Linearized response growth inferred from growth-of-masking slopes in ears with cochlear hearing loss

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(Received 5 July 1996; revised 24 September 1996; accepted 2 December 1996)

Growth of masking for OFF-frequency conditions (probe frequency above the masker spectrum) and ON-frequency conditions (probe within the masker spectrum) was investigated using simultaneous masking in three subjects with normal hearing and nine subjects with high-frequency sensorineural hearing loss. Growth-of-masking functions (probe thresholds as a function of masker intensity) for OFF-frequency conditions were obtained for probe tones placed at six frequencies above a 200-Hz-wide masker with an upper edge at 520 Hz. Growth-of-masking functions for ON-frequency conditions were obtained for probe tones placed within the 200-Hz-wide masker and for probe tones placed within 400-Hz-wide maskers with upper edges at 1040, 1300, 1627, and 2040 Hz (probe tones placed 20 Hz below the upper edge frequency). Growth-of-masking functions were fit with a power function of masker intensity added to an internal noise with intensity equal to the absolute threshold for the probe, and were well described by two free parameters and a threshold constant: the growth-of-masking slope (β), a masking sensitivity constant (κ) that indicated the minimum effective masker level at which masking began, and the intensity of the probe at absolute threshold (I_T). For OFF-frequency masking conditions, growth-of-masking slopes (β) decreased by a factor of 0.8 for every 10 dB of hearing loss. Comparisons with data from previous studies of upward spread of masking, and assumptions about underlying physiological mechanisms, led to the conclusion that more gradual than normal growth-of-masking slopes reflect larger (steeper) growth-of-response slopes at the probe frequency in regions of hearing loss. Derived response-growth exponents increased by a factor of 1.2 for every 10 dB of hearing loss (HL), from an exponent around 0.25 at 0 dB HL to an exponent around 1.0 at 75 dB HL (linear response growth). Masking sensitivity constants (κ), the minimum effective masker levels, indicated that masking began at slightly higher masker levels in subjects with sensorineural hearing loss than in subjects with normal hearing. It was concluded that higher masked thresholds in regions of hearing loss were due primarily to a loss of active gain at the probe frequency and were not due to an excessive response at the probe frequency to the lower-frequency masker. For ON-frequency masking conditions, growth-of-masking slopes were not different from normal in hearing-impaired subjects. ON-frequency masking began when the effective power within an auditory filter at the probe frequency reached elevated absolute threshold at the probe frequency. Critical ratios were normal except for one subject with the most hearing loss. [S0001-4966(97)04304-X]

PACS numbers: 43.66.Ba, 43.66.Dc, 43.66.Mk, 43.66.Sr [WJ]

INTRODUCTION

Masking produced by low-frequency sounds at higher frequency regions, often referred to as *upward spread of masking*, has been thoroughly investigated since Wegel and Lane (1924) demonstrated that masking spreads more toward higher frequencies than lower frequencies. In listeners with high-frequency sensorineural hearing loss, upward spread of masking is typically considered to be ''excessive'' because higher masked thresholds are seen in regions of hearing loss than observed in normal-hearing listeners for the same low-frequency masker (Jerger *et al.*, 1960; Harbert and Young, 1965; Martin and Pickett, 1970; Florentine, 1978; Florentine *et al.*, 1980; Smits and Duifhuis, 1982; Gagne, 1983; Hannley and Dorman, 1983; Picard and Couture-Metz, 1985; Trees and Turner, 1986; Buus and Florentine, 1988, 1989; Klein *et al.*, 1990; Dubno and Schaefer, 1991; Murnane and Turner, 1991; Klein and Dubno, 1993; Dubno and Ahlstrom, 1995a,b; Dubno and Schaefer, 1995). This means that a listener with a high-frequency hearing loss may not hear certain higher-frequency sounds in the presence of a low-frequency masker, even though those sounds may be more intense than the elevated high-frequency threshold, a situation that may be particularly relevant to the problem of listening to speech in background noise.

If the amount of masking in the region of hearing loss is considered, i.e., the amount of threshold shift, then it is typical to observe *less* masking in regions of high-frequency hearing loss than observed in normal-hearing listeners (Martin and Pickett, 1970; Nelson and Bilger, 1974; Smits and Duifhuis, 1982; Gagne, 1983; Trees and Turner, 1986; Klein *et al.*, 1990; Dubno and Schaefer, 1992). Furthermore, in normal-hearing listeners, upward spread of masking is generally characterized by nonlinear growth of masking with masker intensity (Wegel and Lane, 1924; Zwicker, 1970), i.e., for every 1-dB increase in masker intensity the signal must be increased by more than 1 dB. By contrast, in listeners with sensorineural hearing loss, the rate at which masking grows with masker intensity (the growth-of-masking slope) is more gradual than it is in normal-hearing listeners (Nelson and Bilger, 1974; Smits and Duifhuis, 1982; Stelmachowicz *et al.*, 1987; Buus and Florentine, 1989; Murnane and Turner, 1991). Thus, we are faced with a situation in which masked thresholds for low-frequency maskers are higher in regions of high-frequency hearing loss, but the amount of masking is usually less and the rate at which masking grows with masker intensity is more gradual.

The physiological mechanisms underlying these results are not clear. One interpretation is that the higher-than-normal masked thresholds are due to excessive upward spread of excitation into higher frequency regions, where auditory fibers tuned to those higher-frequency regions are responding excessively to the low-frequency masker (Trees and Turner, 1986) due to hypersensitive neural tuning-curve tails, as is sometimes seen in cases of acoustic trauma (Salvi *et al.*, 1977; Cody and Johnstone, 1980; Liberman and Dodds, 1984). Another interpretation is that sensitivity to excitation is reduced by damage to cochlear amplifiers in the hearing-loss region, thereby elevating absolute threshold at those frequencies. In addition, the response growth in those regions, once signals are intense enough to overcome the sensitivity loss, is steeper than normal, thereby reducing the rate at which masked threshold grows with masker intensity. This latter interpretation, which is consistent with changes in basilar membrane (BM) transfer characteristics associated with cochlear damage (Ruggero and Rich, 1990, 1991; Ruggero *et al.*, 1993, 1996), was recently proposed by Nelson and Schroder (1996), as a *linearized response growth* (LRG) model of upward spread of masking. The model accounts for reduced release from masking in regions of high-frequency hearing loss for maskers with fluctuating envelopes (Buus, 1985; Moore and Glasberg, 1987), and is consistent with interpretations of reduced additivity of masking in hearing-impaired ears (Oxenham and Moore, 1995). Nelson and Schroder derived growth-of-masking slope-reduction factors that would be needed to account for reduced masking release in regions of hearing loss and found that those slope-reduction factors were consistent with more gradual growth-of-masking slopes in regions of hearing loss reported by previous investigators (Murnane and Turner, 1991). Their slope-reduction factors were interpreted as normalized growth-of-masking slopes that followed the form

$$\beta_{\mathrm{hls}} = \alpha * \beta_{\mathrm{nrm}}, \tag{1}$$

where β_{nrm} is the growth-of-masking slope at a particular frequency in the normal ear, α is the derived reduction factor for a hearing-impaired ear, and β_{hls} is the growth-of-masking slope in a hearing-impaired ear. The derived slope reduction factor α was a function of the amount of hearing loss as in

$$\alpha = -0.0125(\mathrm{dB\ \ HL}) + 0.93, \tag{2}$$

which implies that the slope of the growth of masking in a region of hearing loss (β_{hls}) decreases proportionately with amount of hearing loss.

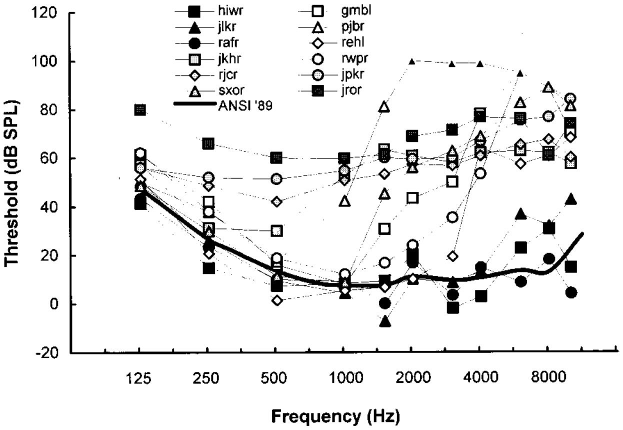

FIG. 1. Absolute thresholds from normal-hearing (dark filled symbols) and hearing-impaired listeners for 200-ms duration tone bursts, measured with a 3AFC adaptive threshold procedure, are shown as a function of the frequency of the test signal. The wide shaded curve shows average normal-hearing thresholds as a function of frequency as defined by ANSI (1989) norms. Small dark triangles indicate intensity limits of the instrumentation (e.g., *pjbr* at 2000 Hz and above).

The purpose of the present investigation was to examine characteristics of upward spread of masking in regions of cochlear hearing loss, *once signals are made sufficiently intense to overcome the hearing loss*. In many patients with cochlear hearing loss, current hearing-aid technology can selectively amplify signals to make them audible at hearing-loss frequencies to overcome frequency-dependent sensitivity losses. What is not well defined is how susceptible those amplified signals might be to masking from unamplified lower-frequency sounds. Specifically, we wished to determine whether slopes of the growth of masking in regions of hearing loss decrease proportionately with hearing loss, as implied by the reduction factor α derived by Nelson and Schroder (1996), and to examine upward-spread-of-masking in terms of the LRG model of masking that associates steeper response growth with cochlear hearing loss. To that end, the growth of upward spread of masking with masker intensity was measured in listeners with cochlear hearing losses, growth-of-masking slopes and masking sensitivity constants (the masker level at which masking begins) were examined as a function of the amount of hearing loss, and the results were compared with data from previous investigations.

I. METHODS

A. Subjects

Three normal-hearing listeners and nine listeners with bilateral sensorineural hearing loss served as subjects. Their absolute thresholds are shown in Fig. 1. Five of the listeners with hearing loss exhibited normal absolute thresholds at the 500-Hz masker frequency and below, with cochlear hearing loss at higher frequencies. Four listeners exhibited mild or moderate hearing losses at the masker frequency as well as significant hearing losses at higher frequencies. Their ages and etiologies are given in Table I.

TABLE I. Demographics of subjects with sensorineural hearing loss.

HF HI subjects	Age	Sex	Etiology
gmbl	62	Female	Hereditary/presbycusis
pjbr	37	Female	Ototoxicity
rehl	56	Male	Unknown/presbycusis?
rwpr	66	Male	Presbycusis
jkhr	47	Female	Hereditary
rjcr	25	Male	Hereditary
sxor	44	Female	Unknown
jpkr	53	Male	Barotrauma
jror	65	Male	Unknown

B. Stimuli

Masked thresholds as a function of masker level, or growth-of-masking functions, were obtained for narrowband (NB) noise maskers with bandwidths of 200 or 400 Hz. The 200-Hz-wide NB noise was centered at 420 Hz, with an upper edge at 520 Hz. It was constructed by multiplying a 100-Hz low-pass noise (135 dB/oct slope) with a pure tone at 420 Hz. The 400-Hz wide NB noises were centered at 840, 1100, 1427, or 1840 Hz. They were constructed by multiplying a 200-Hz low-pass noise with pure tones at the appropriate center frequencies. The mean number of envelope peaks per second in the maskers was about 0.64 of the bandwidth of the low-pass noises (Rice, 1954), or about 64 and 128 Hz for the 200- and 400-Hz NB noises, which were constructed from 100- and 200-Hz low-pass noise, respectively.

Masker and probe (signal) frequencies were chosen so that growth of masking could be examined for six OFF-frequency and six ON-frequency masking conditions. For the OFF-frequency conditions the probe frequency was higher than the passband of the masker, i.e., in the ''upper accessory region'' of the masker (Zwicker, 1970). The 200-Hz NB noise with an upper edge at 520 Hz was used as a masker, with probe frequencies at 650, 814, 1020, 1280, 1607, and 2020 Hz. At 650 Hz, masker energy was attenuated by 43 dB; at the five test frequencies from 814 to 2020 Hz, masker energy was attenuated by more than 87 dB. Thus, at these six frequencies the probe tones were effectively above the passband of the masker, representing OFF-frequency masking conditions. For the ON-frequency conditions, the probe frequencies were within the passband of the masker, i.e., within the ''main excitation region'' of a masker (Zwicker, 1970). Two of the ON-frequency conditions were within the spectrum of the 200-Hz NB noise at probe frequencies of 500 and 520 Hz. The four remaining ON-frequency conditions utilized probe frequencies at four of the same frequencies tested for OFF-frequency masking (1020, 1280, 1607, and 2020 Hz), but the maskers were 400-Hz NB noises with upper edges at 1040, 1300, 1627, and 2040. Thus, in all cases except 520 Hz, the probe frequency was 20 Hz below the upper edge of the masker passband, representing ON-frequency masking conditions.

Maskers and signals were gated with 10-ms cosine-squared rise/decay ramps. The duration of the maskers and signals at peak amplitude were 500 and 250 ms, respectively. The signals were temporally centered within the maskers. Pure tones for signals and for constructing the NB noise maskers were produced by frequency synthesizers (Rockland). The signals and maskers were routed separately through programmable attenuators, added together in a resistive mixer and presented monaurally through a UTC L-33 transformer and a TDH-49 earphone mounted in an MX/AR-1 cushion. Subjects were seated in a double-walled sound-treated booth and conveyed their responses to the computer by pressing buttons on a custom response panel.

C. Psychophysical procedures

Thresholds were determined with a three-alternative forced-choice adaptive procedure. A trial consisted of a 500-ms warning interval followed by three 520-ms observation intervals, each separated by a 250-ms silent interval. Maskers occurred in all three intervals. The signal was presented with the masker in one of the three intervals, chosen randomly from trial to trial. Correct-answer feedback was provided following each trial.

Growth-of-masking functions were collected with two different adaptive procedures: a fixed probe level procedure and a fixed masker level procedure. For the fixed probe procedure, probe level was held constant and masker level was adjusted to reach masked threshold. Probe levels were tested in 5-dB steps beginning at probe levels 5 dB or more above absolute threshold (averaged over multiple test sessions). At probe frequencies where large amounts of hearing loss existed, probe levels were sometimes tested in 3-dB steps (e.g., subject *pjbr* at 1280 and 1607 Hz in Fig. 2). For the fixed masker procedure, masker level was held constant and probe level was adjusted to reach masked threshold. Masker levels were tested in 5-dB steps, beginning with maskers more than 10 dB below the point where any masking began. At probe frequencies where large amounts of hearing loss existed, masker levels were sometimes tested in 3-dB steps (*jror* at 1607 Hz). The fixed-masker procedure was implemented with five of the hearing-impaired listeners (*jkhr*, *rjcr*, *sxor*, *jpkr* and *jror*) to examine more closely the transition region on the masking curve where masking begins. The adaptive procedures estimated the 71% correct threshold with a two-down/one-up (fixed masker) or two-up/one-down (fixed probe) tracking procedure that averaged the last 6 out of 12 reversals, during which the level varied in 2-dB steps for the fixed-masker-level procedure and 1-dB steps for the fixed-probe-level procedure. The first six reversals were used to move quickly into the range of threshold. For the fixed-masker-level procedure, an 8-dB step size existed for the first four reversals and a 2-dB step size existed for the next two reversals, both with a one-down/one-up stepping rule. For the fixed-probe-level procedure, a 4-dB step size existed for the first four reversals and a 1-dB step size existed for the next two reversals, both with a one-up/one-down stepping rule. Each data point represents the mean of at least three threshold estimates.

D. Fitting procedure for growth-of-masking functions

Growth-of-masking curves were specified in terms of probe intensity at masked threshold as a function of masker intensity, in order to simplify comparisons with previous studies of the slopes of the growth of masking in hearing-impaired listeners (Smits and Duifhuis, 1982; Stelmachowicz *et al.*, 1987; Murnane and Turner, 1991). Growth-of-masking curves were fitted with least-squares regressions between probe intensity at masked threshold (I_P) and masker intensity (I_M) to derive the fitting parameters k and β, using probe thresholds 5 dB or more above absolute threshold. Then the intensity at absolute threshold (I_T) was added to represent an internal noise, as in

$$I_P = kI_M^{\beta} + I_T,, \tag{3}$$

with the slope of the growth of masking given by β. All intensity units (I) are expressed here as power ratios between the measured quantity (dB SPL) and the reference intensity at 0 dB SPL (10^{-12} W/cm^2), e.g., $I_M = 10^{(0.1^* \mathrm{Lm})}$, where Lm is the masker level in dB SPL. Equation (3) implies that the intensity of the probe at masked threshold, I_P, is equal to the sum of the internal representation of the masker, kI_M^{β}, and an internal noise that determines absolute threshold, I_T. Typically, as was done in the present study, growth-of-masking parameters are derived by fitting masked thresholds (in dB SPL) as a function of masker level (in dB SPL) with a linear least-squares regression, using only those masked thresholds for which masking is greater than about 5 dB. This avoids the curvilinear portion of the masking function where masked thresholds are close to absolute threshold. Equation (3) is one way to represent masked thresholds close to absolute threshold, where the internal representation of the masker and the internal noise appear to sum together to produce a curvilinear masking function.

From Eq. (3), sensitivity to masking can be specified as the intensity of the masker where the internal representation of the masker, kI_M^{β}, is equal to absolute threshold I_T, as in

$$I_M = (I_T/k)^{1/\beta}, \tag{4a}$$

or in decibels as

$$\kappa = 10 \log\{(I_T/k)^{1/\beta}\}. \tag{4b}$$

The value of κ is the masker level (in dB SPL) where linear extrapolation of the masking curve intersects with absolute threshold, which has been referred to as the Minimum Effective Masker Level (MEML) by Buus and Florentine (1988), and is one convenient and objective way of specifying the masker level at which masking begins for comparisons between normal-hearing and hearing-impaired data. In the present context, as with psychophysical tuning curves, sensitivity to masking is inversely proportional to κ (or MEML), in that a larger κ means that the masker level required to just begin masking has to be increased, therefore, sensitivity to masking is less (in the same sense that an elevated absolute threshold, I_T, indicates a loss of sensitivity).

This reasoning assumes that an elevated absolute threshold at the probe frequency, I_T, reflects changes in cochlear sensitivity for neural fibers with a characteristic frequency (CF) near the probe frequency. That is, neural excitation by a probe tone begins when its intensity reaches absolute threshold at the probe frequency. It is further assumed that sensitivity of the same fibers to a low-frequency masker, at a frequency well below CF, can be inferred from the level of the low-frequency masker at which the CF threshold begins to be masked, which is specified by κ. This inference requires some knowledge about the masker/probe intensity ratio needed to reach masked threshold, which can be estimated from conditions in which both masker and probe stimuli are at the same frequency region.

In tuning-curve terms, a larger κ for a low-frequency masker indicates (for example) an elevated tail to the tuning curve, which indicates less sensitivity to masking by the low-frequency stimulus. The inverse, a smaller κ, indicates more sensitivity to masking, a situation referred to as hypersensitive tuning-curve tails (Salvi *et al.*, 1977; Cody and Johnstone, 1980; Liberman and Dodds, 1984). The most common results observed in physiological experiments involving moderate cochlear damage (Salvi *et al.*, 1977; Cody and Johnstone, 1980; Schmiedt and Zwislocki, 1980; Schmiedt *et al.*, 1980; Liberman, 1984; Liberman and Dodds, 1984) have been elevated tuning-curve tips and normal tail levels. The elevated thresholds at tuning-curves tips indicates a loss of sensitivity for CF tones, which should be reflected psychophysically by an elevated I_T. The demonstration of threshold levels at tail frequencies that were the same as in normal cochleas indicates normal sensitivity for tail-frequency tones, which should be reflected psychophysically by normal κ values for low-frequency maskers.

Because we wished to make comparisons of sensitivity to masking for ON-frequency conditions at different probe frequencies, it was necessary to adjust values of κ for equivalent effective power within an auditory-filter bandwidth at each probe frequency, as in

$$\kappa_{\mathrm{ERB}} = \kappa + 10 \log\{((\mathrm{ERB}/2) + 20)/\mathrm{BW}\}, \tag{5}$$

where ERB is the equivalent rectangular bandwidth of an auditory filter centered at the probe frequency (Glasberg and Moore, 1990), and BW is the masker bandwidth. This was done by assuming that the auditory filter was centered at the probe frequency, that the critical masking band extended to the upper edge of the masking band (20 Hz above the probe except at a probe frequency of 520 Hz), and that it extended to one-half an ERB below the probe. For the present purposes, ERB calculations in subjects with hearing loss were the same as those for normal-hearing subjects.

II. RESULTS

A. Typical growth-of-masking functions

To illustrate the adequacy of Eq. (3) for representing masked thresholds as a function of masker level, both for ON-frequency and OFF-frequency conditions, Fig. 2 shows typical growth-of-masking functions obtained from one normal-hearing listener (*hiwr*) and two hearing-impaired listeners (*jkhr* and *pjbr*). The fits to individual growth-of-masking functions using Eq. (3) are shown by the solid curves in each panel. Those curves represent the individual masked thresholds with considerable accuracy over the range of masker levels tested, which indicates that the parameters k, β, and I_T can accurately specify changes in individual masking curves from both normal-hearing and hearing-impaired listeners, including masked thresholds near abso-

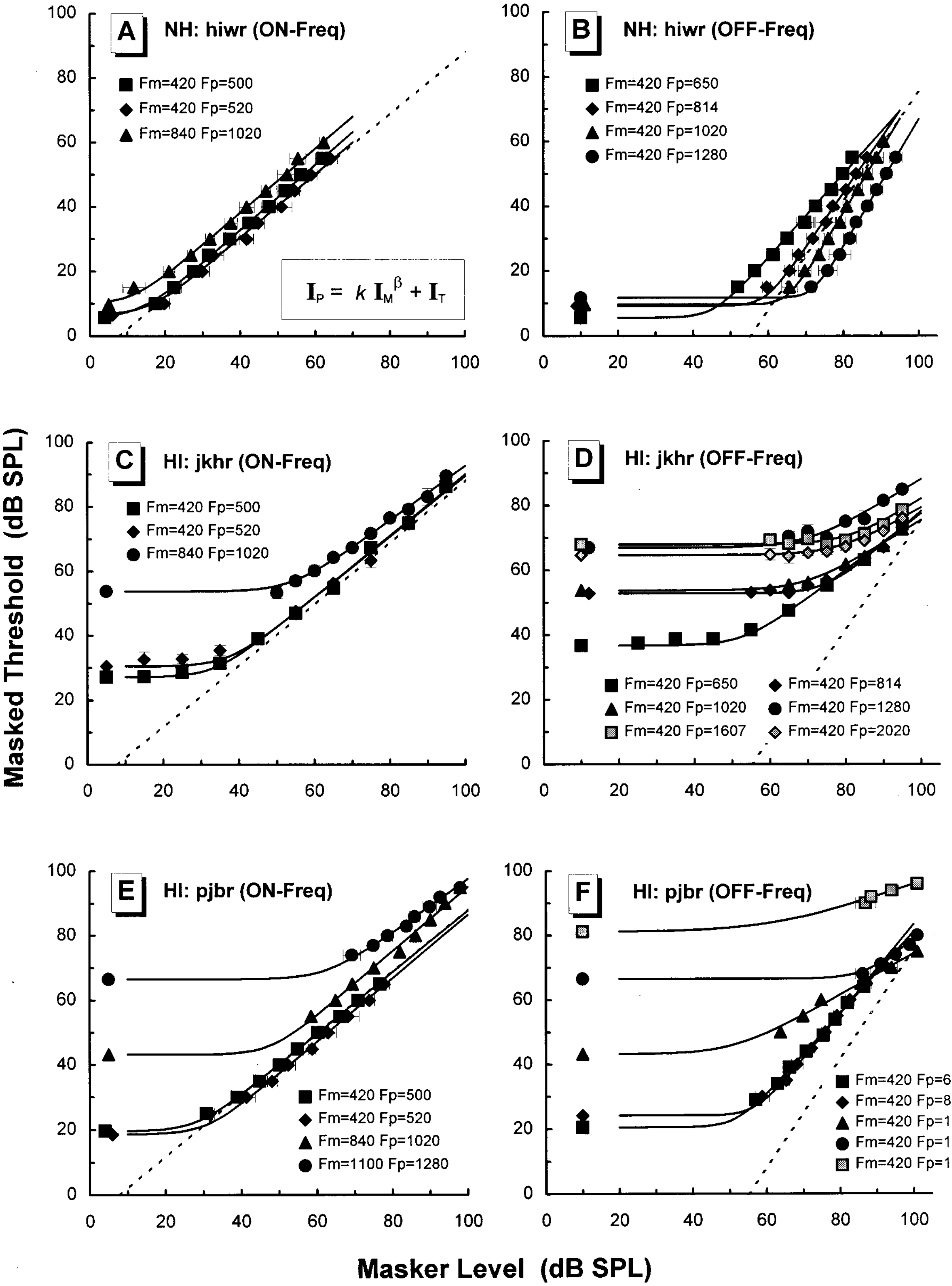

FIG. 2. Representative growth-of-masking functions for normal-hearing listeners (NH) and listeners with high-frequency sensorineural hearing loss (HI). Left panels: Growth-of-masking functions for ON-frequency masking conditions. Probe frequencies (Fp) and masker center frequencies (Fm) are labeled within each panel. Dashed lines show the average normal growth-of-masking slope of 0.96 dB/dB. Right panels: Growth-of-masking functions for OFF-frequency masking conditions. Dashed lines show the average normal growth-of-masking slope at 1280 and 1607 Hz of 1.67 dB/dB. Panels a and b show growth-of-masking functions from a listener with normal hearing (*hiwr*). Panels c and d, and panels e and f, show growth-of-masking functions from two listeners with sensorineural hearing loss (*jkhr* and *pjbr*, respectively). Solid curves in each panel are least-squares fits to the equation shown within panel a. The points to the left of each curve are the absolute thresholds at the probe frequency. Error bars indicate ± one standard deviation from the mean threshold.

lute probe threshold. The three normal-hearing listeners and four of the hearing-impaired listeners (*gmbl*, *pjbr*, *rehl*, *rwpr*) were tested with the fixed-probe-level procedure. The average standard deviation across repeated threshold estimates for both groups was 1.5 dB, with 95% of the standard deviations less than 2.6 dB. The remaining four hearing-impaired listeners were tested with the fixed-masker-level procedure. The average standard deviation across repeated threshold estimates for this group was 1.3 dB, with 95% of the standard deviations less than 2.4 dB. One standard deviation above and below each average masked-threshold estimate can be seen, for some of the functions in Fig. 2, as the horizontal (for fixed-probe-level data) or vertical (for fixed-masker-level data) error bars.

Figure 2 also illustrates the principal differences between growth-of-masking functions in normal-hearing and hearing-impaired listeners, which have been reported in the literature (Nelson and Bilger, 1974; Smits and Duifhuis, 1982; Stelmachowicz *et al.*, 1987; Murnane and Turner, 1991) and are the focus of a more detailed examination here. Slopes of the growth of masking for OFF-frequency conditions are more gradual in hearing-impaired listeners than in normal-hearing listeners. This can be seen by comparing the masking curves for a normal-hearing ear in Fig. 2(b) with the masking curves for hearing-impaired ears in Fig. 2(d) and (e). To facilitate comparisons, the average normal masking slope of 1.67 at 1280 and 1607 Hz (from Table III) is shown by the dashed line in each panel. Notice that masking curves from the two hearing-impaired ears in Fig. 2(d) and (e), at frequencies where absolute threshold is elevated, have dramatically shallower slopes than those from the normal-hearing ear in Fig. 2(b). By way of contrast, slopes of the growth of masking for ON-frequency conditions are essentially the same in hearing-impaired listeners and normal-hearing listeners. This is illustrated by comparing the masking curves for a normal-hearing ear in Fig. 2(a) with the masking curves for hearing-impaired ears in Fig. 2(c) and (e). For comparison, the average normal masking slope of 0.96 (from Table III) is shown by the dashed line in each panel. All masking curves are parallel to one another, except in a few cases where large amounts of hearing loss existed at the probe frequency [e.g., Fm=1100, Fp=1280 for *pjbr* in Fig. 2(e)].

B. ON-frequency growth-of-masking parameters

Since growth-of-masking parameters for ON-frequency conditions were not markedly different in hearing-impaired and normal-hearing ears, they will be examined briefly before OFF-frequency results are considered. Table II contains the fitting parameters β and κ_{ERB} for the ON-frequency masking conditions. For normal-hearing ears, average growth-of-masking slopes (β) varied between 0.93 and 0.99 across probe frequencies, but no significant trend across probe frequency was observed. The average slope across test frequency was 0.96. Similarly, the average masking sensitivity constant, specified by κ_{ERB}, which ranged between 6 and 13.8 dB SPL and averaged 8.7 dB, did not exhibit a significant trend across probe frequency. In both cases a single factor ANOVA failed to yield a significant effect of probe frequency ($p>0.19$).

TABLE II. Growth-of-masking parameters for ON-frequency conditions (signal within masker spectrum) from normal-hearing subjects (bold) and subjects with sensorineural hearing loss (italics). **Fm**=masker center frequency (200-Hz bandwidth for 420 Hz; 400-Hz bandwidth for others). **Fp** =probe frequency. β=growth-of-masking slope. $\kappa_{\mathbf{ERB}}$=level of masker (Lm) at probe threshold (Tp) where masking begins (in dB SPL), corrected for equivalent rectangular bandwidth (ERB).

	ON-frequency conditions (signal within masker spectrum)					
Fm=	420 Hz	420 Hz	840 Hz	1100 Hz	1427 Hz	1840 Hz
Fp=	500 Hz	520 Hz	1020 Hz	1280 Hz	1607 Hz	2020 Hz
Subject	β	β	β	β	β	β
hiwr	101	0.98	1.00	0.88	0.96	0.98
jlkr	0.87	0.99	1.07	1.05	0.99	0.96
rafr	0.94	0.93	0.90	0.91	0.95	0.87
NH Ave	**0.94**	**0.97**	**0.99**	**0.95**	**0.97**	**0.93**
gmbl	1.00	0.97	0.99	1.09	1.00	1.05
pjbr	0.95	0.98	1.00	0.83	⋯	⋯
rehl	0.95	0.94	0.98	0.91	0.95	1.07
rwpr	0.93	0.92	0.97	0.94	1.02	1.00
jkhr	0.95	0.94	0.84	0.95	0.72	0.95
rjcr	0.90	0.90	1.01	0.98	0.87	0.93
sxor	⋯	0.96	0.97	1.01	0.95	0.93
jpkr	0.96	0.98	1.00	0.99	0.94	1.00
jror	0.97	1.04	0.81	0.89	0.91	0.72
Subject	κ_{ERB}	κ_{ERB}	κ_{ERB}	κ_{ERB}	κ_{ERB}	κ_{ERB}
hiwr	7.5	8.0	4.1	9.2	16.9	16.1
jlkr	3.3	9.2	11.8	8.0	3.9	10.6
rafr	7.1	8.6	5.9	4.9	8.5	14.7
NH Ave	**6.0**	**8.6**	**7.1**	**7.3**	**9.7**	**13.8**
gmbl	13.9	17.4	9.6	22.1	32.6	46.9
pjbr	22.7	23.2	40.7	56.3	⋯	⋯
rehl	2.0	4.6	4.5	3.8	11.3	15.7
rwpr	16.7	19.5	12.3	12.2	26.1	28.9
jkhr	28.1	29.5	46.6	57.8	53.8	55.8
rjcr	44.6	40.9	56.3	56.3	59.2	58.8
sxor	⋯	13.0	10.1	24.8	44.3	53.2
jpkr	52.1	52.4	58.4	62.2	62.8	68.2
jror	55.0	56.9	54.1	58.9	61.3	57.3

Growth-of-masking slopes (β) for ON-frequency conditions were generally not different in hearing-impaired ears compared to those in normal-hearing ears. This is evident in Fig. 3(a), which shows slopes normalized to the average slope from normal-hearing ears at each probe frequency (β'), along with the 95% confidence limits expressed as ± 2.1 standard deviations ($N=18$) from the average slope across probe frequency (0.96). Normalized slopes are plotted as a function of probe threshold. Although most of the slopes were within the normal range, even when thresholds exceeded 60 dB SPL, some of the subjects with higher absolute thresholds at the probe frequency (>50 dB SPL) exhibited slopes that were at or below the lower limit of normal (−2.1 sd), e.g., see the masking curve for subject *pjbr* at Fm =1100, Fp=1280 in Fig. 2(e). These latter data points were largely responsible for the significant linear regression between normalized slopes and probe threshold [see inset, Fig. 3(a)].

The masker level at which masking begins in the hearing-impaired ear for ON-frequency conditions, expressed as the effective power within a normal auditory-filter

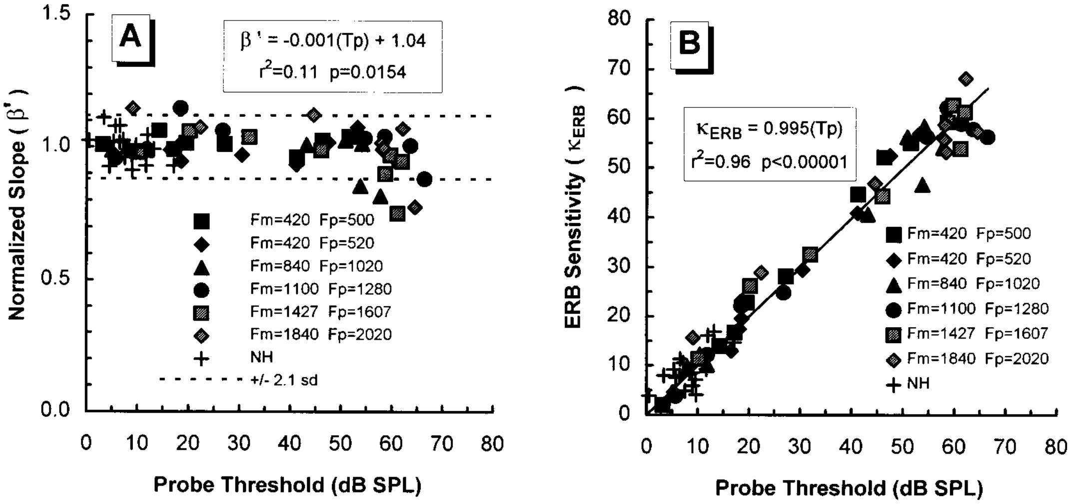

FIG. 3. Fitting parameters for growth-of-masking functions from normal-hearing and hearing-impaired listeners for ON-frequency masking conditions. Fm=center frequency of the masker. Fp=probe frequency. Data for normal-hearing (NH) subjects are shown by plus symbols. Data for hearing-impaired subjects are shown by filled symbols, coded by probe frequency. Panel a: Normalized slope (β') is the slope of the growth of masking normalized to the average slope obtained from normal-hearing ears at each probe frequency. Normalized slopes are plotted as a function of probe threshold. Results of a linear regression between normalized slope (β') and probe threshold (Tp) are given within the panel. Panel b: ERB sensitivity (κ_{ERB}), or masking sensitivity (κ) adjusted for equal power within an auditory-filter bandwidth at each probe frequency, is plotted as a function of probe threshold. ERB=equivalent rectangular-bandwidth (Moore and Glasberg, 1983). Results of a linear regression between ERB sensitivity (κ_{ERB}) and probe threshold (Tp), with the intercept forced through zero, are given within the panel. The dark solid line shows the linear regression with a slope of 0.995.

bandwidth, increased with increasing absolute threshold at the probe frequency. This is shown in Fig. 3(b) by the strong correlation ($r=0.98$) between the sensitivity constant κ_{ERB} and probe threshold. The fact that κ_{ERB} is a direct function of absolute probe threshold indicates that, in a hearing-impaired ear, masking begins when masker level is sufficient to elevate probe threshold in a normal ear to a level equal to the elevated absolute threshold in the hearing-impaired ear. The slope of this relation (0.995) is close to the average growth-of-masking slope in normal ears (0.96). This suggests that sensitivity to ON-frequency masking was not abnormal in these hearing-impaired listeners at the frequency regions where OFF-frequency masking was measured, i.e., critical ratios were within normal limits.

C. OFF-frequency growth-of-masking parameters

Growth-of-masking parameters for OFF-frequency conditions were noticeably different in hearing-impaired and normal-hearing ears. Table III contains the fitting parameters β and κ for the OFF-frequency masking conditions. In normal-hearing ears, average growth-of-masking slopes (β) varied with probe frequency from 1.32 at 650 Hz to 1.65 at 1020 Hz, remained relatively constant up to 1607 Hz, and then decreased to 1.28 at 2020 Hz. The largest growth-of-masking slope of 1.96 was exhibited by subject *hiwr* at a probe frequency of 1280 Hz. Masking sensitivity constants, κ, increased with probe frequency, which indicated that sensitivity to masking decreased with probe frequency, i.e., larger κ values indicated reduced sensitivity to masking. For OFF-frequency masking, the intercept k in Eq. (3) can be interpreted as the amount of reduction in masker intensity provided by the auditory filter at the probe frequency, and κ is inversely related to k by Eq. (4); therefore, the masking

TABLE III. Growth-of-masking parameters for OFF-frequency conditions (signal within masker spectrum) from normal-hearing subjects (bold) and subjects with sensorineural hearing loss (italics). **Fm**=masker center frequency (200-Hz bandwidth). **Fp**=probe frequency. β=growth-of-masking slope. κ=level of masker (Lm) at probe threshold (Tp) where masking begins (in dB SPL).

	OFF-frequency conditions (signal above masker spectrum)					
Fm=	420 Hz	420 Hz	420 Hz	420 Hz	420 Hz	420 Hz
Fp=	650 Hz	814 Hz	1020 Hz	1280 Hz	1607 Hz	2020 Hz
Subject	β	β	β	β	β	β
hiwr	1.30	1.68	1.92	1.96	1.75	1.28
jlkr	1.20	1.31	1.34	1.31	1.51	1.11
rafr	1.46	1.52	1.68	1.73	1.76	1.46
NH Ave	**1.32**	**1.50**	**1.65**	**1.67**	**1.67**	**1.28**
gmbl	1.51	1.93	1.87	1.53	1.60	0.76
pjbr	1.27	1.39	0.64	0.97	0.39	⋯
rehl	1.48	1.88	1.94	1.92	1.83	1.55
rwpr	1.49	1.41	1.91	1.74	1.42	1.05
jkhr	0.87	1.01	0.72	0.70	0.74	0.69
rjcr	0.94	0.97	0.56	0.56	0.58	0.45
sxor	⋯	⋯	1.56	1.41	0.82	0.77
jpkr	0.82	0.75	0.94	0.58	0.56	0.44
jror	0.84	0.76	0.65	0.66	0.94	0.57
Subject	κ	κ	κ	κ	κ	κ
hiwr	45.7	59.2	65.2	71.9	75.6	68.1
jlkr	44.9	53.7	57.5	61.3	67.5	60.3
rafr	51.4	56.8	69.2	72.6	76.9	78.2
NH Ave	**47.3**	**56.6**	**63.9**	**68.6**	**73.3**	**68.9**
gmbl	64.3	70.7	69.0	72.7	84.1	83.2
pjbr	52.1	57.2	51.5	87.6	62.5	⋯
rehl	47.5	58.5	61.7	65.6	68.1	68.8
rwpr	61.8	67.6	74.3	76.7	81.2	72.0
jkhr	53.2	74.9	69.7	69.9	81.1	78.8
rjcr	66.9	78.5	75.6	74.0	81.1	76.5
sxor	⋯	⋯	60.5	65.9	76.6	68.3
jpkr	65.0	72.7	79.5	78.2	82.6	79.3
jror	67.5	71.5	69.1	76.7	84.9	84.3

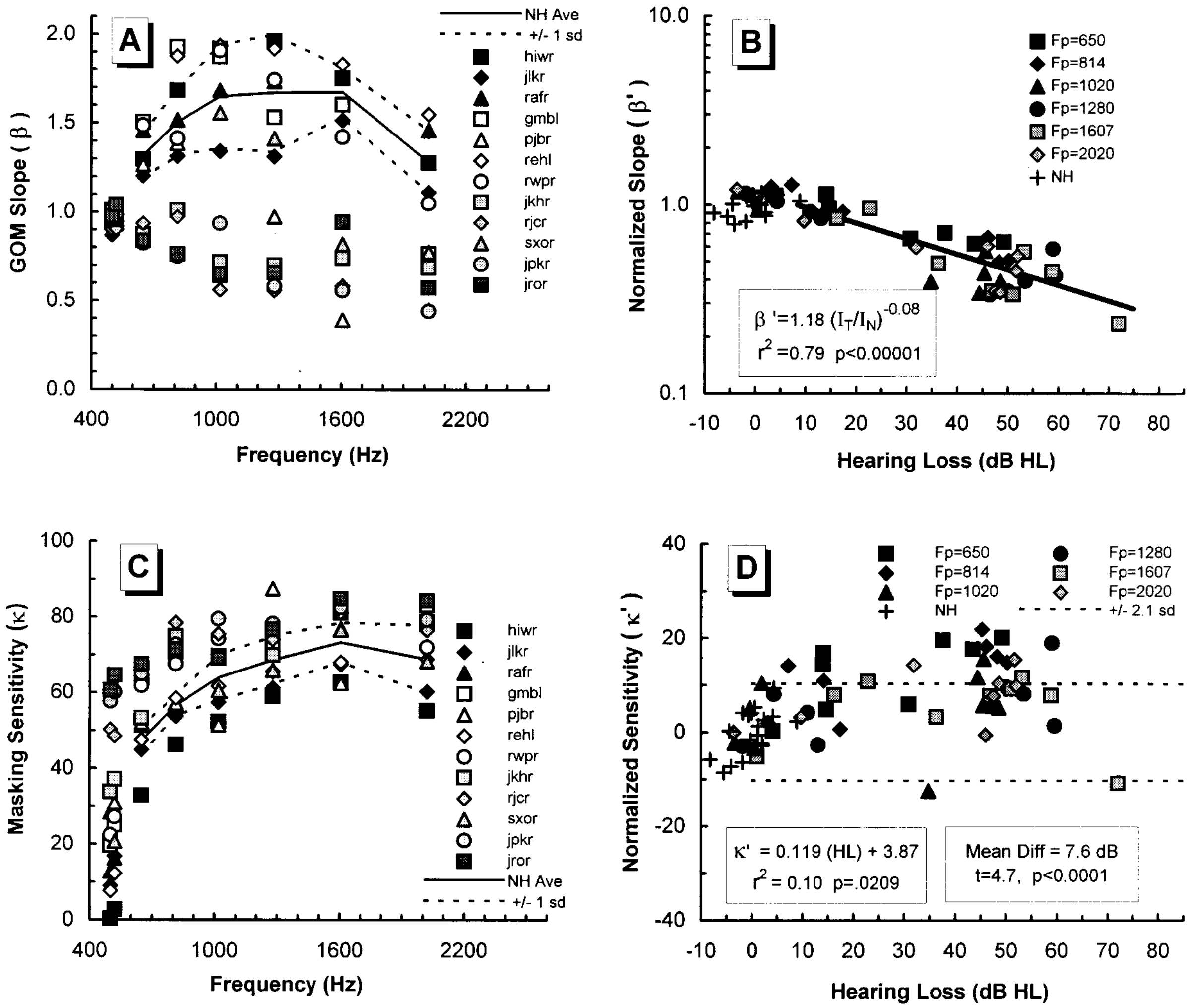

FIG. 4. Fitting parameters for growth-of-masking functions from normal-hearing and hearing-impaired listeners for OFF-frequency masking conditions. The masker was a 200-Hz-wide noise band with an upper edge at 520 Hz. Panel a: Growth-of-masking (GOM) slopes (β) as a function of probe frequency. Data for normal-hearing subjects are shown by dark filled symbols, with the average (NHave) shown by the solid line. Data for hearing-impaired subjects are shown by open and shaded symbols coded by subject. Data derived from ON-frequency masking (Fp=500 and 520 Hz) are also shown for comparison. Panel b: Normalized slopes (β'), which are GOM slopes (β) relative to the average normal-hearing slopes at each probe frequency, are plotted as a function of amount of hearing loss. Data for normal-hearing (NH) subjects are shown by plus symbols and data for hearing-impaired subjects are shown by filled symbols coded by probe frequency. The straight line is the best-fitting least-squares regression to the data, the results of which are included within the inset. Panel c: Masking sensitivity (κ) plotted as a function of probe frequency. Data derived from ON-frequency masking (Fp=500 and 520 Hz) are also shown for comparison. Panel d: Normalized sensitivity (κ'), the difference between κ and the average κ from normal-hearing ears at each probe frequency, as a function of the amount of hearing loss. Statistics of the regression and of the group differences are shown within the insets. Dashed lines indicate 95% confidence limits (±2.1 sd).

sensitivity constant κ can be thought of, at least in part (ignoring signal-to-noise ratio at masked threshold), as the attenuation (in decibels) of masker effectiveness by the auditory filter at the probe frequency. Larger values of κ indicate more attenuation by the auditory filter and, consequently, *less sensitivity* to OFF-frequency masking. Thus, as probe frequency increased above the edge of the masker, attenuation in masker intensity provided by the auditory filter increased from 47 dB at 650 Hz to 69 dB at 2020 Hz, which would be expected for increased frequency distance between masker and probe given a fixed set of filter characteristics.

Growth-of-masking slopes (β) from hearing-impaired listeners for OFF-frequency conditions were sometimes more gradual (shallower) than in normal-hearing ears at the same probe frequencies. Figure 4(a) shows growth-of-masking slopes as a function of probe frequency. Six of the hearing-impaired listeners (*pjbr*, *jkhr*, *rjcr*, *sxor*, *jpkr*, and *jror*) exhibited growth-of-masking slopes more gradual than normal at most of the probe frequencies. These subjects had substantial hearing losses at those probe frequencies. The other three hearing-impaired listeners (*gmbl*, *rehl*, and *rwpr*), who had normal-hearing or mild hearing losses at the probe frequencies, exhibited growth-of-masking slopes well within or above the range of normal (except for *gmbl* at 2020 Hz). Steep growth-of-masking slopes were exhibited in these subjects, despite the fact that they had substantial hearing losses at higher frequencies. This suggests that hearing loss above the probe frequency does not reduce growth-of-masking slopes at the probe frequency; if anything, it may increase them, as will become apparent later.

Figure 4(b) shows normalized growth-of-masking slopes (β') as a function of the amount of hearing loss at the probe frequency. Slopes for individual ears were expressed relative to the average slope in normal-hearing ears at each probe frequency, thereby removing the confounding effects of slope changes with probe frequency seen in Fig. 4(a). Those normalized slopes were then fit to a power function of probe threshold intensity (I_T) relative to average normal threshold intensity (I_N) as in

$$\beta' = \mathbf{m}(I_T/I_N)^{\mathbf{n}}, \tag{6}$$

where **m** and **n** are fitting constants. Figure 4(b) shows that growth-of-masking slopes decreased in an orderly fashion as hearing loss increased. A least-squares regression indicated that a significant inverse relation ($p<0.00001$) existed between growth-of-masking slope and hearing loss [see inset in Fig. 4(b)]. Growth-of-masking slopes decreased by a factor of 0.83 ($10^{\mathbf{n}=-0.08}$) for every 10-dB increase in amount of hearing loss. For a hearing loss of 8.4 dB the normalized slope predicted by Eq. (6) was 1.0; for a hearing loss of 75 dB the normalized slope was 0.3. These results indicate that hearing loss at the probe frequency reduced the slope of the growth of masking in a predictable way. Given an elevated probe threshold, reduced growth-of-masking slopes can be predicted by Eq. (6) with some degree of accuracy, irrespective of probe frequency.

Notice also in Fig. 4(b) that data from hearing-impaired ears who had normal-hearing or mild hearing losses at probe frequencies below 1500 Hz (*gmbl*, *rehl*, and *rwpr*) exhibited growth-of-masking slopes that tended to be slightly larger (steeper), at probe frequencies of 814, 1020, and 1280 Hz, than those from normal-hearing ears (see Table III). This is reflected by $\mathbf{m}=1.18$ from the regression between β' and I_T/I_N [see inset in Fig. 4(b)], and could have been largely due to the data from only one subject, *rehl*, who exhibited absolute thresholds better than 10 dB HL at all the probe frequencies below 3 kHz and sizable hearing losses above 3 kHz. However, an additional regression between β' and I_T/I_N, without subject *rehl*, yielded essentially the same regression parameters. This suggests that, for OFF-frequency conditions, growth-of-masking slopes in regions of normal hearing may tend to be slightly steeper when hearing loss exists at higher frequency regions. This finding should be considered with some caution, however, because only three normal-hearing ears were tested. Had more been tested, perhaps some of them would have exhibited slopes as large as, or larger than, subject *hiwr*.

Sensitivity to OFF-frequency masking was slightly reduced in hearing-impaired listeners. Figure 4(c) shows the sensitivity constant, κ, as a function of probe frequency. The average values of κ in normal-hearing ears, along with the 95% confidence limits specified by ±2.1 standard deviations, are shown in the figure for comparison. Values of κ for listeners with hearing loss tended to be slightly larger than for listeners with normal hearing, particularly at probe frequencies of 650 and 814 Hz, which indicates reduced sensitivity to masking at those probe frequencies (larger κ values reflect poorer sensitivity to OFF-frequency masking).

Figure 4(d) shows normalized masking sensitivity constants (κ') as a function of probe threshold for normal-hearing and hearing-impaired ears. Sensitivity constants (κ) for individual ears are expressed relative to the average in normal-hearing ears at each probe frequency, thereby removing the confounding effects of changes with probe frequency seen in Fig. 4(c). Figure 4(d) shows that normalized sensitivity constants increased moderately with increased hearing loss. A linear least-squares regression indicated a significant relation ($p=0.02$) existed between normalized sensitivity and probe threshold [see inset in Fig. 4(d)]. As a group, sensitivity constants exhibited by listeners with hearing loss were significantly larger than normal ($t=4.7$, $p<0.0001$). On average, listeners with hearing loss exhibited sensitivity constants that were 7.6 dB larger than normal, which indicates that sensitivity to masking at frequency regions above the masker is slightly *reduced* compared to listeners with normal hearing, i.e., masker levels required to produce elevated probe thresholds were, on average, about 7 dB greater than those required in normal-hearing ears.

III. DISCUSSION

A. Growth of masking for OFF-frequency masking conditions

1. More gradual growth-of-masking slopes in the presence of hearing loss

The principal finding of the present study is that, once signals are amplified to overcome the sensitivity loss associated with a cochlear hearing loss, growth-of-masking slopes for upward spread of masking decrease with hearing loss in a predictable way. Three previous studies reported growth-of-masking slopes from listeners with sensorineural hearing loss in sufficient detail to allow accurate comparisons with the present results. Figure 5 shows the growth-of-masking slopes obtained in those studies. They are replotted here in the same form as the present data [Fig. 4(a)], except that slopes are plotted as a function of frequency ratio between probe and masker because the three studies used different maskers. Figure 5(a) shows results from Smits and Duifhuis (1982), who reported growth-of-masking functions from three listeners with sensorineural hearing loss, along with average growth-of-masking functions from two normal-hearing listeners. They used a 50-Hz-wide noise band centered at 1 kHz as a masker. Growth-of-masking functions from their figure 4 were digitized and fit to Eq. (3) to derive growth-of-masking parameters. Figure 5(b) shows results from Stelmachowicz *et al.* (1987), who reported growth-of-masking slopes from five hearing-impaired ears along with the average slopes from five normal-hearing ears. They used 100-Hz-wide noise bands as maskers and a probe tone at 2000 Hz. Figure 5(c) shows results from Murnane and Turner (1991), who obtained growth-of-masking functions from nine listeners with sensorineural hearing loss and three normal-hearing listeners, using a $\frac{1}{3}$-oct band of noise centered at 1 kHz as a masker. They fitted their growth-of-masking functions using only those masked thresholds greater than 5 dB above absolute probe threshold, and reported the growth-of-masking slopes they obtained from each listener.

From Fig. 5, it is apparent that the overall pattern of results is similar across these three studies employing different masker frequencies and masker bandwidths, and it is similar to that seen in the present study [see Fig. 4(a)]. For comparison purposes, slopes from normal-hearing ears in the present study are plotted in each panel (shaded squares). In

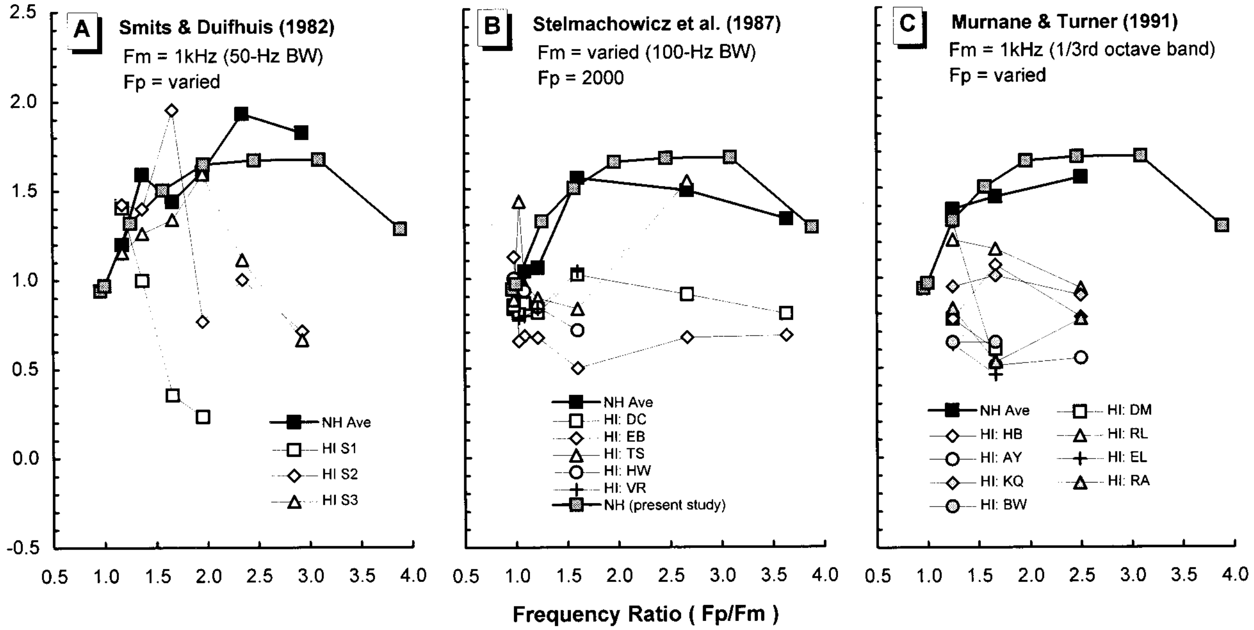

FIG. 5. Growth-of-masking slopes from three previous studies of upward spread of masking, plotted as a function of the frequency ratio between probe frequency and the upper-edge frequency of the masking band. Dark filled squares are the average slopes obtained from normal-hearing listeners in each study (NH Ave). Shaded squares are the average slopes obtained from normal-hearing listeners in the present study. Other unfilled and shaded symbols are for hearing-impaired listeners from each study coded by subject. Fp=frequency of the probe. Fm=center frequency of the masker (bandwidth in parentheses).

normal-hearing ears, growth-of-masking slopes are near 1.0 where probe and masker spectra overlap. Growth-of-masking slopes increase as the probe/masker frequency ratio increases, until, at a frequency ratio of 2.0 and above the average slope reaches asymptote around a slope of about 1.67. In hearing-impaired ears, growth-of-masking slopes tend to cluster around a slope of 1.0 where probe and masker spectra overlap, and as probe/masker frequency ratio increases the slopes tend to remain near unity or become more gradual. Considerable variability exists between individual hearing-impaired listeners, which reflects the degree of hearing loss at the probe frequency, as shown below.

Figure 6(a) shows normalized slopes (β') as a function of amount of hearing loss, calculated for data from two of the previous studies and the present study. Notice that normalized slopes from the previous studies essentially overlay

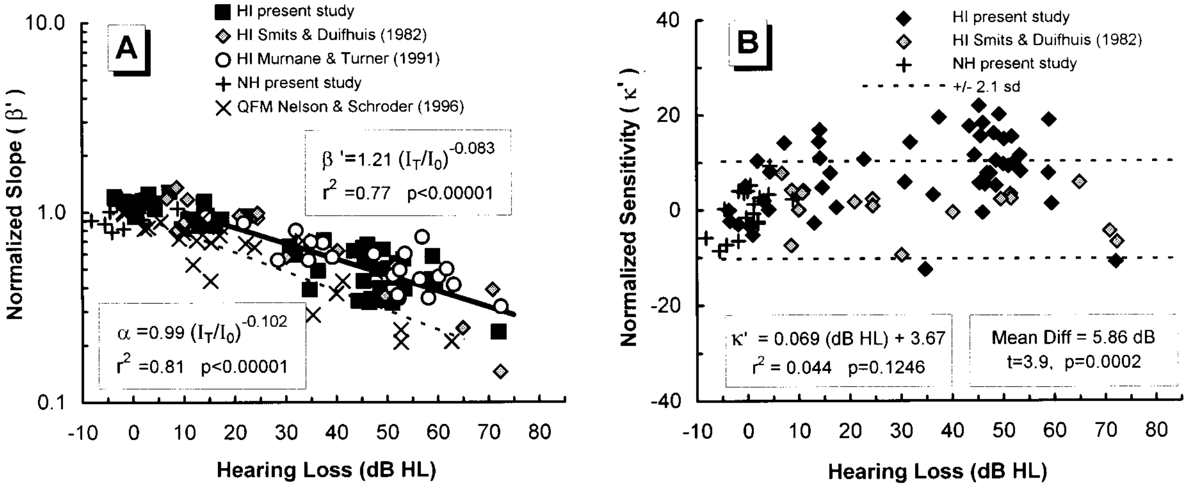

FIG. 6. Growth-of-masking fitting parameters from the present study and two previous studies of upward spread of masking. Dark symbols=data for hearing-impaired subjects from the present study. Shaded symbols=data for hearing-impaired subjects from Smits and Duifhuis (1982). Open symbols=data for hearing-impaired subjects from Murnane and Turner (1991). + symbols=data for normal-hearing subjects from the present study. Panel a: Normalized growth-of-masking slopes (β') plotted as a function of amount of hearing loss (dB HL). The least-squares regression line is shown for the combined subjects (solid line), with the regression results included in the upper inset. × symbols=slope-reduction factors (α) from Nelson and Schroder (1996). Dashed line=regression line for α, with regression parameters given within the lower inset. Panel b: Normalized sensitivity constant (κ') plotted as a function of amount of hearing loss (dB HL), where $\kappa' = \kappa_{\mathrm{HI}} - \kappa_{\mathrm{NH}}$ (average κ for normal-hearing ears subtracted from κ for an individual hearing-impaired ear, at the same probe frequency). Statistics of the regression and of the group differences in κ' are shown within the insets. Thin dashed lines indicate 95% confidence limits (± 2.1 sd).

the normalized slopes obtained in the present study. The parameters defining changes in normalized slope as a function of hearing loss for the previous studies essentially fell on either side of the parameters for the present data. Least-squares regressions between β' and hearing loss, Eq. (6), yielded values of **m** of 1.42 and 1.15 for the Smits and Duifhuis (1982) and the Murnane and Turner (1991) data, respectively, compared to 1.18 for data from the present study and values of **n** of -0.10 and -0.07, respectively, compared with -0.08 for the present data. Thus, there is remarkably good agreement between the results of three separate investigations of the growth of masking for upward spread of masking, despite nearly an octave difference in the frequency region over which measurements were made (520-Hz upper edge in the present study and 1-kHz center frequencies for the other two studies). As indicated within the upper inset of Fig. 6(a), a least-squares regression of the combined data using Eq. (6) yields the fitting constants: $\mathbf{m}=1.21$ and $\mathbf{n}=-0.083$. This indicates that normalized slopes decrease by a factor of 0.83 ($10^{\mathbf{n}}$) for every 10 dB of hearing loss. With a 10-dB hearing loss at the probe frequency, but hearing loss at higher frequencies, the predicted normalized slope is 1.0. For a hearing loss of 75 dB, the predicted normalized slope is 0.3.

Such good agreement among studies with different maskers suggests that the parameters derived from growth-of-masking slopes in the present study should allow accurate predictions of upward spread of masking in persons with sensorineural hearing loss to be made from measurements of upward spread of masking slope in normal-hearing ears using a wide range of maskers. Given the growth of masking slope in normal-hearing ears, for a specific low-frequency masker and a higher-frequency probe, the predicted slope can be obtained from Eq. (6) using the values of $\mathbf{m}=1.21$ and $\mathbf{n}=-0.083$ and the amount of hearing loss at the probe frequency. Further research is needed to test this possibility.

These results support the inferences about growth-of-masking slopes made by Nelson and Schroder (1996), who determined that reduced masking release by envelope fluctuations in listeners with hearing loss could be accounted for by a presumed reduction in the slope of the growth of masking. Although they did not measure growth-of-masking slopes, the slope-reduction factors they derived to fit their data implied that growth-of-masking slopes should be inversely proportional to the amount of hearing loss. The slope-reduction factors (α) they derived to fit their QFM-masker data are replotted in Fig. 6(a) (× symbols) for comparison with the normalized growth-of-masking slopes (β') obtained in the present study. As indicated within the lower inset of Fig. 6(a), a least-squares regression for α using Eq. (6) yields the fitting constants: $\mathbf{m}=0.99$ and $\mathbf{n}=-0.102$. This indicates that growth-of-masking slopes implied by α decreased by a factor of 0.79 for every 10 dB of hearing loss. The actual reduction in growth-of-masking slopes combined across the three studies evaluated here was slightly less, at 0.83 for every 10 dB of hearing loss. When fit with the linear equation used previously by Nelson and Schroder (1996), the fitting parameters compare favorably with the parameters shown in Eq. (2): $\beta'=-0.129(\mathrm{HL})+1.13$. The change in growth-of-masking slopes with hearing loss observed in the present study is essentially the same as that predicted by Nelson and Schroder to account for reduced masking release in regions of hearing loss. They suggested that masking release was reduced in hearing-impaired ears because growth-of-masking slopes decrease with amount of hearing loss, which implies an increase in response growth with amount of hearing loss. Thus, the ''linearized response growth'' explanation for reduced masking release offered by Nelson and Schroder would appear to be reasonable.

2. Steeper slopes at normal-hearing frequencies with hearing loss at higher frequencies

A value of $\mathbf{m}=1.21$ for the combined data implies that growth-of-masking slopes at probe frequencies with normal hearing (0 dB HL) are larger (steeper) than normal when hearing loss exists at higher frequencies. This implies that high-frequency hearing loss may affect slopes in regions of normal hearing at lower frequencies. One explanation for this may be that normal-hearing growth-of-masking slopes are limited by tails of excitation patterns at higher probe levels. At higher probe levels, growth of response at the peak of the probe excitation pattern may be limited by compression, while growth of response at the high-frequency tail of the probe excitation pattern may be more linear because of the lower excitation levels on the tail of the excitation pattern. Steeper probe response growth should result in more gradual growth of masking. Thus, the slope of the growth of masking might be reduced by the steeper response growth at higher frequency regions. The tendency toward steeper slopes from hearing-impaired ears, with near normal probe thresholds but considerable hearing loss at higher frequencies, may reflect the reduced extent of excitation-pattern tails in regions of high-frequency hearing loss (Schroder *et al.*, 1994). Further research with high-pass noise to mask excitation pattern tails in normal-hearing ears might provide some insight into this phenomenon.

3. Reduced masking sensitivity in ears with hearing loss

Another finding of the present study was that the sensitivity constant (κ), was slightly larger in ears with hearing loss than observed in ears with normal hearing. This suggests that sensitivity to upward spread of masking is slightly *reduced* from what is observed in ears with normal hearing (a larger κ value indicates less sensitivity to masking). Figure 6(b) shows normalized sensitivity ($\kappa'=\kappa_{\mathrm{HI}}-\kappa_{\mathrm{NH}}$) from the present study compared with the same parameters from the growth-of-masking functions obtained by Smits and Duifhuis (1982). Masking sensitivity in their hearing-impaired subjects did not differ significantly from masking sensitivity exhibited by their average normal curve. However, even when their data are combined with ours the mean difference in masking sensitivity of 5.86 dB, between normal-hearing and hearing-impaired data, reaches statistical significance ($t=3.9$, $p=0.0002$).

The slightly larger κ values from subjects with hearing loss could be interpreted as indicating they required a larger signal-to-noise ratio at masked threshold than did the normal-hearing subjects. However, the earlier analysis of ON-frequency sensitivity constants showed that critical ratios were essentially normal. This reduced masking sensitivity (larger κ values) could also be interpreted as sharper filtering by the auditory filter at these probe frequencies, which is contrary to expectations of reduced auditory filtering in the presence of a hearing loss. However, the fact that larger κ values than normal tend to occur at 650 and 814 Hz [Fig. 4(c)], and the fact that they occur for subjects with the highest probe thresholds at those frequencies ($rjcr$ and $jkhr$), suggests an alternative interpretation. If masking at 650 and 814 Hz involved spread of physical energy to those frequency regions, as is the case for ON-frequency masking, then one would expect elevated κ values based on the results presented earlier for ON-frequency masking, which indicated that ON-frequency masking does not begin until the masker level is equal to probe absolute threshold [Fig. 3(b)].

It should also be noted that the present method of estimating κ, which involves extrapolation to probe threshold, can be problematic when the slopes of the growth-of-masking vary across subjects. However, in the present case, slopes of the growth-of-masking in hearing-impaired ears were more gradual, which would tend to lower estimates of κ, not elevate them.

Nevertheless, these results demonstrate that upward of spread of masking in the hearing-impaired ear begins at slightly higher masker levels than in the normal-hearing ear. This *does not* support the idea that listeners with hearing loss are more susceptible to upward spread of masking (threshold shift), or that they are hypersensitive to excitation by maskers on the tails of tuning curves, or that a low-frequency masker actually produces more excitation at higher frequencies in an ear with hearing loss. The higher masked thresholds observed in regions of hearing loss, which have been interpreted as excessive upward spread of masking, are primarily due to an elevated absolute threshold at the probe frequency, I_T in Eq. (3), which is associated with a loss of sensitivity (cochlear gain) at the probe frequency only. Sensitivity to masking by low-frequency sounds is not dramatically affected, or, if it is, there is a slight decrease in sensitivity (slightly higher masker levels are needed).

4. Estimating response-growth exponents in hearing-impaired ears

Recently, animal studies have revealed changes in the basilar membrane (BM) transfer function associated with cochlear damage, which are consistent with the more gradual growth-of-masking slopes observed here in regions of hearing loss. Both BM studies (Yates *et al.*, 1990; Ruggero and Rich, 1991; Ruggero *et al.*, 1993, 1996) and neurophysiological studies (Sachs and Abbas, 1974; Harrison, 1981; Gorga and Abbas, 1981a, 1981b) report results consistent with the concept that, in normal-hearing ears, excitation by a tone at its characteristic frequency (CF) involves a relatively *nonlinear* (compressed) BM transfer characteristic (exponent <1), whereas excitation by a tone much lower in frequency (below CF) involves a more *linear* basilar membrane transfer characteristic (exponent $\cong 1$). In ears with cochlear damage, threshold is elevated and the BM transfer characteristic is ''linearized'' (Ruggero and Rich, 1991; Ruggero *et al.*, 1993, 1996), presumably because the active gain mechanism is disrupted. This suggests that excitation by a probe tone in a region of hearing loss is subject to a more *linear* BM transfer characteristic than in a region of normal hearing (Stelmachowicz *et al.*, 1987; Oxenham and Moore, 1995; Moore, 1996; Oxenham and Moore, 1996). This ''linearized response growth'' (LRG) associated with cochlear damage should lead to steeper than normal response growth (sensory excitation) to a probe tone in the region of hearing loss, which, according to the following reasoning, would translate to a more gradual slope to the growth of upward spread of masking.

If it is assumed that masked threshold for a probe tone is reached when the response to the probe tone (R_p) exceeds the response to the masker (R_M) by some critical ratio (k), as in

$$k=R_P/R_M, \tag{7}$$

then it can be shown that the growth-of-masking slope, (β) reflects the LRG characteristic of cochlear damage. Response growth to a probe tone or a masker can be represented as a power function of stimulus intensity relative to absolute threshold at the probe frequency (I_T), as in

$$R_P=(1+I_P/I_T)^{\mathbf{p}} \quad \text{and} \quad R_M=(1+I_M/I_T)^{\mathbf{q}}, \tag{8}$$

with $\mathbf{p}$ and $\mathbf{q}$ reflecting exponents for BM transfer characteristics for the probe and masker, respectively. Given these relations, one can then solve for the intensity of a probe at masked threshold as in

$$I_P=((k(1+I_M/I_T)^q)^{1/p}-1)*I_T, \quad \text{or} \tag{9a}$$

$$I_p=(k^{1/p}(1+I_M/I_T)^{\beta}-1)*I_T, \quad \text{with} \quad \beta=\mathbf{q}/\mathbf{p}. \tag{9b}$$

Since the BM transfer function for a low-frequency masker at a higher-frequency place is assumed to be relatively linear, one can set $\mathbf{q}\cong 1$. Then $\mathbf{p}$ becomes proportional to $1/\beta$. In a normal ear, the nonlinear BM transfer function for a probe tone at some frequency above the masker would lead to a value of $\mathbf{p}<1$; therefore, the slope of the growth of masking β_{NRM}, would be greater than 1. In an ear with sufficient hearing loss to affect the active gain process, the BM transfer function is linearized, which would lead to a value of $\mathbf{p}\cong 1$; therefore, the slope of the growth of masking, β_{HLS}, would be more gradual than in a normal ear ($\cong 1$). Thus, it appears that the LRG associated with cochlear hearing loss may increase the response growth exponent for the probe tone ($\mathbf{p}$) but not for the masker ($\mathbf{q}$); consequently, the slope of the growth of masking (β_{HLS}) is reduced from what it is in the normal-hearing ear.

Unfortunately, response growth to a probe tone ($\mathbf{p}$) in a hearing-impaired ear cannot be directly estimated by $1/\beta$ values for all of the probe frequencies tested in the present study, because the probe/masker frequency ratios used here varied from 1.25 up to 3.88, and $\mathbf{q}=1$ can only be assumed for large probe/masker frequency ratios, perhaps ratios of 2.0 or greater. However, one can estimate response growth for probe and masker in a normal ear at each probe frequency, and then specify response growth in the impaired ear from the change in growth-of-masking slopes relative to normal at

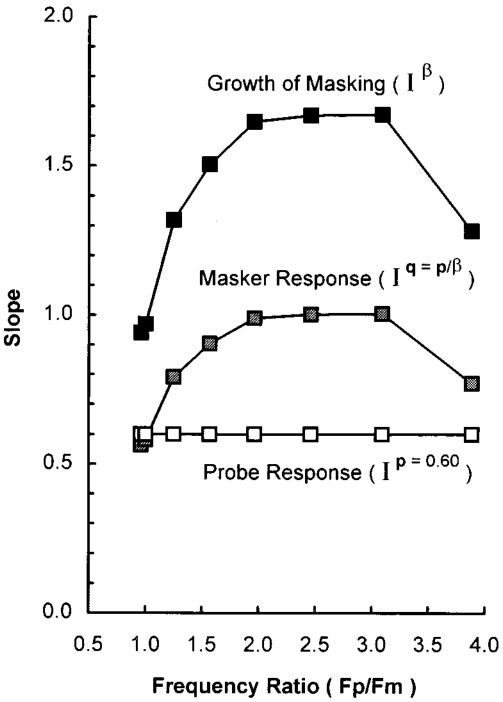

FIG. 7. An illustration of how slopes for probe response growth (**p**) and masker response growth (**q**) were inferred from growth-of-masking slopes (β) in normal-hearing ears. From Eqs. (7)–(9) growth-of-masking slopes were shown to be related to slopes of masker and probe response growth by β=**q**/**p**. Based on reports of basilar membrane measurements in the literature, probe response growth (**p**) was calculated by assuming **q**=1 (linear masker response growth) for large frequency ratios between probe and masker, then **p** became $1/\beta$ and masker response growth became **q**=**p**/β.

each probe frequency. In this way one obtains an estimate of normalized response growth, which can be examined independent of probe frequency.

Estimation of probe and masker response growth from growth-of-masking slopes in the normal-hearing ear is illustrated in Fig. 7. The upper curve shows growth-of-masking slopes from the average normal-hearing ear as a function of frequency ratio between probe and masker. For frequency ratios of 2.0 and larger, the average growth-of-masking slope is around 1.67. At these large probe/masker frequency ratios, the assumption of **q**=1 is reasonable, thus the growth of response to the probe tone (**p**) becomes $1/\beta$, or **p**≅0.60. As indicated by the bottom curve, it is also reasonable to assume that response growth for a probe tone is the same (**p**≅0.60) at all probe frequencies over this limited range of probe frequencies, even though compression varies with level, because the probe levels at masked threshold are all roughly within the same range for all probe frequencies. Then, from Eq. (9), response growth for the masker (**q**) at different probe/masker frequency ratios becomes **p**/β. The middle curve in Fig. 7 shows that response growth to the masker increases from just below 0.60 where probe and masker spectra overlap to 1.0 for large frequency ratios. When the masker and probe are close together they are both subjected to the same compressive nonlinearity given by the 0.60 exponent. Since the slope of the growth of masking (β) is given by **q**/**p**, the growth-of-masking slope is near 1.0. As the masker is moved farther from the probe, toward lower frequencies, it is subjected to less nonlinearity and its response growth approaches linearity. Thus, at large probe/masker frequency ratios, the growth-of-masking slope becomes 1.0/0.60, or 1.67.

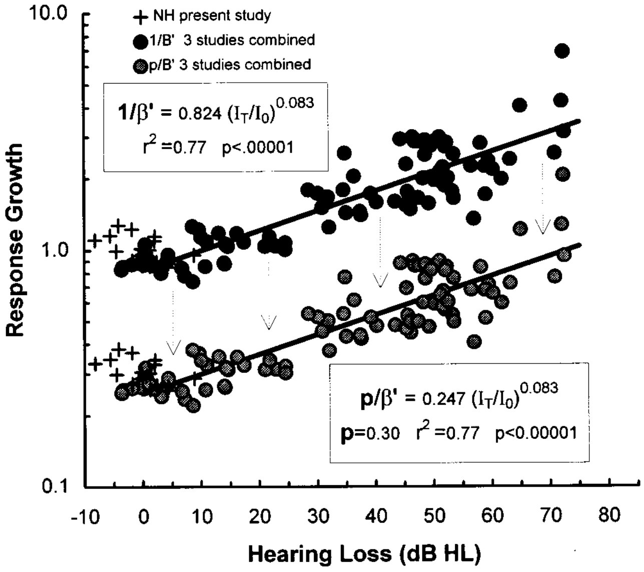

FIG. 8. Response growth normalized to average response growth from normal-hearing listeners at each test frequency (**1**/β') is shown for the normal-hearing listeners in the present study (+ symbols) and for the hearing-impaired listeners combined from three studies (dark filled circles). If normal-hearing response growth at the probe frequency is *assumed* to have a slope of **p**=0.30, then response growth (**p**/β') in ears with hearing loss (shaded symbols) varied from 0.25 at 0 dB HL (normal compression) to 1.0 at 75 dB HL (linear response growth). Regression statistics are shown within the insets.

At the largest frequency ratio (3.88) where the probe frequency is at 2020 Hz, the average growth-of-masking slope decreased to 1.28. The masker levels are about the same as those required for the next lower probe frequency (1607 Hz), as indicated by the values of κ in Fig. 4(c), the probe levels at masked threshold are within the same range, and the growth-of-masking functions were as well fit by Eq. (3) as at the lower probe frequencies, yet growth-of-masking slopes were reduced. We can find no adequate explanation for this result, except that the acoustic reflex may have attenuated the low-frequency masker more than the higher-frequency probes. If that were so, one might expect to see some roll-over in the individual masking functions at higher masker levels where the acoustic reflex might begin to play a role. That, however, was not the case for any of the individual masking functions at 2020 Hz. Of the four studies examined here, only the Stelmachowicz *et al.* (1987) study examined frequency ratios as large [Fig. 5(b)]. Their slopes also showed a tendency to be reduced slightly at large frequency ratios. Further research is needed to explain the reduction in masking slope at very large probe/masker frequency ratios.

Relative response growth at the probe frequency in hearing-impaired ears can be estimated from the change in observed masking slopes relative to the slopes obtained from normal-hearing ears. Response growth relative to normal hearing is illustrated in Fig. 8. The upper set of data points in Fig. 8 (solid circles) shows relative response-growth exponents ($1/\beta'$) calculated from the normalized growth-of-masking slopes (β') combined from three studies and shown in Fig. 6(a). It can be seen that relative response-growth exponents increase as a power function of threshold intensity relative to normal threshold intensity (see upper inset). Relative response-growth exponents vary from near normal at 0 dB HL to more than three times normal at 70 dB HL. This reasoning suggests that response growth increases by a factor of about 1.2 for every 10 dB of hearing loss ($10^{0.083}$).

Values of $\mathbf{p}/\beta'$ can provide estimates of absolute response-growth exponents in hearing-impaired ears, if one assumes an average value for the response growth exponent ($\mathbf{p}$) in normal-hearing ears. In Fig. 7 a value of $\mathbf{p}=0.60$ was derived for normal probe response growth by assuming $\mathbf{q}=1$ for large probe/masker frequency ratios. This value of $\mathbf{p}$ yields estimates of absolute response-growth exponents in hearing-impaired ears from around 0.60 at 0 dB HL to around 2.0 at 75 dB HL. A response-growth exponent of 2.0 for a hearing loss of 75 dB is inconsistent with BM measurements that suggest the system is linear ($\mathbf{p}=1.0$) in the presence of cochlear damage (Ruggero and Rich, 1990, 1991; Ruggero *et al.*, 1993, 1996). Thus it appears that our response growth estimates are in error by about a factor of 2. If our estimate of normal-hearing $\mathbf{p}$ is reduced by a factor of 2 (to $\mathbf{p}=0.30$), then absolute response growth estimates in hearing-impaired ears become consistent with BM transfer characteristics. This is shown by the bottom set of data points in Fig. 8, which show $\mathbf{p}/\beta'$ calculations as a function of amount of hearing loss, with $\mathbf{p}=0.30$. With a factor of 2 adjustment to the exponent for normal response growth, response-growth exponents in hearing-impaired ears vary from around 0.25 at 0 dB HL to around 1.0 at 75 dB HL. Now response growth is linear for a large sensorineural hearing loss, which is consistent with BM transfer characteristics in the presence of cochlear damage. Furthermore, normal response growth at the probe frequency is more consistent with BM transfer characteristics found in undamaged cochleas ($\mathbf{p}=0.20$) and it is also consistent with exponents for the growth of loudness in normal-hearing ears ($\mathbf{p}=0.30$).

One possible complicating factor might be our failure to take suppression mechanisms into account (Javel *et al.*, 1983; Delgutte, 1990). The BM transfer characteristics were measured with single tones that would not reflect suppression. The simultaneous-masking measures made here from normal-hearing ears most certainly involved suppression by the masker at the probe frequency, in addition to swamping of neural response at the probe frequency due to excitation by the masker. Therefore, accurate estimates of probe response growth from simultaneous growth-of-masking data should probably include a slope adjustment for the effects of suppression, such as $\mathbf{p}=1/\beta-\mathbf{s}$, where $\mathbf{s}$ is the exponent defining the growth of suppression with intensity, which, from our factor of 2 error, might be around $\log(2)=0.30$. However, the situation is likely to be much more complex because suppression varies with frequency ratio between probe and masker. Further research is needed to clarify this issue. An obvious approach would be to obtain growth-of-masking slopes under nonsimultaneous masking conditions where suppression effects will not occur. Recently, a response growth exponent of 0.16 was derived for moderate signal levels with a 6-kHz probe tone and a 3-kHz nonsimultaneous masker by Oxenham and Plack (1996, 1997), which is more in line with what one might expect at moderate probe levels, and is consistent with the interpretation here that suppression may reduce growth-of-masking slopes and elevate estimates of response growth.

B. Growth of masking for ON-frequency masking conditions

Results of the present study indicated that, for hearing-impaired subjects, growth-of-masking slopes for ON-frequency conditions were not markedly different from normal. Slopes did not change with probe frequency or with probe threshold. These are conditions where the spectrum of the masker and the probe are the same and subject to the same BM transfer function and the same cochlear nonlinearities. In this situation, detection threshold may involve the physical addition of stimulus power from masker and probe before exciting the auditory system, as compared to the OFF-frequency case where the combined sensory response to stimuli at different frequencies very likely involves different BM transfer functions and cochlear nonlinearities for masker and probe.

For ON-frequency conditions, masking began when the power within an auditory-filter bandwidth was approximately equal to absolute threshold at the probe frequency. Examination of individual data in Fig. 3(b) indicates that masking sensitivity seemed to be slightly greater (sensitivity constants κ were smaller) in some of subjects with larger hearing losses, which could mean that critical masking bands in those subjects might have been wider. This interpretation is consistent with results reported by Nelson (1991), where markedly abnormal tuning was only seen when absolute thresholds exceeded 60 dB SPL. That abnormal tuning was exhibited by abnormal downward spread of masking, not abnormal upward spread of masking, i.e., only the high-frequency sides of forward-masking psychophysical tuning curves were flatter than normal. However, that explanation is problematic because the masking bands were not more than 2.5 ERBs wide, which should only lead to a 4-dB reduction in κ. An alternative explanation might be that those subjects with larger hearing losses exhibited smaller sensitivity constants κ because their internal noise effectively had a larger variance requiring a larger signal-to-noise ratio to reach detection threshold.

IV. CONCLUSIONS

(1) OFF-frequency growth-of-masking slopes decrease with amount of sensorineural hearing loss in a predictable fashion. An analysis of results from four studies of upward spread of masking that employed different types of low-frequency maskers indicates that growth-of-masking slopes decrease as a power function of threshold stimulus intensity relative to normal threshold intensity, i.e., growth-of-masking slopes decrease by a factor of about 0.8 for every 10 dB of hearing loss. The parameters derived from growth-of-masking slopes in the present

study should allow accurate predictions of upward spread of masking in persons with sensorineural hearing loss to be made from measurements of upward spread of masking in normal-hearing ears.

(2) More gradual OFF-frequency growth-of-masking slopes from ears with hearing loss reflect steeper-than-normal response growth slopes at the probe frequency. Assumptions about underlying physiological mechanisms lead to the conclusion that probe-tone response-growth exponents vary from around 0.3 at 0 dB HL to near 1.0 at 75 dB HL.

(3) Subjects with normal hearing at the probe frequency, but significant hearing loss at higher frequency regions, may exhibit larger (steeper) than normal growth-of-masking slopes in regions of normal hearing. This could reflect a reduction in excitation pattern tails associated with high-frequency hearing losses.

(4) Sensitivity to OFF-frequency masking is slightly *reduced* in regions of hearing loss, i.e., upward spread of masking begins at slightly higher masker levels in persons with hearing loss than in persons with normal hearing. Persons with sensorineural hearing loss exhibit higher masked thresholds primarily because they have elevated absolute thresholds at the probe frequency, which is due to a loss of active gain at that frequency, they do not demonstrate an excessive response to lower-frequency maskers (excessive upward spread of excitation).

(5) ON-frequency growth-of-masking slopes are approximately the same in normal-hearing and hearing-impaired ears, although more gradual slopes in some subjects at frequencies with larger hearing losses suggest additional research is needed with subjects who have large amounts of hearing loss.

(6) ON-frequency masking begins when effective masker power within the auditory-filter bandwidth at the probe frequency reaches elevated absolute threshold at the probe frequency.

(7) Growth-of-masking functions are well fit as a power function of masker intensity. Curvilinear masking function, observed for masked probe thresholds near absolute probe threshold (small amounts of masking), are well fit by assuming a power summation at the probe frequency between an internal representation of masker intensity and an internal noise at absolute threshold intensity.

ACKNOWLEDGMENTS

This work was supported largely by grants DC00149 and DC00110 from NIDCD. This research was also supported in part by the Lion's 5M International Hearing Foundation. We wish to thank Gail Donaldson for her valuable suggestions to previous versions of this manuscript as well as Søren Buus and Brian Moore for their helpful reviews.

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