophysical, mechanical and physiological tuning curves (Evans, 1974; Salvi et al., 1982b; Wightman, 1982; Patuzzi, 1986). In a simple resonant system, tuning is related to the temporal response characteristics of the system such that the broader the tuning the faster the response time and greater the damping. If the assumption is made that the ear behaves like a simple resonant system, then one would predict that the temporal response time and damping of a listener with sensorineural hearing loss would be superior to that of a normal listener. The response time and damping characteristics of hearing impaired listeners have been indirectly assessed through a variety of psychophysical tasks. In gen-

eral, the results of these studies indicate that temporal resolution does not improve, but rather deteriorates with sensorineural hearing loss.

One psychophysical measure that has been used extensively to study the temporal resolving power of the ear is gap detection. Normal hearing listeners can detect brief silent intervals, or gaps, in an acoustic waveform down to durations as short as 2–3 ms (Plomp, 1964; Giraudi et al., 1980). Gap detection thresholds are shortest at the high frequencies where the internal filter bandwidths are widest, as one would expect from a linear filter model of the auditory system (Fitzgibbons and Wightman, 1982; Fitzgibbons, 1983). The model, however, cannot account for the results from listeners with sensorineural hearing loss and broad tuning since these subjects have gap thresholds that are longer than normal once the hearing loss exceeds 30 dB (Fitzgibbons and Wightman, 1982; Giraudi-Perry et al., 1982; Salvi and Arehole, 1985). The loss of temporal acuity as assessed by gap detection has broad implications since it has been viewed as one of the factors that may contribute to poor speech discrimination in hearing-impaired listeners (Tyler et al., 1982;

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Dreschler and Plomp, 1985; Tyler, 1986).

Other measures of auditory temporal resolution have also been shown to deteriorate with sensorineural hearing loss. For example, in animals with high frequency hearing loss, the threshold for detecting sinusoidally amplitude modulated noise increased at a faster than normal rate as modulation frequency increased (Henderson et al., 1984). Apparently, when the modulation frequency increases, impaired listeners are poorer than normal listeners in resolving the peaks and valleys in the stimulus envelope.

Forward masking is yet another measure of temporal processing that is adversely affected by sensorineural hearing loss. Nelson and Turner (1980) and Cudahy (1982) have shown that the time course of forward masking is prolonged in hearing impaired listeners. Time constants increased only in frequency regions where thresholds were elevated and tuning was abnormally broad. Furthermore, the time constant of forward masking showed a significant increase only when the hearing loss exceeded 25–30 dB. More recent studies have confirmed and extended these findings (Trinder, 1979; Feston and Plomp, 1983; Dreschler and Plomp, 1985).

While psychophysical studies indicate that temporal resolution deteriorates in hearing impaired listeners, there is little direct evidence regarding the physiological processes that may be involved. One common physiological measure of auditory temporal processing is the phase-locking of spike discharges to a preferred phase within the stimulus period. Woolf and Ryan (1985) have reported that the loss of outer hair cells due to ototoxic drugs results in a reduction of phase-locking in units from the cochlear nucleus and auditory nerve; however, Harrison and Evans (1979) found no change in the phase-locking of auditory nerve fibers under similar conditions. In any case, the link between neural phase-locking and psychophysical measures of temporal processing is indirect and somewhat tenuous.

Other physiological mechanisms that may be linked to forward masking are short-term neural adaptation and the recovery from adaptation which are first seen in the auditory pathway at the level of the auditory nerve (Furakawa and Matsuura, 1978). Most evidence suggests that short-term

adaptation is not altered by cochlear trauma in units from the cochlear nucleus and auditory nerve (Salvi, 1976; Henderson et al., 1982; Salvi et al., 1982b). Short-term adaptation and recovery have also been observed indirectly by measuring the gross action potential (AP) from the auditory nerve using a forward masking stimulus paradigm (Gorga and Abbas, 1981). No change in the time course of adaptation or recovery were noted in animals with permanent hearing loss. However, the AP amplitude-intensity functions to the masker were steeper than normal. The lack of change in the time course of AP recovery suggested to us that the physiological processes underlying abnormal temporal processing might be occurring in the central auditory pathway. In order to explore this issue, estimates of the time course of forward masking were obtained from the inferior colliculus of the chinchilla using the auditory evoked response. The time course of the evoked response forward masking data was measured from the same animal both before and during a temporary hearing loss.

## Materials and Methods

### *Subjects*

Ten adult chinchillas weighing between 400 and 800 g were used as subjects. Each animal was anesthetized (ketamine, 0.1 mg/kg; acepromazine, 0.03 mg/kg; rompun, 0.1 mg/kg) and the left cochlea was surgically destroyed in order to test the response of just the right ear. An electrode was stereotaxically implanted into the inferior colliculus along with a reference electrode near the dura mater (Henderson et al., 1973; Salvi et al., 1982b). The animals were allowed to recover for at least one week before testing began. Testing was carried out in a sound-attenuating booth lined with sound-absorbing foam. The animals were placed in a yoke-like restrainer in order to fix the orientation of the head within the calibrated sound field.

### *Recording*

The output of the electrode was filtered (30–3000 Hz), amplified (20 000 ×) and led to the A/D converter of a computer (PDP 11/23) with artifact reject capabilities. The signal was sampled for 30 ms (20 kHz, 600 points) beginning at the

onset of the probe tone. A total of 125 sweeps were averaged per waveform. The averaged waveforms were stored on disc for later analysis.

### *Stimuli*

A probe tone, 10 ms in duration with a 1 ms rise-fall time, was used to elicit the evoked response both for threshold measurements as well as in the forward masking paradigm. During threshold testing, the probe was presented at the rate of  $10 \text{ s}^{-1}$ . During the forward masking procedure, the probe tone was preceded by a pure tone masker of the same frequency as the probe. The masker was 100 ms in duration with a 1 ms rise-fall time. The interval between masker offset and probe onset (DT) was varied from 2 to 100 ms. The stimuli were presented once every 400 ms.

### *Experimental protocol*

The overall design of the experiment was as follows. At the start of the experiment, the evoked response thresholds were measured followed by the forward masking data. After all normal measurements were completed, the animals were exposed to a 2 kHz continuous tone of 85 dB SPL (re  $0.0002 \text{ dynes/cm}^2$ ). The duration of the exposure ranged from 5 to 8 days. Within 48 h of exposure onset, the animals had developed a temporary asymptotic threshold shift (ATS) (Carder and Miller, 1972). Beginning 48 h after the start of the exposure, the animals were removed from the noise at regular intervals and their thresholds and forward masking data were remeasured in order to assess the effects of the hearing loss.

### *Threshold*

Evoked response thresholds in quiet were measured in octave intervals from 0.5 to 16 kHz. Threshold was defined as a just-noticeable deflection from the baseline activity. Three threshold measurements were obtained before exposure and during ATS. The difference between the mean threshold obtained pre-exposure and during ATS post-exposure was used to estimate the magnitude of the hearing loss.

### *Forward masking*

Evoked response forward masking data were

obtained at 0.5, 2, 4, and 8 kHz by adjusting the intensity of a forward masker until it produced a 50% reduction in the amplitude of the response evoked by a low-level probe tone. The probe tone was presented 10 dB above the evoked response threshold in order to elicit a small, but consistent evoked response. After each masker plus probe response was collected, a control measure was taken in which the probe was alone; this allowed the probe-evoked response to be measured in its unadapted state. The measurements were repeated twice at each frequency. The peak-to-trough amplitude of the probe-evoked response obtained in the presence of the masker was normalized to the amplitude of the evoked response obtained without the masker. The normalized probe amplitude was plotted as a function of masker level and a straight line was fitted to the steeply rising portion of the function. The slope of the function (i.e., percent reduction in probe-evoked response amplitude per dB of masker level) was used to estimate the growth of masking. The intensity needed to produce a 50% reduction in the probe evoked response was interpolated from the straight line. The 50% point was used to define the masked threshold at each DT. The masked threshold plotted as a function of DT was then used to delineate the time course of forward masking data at each frequency. It is important to note that the 50% reduction point is not the same as the masked threshold in a psychophysical experiment; however, since the probe tone is only 10 dB above threshold, a 50% reduction in the response probably provides a reasonable estimate of the actual threshold.

Two sets of forward masking data were obtained before exposure and two during ATS. The average of the two measures defined the mean pre-exposure and ATS forward masking patterns. An exponential function of the form  $L_m = Ae^{(DT/\text{Tau})}$  was then fitted to the mean forward masking data by adjusting the constants,  $A$  and  $\text{Tau}$ , to minimize the mean squared error term (Vogten, 1978; Nelson and Turner, 1980; Cudahy, 1982). This equation has been shown to give a good fit to the evoked response data from normal chinchillas (Arehole, 1986).

## Results

### Threshold and threshold shift

The mean pre-exposure thresholds of the 10 animals used in this study were comparable to those observed by others (Henderson et al., 1973; Salvi et al., 1982a). The mean threshold ranged from a low of 3 dB SPL at 4 kHz up to 24 dB SPL at 16 kHz. These results confirm that hearing was normal at the start of the experiment. After the animals had been exposed to the noise for two days, their thresholds were remeasured during days two through seven in order to estimate the degree of temporary asymptotic threshold shift. Exposure to the 2 kHz tone caused a significant increase in thresholds at the mid frequencies as illustrated in Fig. 1. The maximum temporary threshold shift occurred an octave above the exposure frequency. The mean threshold shift at 4 kHz was 35 dB with a standard deviation of 7 dB. The mean threshold shift at 2, 8 and 16 kHz averaged 25, 18, and 5 dB, respectively. It is important to note that there was no hearing loss at 0.5 kHz. Thus, 0.5 kHz can serve as a within subject control for evaluating the changes in the forward masking data.

### Normal forward masking patterns

Before examining the effects of temporary hearing loss on the forward masking patterns, it may be useful to briefly illustrate the results from normal hearing chinchillas. Fig. 2 shows the intensity of the masker needed to produce a 50% reduction (i.e., masked threshold) in the evoked re-

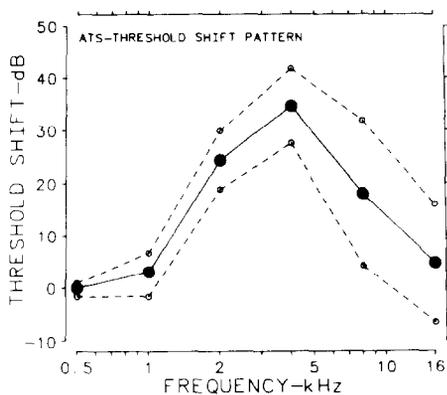


Fig. 1. Average level of asymptotic temporary threshold shift (filled circles,  $N=10$ )  $\pm 1$  s.d. (dashed line) measured during the exposure to the 2 kHz pure tone.

sponse elicited by the probe tone as a function of DT. The masked thresholds are lowest at short DTs and increase in an approximately exponential fashion as the time interval between masker and probe increases. In order to evaluate the results quantitatively, an equation of the form,  $L_m = Ae^{(DT/Tau)}$ , was fitted to the data. The time constant giving the best fit at each frequency is indicated in each panel of Fig. 2. The time constants ranged from 37 ms at 4 kHz to 90 ms at 0.5 kHz. The degree of variance ( $R^2$ ) accounted for by the model ranged from 0.7 to 0.96; this indicates that the model provides a reasonably good fit to the data as shown earlier (Arehole, 1986). The constant,  $A$ , in the model represents the predicted masked threshold at a DT of 0 ms. In general, the higher the quiet threshold, the higher the SPL of the masker needed to mask the probe, and the larger the value of the  $A$  term. In Fig. 2, the values of  $A$  were 30, 13, 5 and 29 dB at 0.5, 2, 4, and 8 kHz, respectively. Table I shows the mean, standard deviation, and range of values for the constants  $A$  and  $Tau$  for all 10 animals before the exposure.

### ATS forward masking patterns

In order to assess the effects of temporary hearing loss, one can compare each animal's forward masking data obtained during ATS against the pre-exposure forward masking data. Fig. 3A shows the typical change that occurred at 4 kHz, the region of greatest hearing loss. During ATS, the masked thresholds at short values of DT are elevated relative to the pre-exposure condition. However, as DT increases, the difference between the masked threshold obtained before exposure and during ATS decreases. This illustrates that the evoked response forward masking data are not simply shifted upward by an amount equal to the hearing loss. Instead, the forward masking pattern appears to recover much more slowly than the pre-exposure pattern. In order to help visualize the change in time course of forward masking, all of the masked thresholds were normalized to a DT of 2 ms as shown in Fig. 3B. The change in the time course of forward masking is reflected as an increase in the time constant from 62.5 ms before the exposure to 208.3 ms after the exposure. Note that the difference in the masked threshold be-

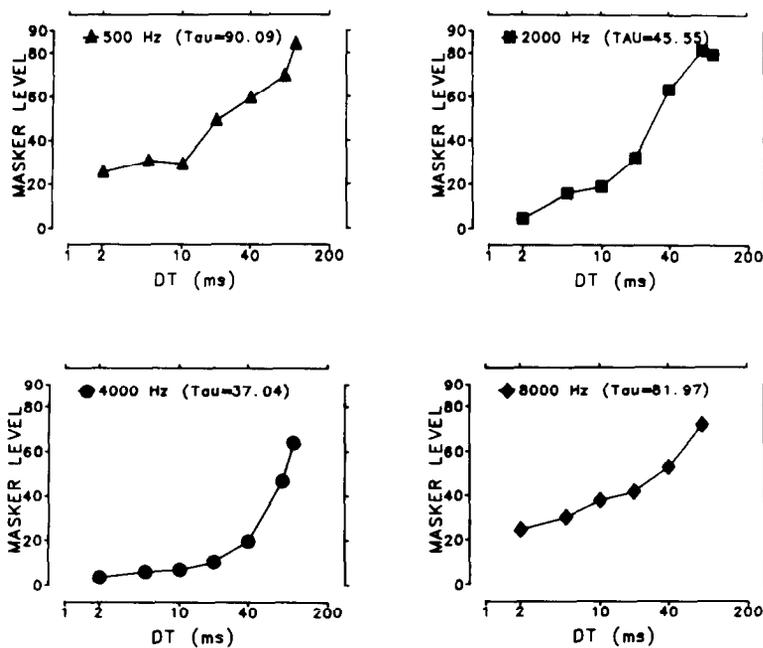


Fig. 2. Typical pre-exposure evoked response forward masking functions obtained at the four probe frequencies. Masked threshold expressed in dB SPL and interval between masker offset and probe onset (DT) plotted in log time. Chinchilla 1622: 0.5 kHz, Tau = 90.09,  $R^2 = 0.85$ ; 2 kHz, Tau = 45.55,  $R^2 = 0.69$ . Chinchilla 1544: 4 kHz, Tau = 37.04,  $R^2 = 0.96$ ; 8 kHz, Tau = 81.97,  $R^2 = 0.88$ .

tween 2 ms and 100 ms is approximately 75 dB when hearing is normal but less than 25 dB during ATS.

The forward masking pattern was altered to a lesser extent at other frequencies. At 0.5 kHz, where quiet threshold remained completely normal, the time course of forward masking was essentially unchanged (Fig. 4A). However, at 2 kHz where the threshold shift was 22 dB, the forward masking time constant increased from 81 to 111 ms (Fig. 4B). The threshold shift at 8 kHz was slightly higher than at 2 kHz, and the time constant of forward masking increased from 50 to 182 ms (Fig. 4C).

The trend shown above for individual animals was also reflected in the group data shown in Table I. The constant,  $A$ , which represents the masked threshold at  $DT = 0$ , increased in proportion to the hearing loss as one would expect. Thus, increases in the constant  $A$  were seen at 2, 4, and 8 kHz, but not at 0.5 kHz. In regions where there was a significant hearing loss, the time constant

increased by a factor of 2–4. The largest increase in the time constant (51 ms to 195 ms) was seen at 4 kHz where the hearing loss was greatest. A statistical analysis was carried out on the time constants using analysis of variance (Dixon, 1981). The time constants obtained at 2, 4, and 8 kHz during ATS were significantly greater than those obtained before exposure ( $P < 0.01$ ); no significant change was seen at 0.5 kHz. Nevertheless, there was a slight increase in the mean time constant at 500 Hz which caused some concern. Inspection of the individual data revealed that this small upward drift in the mean time constant was due exclusively to one animal. When the results from this animal were eliminated, the mean time constant at 0.5 kHz was unchanged.

Both the individual and group data suggest that the time constant of forward masking increases in proportion to the degree of hearing loss. In order to evaluate this relationship in more detail, the ratio between the ATS and pre-exposure time constant was computed as well as the difference

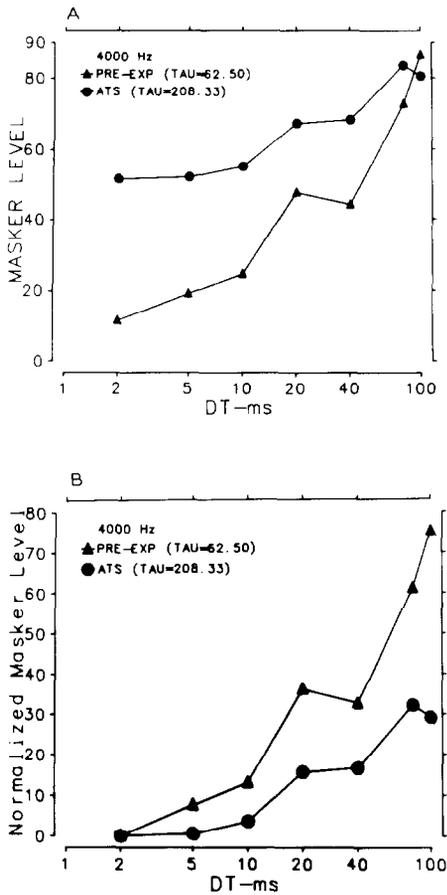


Fig. 3. (A) Forward masking function obtained at 4 kHz for chinchilla 1810 before and during temporary asymptotic threshold shift. Masker threshold in dB SPL. Pre-exposure time constant: 62.5 ms,  $R^2 = 0.79$ ; ATS time constant: 208.33 ms;  $R^2 = 0.87$ . (B) Same data as in panel A except that the masked thresholds have been normalized using the masked thresholds at a DT of 2 ms.

between the ATS and pre-exposure time constants. The scatter plot in Fig. 5 relates the Tau ratio and Tau difference scores at 4 kHz to the degree of hearing loss. Both the Tau ratio and Tau difference increase with hearing loss; however, the correlation was much higher for the Tau ratio ( $r = 0.93$ ) than for the Tau difference ( $r = 0.54$ ). Consequently, the Tau ratio was used for further analysis.

It is important to note that the relationship shown in Fig. 5 is based on only one frequency and a limited range of threshold shift values (22–48 dB). To extend the range of the analysis, the Tau

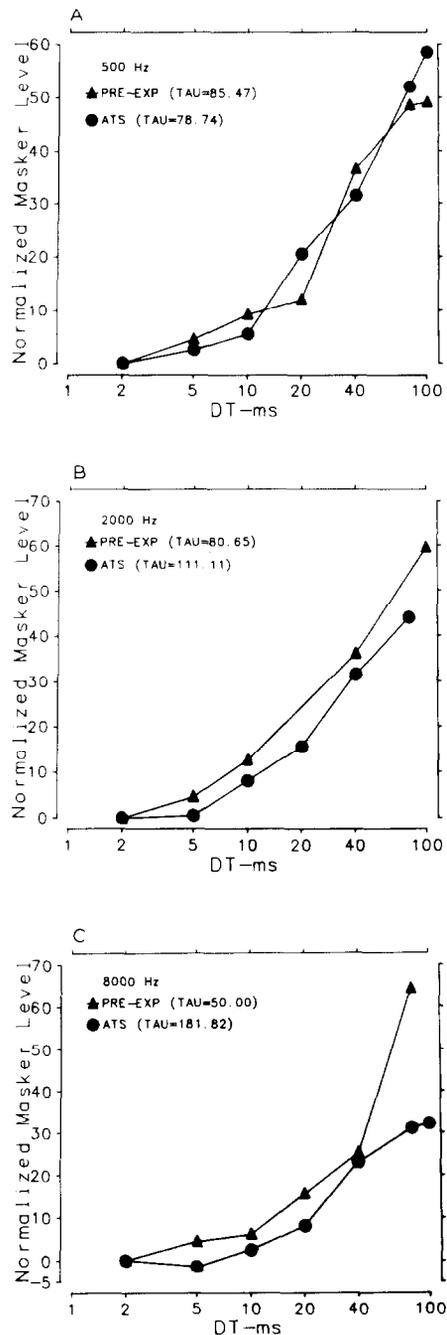


Fig. 4. Normalized pre-exposure and ATS forward masking functions for chinchilla 1810 at 0.5, 2 and 8 kHz. Time constants indicated in parentheses.

ratios were computed at all four frequencies and plotted as a function of threshold shift as shown in Fig. 6. The correlation between Tau and

TABLE I  
FORWARD MASKING PARAMETERS

Condition		550 Hz	2000 Hz	4000 Hz	8000 Hz
<b>NORMAL</b>					
TAU (ms)	Mean	89	55	51	68
	S.D.	20	17	18	22
	Range	60-118	28-80	25-81	26-107
A (dB)	Mean	29	18	13	22
	S.D.	1.2	1.7	1.9	1.4
	Range	20-39	5-34	5-29	13-31
R <sup>2</sup>	Mean	0.77	0.81	0.82	0.88
	S.D.	0.08	0.11	0.10	0.08
	Range	0.64-0.88	0.64-0.99	0.67-0.96	0.74-0.97
<b>ATS</b>					
TAU (ms)	Mean	104	100	195	159
	S.D.	44	28	50	86
	Range	67-217	56-152	135-278	48-286
A (dB)	Mean	31	43	50	47
	S.D.	1.2	1.1	1.7	1.2
	Range	24-40	34-48	37-65	21-64
R <sup>2</sup>	Mean	0.83	0.85	0.77	0.88
	S.D.	0.06	0.09	0.11	0.08
	Range	0.74-0.93	0.72-0.97	0.57-0.97	0.68-0.94

threshold shift was high at 8 kHz ( $r = 0.75$ ), but dropped to a much lower value at 0.5 ( $r = 0.16$ ) and 2 kHz ( $r = 0.17$ ) where the threshold shift seldom exceeded 25 dB. Visual inspection of Fig. 6 reveals two general regions. For threshold shifts less than 25 dB, the Tau ratio increased gradually with increasing hearing loss ( $r = 0.63$ ). However, once the threshold shift exceeds 25 dB, the Tau ratio increases rapidly (approximately a 3-fold increase per 10 dB of shift;  $r = 0.85$ ).

#### *Growth of masking*

The growth of masking (rate of response decrement) was quantified by determining the percent change in the probe-evoked response amplitude per dB increase in masker level at each DT. Prior to exposure, the slopes of the masking functions ranged from approximately 6%/dB to 2%/dB across the seven DTs. In general, the slopes of the masking functions tended to decrease with DT out to approximately 40 ms.

One factor that could indirectly cause an increase in the time constant of forward masking

without actually affecting the time course of forward masking would be an increase in the slope of the masking functions, i.e., the percent decrease in probe response amplitude per dB increase in masker level (Jesteadt, 1980; Gorga and Abbas, 1981). If this "recruitment-like" effect were present in impaired ears, it would cause a greater increase in the effectiveness of the masker at long DTs than at short DTs because of the general increase in masker level with DT. Thus, an abnormally rapid growth of masking would tend to flatten the evoked response forward masking pattern. To test for this effect, the masking function slopes at 4 kHz were measured at each DT before exposure and during ATS. Only the results at 4 kHz were analyzed in detail since the shifts in threshold and time constants were greatest at this frequency. Table II shows the results from seven one-way analysis of variance measures which compare the pre-exposure and ATS slope values at the seven values of DT (Zar, 1974). Only the slope at DT = 40 ms was found to be statistically different from its pre-exposure value ( $P < 0.05$ ); the slopes at the other six DTs had not changed significantly.

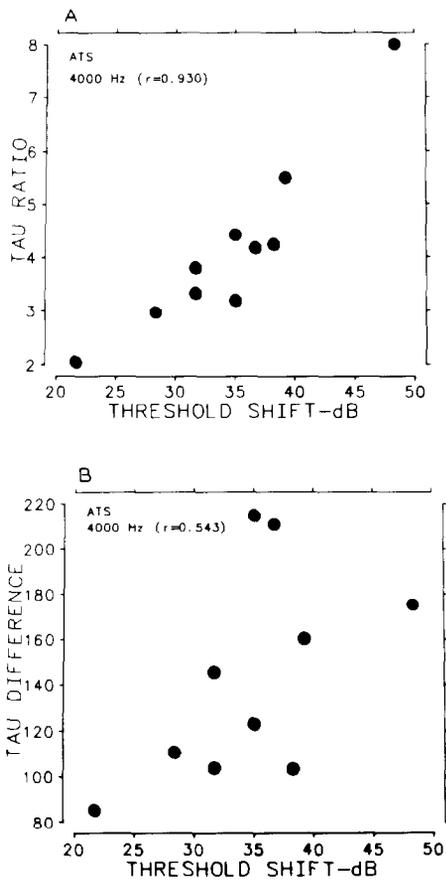


Fig. 5. (A) Difference between ATS and pre-exposure forward masking time constant plotted as a function of dB threshold shift at 4 kHz. (B) Ratio of ATS and pre-exposure forward masking time constant plotted as a function of threshold shift at 4 kHz. Data fitted by linear regression: correlation indicated in parentheses in each panel.

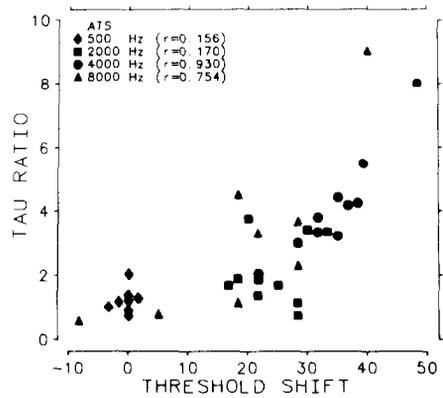


Fig. 6. Ratio of ATS and pre-exposure forward masking time constants plotted as a function of threshold shift. Data fit by linear regression: correlation coefficient for each frequency indicated in parentheses.

**Discussion**

The goal of the present study was to determine if the time course of the evoked response “forward masking” pattern would be altered by a tone exposure that produced a significant temporary hearing loss and little or no permanent threshold shift. Two parameters of an exponential model were used to quantify the changes in the time course of forward masking: a sensitivity factor, *A*, which is related to the absolute threshold in quiet and a time constant, *Tau*, which provides an index of the time course of recovery. Our primary concern was to determine if temporary hearing loss

TABLE II

COMPARISON OF PRE-EXPOSURE AND ATS MASKING FUNCTION SLOPES: ONE-WAY ANALYSIS OF VARIANCE

NS, not significant.

DT (ms)	DT *	F	Probability
2	1, 61	0.305	NS
5	1, 72	0.057	NS
10	1, 60	3.920	NS
20	1, 67	2.670	NS
40	1, 77	7.670	<i>P</i> < 0.05
80	1, 71	0.028	NS
100	1, 58	2.350	NS

\* Degrees of freedom vary since the number of intensities used to estimate the slope varied with DT.

would alter the time constant of forward masking as has been suggested by earlier psychophysical studies from human listeners with permanent hearing loss (Nelson and Turner, 1980; Cudahy, 1982). The main finding of this study was that the time constant of the evoked response forward masking pattern increased at frequencies with temporary hearing loss, but not at frequencies with normal hearing. Since our stimulus paradigm is almost identical to the psychophysical study of Nelson and Turner (1980), it may be useful to compare our physiological results with their psychophysical data in more detail. First, the psychophysical time constants obtained in listeners with normal sensitivity ranged from 50 to 100 ms whereas the average evoked response time constants for normal chinchillas ranged between 51 and 89 ms. Second, human listeners with hearing losses of more than 30 dB exhibited forward masking time constants greater than 200 ms. The mean time constant for the evoked response was 195 ms when the average hearing loss was 35 dB (4 kHz). The slight difference may be due to somewhat greater amounts of hearing loss in the human subjects compared to the chinchilla. Third, the psychophysical time constants increased with hearing loss, particularly when the hearing loss exceeded 30 dB. This same trend was seen in the evoked response time constant data (Fig. 6). Thus, there is remarkably good agreement between the psychophysical and physiological results particularly when one considers the differences in species and measurement technique.

#### *Degree of hearing loss*

The tendency for the time constant of forward masking to increase significantly once the hearing loss exceeds 25–30 dB is a trend that has been observed in other psychophysical studies. Using a somewhat different forward masking paradigm, Feston and Plomp (1983) noted that the slope of forward masking decreased with hearing loss in patients with threshold shifts ranging from 30 to 60 dB. There was a strong correlation between the degree of hearing loss and the slope of the forward masking pattern in the present study. Other measures of temporal resolution, such as gap detection, show a similar dependence on the magnitude of hearing loss. The gap detection thresholds of

the chinchilla, for example, begin to increase only when the hearing loss exceeds 30 dB (Giraudi-Perry et al., 1982). Ludvigsen (1985) used the masking periodic pattern to estimate temporal resolution in subjects with 30–60 dB of hearing loss. He reported an almost linear relationship between the degree of hearing loss and loss of temporal resolution.

Changes in temporal resolution have not always been seen with sensorineural hearing loss (Jesteadt et al., 1976; Church and Cudahy, 1978; Jesteadt, 1980; McFadden et al., 1984). McFadden et al. (1984), for example, induced temporary threshold shifts of 17 dB or less using salicylates, but found little or no change in the time course of forward masking. One interpretation of these results is that salicylates do not disturb the underlying physiological mechanisms involved with forward masking. However, an alternative and more parsimonious explanation is that the amount of salicylate-induced threshold shift is simply not sufficient to produce a significant change in forward masking. This may explain why others have not seen changes in temporal resolution in some listeners with sensorineural hearing loss.

#### *Growth of masking*

Based on psychophysical data obtained with a fixed intensity masker and variable intensity probe, Jesteadt (1980) has argued that the time course of forward masking might be altered by an abnormally rapid growth of masking in impaired listeners rather than from any inherent change in temporal processing. According to this view, the effectiveness of the masker would increase at an abnormally rapid rate as intensity increased; therefore, in our experiment, the masked threshold would be expected to rise at a slower than normal rate as DT increased. This would tend to flatten the evoked response forward masking pattern and presumably account for the increase in the time constants seen in our study. Since the slopes of the masking functions for the evoked response measured failed to increase with noise-induced hearing loss, this argument cannot account for the prolonged time constants in our physiological study.

In terms of psychophysics, the rapid growth of masking argument does not easily account for the prolonged gap-detection thresholds seen in hear-

ing-impaired listeners. Specifically, the noise bursts on either side of the gap are of equal intensity and therefore are subjected to the same recruitment-like effect. This would be equivalent to increasing the overall sensation level of the signal which leads to an improvement in gap detection in both normal and hearing impaired listeners. Thus, the prolonged gap thresholds seen in impaired listeners would seem to be due to abnormal temporal resolution in impaired listeners rather than to an abnormally rapid growth of masking. The same reasoning applies to the detection of the peaks and valleys in amplitude modulated noise.

#### *Physiological results*

Gorga and Abbas (1981) measured the compound action potential (AP) forward masking patterns from the auditory nerve using a group of normal and a group of noise-exposed animals with 20–40 dB of permanent hearing loss. They indicated that there was no change in the AP forward masking time constants, but did report a change in the growth of masking. Their results thus provide some support for Jesteadt's contention that an abnormally rapid growth of masking may be responsible for the prolonged forward masking time constants seen in hearing impaired subjects.

Our results, however, differ from those of Gorga and Abbas (1981) in two respects. First, the evoked response forward masking time constants systematically increased with hearing loss. Second, the slopes of the masking functions were unchanged; thus, the increase in the forward masking time constant cannot be explained on the basis of an abnormal growth of masking. What factors could potentially account for the differences between our results and those of Gorga and Abbas (1981)? One possibility is that forward masking only changes during temporary hearing loss, but not during permanent hearing loss. This explanation seems unlikely given that changes in forward masking have occurred in other psychophysical studies using listeners with permanent hearing loss (Nelson and Turner, 1980; Cudahy, 1982; Feston and Plomp, 1983). An alternative explanation is that noise-induced hearing loss disrupts some physiological process proximal to the auditory nerve which is involved with forward masking (Gorga and Abbas, 1981). However, this seems

unlikely based on single auditory nerve fiber data discussed below.

Some insights into the origins of the effects seen in the present study may be gleaned from the response patterns of single auditory nerve fibers obtained in hearing impaired animals. Smith (1977) used a forward masking stimulus paradigm to estimate the rate at which neural discharge rate recovered following a masker. While his report focused on the time course of recovery in normal fibers, Smith indicates in the discussion that the time course of recovery was abnormally long when the physiological condition of the animal deteriorated. Smith's observations are supported by our own data obtained from chinchillas with 40–60 dB of noise-induced temporary threshold shift (Salvi et al., 1986). The auditory nerve fiber forward masking time constants were longer in the noise-exposed animals than in normal animals at masker intensities 20 dB or more above threshold. These results suggest that changes in the periphery may contribute to the prolonged evoked response forward masking time constants measured at the inferior colliculus.

The single unit data are also relevant to the issue of whether or not there is an abnormally rapid growth of masking in hearing impaired subjects. Since the effectiveness of a masker is presumably related to the discharge rate it evokes in auditory nerve fibers, an abnormally rapid growth of masking in a hearing impaired subject would imply that there is an abnormally steep discharge rate–intensity function. A few investigators have reported steeper than normal slopes in the discharge rate–intensity functions of some units in impaired animals (Evans, 1974; Harrison, 1981). The increase in the slope of rate–intensity functions above CF has been linked to the loss of two-tone suppression (Schmeidt et al., 1980; Schmeidt and Zwislocki, 1980), but not to threshold, i.e., units with elevated threshold and normal two-tone suppression have normal rate–intensity functions. Thus, threshold elevation per se does not necessarily imply that there is an increase in the slope of the rate–intensity function.

In contrast to the preceding studies, other investigators have failed to detect any significant change in the slope of the rate–intensity function

in units from hearing impaired animals (Kiang et al., 1970; Salvi, 1976; Dallos and Harris, 1978; Salvi et al., 1983). Using a forward masking stimulus paradigm, Salvi et al. (1986) reported that the slopes of the rate-intensity functions to the masker were the same for normal and noise-exposed animals; however, the forward masking time constants were longer for the noise-exposed animals. Thus, it is difficult to account for the prolonged forward masking time constants on the basis of steeper than normal rate-intensity functions

#### *Long term adaptation*

An alternative explanation for the prolonged "forward masking" function is one that involves the effect of long term adaptation. Since the evoked responses were averaged over 125 sweeps, there is a possibility that the high masker levels would result in long term adaptation over and above the short term adaptation effect which is thought to be involved with forward masking. Specifically, the inter-masker interval might not be long enough to allow the auditory system to completely recover before presenting the next masker-probe pair. This could potentially alter the time course of the forward masking functions particularly when high masker levels are used as with the hearing impaired subjects. To determine if any long-term adaptation effect might occur, a pilot study was carried out in which the masked threshold was measured at a long DT (80 and 100 ms): this required the use of high intensity maskers. The masked threshold was measured using a long inter-masker interval (1000 ms): this presumably would eliminate any build-up of long-term adaptation effects. The masked thresholds obtained with the long inter-masker interval were similar to those obtained at the standard inter-masker interval. Thus, it is unlikely that the forward masking results obtained during ATS can be due to the effect of long-term adaptation.

#### *Probe level*

Throughout the experiment, the probe intensity used to obtain the forward masking data was always set at a level 10 above threshold. Thus, the absolute intensity of the probe was much higher

during the hearing loss than before the exposure. Consequently, the forward masking data obtained at high intensities could potentially be longer than those obtained at low levels. However, this explanation seems unlikely based on other experimental results. First, psychophysical studies employing a forward masking paradigm similar to that used in the present study have found either no change in the time constant (Nelson and Turner, 1980) or a decrease in the time constant (Cudahy, 1982) when the intensity of the probe was increased. Using normal hearing cats, Gorga and Abbas (1981) found no change in the time constant of forward masking of the AP when the probe intensity was increased from 20 dB above threshold to 75 dB SPL. Our pilot studies also indicate that there was no change in the evoked response forward masking time constants when the intensity of the probe was increased from 10 dB to 25 dB above threshold. Thus, it is unlikely that the increase in the SPL of the probe can account for the increase in the time constant of the hearing impaired animals.

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