Gap detection and masking in hearing-impaired and normal-hearing subjects

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Subjects with cochlear impairments often show reduced temporal resolution as measured in gap-detection tasks. The primary goals of these experiments were: (1) to assess the extent to which the enlarged gap thresholds can be explained by elevations in absolute threshold; and (2) to determine whether the large gap thresholds can be explained by the same processes that lead to a slower-than-normal recovery from forward masking. In experiment I gap thresholds were measured for nine unilaterally and eight bilaterally impaired subjects, using bandlimited noise stimuli centered at 0.5, 1.0, and 2.0 kHz. Gap thresholds were usually larger for the impaired ears, even when the comparisons were made at equal sensation levels (SLs). Gap thresholds tended to increase with increasing absolute threshold, but the scatter of gap thresholds was large for a given degree of hearing loss. In experiment II threshold was measured as a function of the delay between the onset of a 210-ms masker and the onset of a 10-ms signal in both simultaneous- and forward-masking conditions. The signal frequency was equal to the center frequency of the bandlimited noise masker, which was 0.5, 1.0, or 2.0 kHz. Five subjects with unilateral cochlear impairments, two subjects with bilateral impairments, and two normal subjects were tested. The rate of recovery from forward masking, particularly the initial rate, was usually slower for the impaired ears, even when the maskers were presented at equal SLs. Large gap thresholds tended to be associated with slow rates of recovery from forward masking.

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INTRODUCTION

Several groups of workers have reported that thresholds for the detection of temporal gaps in noise stimuli are usually larger for subjects with cochlear hearing impairments than for normally hearing subjects. This is true both for broadband noise stimuli (e.g., Irwin *et al.*, 1981; Florentine and Buus, 1984) and for bandpass noise stimuli presented in a broadband or bandstop background (e.g., Fitzgibbons and Wightman, 1982; Tyler *et al.*, 1982; Buus and Florentine, 1985; Moore *et al.*, 1985b). However, in making comparisons between normal and impaired hearing, two important factors have to be taken into account. The first is the effective frequency range available to the subject. There is considerable evidence that, for normally hearing subjects, thresholds for the detection of gaps in bandlimited noise decrease with increasing center frequency and with increasing bandwidth (Fitzgibbons and Wightman, 1982; Shailer and Moore, 1983, 1985; Florentine and Buus, 1983). For broadband stimuli, it appears that subjects primarily use information from the highest frequency region available (Shailer and Moore, 1983, 1985). For subjects with high-frequency hearing losses, performance might be poorer simply because the higher frequency components in the stimuli are inaudible (Bacon and Viemeister, 1985a). This would decrease both the effective bandwidth and the effective upper cutoff frequency. While this is mainly a problem in studies using broadband noises to mark the temporal gaps, it may also affect results using bandpass noises in cases where the noises have relatively large bandwidths and where subjects have losses that increase with increasing frequency over the range covered by the stimuli (as was true for most of the subjects in the studies by Fitzgibbons and Wightman, 1982; Tyler *et al.*, 1982; Buus and Florentine, 1985; and Moore *et al.*, 1985b).

A second important factor to consider when making comparisons between normal and impaired hearing is the level at which subjects are tested. Gap thresholds decrease with increasing level both for normal and for impaired subjects (Shailer and Moore, 1983; Florentine and Buus, 1983, 1984; Buus and Florentine, 1985). It remains unclear whether impaired and normal subjects should be compared at equal sound pressure levels (SPLs), equal sensation levels (SLs), or some other level, such as equal loudness. Fitzgibbons and Wightman (1982) found that impaired subjects had larger gap thresholds than normal subjects regardless of whether the comparison was made at equal SPL or equal SL; the difference was, however, considerably smaller in the lat-

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ter case. Tyler *et al.* (1982) found that at (approximately) equal SL impaired subjects had larger gap thresholds than normal at 4 kHz but not at 0.5 kHz.

Florentine and Buus (1984) attempted to assess the influence both of the level of testing and of restrictions in bandwidth by comparing impaired subjects with normal subjects who had simulated hearing losses. This was achieved by testing the normal subjects in the presence of a spectrally shaped masker chosen to produce audiograms similar to those of impaired subjects. They found that only three out of seven impaired subjects showed gap thresholds consistently larger than those found for the subjects with simulated impairments. For the others, Florentine and Buus concluded that the results could be accounted for entirely by their elevated pure-tone thresholds.

The first experiment reported here was an attempt to provide further information on the degree to which subjects with cochlear hearing losses show deficits in gap detection over and above those which might be expected on the basis of the elevation in pure-tone thresholds. We used 17 subjects with cochlear impairments, 9 of whom had unilateral losses; each of these 9 subjects served as his/her own control, the normal ear being compared with the impaired ear. Most of the subjects had relatively uniform absolute thresholds in their impaired ears over the frequency range tested (0.5–2.0 kHz), and the noise bands used to mark the gaps were relatively narrow (bandwidth one-half of the center frequency). Thus the results should not be confounded by variations in absolute sensitivity across the frequency range covered by each noise band. The impaired ears (unilaterally and bilaterally impaired subjects) were tested at a constant SPL. The normal ears of the unilaterally impaired subjects were tested both at the same SPL, and, for each subject, at the same SL as for the impaired ear.

The purpose of the second experiment was to examine the possible link between gap detection and forward masking (Plomp, 1964; Smiarowski and Carhart, 1975; Penner, 1977; Evans, 1985). In particular, we wanted to test the possibility that poor gap detection in impaired ears might be associated with a slower-than-normal rate of recovery from forward masking (Nelson and Turner, 1980; see also the comment by Evans following that paper).

To test this idea, we measured threshold for a brief tonal signal as a function of time after the offset of a bandlimited noise masker. The masker had similar characteristics to the noise used to mark the temporal gaps in the first experiment, and the signal frequency was equal to the center frequency of the masker. Since the rate of recovery from forward masking appears to depend on the SL of the masker (Jesteadt *et al.*, 1982; Moore and Glasberg, 1983), the normal ears were tested both with the masker at the same SPL and with the masker at the same SL as for the impaired ear of each subject.

I. EXPERIMENT I. GAP DETECTION

A. Subjects

Nine subjects with unilateral cochlear impairments and eight subjects with bilateral impairments were used. Subjects were paid for their services. They were highly experienced in psychoacoustic tasks, and were given sufficient practice for their performance to stabilize. Subjects were carefully screened to exclude the possibility of conductive or retrocochlear involvement. Details of testing may be found in Moore *et al.* (1985a). Table I gives the audiograms and probable causes of hearing loss. Thresholds in the normal ears are generally slightly higher than 0 dB HL, particularly at high frequencies. However, thresholds are not markedly higher than normal given the ages of the subjects. Most subjects had losses that did not vary markedly over the frequency range tested (0.5–2.0 kHz). However, this was not true for subjects 9, 14, and 15; their thresholds were higher at 2.0 kHz than at lower frequencies in at least one ear.

B. Stimuli

Subjects were required to detect a temporal gap in a gated bandpass noise, presented in a continuous complementary band-reject background (see Shailer and Moore, 1983, for details). The bandpass noise was arithmetically centered at 0.5, 1.0, or 2.0 kHz and the bandwidth was one-half of the center frequency (all bandwidths are specified at the 3-dB down points). The notch in the background noise was of the same width.

Each ear of each subject was tested separately. For the subjects with unilateral impairments, pink noise with a spectrum level of 25 dB at 1.0 kHz was presented to the normal ear when the impaired ear was being tested. For testing the impaired ears, the spectrum level of the bandpass noise, in its passband, was 60 dB at 0.5 kHz, 57 dB at 1.0 kHz, and 54 dB at 2.0 kHz, giving an overall level of 84 dB SPL. The spectrum level of the background noise was 20 dB below that of the bandpass noise. The normal ear of each unilaterally impaired subject was tested both at the same SPL and at the same SL as for the impaired ear. The overall level of 84 dB SPL for the impaired ears was chosen since it was expected to give near-asymptotic performance for most subjects (Florentine and Buus, 1984; Buus and Florentine, 1985). This may not have been true in a few cases, but it would have been difficult to test at a higher level, owing to the presence of recruitment in these subjects.

The overall duration of each burst of noise in a trial was 410 ms at the 6-dB down points, and onsets and offsets were shaped with 10-ms raised-cosine functions. The gap was temporally centered in either the first or second burst. Both the fall and rise time of the gap were 0.5 ms (raised-cosine function), giving a minimum gap, measured at the 6-dB down points, of 0.5 ms. The interval between the two bursts in each trial was 500 ms. Absolute thresholds for pure tones were determined using tone bursts with 200-ms steady-state portions and 10-ms raised-cosine onset and offset ramps (overall duration 210-ms at the 6-dB down points).

Stimuli were delivered via Sennheiser HD414 earphones. Subjects were tested in a double-walled sound-attenuating chamber.

C. Procedure

All thresholds were measured using an adaptive two-alternative forced-choice procedure that estimates the 71%

TABLE I. Summary of the characteristics of the hearing-impaired subjects. Subjects 1–9 had unilateral cochlear impairments, while subjects 10–18 had bilateral impairments. For each subject, the table shows age, sex, absolute thresholds in each ear in dB HL at six frequencies, and the clinical diagnosis. Absolute thresholds were determined by standard audiometric methods using TDH 39 earphones.

Subject	Age	Sex	Ear	Threshold, dB HL 0.25	0.5	1.0	2.0	4.0	8.0	Diagnosis
1	70	M	Normal (R)	20	15	5	10	20	35	Nonprogressive cochlear loss
			Impaired	40	30	55	55	40	65	
2	58	F	Normal (R)	10	15	25	35	45	55	Progressive cochlear loss
			Impaired	50	55	55	55	60	70	
3	68	F	Normal (L)	20	15	10	15	30	60	Meniere's
			Impaired	65	60	55	50	55	70	
4	47	M	Normal (L)	5	10	0	5	15	10	Meniere's
			Impaired	65	70	60	55	70	80	
5	72	M	Normal (R)	25	20	15	10	50	70	Meniere's
			Impaired	60	55	45	35	50	85	
6	71	M	Normal (L)	20	15	10	15	30	50	Nonprogressive cochlear loss
			Impaired	50	55	55	40	30	50	
7	59	M	Normal (R)	15	15	20	10	35	15	Meniere's
			Impaired	65	65	70	70	80	90	
8	44	M	Normal (R)	10	10	5	0	10	40	Meniere's
			Impaired	75	70	60	45	50	55	
9	51	F	Normal (R)	15	10	10	5	15	10	Nonprogressive cochlear loss
			Impaired	40	45	40	70	75	90	
10	63	M	Impaired (L)	50	50	55	45	65	70	Nonprogressive cochlear loss
			Impaired (R)	45	60	55	55	70	70	
11	20	M	Impaired (L)	35	45	50	65	55	55	Alport's syndrome
			Impaired (R)	35	45	55	60	55	60	
12	56	F	Impaired (L)	50	45	35	65	55	80	Progressive cochlear loss
			Impaired (R)	50	50	50	60	85	100	
13	69	F	Impaired (L)	35	45	55	50	50	50	Progressive cochlear loss
			Impaired (R)	35	45	45	40	45	50	
14	65	F	Impaired (L)	40	35	40	40	65	95	Childhood infection
			Impaired (R)	60	55	70	80	100	>100	
15	68	M	Impaired (L)	25	25	25	55	85	75	Noise exposure
			Impaired (R)	35	30	35	60	85	75	
16	18	M	Impaired (L)	35	40	45	45	30	50	Alport's syndrome
			Impaired (R)	35	40	50	45	30	40	
17	56	M	Impaired (L)	20	20	15	40	55	75	Meniere's?
			Impaired (R)	55	50	35	25	50	50	

point on the psychometric function (Levitt, 1971). A run always started with the relevant stimulus characteristic easily audible. After two correct responses the task was made one step harder and after each incorrect response it was made one step easier. For determining absolute thresholds the step size was 2 dB. For determining gap thresholds the gap was changed by a factor of 1.4. The factor of 1.4 was chosen to give a reasonable compromise between resolution and rapid convergence to the threshold value. Testing continued until 16 turnarounds had occurred. Absolute thresholds were estimated as the arithmetic mean of the levels at the last 12 turnarounds. Gap thresholds were estimated as the geometric mean of the gap durations at the last 12 turnarounds. Each threshold was estimated at least twice. Feedback was provided by lights on the response box.

D. Results and discussion

The results for the subjects with unilateral impairments are shown in Fig. 1. The numbering of the subjects is the

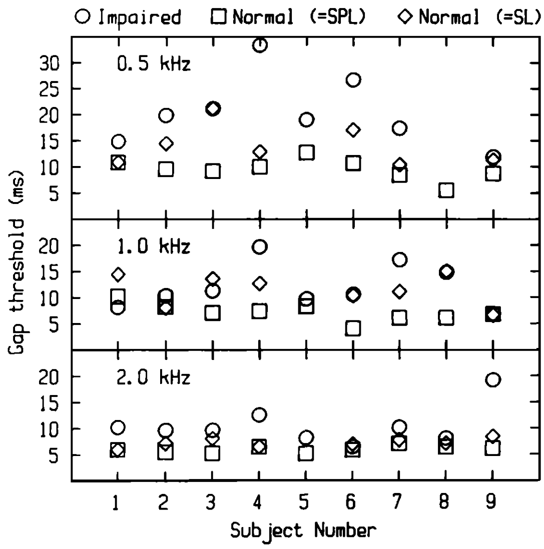

FIG. 1. Gap thresholds for the subjects with unilateral cochlear impairments at three center frequencies: 0.5 kHz (top), 1.0 kHz (middle), and 2.0 kHz (bottom). Results for the impaired ears, tested at a level of 84 dB SPL, are shown by circles. Results for the normal ears are shown by squares (equal SPL) and diamonds (equal SL).

same as in Table I. Subject 5 was not available to complete testing for the equal-SL condition. For subject 8, the SL of the noise stimulus in the impaired ear at 0.5 kHz was too low for the gap threshold to be determined reliably. Complete results are available for all other subjects. Gap thresholds for the impaired ear (circles) are usually, but not always, larger than those for the normal ear of a given subject when the comparison is made at equal SPL (squares), but this is not always true at equal SL (diamonds), particularly at 1.0 kHz. Gap thresholds for subject 1 at 1.0 kHz are slightly lower for the impaired ear than for the normal ear, even at equal SPL. This result was confirmed by repeated testing. Some subjects (2, 4, 5, and 7) show larger gap thresholds in their impaired ears at all three center frequencies, even when the comparison is made at equal SL.

A Wilcoxon matched-pairs signed-ranks test showed that the gap thresholds for the impaired ears were significantly ($p < 0.05$) larger than those for the normal ears at all three center frequencies when the comparison was made at equal SPL. However, at equal SL, the difference was only significant at 0.5 and 2.0 kHz.

Table II shows means of the gap thresholds at each center frequency for the unilaterally impaired subjects who completed testing in all conditions (seven subjects at 0.5 kHz, eight subjects at 1.0 and 2.0 kHz). The table also shows mean gap thresholds for the subjects with bilateral impairments (individual thresholds are shown in Fig. 2). The gap thresholds for the normal ears are slightly smaller than those found by Shailer and Moore (1983), probably because both the signal-to-background ratio and the overall level were higher in the present experiment. However, the variation with frequency is similar to that found by Shailer and Moore and by others (Fitzgibbons, 1983; Florentine and Buus, 1983). The mean gap thresholds for the impaired ears also decrease with increasing frequency, as reported by Fitzgibbons and Wightman (1982) and Tyler *et al.* (1982), although this trend is less clear for the subjects with bilateral impairments.

We and others have argued that, for normal subjects, gap detection for noise bands at low center frequencies is partly limited by "ringing" in the auditory filters (Florentine and Buus, 1983; Fitzgibbons, 1983; Shailer and Moore, 1983; Buus and Florentine, 1985). This could account for the increase in gap thresholds with decreasing center frequency. If this is so, we might expect that subjects with cochlear impairments would be *better* than normal at gap detection, since their auditory filters are usually broader than normal, and would therefore be expected to ring for a shorter time. We have confirmed in a separate experiment that the auditory filters of our subjects were broader in their impaired ears than in their normal ears (Glasberg and Moore, 1986). The fact that gap detection is not better for the impaired ears suggests that some factor other than ringing in the auditory filters limits performance for the impaired ears. Thus we must seek another explanation for the variation of the gap threshold with center frequency in the impaired ears.

One possible explanation for the decrease in gap thresholds with increasing center frequency is that the inherent fluctuations in the noise become less confusable with the gap as the noise bandwidth passing through the auditory filter increases; this explanation is elaborated in Sec. III. A second possibility is that, in spite of the relatively flat audiograms of our subjects, the functioning of their cochleas was more disrupted towards the apical end than towards the basal end. This idea is supported by the fact that measures of other auditory functions in the same subjects, such as auditory-filter bandwidths (Glasberg and Moore, 1986) and frequen-

TABLE II. Results of experiment I showing the mean gap thresholds in ms for the subjects with unilateral impairments and the subjects with bilateral impairments (standard deviations in parentheses).

Subject/ear	Condition	Center frequency, kHz 0.5	 1.0	 2.0
Unilateral, impaired ear	84 dB SPL	20.8(7.3)	12.4(4.5)	10.8(3.8)
Unilateral, normal ear	84 dB SPL	9.1(1.7)	7.0(1.7)	6.1(0.6)
Unilateral, normal ear	Equal SL	14.0(3.9)	11.5(3.0)	7.3(0.8)
Bilateral, impaired ear(L)	84 dB SPL	12.8(5.5)	10.7(4.7)	10.0(6.4)
Bilateral, impaired ear(R)	84 dB SPL	12.8(3.3)	10.7(4.0)	10.4(5.9)

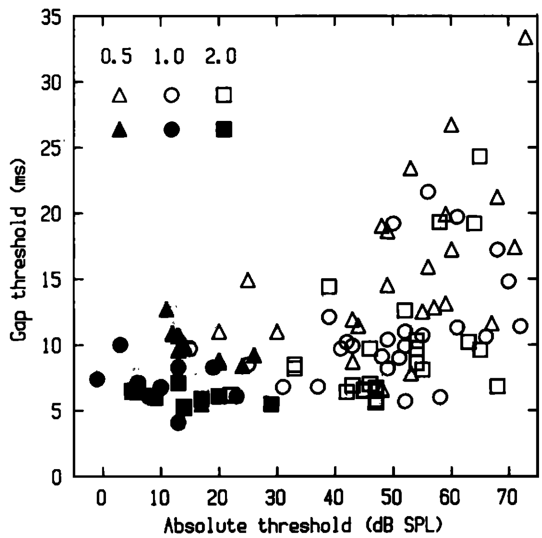

FIG. 2. Gap thresholds as a function of absolute threshold at the test frequency, which was either 0.5 kHz (triangles), 1.0 kHz (circles), or 2.0 kHz (squares). Filled symbols show results for the normal ears of subjects with unilateral cochlear impairments. Open symbols show results from the impaired ears (both unilateral and bilateral). Absolute thresholds were determined using 210-ms tones.

cy discrimination (Moore and Glasberg, 1986), showed greater impairments at low center frequencies than at high. It is noteworthy that not all subjects showed a consistent decrease in threshold with increasing center frequency for their impaired ears (for example, subjects 9, 11, 13, and 14). One subject (13) had a gap threshold in the left ear at 0.5 kHz which was smaller than normal (6.6 ms versus a mean of 9.1 ms for the normal ears at 84 dB). Her results, and those of subject 1, are consistent with the idea that broader auditory filters can sometimes give rise to improved gap detection.

The relationship of gap thresholds to absolute thresholds is shown in Fig. 2. Gap thresholds in this figure were all obtained with a noise level of 84 dB SPL, so increasing absolute threshold corresponds to decreasing SL of the noise. The scatter of the gap thresholds increases markedly for absolute thresholds above about 45 dB SPL. Thus, while there is a tendency for gap thresholds to increase with increasing absolute threshold, the range of gap thresholds may be considerable for any given absolute threshold. Table III gives the correlation between gap threshold and absolute threshold at each center frequency, and for all frequencies combined. Overall, the results suggest that, while differences in the SL of the stimuli can account for some of the differences between the normal and impaired ears, there is a substantial source of variation that is not explicable in this way. Our second experiment investigates the possibility that differences in the rate of recovery from forward masking may account for this variation.

II. EXPERIMENT II. THE TEMPORAL COURSE OF SIMULTANEOUS AND FORWARD MASKING

A. Rationale

There are at least two possible reasons why gap detection might be related to forward masking. The first is that both reflect the operation of the same temporal integration mechanism (Penner, 1977). The second is that both depend upon the rate of recovery from adaptation (Evans, 1985). According to the second explanation, large gap thresholds would be associated with slower-than-normal recovery from adaptation. It has been suggested that changes in the threshold of a signal as a function of its temporal position within a simultaneous masker may also depend on adaptation, although in this case the important factor is the growth of adaptation during the presentation of the masker (Green, 1969; Smith, 1979; Bacon and Viemeister, 1985b,c; Bacon and Moore, 1986). If the recovery from adaptation is abnormal in cases of cochlear impairment, then it is possible that the growth of adaptation is also abnormal. Thus, in addition to measuring the recovery from forward masking, we measured threshold as a function of the temporal position of the brief signal within the bandlimited noise masker.

B. Subjects

Each ear of five of the unilaterally impaired subjects (1, 2, 3, 4, and 9) and the left ears of two of the bilaterally impaired subjects (10 and 11) from experiment I were tested. The two bilaterally impaired subjects were chosen since they had similar audiograms to one another, but one (10) had consistently smaller gap thresholds than the other (11). Finally, two subjects (authors BG and SB) with bilaterally normal hearing were tested using their preferred ear. This was the left for BG and the right for SB. Absolute thresholds for the 10-ms signal used in experiment II are given in Table

TABLE III. Correlations between the absolute thresholds and the gap thresholds for the data shown in Fig. 2. The correlations are given separately for the impaired ears, the normal ears, and all ears combined. They are also given separately for each center frequency and for all frequencies combined. Figures in parentheses give the number of data points for each correlation. Asterisks indicate significant correlations and the level of significance: * = 0.05; ** = 0.01; *** = 0.001.

	Center frequency, kHz			
	0.5	1.0	2.0	Overall
Impaired ears	0.50 (24)**	0.40 (25)*	0.46 (24)*	0.44 (73)***
Normal ears	−0.52 (9)	−0.29 (9)	−0.44 (9)	−0.08 (27)
All ears	0.62 (33)***	0.54 (34)***	0.54 (33)***	0.53 (100)***

IV, averaged for the different subject groups.

C. Stimuli and procedure

The noise masker had exactly the same spectral characteristics as the noise used in the first experiment; it consisted of a bandpass noise (bandwidth one-half of the center frequency) in a complementary band-reject background. The masker had 10-ms rise/fall times, shaped with a raised-cosine function, and a steady-state duration of 200 ms, the same as the duration of the marker preceding the gap in experiment I. The band-reject background was gated on and off with the bandpass noise. The sinusoidal signal had a raised-cosine envelope with a duration of 10 ms at the 6-dB down points (20 ms at 0-voltage points). The signal frequency was always equal to the center frequency of the bandpass noise, which was 0.5, 1.0, or 2.0 kHz. The signal was presented at the start of the masker, close to its temporal center, at the end of the masker, and at three times following the masker. The time between the onset of the masker and the onset of the signal was 0, 90, or 200 ms in simultaneous masking and 220, 240, or 280 ms in forward masking. Both the normal and the impaired ears were tested with the masker level set to 84 dB SPL. The normal ear of each subject with a unilateral impairment was also tested with the masker level at the same SL as for the impaired ear. The subjects with bilaterally normal hearing were tested with the masker level at 49 dB SPL, which gave an SL similar to that for the two bilaterally impaired subjects.

Other aspects of the stimuli, equipment, and procedure were the same as for experiment I.

D. Results and discussion

The thresholds in simultaneous masking varied little across subjects. The thresholds in forward masking varied more, but, considering the impaired ears and normal ears separately, the general form of the functions relating threshold to signal delay was similar for the different subjects. Therefore, it seemed reasonable to average the results to show their general form. Figure 3 shows average results for the five subjects with unilateral impairments. When the maskers were at equal SPLs, thresholds in simultaneous masking were similar for the normal and impaired ears.[1] Thresholds in forward masking were considerably different for the normal and impaired ears; the normal ears show a much more rapid rate of recovery from forward masking.

TABLE IV. Absolute thresholds in dB SPL for the 10-ms signal used in experiment II, averaged for the different groups of subjects. Standard deviations are given in parentheses.

Subject group/ear	Center frequency, kHz 0.5	1.0	2.0
Unilateral, normal ears	35.5 (7.3)	22.1 (7.9)	26.7 (8.8)
Unilateral, impaired ears	65.1 (15.3)	57.6 (11.8)	63.6 (6.7)
Bilateral, left ears	59.9 (0.1)	60.3 (2.4)	58.1 (3.3)
Normal, one left, one right	21.4 (3.9)	11.4 (2.4)	9.6 (2.4)

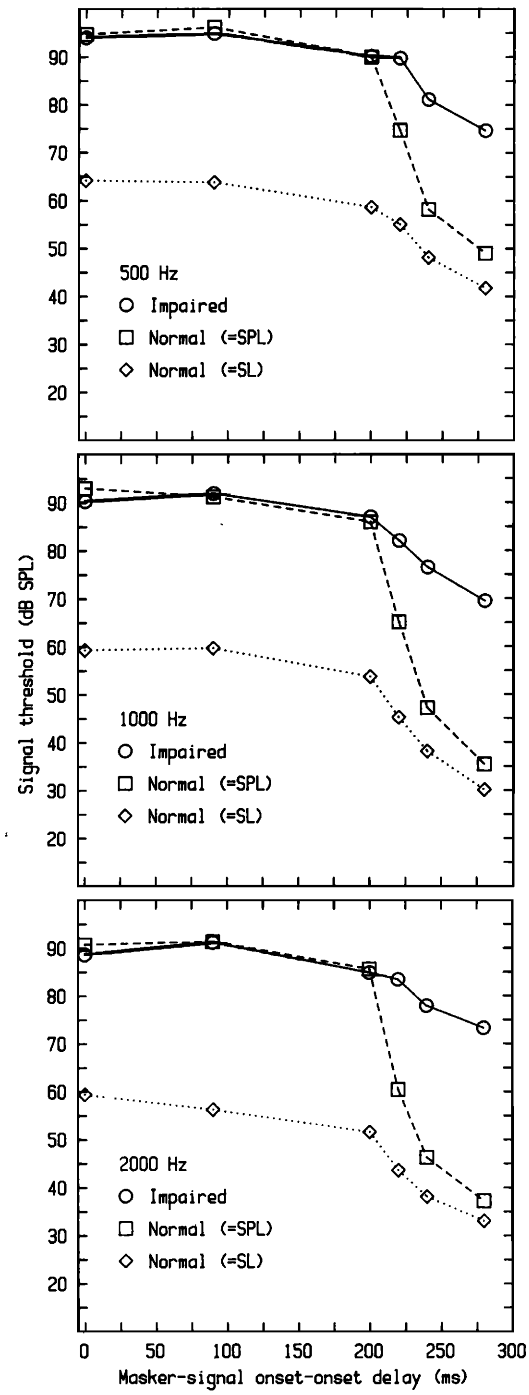

FIG. 3. Mean results for five subjects with unilateral cochlear impairments showing the threshold for a 10-ms signal as a function of its temporal position relative to a 210-ms masker. Thresholds are plotted as a function of masker-signal onset–onset delay. The three leftmost points are for simultaneous masking and the three rightmost points are for forward masking. Results are shown for three center frequencies: 500 Hz (top), 1000 Hz (middle), and 2000 Hz (bottom). Results for the impaired ears, tested with a masker level of 84 dB SPL, are shown by circles and solid lines. Results for the normal ears are shown by squares and dashed lines (equal SPL) and diamonds and dotted lines (equal SL).

However, when the normal ears were tested at equal SL, the rate of recovery from forward masking was much closer to that for the impaired ears. Overall, this result is consistent with the idea that the rate of recovery from forward masking is determined primarily by the SL of the masker. On this line of argument, the rate of recovery shown by the impaired ears does not indicate an abnormality, but merely reflects the low SL of the masker (Jesteadt, 1980).

There are two aspects of the data which suggest that the SL of the masker is not the only factor determining the rate of recovery from forward masking. First, the rate of recovery for the impaired ears differed across listeners even when the maskers were at similar SLs. Second, in the transition from simultaneous to forward masking (masker-signal onset–onset delays of 200 and 220 ms), the threshold often dropped little, if at all, for the impaired ears, but dropped by several decibels for the normal ears, even at equal SL. For the impaired ears the average drop was 0.3, 4.9, and 1.5 dB at 0.5, 1.0, and 2.0 kHz, respectively. For the normal ears at equal SL the corresponding decreases in threshold were 4.6, 8.5, and 8.0 dB. The differences between the normal and impaired ears are statistically significant ($p < 0.05$) at all three center frequencies. These results suggest that there are differences between the normal and impaired ears in the *initial* rate of recovery from forward masking.

Figure 4 shows the mean results for the two subjects with bilateral impairments and the two normally hearing subjects. The general pattern of the results is similar to that in Fig. 3. However, the rate of recovery from forward masking for the normal subjects is greater than that for the impaired subjects even when the comparison is made at similar SLs. The largest difference is in the initial rate of recovery. The average decrease in signal threshold as the masker-signal onset–onset delay is increased from 200 to 220 ms is 2.2, 2.5, and 3.3 dB at 0.5, 1.0, and 2.0 kHz for the impaired ears, and 11.7, 15.1, and 17.3 dB for the normal ears (for the masker at 49 dB SPL).

Overall, the results in Figs. 3 and 4 suggest that differences in the rate of recovery from forward masking between normal and impaired ears depend partly upon the level at which the comparison is made. At equal SL, the differences are reduced, but are not eliminated, particularly for short signal delays.

We turn now to the question posed earlier: Is there a relationship between gap thresholds and the rate of recovery from forward masking? As an index of the rate of recovery, we used the decrease D in signal threshold as the masker-signal onset–onset delay was increased from 200 ms (end of simultaneous masker) to 240 ms (silent interval of 20 ms between masker and signal). At the 240-ms delay the masked threshold of the signal was at least 8 dB above absolute threshold both for the impaired ears and for the normal ears (equal-SL condition) for all subjects. Figure 5 shows gap thresholds determined in experiment I plotted as a function of D. Each point shows results for one subject, and the figure includes data from both the unilaterally and bilaterally impaired subjects tested in experiment II.

There does seem to be a relationship between gap thresholds and D, but it is not a very close relationship. Large values of D are always associated with small (normal) gap thresholds. Values of D less than about 15 dB (10 dB at 2.0 kHz) tend to be associated with larger gap thresholds, and values of D less than 5 dB are nearly always associated

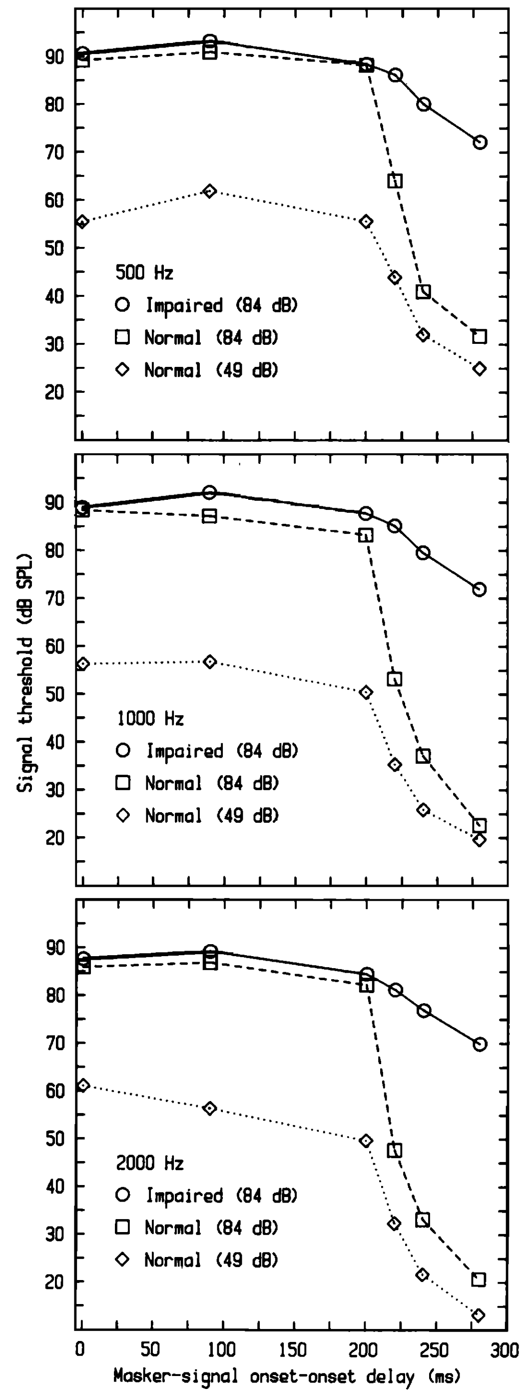

FIG. 4. As in Fig. 3, but showing the mean results for two subjects with bilateral impairments (circles and solid lines), and two subjects with normal hearing tested at the same SPL (squares and dashed lines) and with a masker at a similar SL to that for the impaired ears (diamonds and dotted lines).

with large gap thresholds. There are, however, some exceptions to this general pattern. In particular, at 1.0 kHz, two subjects (2 and 3) had relatively small gap thresholds in their impaired ears (10.4 and 11.3 ms, respectively) but had only small values of D (3.6 and 3.5 dB, respectively).

In summarizing the results of experiment I, we concluded that the increased gap thresholds found for some of the impaired subjects could not be accounted for entirely by ele-

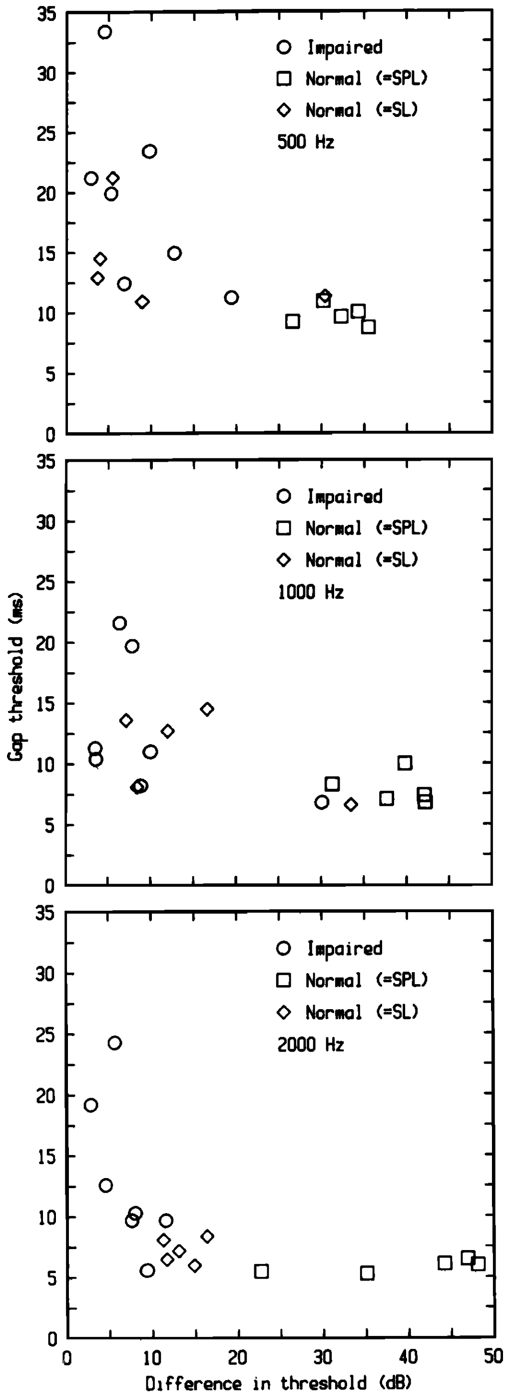

FIG. 5. Comparison of the results of experiments I and II. Each point shows results for one ear at one center frequency. The gap thresholds are plotted against the difference in threshold between the signal at the end of the simultaneous masker (masker-signal onset–onset delay 200 ms), and the signal after the end of the masker (masker-signal onset–onset delay 240 ms). Results for the impaired ears are shown by circles. Results for the normal ears are shown by squares (equal SPL) and diamonds (equal SL). Center frequencies were: 500 Hz (top), 1000 Hz (middle), and 2000 Hz (bottom).

vations in absolute threshold. We hoped that individual differences in the rate of recovery from forward masking might account for some of the variability between subjects over and above the variability accounted for by differences in absolute threshold. Unfortunately, this does not appear to be the case. Considering the results for the impaired ears only, the gap thresholds are correlated with the threshold decreases D, but the correlation is low, and only just significant ($r = -0.41$, $p = 0.05$). Furthermore, both gap thresholds and the values of D are correlated with absolute thresholds ($r = 0.64$, $p < 0.01$ and $r = -0.68$, $p < 0.01$, respectively). After partialing out the effect of absolute threshold, the correlation of the gap thresholds with the values of D becomes close to zero ($r = 0.04$).[2] Thus we cannot rule out the possibility that the relationship between gap thresholds and the rate of recovery from forward masking is mediated by the relationship of both to absolute threshold.

Consider now the results for simultaneous masking. The threshold for a brief signal presented in a gated masker is often higher when the signal is close to the onset of the masker than when it is presented later in the masker, an effect which Zwicker (1965a,b) called the overshoot effect. Since adaptation may be involved in producing this effect (Green, 1969; Smith, 1979; Bacon and Viemeister, 1985b,c; Bacon and Moore, 1986), we were interested in determining whether it would occur for our stimuli, and whether the results would differ for the normal and impaired ears. However, our data do not show the overshoot effect. Rather, the thresholds tend to increase slightly as the masker-signal onset–onset delay is increased from 0 to 90 ms, and then to decrease as the delay is increased to 200 ms (signal at end of masker). This is not inconsistent with Zwicker's data, obtained using bandpass noise maskers, since he found that the largest overshoot effect was observed when: (1) the signals were very brief; (2) the signals were of high frequency; (3) the masker bandwidth was considerably larger than the signal bandwidth. Our stimuli did not fulfill these conditions, although our signal durations were similar to those which can give large temporal effects for sinusoidal maskers (Bacon and Viemeister, 1985b,c; Bacon and Moore, 1986).[3] This suggests that temporal effects for broadband maskers and sinusoidal maskers have different underlying causes.

III. GENERAL DISCUSSION

At least five factors have been suggested to have an influence on gap thresholds for noise stimuli. The first factor is the bandwidth of the auditory filter at the test frequency. Increases in filter bandwidth might be expected to improve performance for two reasons. First, the duration of the ringing of the output of the filter during the gap should decrease with increasing bandwidth. Second, for a given integration time, the fluctuations in the noise, which limit the ability to detect small decreases in level at the output of the auditory filter, reduce as the filter bandwidth increases, up to the point where the filter bandwidth equals the signal bandwidth (Green, 1985). If this were the only factor involved, then our subjects should have shown better-than-normal performance in their impaired ears, since their auditory filters were broader than normal. This was true for a few subjects and center frequencies when the normal and impaired ears were compared at equal SLs, but was true only for subject 1 at 1.0 kHz and subject 13 at 0.5 kHz when the comparison was at equal SPL. Using Huffman sequences to measure temporal acuity, Jesteadt *et al.* (1976) also found that impaired ears sometimes showed better temporal resolution than normal when compared at equal SLs, but rarely did so when compared at equal SPLs.

The idea that gap threshold is partly limited by fluctuations in the noise could account for our finding that gap thresholds tend to decrease with increasing center frequency even for the impaired ears (as found also by Fitzgibbons and Wightman, 1982; and Tyler *et al.*, 1982). For many of our impaired subjects the auditory filter bandwidth was comparable to or greater than the signal bandwidth. Since both the absolute filter bandwidth and the signal bandwidth increased with increasing center frequency, the fluctuations at the output of the auditory filter would have been reduced as center frequency increased.

The second factor which may influence gap threshold is the rate of recovery from adaptation during the gap. This would be expected to influence the size of the neural onset response following the gap, and this onset response might be the cue used to detect the gap. It has been suggested by several workers that forward masking reflects the recovery from adaptation (Harris, 1977; Smith, 1977; Harris and Dallos, 1979). This provides one reason for believing that there should be a link between gap detection and forward masking. The results of our experiment II suggest that, while gap thresholds are related to the rate of recovery from forward masking, the relationship may be mediated by the fact that both are related to absolute threshold; the higher the SL of the stimuli, the smaller the gap threshold and the greater the rate of recovery from forward masking. The form of the results in Fig. 5 suggests that the rate of recovery from forward masking is only a limiting factor when that rate is rather slow. When the rate exceeds a certain amount (a value of our measure D of about 15 dB) then gap thresholds are independent of the rate of recovery from forward masking. If forward masking reflects the recovery from adaptation, then our results suggest that the recovery from adaptation is probably not a factor limiting gap detection for normally hearing subjects, except possibly at very low SLs.

The third factor that may influence gap thresholds is the time constant of the temporal integrator, which is often assumed to operate on the instantaneous power of the output of the peripheral filter (Zwislocki, 1960, 1969; Penner, 1977; Irwin and Purdy, 1982; Buus and Florentine, 1985; Green, 1985). Such an integrator can be used to account both for gap thresholds and for forward masking, and it provides a second explanation for why gap thresholds and forward masking might be related. The integrator has usually been assumed to be central to the cochlea, so there is no obvious reason why it should be affected by cochlear impairment. However, if the time constant of the integrator were increased in cases of cochlear impairment, this could lead to increased gap thresholds (Irwin and Purdy, 1982). Some data, however, suggest a change in the opposite direction. Temporal integration at absolute threshold is generally reduced in cases of cochlear impairment, consistent with a shorter time constant for the temporal integrator. For the five subjects with unilateral impairments who took part in experiment II, a measure of temporal integration can be obtained from the difference in absolute threshold for 210-ms tones and for the 10-ms tones used in that experiment (durations specified at the 6-dB down points). This difference was greater for the normal ear than for the impaired ear of each subject at all center frequencies except for subject 3 at 0.5 kHz and subject 9 at 2.0 kHz. The average threshold differences for the normal ears were 18.5, 15.9, and 11.3 dB at 0.5, 1.0, and 2.0 kHz, respectively. Corresponding differences for the impaired ears were 11.5, 6.2, and 9.6 dB. These results are not consistent with the idea that the time constant of the temporal integrator increases in cases of cochlear impairment. Of course, the temporal integrator involved with absolute threshold may not be the same as that involved with gap detection. Indeed, the time constants of the two appear to be different (de Boer, 1985; Green, 1985). Nevertheless, there seems to be no compelling evidence to support the idea that the large gap thresholds found for some hearing-impaired subjects can be explained by an increase in the time constant of the temporal integrator.

Most models involving a temporal integrator have assumed that it is intensity which is integrated over time. However, some workers (e.g., Penner and Shiffrin, 1980; Penner, 1980; Divenyi and Shannon, 1983) have postulated the existence of a compressive nonlinearity before the temporal integrator. Divenyi and Shannon suggested that it is neural activity and not intensity which is integrated, and it is widely accepted that neural activity is a nonlinear compressive function of input intensity. In this case, an integrator with a relatively short time constant, say 10 ms, can produce apparent integration times at absolute threshold of 100–300 ms, depending on the amount of compression (Divenyi and Shannon, 1983). Also, the rate of recovery from forward masking will depend on the amount of compression. Decreases in compression lead to a slower rate of recovery from forward masking, even when the time constant of the integrator remains the same (Shannon, personal communication).

This viewpoint leads to a fourth factor that may have influenced our results, namely, the form of the function relating stimulus intensity to neural activity. It is entirely possible that this function is steeper than normal (i.e., there is less compression) in subjects with cochlear impairments, as has been suggested by some studies of loudness recruitment (Florentine and Zwicker, 1979; Moore *et al.*, 1985a) and forward masking (Jesteadt, 1980). The slower-than-normal rate of recovery from forward masking in the impaired ears might be a consequence of this, rather than reflecting a change in the time constant of the temporal integrator or an abnormal rate of recovery from adaptation.

At first sight, a steeper input–output function might be expected to lead to better-than-normal gap detection. However, this might not be true for bandpass-noise stimuli, since a steeper function would also increase the neural fluctuations associated with fluctuations in the noise, making dips in the noise more confusable with the gap. This fits in with the subjective reports of the subjects that in their impaired ears they often heard a gap in both intervals of a trial.

The fifth factor that may affect gap thresholds is the smallest detectable change in the output of the hypothetical temporal integrator. The smaller that change, the smaller will be the gap threshold. If this factor accounted for a significant proportion of the variability between subjects, we would expect gap thresholds to be correlated with measures of intensity discrimination. Such measures were available for these subjects, since in a previous experiment we had measured both intensity DLs for 210-ms pulsed tones and thresholds for the detection of amplitude modulation (1010-ms tones, 4-Hz rate) at center frequencies of 0.5, 1.0, and 2.0 kHz (see Moore and Glasberg, 1986, for details).[4] We determined correlations between the gap thresholds and the measures of intensity discrimination for all of the impaired ears, separately for each center frequency. The correlations were generally positive but small, and failed to reach statistical significance with one exception. Gap thresholds at 1.0 kHz were significantly correlated with intensity DLs for pulsed tones ($r = 0.48, p < 0.05$). This correlation increased slightly after partialing out the effect of absolute threshold ($r = 0.53, p < 0.02$). Thus there is some weak evidence that differences in the sensitivity of the detector mechanism following the temporal integrator may influence gap thresholds.

In summary, at least five factors may influence gap thresholds. In hearing-impaired subjects any combination of these factors might be different from normal, making it very difficult to tease out their separate effects. A few subjects show better-than-normal gap thresholds in their impaired ears, an effect that is perhaps caused by a broadening of their auditory filters. For most subjects, the improvement to be expected from broadened filters is more than offset by other factors. One such factor is the rate of recovery from forward masking, especially when that rate is slow. However, we cannot rule out the possibility that the relationship of gap thresholds to the rate of recovery from forward masking is mediated by the relationship of both to absolute threshold. Individual differences in the functions relating stimulus intensity to amount of neural activity, and in the sensitivity of the detector mechanism following the hypothetical temporal integrator may also play a role.

IV. SUMMARY AND CONCLUSIONS

(1) For subjects with moderate unilateral cochlear hearing losses, gap thresholds for bandlimited noise signals are usually larger for the impaired ear than for the normal ear when the comparison is made with stimuli at equal SPLs. When the comparison is made at equal SLs, the differences are reduced and, for some subjects, are eliminated. We would expect results obtained at equal loudness to give results intermediate between those for equal SL and equal SPL. For both normal and impaired ears, gap thresholds tend to decrease with increasing center frequency.

(2) Considering the combined results for subjects with unilateral and bilateral cochlear impairments, gap thresholds tend to increase as absolute threshold increases, but the spread of gap thresholds for a given degree of hearing loss can be considerable. A few cases were found where gap thresholds were smaller than normal in the impaired ears, an effect that might be related to a broadening of the auditory filters.

(3) For subjects with unilateral impairments, the rate of recovery from forward masking is lower in the impaired ear than in the normal ear when the comparison is made with maskers at equal SPLs. The difference is considerably reduced when the comparison is made with maskers at equal SLs, but the impaired ears consistently show a slower initial rate of recovery.

(4) Large gap thresholds tend to be associated with slow rates of recovery from forward masking, but it is difficult to rule out the possibility that this effect is mediated by the relationship of both quantities to absolute threshold. The rate of recovery from forward masking does not seem to be a significant factor limiting gap detection in normally hearing subjects, except possibly at very low SLs.

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[1]This aspect of the results is curious, since the auditory filter bandwidths were considerably greater in the impaired ears than in the normal ears. These results are quite different from those which we obtained for long-duration signals using the same unilaterally impaired subjects (Glasberg and Moore, 1986). Using a 210-ms signal gated with a broadband masker, thresholds were usually greater for the impaired ear than for the normal ear.

For the brief signals used in experiment II, the main cue for detection may be the transient increase in power or amplitude at the output of the auditory filter tuned to the signal frequency. The inherent fluctuations in the noise will limit the effectiveness of this cue. If the auditory filter bandwidth is increased, because of hearing impairment, then more noise will pass through the filter, but at the same time the increase in noise bandwidth will cause the fluctuations in power to be more rapid. After smoothing by the temporal integrator, the wider bandwidth will lead to smaller inherent fluctuations in power, thus enhancing the detectability of the fluctuation associated with the signal. In other words, the increase in threshold that would be expected from the increase in noise power passing through the filter is offset by the reduced fluctuations in power at the output of the temporal integrator.

[2]Since the data in Fig. 5 suggest a curvilinear relationship between D and gap thresholds, it might be better to calculate correlations on scales for which the relationship is more nearly linear. However, doing this does not change our conclusions. For example, the correlation of the values of D with the logarithms of the gap thresholds is -0.46 ($p < 0.05$), but after partialing out the effect of absolute threshold the correlation reduces to -0.08.

[3]Although our stimulus conditions were not optimal for producing the overshoot effect, it is puzzling that the thresholds tend to be greatest for the signal in the temporal center of the masker. One possible explanation for this is that there is a temporal integrator (discussed in more detail in Sec. III) that has a minimum integration time (Penner *et al.*, 1972). Thus the subject is unable to exclude portions of the masker that precede and follow a brief signal. The threshold would be lower for a signal at the beginning or end of a masker since there would be no masker present for part of the integration period. This effect would be increased if subjects were able to do "off-time listening" whereby the integration period was centered before the onset of the masker (for the signal at onset) or after the end of the masker (for the signal at offset). To account for the fact that thresholds were typically 5–6 dB lower for the signal at the end of the masker than for the signal at the center, the minimum integration time would have to be 3–4 times longer than the signal duration (20 ms overall, 10 ms at the 6-dB down points). Estimates of the minimum integration time are typically between 5 and 30 ms (Penner *et al.*, 1972; Trahiotis *et al.*, 1972; Penner and Cudahy, 1973), but some data suggest that the minimum integration time might be longer at low frequencies (Penner and Cudahy, 1973; Carlyon

and Moore, 1986; Carlyon, 1986). It is difficult, however, to explain the fact that thresholds were 3–6 dB lower for the signal at the end of the masker than for the signal at the start. This would require a temporal window with an asymmetry opposite to that which is normally assumed.

[4]These thresholds were determined in the presence of high-pass noise to mask the upper sides of the excitation patterns of the tones to be discriminated; this was done to prevent the results from being influenced by the nonlinear growth of excitation on the high-frequency sides of the excitation patterns, a factor that would not have affected the gap-detection results owing to the presence of the continuous band-reject background noise.

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