Temporal gap resolution in listeners with high-frequency sensorineural hearing loss

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Temporal gap resolution was measured in five normal-hearing listeners and five cochlear-impaired listeners, whose sensitivity losses were restricted to the frequency regions above 1000 Hz. The stimuli included a broadband noise and three octave band noises centered at 0.5, 1.0, and 4.0 kHz. Results for the normal-hearing subjects agree with previous findings and reveal that gap resolution improves progressively with an increase in signal frequency. Gap resolution in the impaired listeners was significantly poorer than normal for all signals including those that stimulated frequency regions with normal pure-tone sensitivity. Smallest gap thresholds for the impaired listeners were observed with the broadband signal at high levels. This result agrees with data from other experiments and confirms the importance of high-frequency signal audibility in gap detection. The octave band data reveal that resolution deficits can be quite large within restricted frequency regions, even those with minimal sensitivity loss.

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INTRODUCTION

One psychophysical estimate of auditory temporal acuity can be obtained by measuring the threshold duration of a brief temporal gap in a noise signal. For listeners with sensorineural hearing loss, the measured gap threshold is frequently observed to be larger than normal (Boothroyd, 1973; Irwin *et al.*, 1981; Irwin and Purdy, 1982; Giraudi-Perry *et al.*, 1982; Fitzgibbons and Wightman, 1982; Tyler *et al.*, 1982; Florentine and Buus, 1984; Salvi and Arehole, 1985). The source of the resolution deficit in the impaired listeners is unknown, although variables such as subject age, and the degree, configuration, and etiology of impairment have been suggested as potential contributing factors. Of these variables, however, only the degree of high-frequency loss provides some predictive index of a listener's resolution performance. This follows from the collective evidence that optimal temporal resolution in normal-hearing listeners is mediated by stimulus energy in the high-frequency listening channels; below about 4000 Hz, gap resolution becomes progressively poorer with a lowering of signal frequency (Fitzgibbons and Wightman, 1982; Fitzgibbons, 1983; Tyler *et al.*, 1982; Shailer and Moore, 1983; Florentine and Buus, 1982; Buus and Florentine, 1985). Therefore, if the stimulus is broadband, many of the listeners with high-frequency impairment could be expected to show enlarged gap thresholds, simply due to limitations in signal audibility imposed by their audiometric configurations.

Florentine and Buus (1984) examined these predictions by using a broadband noise to compare gap thresholds of cochlear-impaired subjects to those of normal-hearing subjects with simulated impairments produced by spectrally shaped masking noises. At high signal levels (e.g., 80–90 dB SPL) some of the cochlear-impaired subjects showed suprathreshold resolution deficits by producing larger gap thresholds than their simulated-loss counterparts. However, for most comparisons, the real and simulated losses produced similar gap thresholds over a broad range of signal intensity. This outcome indicates that the audiometric configurations of the subjects were primarily responsible for the observed enlargement of gap thresholds. The effects of audiometric configuration were particularly evident for listeners with steeply sloping high-frequency losses, where the real and simulated impairments produced almost identical elevations in gap threshold.

Similar configuration effects appear in the gap-detection data reported by Salvi and Arehole (1985) for chinchillas with temporary noise-induced high-frequency hearing loss. Broadband noise was the stimulus, and the measured gap thresholds showed a systematic increase as the induced loss was made to extend progressively into the lower frequency regions. Performance trends displayed in these animal data are much the same as those observed with normal-hearing human subjects, when tested under progressive degrees of low-pass signal filtering (Fitzgibbons, 1983).

These recent experiments demonstrate that abnormal gap thresholds in impaired listeners do not necessarily indicate a suprathreshold deficit in temporal resolution. In fact, much of the broadband data collected thus far on listeners with high-frequency impairments appear to reflect the normal deterioration in gap resolution associated with low-pass signal filtering. Thus gap resolution in the lower frequency listening channels of these subjects may be quite normal. Buus and Florentine (1985) found this to be the case for one of their subjects with a high-frequency loss and steeply sloping audiogram. The testing of this subject with octave band signals centered at 0.5 and 1.0 kHz revealed normal gap resolution, despite the presence of a 35-dB hearing loss at the latter frequency. Octave band data for another of their sub-

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jects with a high-frequency loss and gradually sloping audiogram revealed abnormal gap resolution throughout most of the audible frequency range. Broadband data for these two subjects were quite similar, which illustrates the difficulty in using these results alone to draw inferences about temporal resolution in restricted lower frequency regions. In the present experiment, we examine this issue more closely by using broadband and bandlimited signals to assess gap resolution in listeners with high-frequency hearing loss and closely matched audiometric configurations. As a control measure, selection of hearing-impaired subjects for the experiment was restricted to those with a suspected etiology of noise-induced hearing loss.

I. METHODS

A. Subjects

Five normal-hearing and five hearing-impaired listeners participated in the experiment. The normal-hearing subjects (ages 25–40 years) had pure-tone audiometric thresholds (*re*: ANSI S3.6, 1969) of 10 dB HL or less at the octave-interval frequencies between 250 and 8000 Hz. The hearing-impaired subjects (ages 43–60 years) had bilateral symmetrical high-frequency hearing losses, with normal sensitivity within the lower frequency regions. Mean tone thresholds for the test ears of these subjects were less than 10 dB HL between 250 and 1000 Hz, with a shift to 43, 70, and 60 dB HL at 2000, 4000, and 8000 Hz, respectively. Individual thresholds fell within 10 dB of the mean at each frequency, except at 2000 Hz, where one subject's threshold fell 30 dB below the mean. Each of the hearing-impaired subjects was selected from patient files at the University of Maryland Hearing Clinic. Audiometric test data for these subjects revealed that hearing loss in each case was relatively stable (5-year interval), contained no significant middle-ear component, and was of probable cochlear origin. In addition, medical and audiological case histories of each hearing-impaired subject were consistent with a diagnosis of noise-induced impairments incurred during periods of military service. None of the ten subjects had served in previous listening experiments, and each was paid for participating in the study.

B. Stimuli and procedures

Three of the test stimuli were continuous octave band noises centered at 0.5, 1.0, and 4.0 kHz, each with off-band attenuation rates of 96 dB/oct. A fourth signal was a continuous broadband noise with an amplitude spectrum that was shaped by the response characteristics of a TDH-49 earphone; this was relatively uniform up to 6 kHz with 10 dB of attenuation by 7.5 kHz. Each signal was fed through an electronic switch that was triggered to produce a periodic temporal gap at the rate of 1 Hz. Waveforms at the gap were shaped with 1-ms cosine rise–fall envelopes, and gap duration was defined as the interval between the 3-dB down points of this envelope. Each of the octave band signals was subsequently mixed with a broadband masking noise that was filtered to have an attenuation band, or spectral notch, positioned at the signal center frequency. The spectral notches featured attenuation skirts of 96 dB/oct and reached a maximum depth of 45 dB at the center frequency. The notch cutoff frequencies (− 3 dB) were set to match the − 25-dB frequencies on the signal spectrum; the masker spectrum level outside the notch region was 20 dB below that of the signal, providing a signal-to-masker ratio of 65 dB at the octave band centers. As described in an earlier report (Fitzgibbons and Wightman, 1982), the notched maskers were added to restrict the subjects' listening band and mask off-band energy splatter produced by the rapid waveform transitions at the temporal gap. No masker is required with the broadband stimulus.

The threshold procedure is the same as described in some earlier experiments with normal-hearing listeners (Fitzgibbons, 1983, 1984). Each signal–masker combination, in fixed S/N ratio, was fed through a Bekesy tracking attenuator to a TDH-49 earphone mounted in an MX41/AR cushion. The attenuator characteristics (linearity and frequency response) preserved the input S/N ratio at its output throughout its 120-dB operating range. With each continuous signal, the duration of the once-per-second gap was preset and subjects tracked the minimum signal intensity needed to maintain the gap at threshold.[1] Below this criterion level, the noise signal remained audible, but it was perceived to be continuous rather than interrupted. For each of several gap values tested in this manner, the average of about 25 midpoints in the up–down intensity excursions was taken as a trial estimate of intensity threshold. Successive trial estimates were collected until the most recent three fell within 5 dB, which usually occurred within five or six trials. A mean of the last three trial estimates was then recorded as a final threshold estimate for the particular gap value. Gap durations were tested in descending order using values of 25, 15, and 10 ms, followed in turn by values that were decreased in 2-ms steps until the subject failed to track a final threshold. At this point, additional gap values were tested by progressively halving the previous 2-ms step size to determine the minimum trackable gap (MTG) to the nearest 0.25 ms. Overall, the procedure produced four to six data points per signal for construction of sensitivity curves showing intensity threshold as a function of gap duration. Subjects were tested initially with the broadband signal, which served as practice for the other signals and as a reference for comparison with other published data for this type of signal. The octave band signals were tested in a different order across subjects.

Other data collected from each subject included measurements of quiet thresholds in dB SPL for each signal presented continuously without the notched masker, and measurement of the signal sound pressure level in dB and sensation level in dB (*re*: masked threshold) associated with the tracked intensity threshold for each gap value. The sensation-level data were obtained subsequent to testing with each gap by adding the notched masker to the continuous signal without gaps at the output of the attenuator, and having subjects track a signal detection threshold in the usual manner. The masked detection thresholds were not significantly different from the quiet detection thresholds, indicating that the notched maskers had little effect on signal audi-

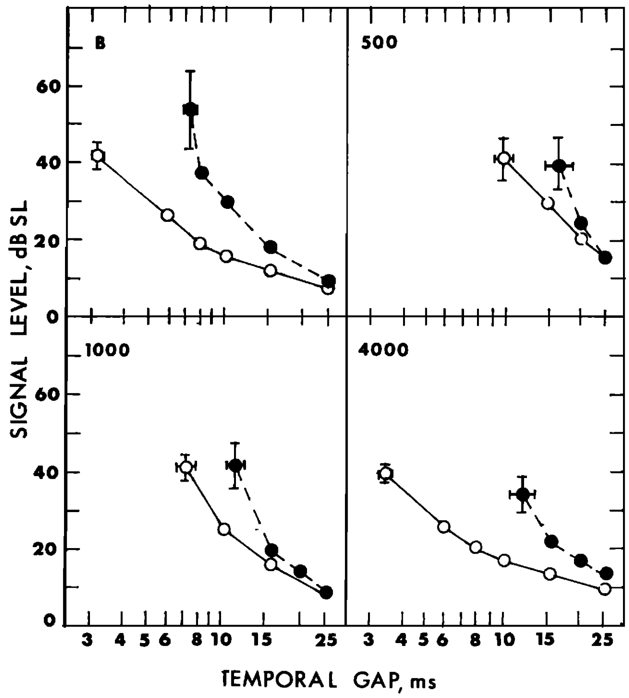

FIG. 1. Mean signal level in dB SL as a function of gap duration in ms for the normal-hearing (open circles) and hearing-impaired (filled circles) subjects. The parameter in the upper left of each quadrant specifies the octave band center frequency in Hz, with B representing the broadband noise. Vertical and horizontal bars represent the size of one standard deviation about the means.

bility for the intensity range of stimuli in the experiment. Subjects listened monaurally in a sound-treated booth for 1- or 2-h sessions that were distributed over a 3-week period.

II. RESULTS AND DISCUSSION

The sensitivity curves derived from the mean data of the five normal-hearing and five hearing-impaired subjects for each signal are displayed in the separate quadrants of Fig. 1. Each curve describes the mean intensity threshold in dB SL as a function of gap duration in ms. Vertical bars represent one standard deviation about the mean intensity; error bars of lesser magnitude are omitted for clarity at other points on the curves. Positioning of the leftmost point on each curve along the abscissa represents the mean value of the five subjects' MTG values in ms; horizontal error bars indicate one standard deviation about this mean. Each curve reveals the same general trend, showing that the resolution of progressively smaller gaps required an increase in signal level. The minimum gap was tracked at 30–40 dB SL for most of the signals. The curves for the normal listeners (open circles) and the impaired listeners (filled circles) converge at large gap durations, but separate progressively for smaller gaps. The MTG for the impaired listeners is larger than that of the normal listeners with each of the signals.

Table I provides numerical values for the data associated with the leftmost point on the curves in Fig. 1. The table entries include mean values of the MTG in ms, together with the corresponding intensity thresholds in units of dB SL and dB SPL for each signal and subject group. Data for the normal-hearing subjects show the expected decrease in size of

TABLE I. Mean data of the normal and impaired listeners for each noise signal. Entries are means and standard deviations (in parentheses) of the MTG in ms and the intensity thresholds in dB SPL and dB SL.

		Signal center frequency (kHz)			
Subjects		0.5	1.0	4.0	Broadband
	MTG	9.7 (0.84)	7.2 (0.57)	3.5 (0.35)	3.3 (0.27)
Normal	dB SPL	53.7 (9.8)	52.0 (7.4)	47.3 (2.1)	53.0 (5.1)
	dB SL	41.0 (10.4)	41.4 (6.7)	38.8 (1.9)	42.0 (4.5)
	MTG	16.6 (2.6)	11.2 (1.9)	11.8 (2.5)	7.3 (1.1)
Impaired	dB SPL	60.4 (10.2)	57.8 (3.6)	92.4 (6.0)	80.0 (14.6)
	dB SL	39.2 (12.5)	42.4 (4.1)	33.4 (7.8)	53.8 (17.6)

the MTG as a function of signal frequency, with the value for the broadband signal being about the same as that for the octave band signal at 4.0 kHz. The variability among individual subject's estimates of the MTG is somewhat greater for the lower frequency signals, but is relatively small for all signals. The intensity thresholds for the MTG are about 40 dB SL, or alternatively about 50 dB SPL, across signals, with the greatest variability also occurring at the lower frequencies. These normative data are quite similar to those reported previously by Fitzgibbons (1984). Data from other experiments with bandlimited stimuli also reveal similar frequency effects on gap resolution, although estimates of gap threshold at corresponding signal frequencies differ across studies (e.g., Fitzgibbons, 1983; Shailer and Moore, 1983, 1985; Buus and Florentine, 1985). Most of the differences can be attributed to variation in parameter settings (e.g., S/N ratios) for the signal–masker combinations used in the different experiments.

Inspection of the tabled values for the impaired listeners reveals some of the differences and similarities in comparison to the normative data. Values of the MTG for the impaired listeners are smallest for the broadband signal, greatest at 0.5 kHz, and essentially equivalent for signals at 1.0 and 4.0 kHz. Thus the expected relationship between the MTG and signal frequency is not entirely evident. Variability in the MTG values of the impaired listeners is also larger than normal, although no overlap existed between the MTGs of the normal and impaired listeners. An analysis of variance performed on the minimum gap values revealed significant differences between the two subject groups for each of the signals [$F(1,32) > 16, p < 0.001$]. The intensity thresholds in dB SL and dB SPL of the impaired listeners were similar to normal at 0.5 and 1.0 kHz, where hearing sensitivity was also close to normal. As expected, the threshold SPLs for the impaired listeners are elevated at 4.0 kHz and for the broadband signal, reflecting the high-frequency hearing loss of the subjects. The threshold SL for the impaired listeners at 4.0 kHz appears close to normal, but this value is probably affected by the subjects' better hearing sensitivity below 4.0 kHz. This is suspected because the audibility threshold for the octave band signal at 4.0 kHz is much less than expected on the basis of the subjects' pure-tone sensitivity loss at 4.0 kHz. For similar reasons, the highly variable SL values among impaired listeners for the broadband signal are difficult to interpret with reference to specific frequency regions of sensitivity loss.

Some of these findings allow comparison to previously reported data for listeners with high-frequency sensorineural hearing loss. For example, the gap-detection experiments of Florentine and Buus (1984) and Irwin *et al.* (1981) produced estimates of gap threshold of about 7.3 and 7.5 ms, respectively, for subjects with steeply sloping audiograms tested with broadband noises. Our corresponding estimate of 7.3 ms for similar test conditions shows excellent agreement with their values. However, the broadband estimates, which are about twice the value observed with normal-hearing subjects, may not reflect diminished temporal resolution in all cases. As Florentine and Buus demonstrated in their simulation experiment, the enlargement in gap thresholds observed with broadband stimuli may be the consequence of insufficient audibility of the high-frequency signal spectrum for the impaired listeners.

The measurements obtained with the octave band signals seem to produce less equivocal results and indicate that the impaired listeners in the present study exhibit resolution deficits over a broad frequency range. Relative to normal, the performance of the impaired listeners was poorest in the regions of greatest hearing loss at 4.0 kHz, where the observed MTG of 11.8 ms is 3.4 times larger than normal. By comparison to these data at 4.0 kHz, the smaller MTG observed with the broadband signal probably reflected the impaired listeners' ability to use stimulus energy above 4.0 kHz, where the hearing losses were uniformly less in degree. The enlargement in gap thresholds at 4.0 kHz might also indicate the presence of an underlying relationship between the MTG and the degree of hearing loss. However, the generality of such an argument is weakened by the data collected with the two lower frequency signals. Each of the impaired listeners had normal hearing sensitivity within the octave bands at 0.5 and 1.0 kHz, yet the MTG of each subject was elevated within these regions. Thus pure-tone sensitivity loss does not appear to be a prerequisite for abnormal temporal resolution and, conversely, the presence of hearing loss will not always effect a resolution deficit (Buus and Florentine, 1985).

Unfortunately, we have no simple explanation for the finding of diminished resolution in the low-frequency regions with normal hearing sensitivity. One possibility to consider is that the low-frequency signals produced a spread of excitation along the basilar membrane to regions that are maximally tuned to frequencies well above the nominal limits of the signal band. With the notched masker at -20 dB relative to the signal level, the normal-hearing subjects may have listened at these higher frequencies to resolve smaller gaps than could subjects with hearing loss at those same higher frequencies. However, an account on this basis for the large differences in low-frequency MTGs between the normal and impaired listeners (e.g., about 7 ms at 0.5 kHz) would seem to require the availability of significant levels of suprathreshold excitation 3–4 oct above the signal band. This follows from the evidence that gap threshold for clearly audible signals decreases by only about 2 ms/oct as frequency increases within the approximate range 0.5–4.0 kHz (Fitzgibbons and Wightman, 1982; Fitzgibbons, 1983; Shailer and Moore, 1983). Also, results of subsequent testing at 0.5 and 1.0 kHz with two of our normal-hearing subjects revealed that increasing the spectrum level of the notched masker from -20 to -10 dB (*re*: signal level) produced decreases of about 1 ms in the MTGs of one subject, and had a negligible effect on resolution of the other subject. These limited data do not allow us to rule out the possibility of off-band listening. However, it seems an unlikely general explanation for the major differences in resolution between the normal and impaired listeners.

It is interesting to note that results similar to the present findings have been reported for other psychoacoustic measures obtained from subjects with noise-induced hearing loss. For example, several studies report cases of abnormal psychophysical tuning curves measured in lower frequency regions with normal sensitivity in noise-exposed listeners (McFadden and Pasanen, 1979; Feth *et al.*, 1980; Nelson and Turner, 1980; Mills, 1982). Other experiments produced data showing abnormal frequency discrimination (Turner and Nelson, 1982) and abnormal masking patterns (Humes, 1983; Trees and Turner, 1986) in noise-exposed subjects tested in similar regions of normal hearing sensitivity. It appears from these results, and from the present gap-resolution data, that various suprathreshold auditory tasks may be sensitive to subtle effects of cochlear dysfunction resulting from noise exposure.

It is also worth mentioning that, despite the consistent findings with our impaired listeners, not all subjects with high-frequency hearing loss perform in a similar mannner. We have recently tested a subject with a hereditary impairment whose audiometric configuration closely matches the mean loss configuration of the noise-exposed subjects. Values of the MTG for this subject were quite normal for the octave band signals at 0.5 and 1.0 kHz, and for the broadband signal, but were abnormal at 8 ms for the octave band centered at 4.0 kHz. These results indicate that some etiologies of impairment can produce quite localized regions of diminished temporal resolution.

In summary, it is evident that the effects of cochlear damage on temporal resolution are not well understood. Earlier experiments with broadband stimuli demonstrated the importance of considering high-frequency signal audibility in assessing optimal gap resolution. The present results support that conclusion, but show also that resolution deficits within restricted frequency regions can be more pronounced than might be inferred from examination of broadband data alone. With regard to temporal resolution, it seems that some hearing-impaired listeners suffer not only the disadvantage of high-frequency hearing loss, but also processing deficits within their restricted regions of normal hearing sensitivity.

[1]Normative data from experiments using forced-choice procedures with broadband sitmuli (e.g., Plomp, 1964) and bandlimited stimuli (e.g., Shailer and Moore, 1983; Buus and Florentine, 1985) reveal that gap

threshold remains largely invariant with changes in signal intensity above some minimal sensation level. In the present tracking procedure, we reversed the dependent variable of earlier forced-choice experiments by having subjects vary signal intensity to detect a gap of fixed duration. This approach was taken in order to obtain reliable estimates of gap threshold as well as estimates of the corresponding intensity threshold.

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