Minimum stimulus levels for temporal gap resolution in listeners with sensorineural hearing loss

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The minimum sensation levels required for optimal temporal gap resolution were measured in five listeners with moderately severe degrees of sensorineural hearing loss. The stimuli were three continuous octave-band noises centered at 0.5, 2.0, and 4.0 kHz. Subjects used a Békésy tracking procedure to determine the minimum signal levels needed to resolve periodic temporal gaps of fixed durations. Analysis of data across subjects and signal revealed only a weak correlation between this minimum SL and the corresponding HLs; most listeners resolved threshold gaps at minimum levels of 25–35 dB SL, independent of degree of hearing loss. The results differ from those of normal subjects with masking-induced hearing loss [Fitzgibbons, Percept. Psychophys. **35**, 446–450 (1984)], which showed an inverse relationship between HL and the SLs required for gap threshold. The findings indicate that assessment of optimal gap resolution in listeners with cochlear impairment requires stimulus presentation levels of at least 25–35 dB SL. Even with sufficient stimulus intensity, each of the hearing-impaired listeners exhibited abnormal gap resolution for each octave-band signal.

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INTRODUCTION

Several recent studies report that many listeners with sensorineural hearing loss have difficulty detecting brief temporal gaps in noise signals. Some of the investigations employed broadband stimuli and tested subjects over a wide range of intensity (Irwin *et al.*, 1981; Irwin and Purdy, 1982; Giraudi-Perry *et al.*, 1982; Salvi and Arehole, 1985), while others used bandlimited signals and tested at a single high-intensity level (Fitzgibbons and Wightman, 1982; Tyler *et al.*, 1982). For some of the impaired listeners, elevated gap thresholds appear to reflect suprathreshold deficits in temporal acuity resulting from cochlear impairment. For other listeners, the results are less clear because some of the abnormal gap thresholds observed with broadband stimuli may have been a consequence of frequency-specific limitations in signal audibility imposed by the listeners' audiometric configurations. Florentine and Buus (1984) and Buus and Florentine (1985) demonstrated the latter possibility by observing that normal-hearing subjects with sensitivity loss induced by spectrally shaped masking noises could exhibit elevations in gap thresholds much like those of some listeners with cochlear impairment. This outcome pertained primarily to simulations of high-frequency sensitivity losses, which restricted signal audibility in the frequency regions that are known to be most important for optimal gap resolution (Fitzgibbons, 1983; Shailer and Moore, 1983; Florentine and Buus, 1984).

Results of the simulation experiments indicate the need to examine resolution deficits in hearing-impaired listeners at signal intensities that are sufficiently above the subjects' elevated thresholds. It is not clear, however, what constitutes sufficient audibility for optimal resolution in listeners

with hearing impairment. The normative data generally reveal that gap thresholds remain largely invariant for stimulation levels exceeding 25–30 dB SL (e.g., Plomp, 1964). However, results from an earlier experiment (Fitzgibbons, 1984) suggest that the minimum signal level in dB SL for optimal resolution may depend on the degree of hearing loss in the listener. In this experiment, normal-hearing subjects used a Békésy procedure to track the minimum signal levels needed to resolve temporal gaps of fixed duration in octave-band stimuli. The smallest detectable gaps were tracked at 35–40 dB SL, a value that is somewhat greater than the intensity asymptote observed by Plomp using forced-choice procedures. The tracking measurements were also repeated with different levels of broadband noise added to induce sensitivity losses of 20–55 dB in the normal-hearing subjects. The addition of masking had little effect on the magnitude of gap thresholds, but the stimulus sensation levels required for resolution of the threshold gaps decreased progressively to about 15 dB as the induced sensitivity loss increased to its maximum. Thus, for these listeners, the required SL for optimal resolution varied inversely with the degree of sensitivity loss.

It is well known that noise masking in normal-hearing subjects produces the reduced dynamic range and loudness recruitment commonly found with cochlear impairment (Steinberg and Gardner, 1937). It can be inferred from the recruitmentlike effects observed in the normal subjects with masking-induced losses that altered intensity processing in cochlear-impaired listeners would have similar effects on gap resolution. Confirmation of this inference would permit less equivocal interpretation of gap thresholds measured in cases where the degree of hearing loss precludes testing at stimulus levels well above the listener's elevated thresholds.

In the present experiment, we examine this inference by using octave-band stimuli to measure the minimum SLs in dB required for gap resolution in listeners with different degrees of sensorineural hearing loss.

I. METHOD
A. Subjects

The subjects were five listeners (ages 25–55 years) with bilateral sensorineural hearing loss of either moderate or moderately severe degree; etiology of the impairments is unknown. The pure-tone audiometric thresholds (re: ANSI, 1969) at octave-interval frequencies from 0.25–8.0 kHz are shown in Table I for the test ear of each subject. Additional audiometric data, including tympanometric measures and measures of the acoustic reflex and reflex decay, indicated hearing losses of cochlear origin in each subject. The subjects had no previous experience in listening experiments, and each was paid for participating in the study.

B. Stimuli and procedures

The stimuli were three continuous octave-band noises centered at 0.5, 2.0, and 4.0 kHz, each with off-band attenuation rates of 96 dB/oct. Each signal was fed through an electronic switch that was triggered periodically to produce a temporal gap once per second; gap waveforms were shaped by 1-ms cosine rise–fall envelopes, with gap duration defined by the interval between 3-dB down points of the envelope. As in the earlier simulation experiment (Fitzgibbons, 1984), each octave-band signal was subsequently mixed with a broadband noise that was filtered to have an attenuation band, or spectral notch, centered at the octave-band center frequency; attenuation rates within the spectral notch were 96 dB/oct, and the − 3 dB notch bandwidth was adjusted to match the − 25-dB bandwidth of the octave-band signal. The spectrum level of the masker outside the notch was set − 20 dB relative to that of the signal, providing a S/N ratio of at least 65 dB at the octave-band centers. The maskers were added to restrict the subject's listening band, and prevent off-band energy splatter as a spectral cue to gap detection.

Each signal-masker combination, in fixed S/N ratio, was fed through a Békésy tracking attenuator to a TDH-49 earphone mounted in an MX41/AR cushion. The attenuator characteristics preserved the S/N ratio at the output throughout its operating range of 120 dB. With each continuous signal, the duration of the periodic gap was preset and subjects tracked the minimum signal intensity required to maintain the gap at threshold; below this minimum level, the signal was still audible, but it was perceived to be continuous without gaps. For each of several gap values tested in this manner, the average of about 25 midpoints in the up–down excursion was taken as a trial estimate of intensity threshold. Successive trial estimates were collected until the last three fell within 5 dB, which usually occurred within five or six trials. A mean of these three trial estimates was then recorded as a final estimate of intensity threshold for a particular gap value. Gap durations were tested in descending order, generally using values of 30, 20, 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 in the same manner by progressively halving the previous 2-ms step size to determine the minimum detectable gap to the nearest 0.25 ms. The data collected for each signal were subsequently used to construct performance curves showing intensity threshold as a function of gap duration. The octave-band signals were tested in a different order for each subject.

The data collected from each subject included measurement of the quiet threshold in dB SPL for each signal presented continuously without the masker, and measurement of the SPL in dB and the SL in dB (re: masked threshold) of the intensity threshold tracked for each gap value. The stimulus SLs were determined subsequent to testing with each gap duration by adding the notched masker to the signal at the output of the attenuator, and having subjects track a signal threshold in the usual manner. The masked signal thresholds were observed to be equivalent to the subject's quiet signal thresholds, indicating that the maskers with deep attenuation notches had little effect on audibility within the signal bands. Thus, despite the presence of the notched masker, the SL estimates derived for each subject can also be interpreted as dB above quiet threshold. Subjects listened monaurally in a sound-treated booth for 1- and 2-h sessions that were distributed over a 4-week period.

II. RESULTS AND DISCUSSION

The results obtained for each subject are shown in the separate panels of Fig. 1, which displays the performance curves describing intensity threshold in dB SL as a function of gap duration in ms for each octave-band signal. All curves reveal the same general trend showing an increase in signal level required by the subjects to track progressively smaller gaps; the threshold gap for each signal is designated by the position of the leftmost curve point along the abscissa. With the exception of the data for subject S2, most of the performance curves span a range from about 10 dB SL for 30-ms gaps to 25–30 dB SL for the threshold gap for each signal. By comparison, the curves for S2 are compressed within an intensity range of about 10 dB, primarily as a result of the reduced SL for gap threshold with each of the signals. Numerical data associated with the leftmost point on each performance curve are shown in Table II; the table entries include the individual and mean values of the subjects' gap threshold, along with the corresponding intensity thresholds in dB SL and dB SPL for each signal. Inspection of the mean

TABLE I. Pure-tone thresholds in dB HL (re: ANSI, 1969) of the hearing-impaired subjects.

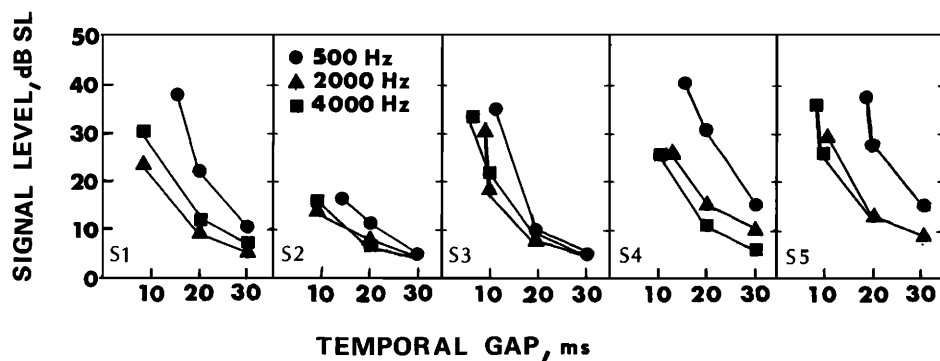| Subjects	Frequency in Hz					
	250	500	1000	2000	4000	8000
1	30	45	55	50	50	45
2	35	40	45	50	50	55
3	25	25	35	45	60	60
4	5	10	30	65	70	65
5	15	10	5	45	65	65

FIG. 1. Intensity threshold in dB SL as a function of gap duration in ms for each subject and octave-band signal.

data reveals that intensity thresholds in dB SPL increased progressively from low to high signal frequency, a trend that corresponds generally with the subjects' increasing hearing levels (Table I) across the same frequency range. In units of dB SL, the mean thresholds are greatest at 0.5 kHz, and lower, but similar in magnitude, at 2.0 and 4.0 kHz; variability among the individual values of SL is attributed largely to the low values for S2.

With some exceptions, these results for the cochlear-impaired subjects do not reflect the same systematic trends observed in the earlier data collected from normal subjects with hearing loss simulated by masking. Of the present subjects, only S2 produced intensity thresholds like those observed for the normal subjects with an equivalent degree of simulated loss. With the data of S2 omitted, the mean SL of the other four cochlear-impaired subjects is somewhat reduced relative to normal (i.e., 35–40 dB SL) at 2.0 and 4.0 kHz, but not at 0.5 kHz. An analysis of trends in the individual data revealed only a weak product-moment correlation ($r = -0.47$) between the subjects' pure-tone thresholds at the octave-band center frequencies and the measured SL in dB required for gap threshold across signals. By contrast, the data of the normal subjects with simulated hearing loss exhibited a strong correlation ($r = -0.97$) between threshold elevation induced by masking and the minimum SL required for gap threshold. Therefore, the present findings indicate no predictable relationship between the degree of hearing in the cochlear-impaired subjects and the minimum sensation levels required for detection of threshold gaps.

The gap threshold values displayed in Table II are characterized by relatively small subject variability, and the mean values are shown to decrease progressively with an increase in octave-band signal frequency. This spectral dependence in the gap thresholds is similar in kind to that observed previously for normal-hearing subjects tested with bandlimited stimuli. Most of the individual data in Table II reveal a similar spectral dependence, except for two subjects (S1 and S2), whose gap thresholds are nearly the same at 2.0 and 4.0 kHz. The normal subjects with simulated sensitivity losses produced gap thresholds of 9.1, 4.9, and 3.3 ms, respectively, from low to high frequency for the same octave-band signals and test procedures. Relative to those normative estimates, gap thresholds for each cochlear-impaired subject are abnormal at each signal frequency. Also, there appears to be no strong relationship between gap threshold and the degree of sensitivity loss in the subjects; this is particularly evident at 0.5 kHz, where two subjects (S4 and S5) with relatively normal hearing sensitivity produced the largest gap thresholds. Similar observations of abnormal gap resolution in regions of normal hearing sensitivity were made recently (Fitzgibbons and Gordon-Salant, 1987) for listeners with noise-induced hearing loss. Apparently, cochlear damage that is insufficient to produce sensitivity loss may be sufficient to degrade temporal acuity.

Overall, the results of the experiment do not provide strong support for the inference that the stimulus SL needed to assess optimal gap resolution varies inversely with HL in cochlear-impaired listeners. Some of the individual data pro-

TABLE II. Individual and mean data for the hearing-impaired subjects. Table entries include values of the gap threshold in ms, and the corresponding signal intensity thresholds in dB SL and dB SPL.

| Subjects | Octave-band center frequency in Hz | | | | | | | | |
| | 500 | | | 2000 | | | 4000 | | |
	Gap	SL	SPL	Gap	SL	SPL	Gap	SL	SPL
1	15.50	34	89	8.75	23	77	8.25	30	90
2	14.75	16	70	9.50	16	71	9.25	15	75
3	11.75	35	80	8.50	30	85	6.75	34	104
4	16.00	40	65	13.50	25	100	12.00	25	103
5	18.50	37	60	10.25	29	83	8.50	35	105
Mean	15.30	32.4	72.8	10.10	24.6	83.2	8.90	27.8	95.4
s.d.	2.4	9.4	11.7	2.0	5.6	10.9	1.9	8.2	12.9

vide limited support for this contention, but most of the subjects resolved threshold gaps at approximately equivalent SLs in the range of 25–35 dB, independent of the degree of hearing loss. Consequently, for some of the listeners, the limits of resolution could be assessed only at relatively high SPLs in their frequency regions of greatest hearing loss. It is difficult to generalize from our small-sample estimates of the signal levels required for gap resolution. However, if SLs of similar magnitude (i.e., 25–35 dB) are required by other subjects with HLs exceeding 60–70 dB, problems with loudness tolerance may preclude obtaining unequivocal estimates of the listeners' optimal resolving capacity. The present findings, like those resported by Buus and Florentine (1985), support the conclusion that gap resolution in hearing-impaired subjects should be measured at signal levels that are well above the listeners' elevated thresholds. Unlike some findings of Buus and Florentine, the enlarged gap thresholds measured in the present experiment cannot be attributed directly to the listeners' configuration of sensitivity loss. For clearly audible signals, each of our subjects exhibited diminished temporal resolution within a broad frequency range. However, it does not appear to be the case that the suprathreshold intensity cues for gap detection in cochlear-impaired listeners are necessarily the same as those used by normal listeners with sensitivity losses simulated by masking.

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