Release from upward spread of masking in regions of high-frequency hearing loss

David A. Nelson and Anna C. Schroder
Clinical Psychoacoustics Laboratory, Department of Otolaryngology, and Department of Communication Disorders, University of Minnesota, Minneapolis, Minnesota 55455

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The upward spread of masking was compared for 500-Hz quasifrequency-modulated (QFM) and sinusoidally amplitude-modulated (SAM) maskers. The modulation rate was 20 Hz. These maskers had identical magnitude spectra but different envelopes, which were relatively flat for the QFM masker and strongly fluctuating for the SAM masker. At signal frequencies more than an octave above the masker, masked thresholds for the SAM masker were lower than for the QFM masker, revealing ''masking release'' (QFM-SAM masked threshold differences) exceeding 30 dB in normal-hearing ears. In ears with high-frequency sensorineural hearing loss, but normal hearing in the region of the masker, masking release was markedly reduced or completely absent in regions of hearing loss. The data were evaluated with a model of masking based on the *linearized response growth* (LRG) of basilar membrane transfer functions associated with cochlear damage in animals. The LRG model predicted more gradual slopes of the growth of masking and reduced amount of masking in regions of hearing loss. The reduced masking release seen in regions of hearing loss could be largely accounted for by a more rapid growth of response to the probe tone in regions of hearing loss. © *1996 Acoustical Society of America.*

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INTRODUCTION

Short-term energy fluctuations in a masker can improve thresholds for tones at frequency regions above the masker (Fastl, 1975; Buus, 1985; Mott and Feth, 1986). This improvement in threshold has been termed a masking release due to across-channel cues such as ''listening in the valleys'' (Buus, 1985) or modulation of phase locking (Moore and Glasberg, 1987), and is similar to the phenomenon of comodulation masking release (Hall *et al.*, 1984a). Buus provided particularly cogent demonstrations of the release from upward spread of masking. A 90-dB SPL masker consisting of two equally intense tones at 1060 and 1075 Hz produced 25 dB less masking than a 90-dB SPL pure-tone masker at 1075 Hz. Release from upward spread of masking was also demonstrated using noise bands of different bandwidths. For noise bands with equal power within an auditory critical bandwidth, and with upper edges aligned at 1075 Hz, a 150-Hz bandwidth (BW) noise with slower envelope fluctuations produced around 15-dB lower masked thresholds two octaves above the masker than a 450-Hz BW noise with faster envelope fluctuations. Mott and Feth also demonstrated release from upward spread of masking with noise bands, but they controlled the envelope fluctuations in the noise bands directly, while keeping the bandwidth of their stimuli around 50 Hz and thereby the fluctuation rate constant. Their subjects showed an average masking release of about 20 dB at test frequencies about an octave above the masker frequency.

This release from upward spread of masking, for maskers with fluctuating amplitude envelopes, may be the mechanism behind improved speech recognition in the presence of fluctuating noise (Festen and Plomp, 1990; Takahashi and Bacon, 1992; Eisenberg *et al.*, 1994; Gustafsson and Arlinger, 1994). Festen and Plomp reported that normal-hearing listeners achieve 6–8 dB better speech reception threshold (SRTs) in an interfering noise consisting of competing voices, and 4–6 dB better SRTs in modulated noise, than in a steady-state noise. The normal-hearing ears may have been able to take advantage of the brief moments of lower energy in the fluctuating maskers to detect speech information critical to decoding the message. On the other hand, listeners with moderate sensorineural hearing losses exhibited elevated SRTs and showed no improvement in fluctuating noise relative to steady-state noise. This suggests that ears with hearing loss might not be able to take advantage of brief moments of lower energy in fluctuating maskers to improve performance.

The present study examines the extent to which ears with high-frequency hearing loss can take advantage of lower-energy epochs in fluctuating maskers to improve detection thresholds. Masking patterns for maskers with equal magnitude spectra, but different envelope fluctuation magnitudes and rates, were obtained from normal-hearing ears and from ears with high-frequency hearing loss. Release from upward spread of masking in regions of hearing loss is compared with masking release in normal-hearing listeners, and possible physiological mechanisms behind the release from masking are examined.

I. METHODS

A. Subjects

Two normal-hearing listeners and four listeners with high-frequency sensorineural hearing loss served as subjects. Three of the hearing-impaired listeners had bilateral losses and one had a unilateral loss. They exhibited normal hearing

TABLE I. Demographics of subjects with high-frequency cochlear hearing loss.

HF HI subjects	Age	Sex	Etiology
EIP	65	Male	Noise-induced/presbycusis
CLK	45	Female	Sudden hearing loss
HMG	54	Female	Congenital/noise induced
PJB	40	Female	Ototoxicity

at lower frequencies and audiological findings consistent with cochlear hearing loss at moderate to high frequencies (no air–bone gap, normal tympanometry, no acoustic reflex decay, good speech discrimination). Their ages and etiologies are given in Table I. All listeners were inexperienced with the task when beginning the experiment.

B. Stimuli

Masking patterns were obtained for sinusoidally 100% amplitude-modulated (SAM) and quasifrequency-modulated (QFM) maskers centered at 500 Hz and modulated at a rate of 20 Hz. These maskers had equal long-term spectra consisting of three tones at 480, 500, and 520 Hz, with the upper and lower tones 6 dB less intense than the center tone. The only difference in the spectra of the two maskers was a 90-deg phase shift on the center component for the QFM masker. The overall level of the maskers was 90 dB SPL. The SAM masker had large peak-to-valley envelope fluctuations (greater than 90 dB) that occurred at a rate of 20 Hz; it will be referred to as the masker with the ''fluctuating'' envelope. The QFM masker had small peak-to-valley envelope fluctuations (less than 3 dB) that occurred at a rate of 40 Hz; it will be referred to as the masker with the ''flat'' envelope. Even though it has minor envelope fluctuations, it is considered to have a relatively flat envelope when compared to the strongly fluctuating envelope of the SAM masker.

Signal frequencies were at 500, 550, 650, 810, 1020, 1280, 1610, 1800, 2020, 2540, 2850, and 3200 Hz. When the signal was at 500 Hz, it was in quadrature phase with the 500-Hz component of the masker. 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 in the maskers. Masking noise was delivered to the nontest ear of the unilaterally impaired listener (CLK).

Signals and maskers were digitally generated by a computer, played through separate 14-bit digital-to-analog converters at a 20-kHz sampling rate and low-pass filtered at 10 kHz (135 dB/oct roll-off). They 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 for signal tone bursts in the presence of the gated QFM or SAM maskers were determined with a four-alternative forced-choice adaptive procedure. A trial consisted of a 500-ms warning interval followed by four 520-ms observation intervals, each separated by a 250-ms silent interval. Maskers occurred in all four intervals. The signal was presented with the masker in one of the four intervals, chosen randomly from trial to trial. Correct-answer feedback was provided following each trial. The adaptive procedure estimated the 71% correct threshold with a two-down one-up tracking procedure that averaged the last 6 out of 12 reversals, during which the level varied in 2-dB steps. Each data point represents the mean of at least three threshold estimates. Standard deviations of the repeated masked-threshold estimates averaged 1.4 dB, with 85% of them below 2.2 dB and only one of them above 3 dB.

II. RESULTS AND DISCUSSION

A. Masked thresholds and masking release in normal-hearing ears

Figure 1(a) and (b) show the masked thresholds obtained from the two normal-hearing listeners. In both subjects, masked thresholds for both the QFM and SAM masker were the highest at 500 Hz, which is the center spectral component of the maskers. The average masked thresholds were 78 dB SPL for the QFM masker and 72 dB SPL for the SAM masker. The 6-dB difference between masked thresholds for the flat-envelope and fluctuating-envelope maskers can be considered ''masking release.'' Presumably the 6-dB masking release at 500 Hz occurs because the large and resolvable envelope fluctuations allow the auditory system to utilize information during brief moments of lower masker energy.

As the test frequency increased from 500 to 650 Hz, masked thresholds for QFM and SAM maskers decreased rapidly, with little difference between them. The precipitous decrease in masked threshold most likely reflects sharp auditory filtering around the masker channel, although it can be confounded by the detection of beats between frequency components in the masker and the signal (Wegel and Lane, 1924; Carney and Nelson, 1983). The similarity of QFM and SAM masked thresholds in this frequency region is notable for two reasons. On the one hand, based on the 6-dB average masking release at 500 Hz, as the signal moves above the masker edge frequency one might expect masked thresholds for the fluctuating-envelope masker to be somewhat lower than for the flat-envelope masker, thereby increasing the masking release. On the other hand, as the signal moves above the masker edge frequency, one might expect the flat-envelope masker to yield more perceptible beats than the masker with large envelope fluctuations. Consequently, beats would lower masked thresholds more for the QFM than the SAM masker, thereby reducing masking release. Because the QFM and SAM masked thresholds were so similar, neither of these scenarios seems adequate, although one could speculate that the two opposite effects might have canceled one another.

At test frequencies between 650 and 1020 Hz, masked thresholds for the QFM masker increased as those for the SAM masker continued to decline. That is, a ''notch'' is apparent in the QFM masking pattern but not in the SAM masking pattern. As discussed above, the falling portion of

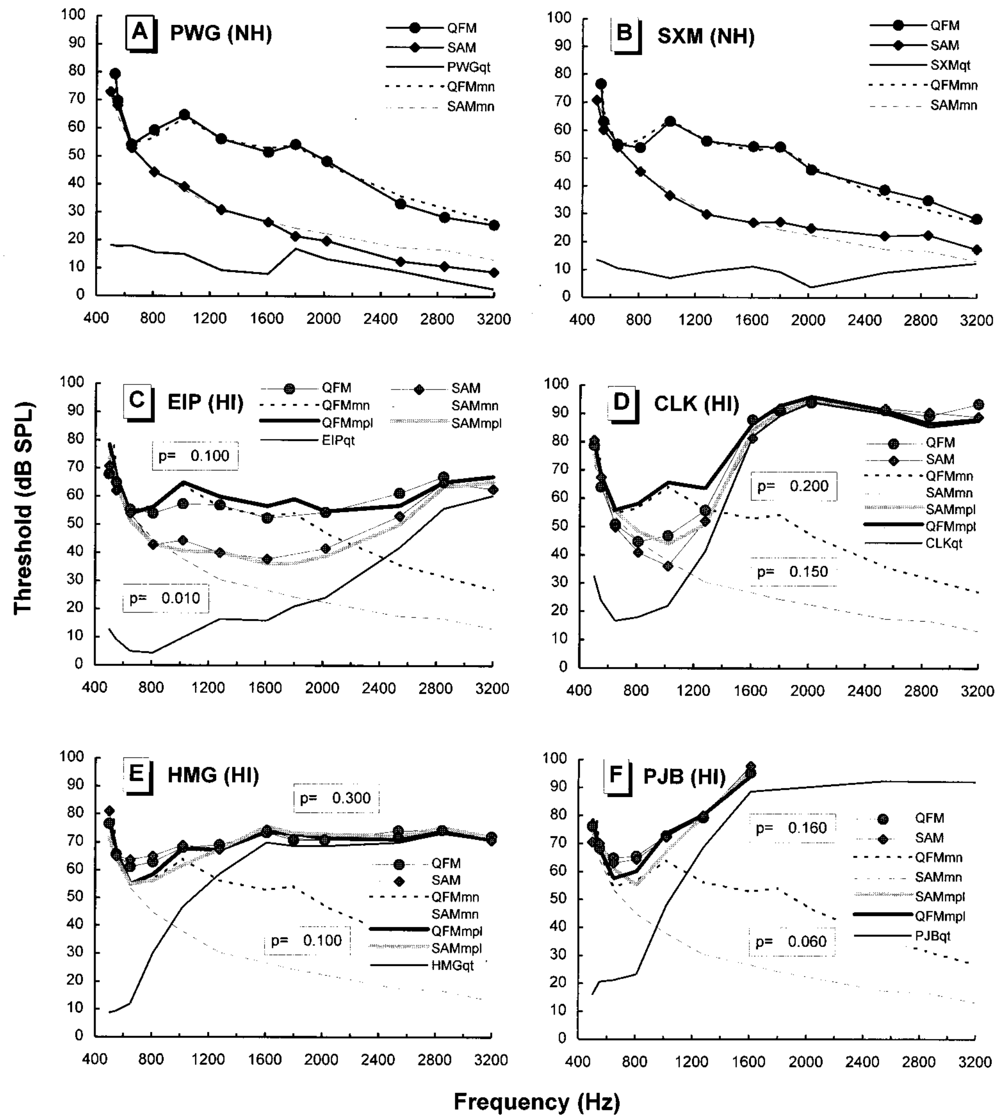

FIG. 1. Masked thresholds for quasifrequency-modulated (QFM) and sinusoidally amplitude-modulated (SAM) maskers as a function of frequency for two normal-hearing subjects [panels (a) and (b)] and four subjects with high-frequency hearing losses [panels (c), (d), (e), and (f)]. The maskers were constructed from 500-Hz sine waves modulated at 20 Hz and presented at 90 dB SPL. Masked thresholds for the flat-envelope QFM masker are indicated by filled circles; those for the fluctuating-envelope SAM masker are indicated by filled diamonds. Absolute thresholds are shown by solid curves below the masked thresholds. In all panels, the average masked thresholds from the two normal-hearing ears are indicated by dark dashed lines for the QFM masker (QFM*mn*) and by light dashed lines for the SAM masker (SAM*mn*). Masked thresholds predicted by an MPL model of masking (see text) for QFM and SAM maskers are shown by the wide dark curve (QFMmpl) and the wide shaded curve (SAMmpl). The exponents used for those predictions are indicated for QFM and SAM maskers within the upper and lower insets, respectively.

this notch is due to sharp filtering and/or beats. The rising portion of this notch can be attributed to the declining influence of combination tone cues. In the frequency region between 650 and 1020 Hz, where the frequency ratio between masker and signal varies from around 1.3 to 2.0, it is well known that combination tones at frequency $2f1-f2$ are generated within the cochlea for simultaneous masking conditions, where $f1$ is a frequency component within the masker and $f2$ is the frequency of the signal (Goldstein, 1967; Greenwood, 1971; Smoorenburg, 1972a,b; Nelson and Fortune, 1991). These combination tones can lead to spuriously low masked thresholds due to the detection of distortion components below the masker, which are manifested in the rising portion of the notch in the masking pattern as combination-tone cues become less salient with increased frequency ratio between masker and probe. Such notches for flat-envelope maskers were attributed to combination tones by Mott and Feth (1986) because an additional low-pass noise below the masker raised masked thresholds in the notch region. Their subjects did not demonstrate the notch with fluctuating-envelope maskers, as was also the case in the present data with the SAM masker. Thus for probe tones between 650 and 1020 Hz, it is likely that masked thresholds for the QFM masker are influenced by the detection of combination tones at frequencies below the masker. Therefore, these masked thresholds do not accurately reflect upward spread of masking, and masking release cannot be evaluated in this frequency region.

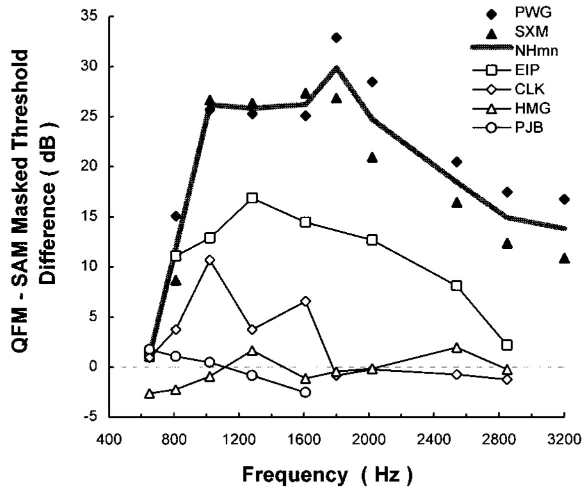

FIG. 2. Amount of masking release as a function test frequency. Masking release is specified as the level difference between masked thresholds for the QFM and the SAM maskers. Masking release from two normal-hearing ears is shown by the filled symbols; average masking release for those two ears is shown by the dark heavy curve (NH*mn*). Masking release for individual subjects with high-frequency hearing losses are shown by the unfilled symbols.

Of the two maskers investigated here, the QFM masker is most like a simultaneous masker because it has a relatively flat envelope and its masking patterns exhibited evidence of combination tones, which are only found in simultaneous masking conditions. On the other hand, the SAM masker is most like a nonsimultaneous masker. The temporal envelope of the SAM masker has large resolvable amplitude fluctuations that provide moments of low energy during which time the auditory system can ''listen'' for signal energy (Buus, 1985). Masked thresholds during those ''valleys'' are most likely determined by forward and backward masking (Fastl, 1975). In addition, the combination-tone notch is not seen in the SAM masking pattern. The presence of large amplitude fluctuations and the lack of combination-tone involvement both suggest that the SAM masked thresholds involved nonsimultaneous masking.

Finally, with further increases in test frequency above 1020 Hz, masked thresholds declined almost monotonically for both QFM and SAM maskers. At these frequencies, more than an octave above any spectral component within the masker and where combination-tone detection is no longer involved, masked thresholds in the presence of the fluctuating-envelope masker averaged more than 25 dB better than those in the flat-envelope masker, demonstrating masking release.

The amount of masking release is shown more clearly in Fig. 2. At 500 Hz, the masking release averaged 6 dB (not shown). Between 550 and 650 Hz masking release was absent (not shown). Between 650 and 1020 Hz, as combination tones became less salient at larger frequency ratios between masker and probe, masking release grew from zero at 650 hz to about 25 dB at 1020 Hz. On average, the masking release remained around 25 dB from 1020 through 2020 Hz, although subject PWG exhibited a masking release as large as 33 dB at 1800 Hz. Masking release then decreased consistently with increased test frequency for test frequencies above 2020 Hz. These results from normal-hearing ears, at frequencies far removed from the masker, are consistent with findings reported by Buus (1985) and by Mott and Feth (1986) for slightly faster modulation rates. They are also consistent with masking release exhibited for slower (4-Hz) amplitude-modulated maskers (Zwicker, 1976; Nelson and Swain, 1996).

B. Masked thresholds and masking release in hearing-impaired ears

Masked thresholds for QFM and SAM maskers from individual ears with high-frequency hearing loss are shown in Fig. 1(c)–(f). Subject EIP [panel (c)] had a gradual sloping hearing loss, with normal thresholds at 500 Hz rising to thresholds near 60 dB SPL at 3200 Hz. Subjects CLK, HMG, and PJB [panels (d)–(f)] exhibited more precipitous high-frequency hearing losses, rising to thresholds over 70 dB SPL by 1600 Hz.

In regions of normal sensitivity just above the masker, masked thresholds in the hearing-impaired ears decreased with test frequency, very much like those in normal-hearing ears. In regions of hearing loss, masked thresholds were usually higher than in normal-hearing ears. Both outcomes are consistent with upward spread of masking data from previous studies (Martin and Pickett, 1970; Florentine *et al.*, 1980; Smits and Duifhuis, 1982; Hannley and Dorman, 1983; Trees and Turner, 1986; Gagne, 1988; Klein *et al.*, 1990). However, for subject CLK, masked thresholds in the QFM condition were actually better than in the normal-hearing ears between 650 and 1280 Hz. This result was also found in one subject by Klein *et al.* (1990).

The results at 500 Hz, where masker and probe frequen-

TABLE II. Masked thresholds (dB SPL) at 500 Hz for QFM and SAM maskers.

Subjects		QFM	dB *re*: NH mean	SAM	dB *re*: NH mean	QFM-SAM
NH:	PWG	79.2	+1.3	72.9	+1.0	+6.3
	SXM	76.6	−1.3	70.8	−1.1	+5.8
	Mean	77.9		71.9		+6.0
HI:	EIP	67.8	−10.1	70.7	−1.2	−2.9
	CLK	78.7	+0.8	80.6	+8.7	−1.9
	HMG	76.6	−1.3	81.0	+9.1	−4.4
	PJB	76.2	−1.7	70.6	−1.3	+5.6

cies were the same, are summarized in Table II. Subject PJB exhibited normal masked thresholds for both QFM and SAM maskers, despite a precipitous high-frequency hearing loss. Thus the masking release of 5.6 dB for subject PJB was similar to that seen in the normal-hearing ears. Masking release at 500 Hz in the other three ears was completely absent, but for different reasons. For subject EIP, masked threshold for the SAM masker was normal while masked threshold for the QFM masker was lower than normal. Consequently the amount of masking release was negative. This absence of masking release was not due to poor envelope following of the SAM masker but to some other enigmatic factor that led to an extremely sensitive QFM masked threshold. For subjects CLK and HMG, masked thresholds for the QFM masker were normal. However, masked thresholds for the SAM masker were about 9 dB higher than normal, resulting in negative masking release. For these two subjects, apparently, masking release at 500 Hz was absent because of the inability to follow the temporal envelope of the SAM masker.

At frequencies above 650 Hz, masked thresholds for the SAM masker were lower than for the QFM masker in two ears (EIP and CLK) and were essentially the same in the other two ears (HMG and PJB). The amount of masking release, the difference between QFM and SAM masked thresholds, is shown more clearly in Fig. 2. Masking release in the regions of high-frequency hearing loss was present but reduced in two subjects (unfilled squares and diamonds) and was completely absent in the other two (unfilled triangles and circles). In most cases, masked thresholds for the SAM masker were still well above absolute threshold, presumably leaving adequate room for better masked thresholds to occur.

These results clearly demonstrate that masking release for fluctuating maskers, like the SAM masker used here with regular and large amplitude fluctuations, is considerably reduced or completely absent in regions of high-frequency hearing loss. These results suggest that persons with high-frequency hearing loss cannot take advantage of moments of low masker energy in low-frequency temporally fluctuating maskers to detect important signals at higher frequencies. This is consistent with the observation that persons with hearing loss do not improve their speech recognition in modulated noise (Festen and Plomp, 1990; Takahashi and Bacon, 1992; Eisenberg *et al.*, 1994; Gustafsson and Arlinger, 1994). It should be noted, however, that the masking sounds used in those speech studies differed significantly from the masking sounds used in the present study. The speech studies used maskers with spectra similar to the spectra of running speech. This means that there was always some fluctuating masker energy at the same frequency region as the signal (speech). Thus the effects of upward spread of masking cannot be isolated from the effects of direct masking in those experiments. Additional speech research is needed to do that.

III. GENERAL DISCUSSION: MECHANISMS OF MASKING

One could attribute the reduced masking release exhibited here in regions of high-frequency hearing loss to a reduced ability to utilize across-frequency cues in the masker envelope, as is postulated in comodulation masking release experiments (Hall *et al.*, 1984a, b). However, it is likely that the physiological processes responsible for such across-frequency cueing involve higher-level auditory centers, while the physiological processes responsible for the high-frequency hearing losses seen here are clearly cochlear in origin. To explain reduced masking release in the presence of high-frequency hearing loss one must postulate that peripheral hearing loss modifies the input to a higher-level processing center. Therefore, it would seem most fruitful to pursue explanations of masking release that involve peripheral mechanisms of cochlear processing. In the discussion that follows, we examine various models of upward spread of masking and determine which peripheral transformations, beyond a shift in absolute sensitivity caused by cochlear damage, are necessary to account for reduced masking release in regions of hearing loss.

A. Models of upward spread of masking

1. Linear power summation model

One simple model of upward spread of masking, a linear power summation model, assumes that the intensity of a probe signal at masked threshold in a hearing-impaired ear (I_P) can be predicted by the sum of the intensity at masked threshold in the normal ear (I_N) and the intensity of an internal noise used to represent elevated absolute threshold in the hearing-impaired ear (I_{th}), as in: $I_P = I_N + I_{\mathrm{th}}$. In this model of masking, the effect of the auditory filter (W_F) in the normal ear is implicit in the measurement of I_N, which weights the masker intensity as in $I_N = W_F * I$. Previous research has shown that this linear power summation model is inadequate because it under predicts masked thresholds in regions of hearing loss (Gagne, 1983; Trees and Turner, 1986; Gagne, 1988), which is the case for the present data as well.[1]

Besides the fact that actual masked thresholds are higher than predicted with the linear power summation model, it is particularly puzzling why masked threshold (I_P) should be higher than elevated absolute threshold (I_{th}) at those frequencies where the elevated absolute threshold is considerably larger than normal masked threshold (I_N). This well replicated result has suggested to some that the *effect* of the masker in the normal ear, or normal amount of masking, is somehow added to the amount of hearing loss (Smits and Duifhuis, 1982). Smits and Duifhuis found that masked thresholds were well predicted by adding the normal masking effect (as measured by the amount of masking) to the amount of hearing loss, but only for hearing losses less than about 30 dB. This procedure over predicted masked threshold for hearing losses greater than 30 dB. Thus it seems that to accurately predict upward spread of masking one must add the normal masking effect, or a somewhat reduced version of the normal masking effect, to elevated absolute threshold. Although nontraditional, this class of model is useful for predicting upward spread of masking in regions of hearing loss from measurements of upward spread of masking in ears with normal hearing. Furthermore, it will prove to be useful for relating psychophysical masking data to physiological phenomena.

2. Modified power law model

One such model that adds a reduced version of the normal masking effect to elevated absolute threshold is the modified power-law (MPL) model (Humes *et al.*, 1988; Humes *et al.*, 1992). The MPL model adds the compressed *effect* of a low-frequency masker in a high-frequency channel from a normal-hearing ear ($I_N^{\mathbf{p}} - I_0^{\mathbf{p}}$) to a compressed internal noise representing elevated threshold ($I_{\mathrm{th}}^{\mathbf{p}}$), as in $I_P = I_N^{\mathbf{p}} - I_0^{\mathbf{p}} + I_{\mathrm{th}}^{\mathbf{p}}$, where I_0 is the intensity at absolute threshold at the probe frequency in a normal-hearing ear. As with the linear power summation model, the frequency weighting function (W_F) in the normal ear is implicit in the measurement of I_N. The principal contribution that leads this model to accurately predict higher masked thresholds in regions of hearing loss is the compression factor given by the exponent $\mathbf{p}$, which operates on the normal masking effect and is usually between 0.1 and 0.2 in hearing-impaired ears (Humes and Jesteadt, 1991; Humes *et al.*, 1992). Essentially, the masking effect in the normal ear, or normal amount of masking, is compressed and is then added to the compressed absolute threshold in the impaired ear. This model is attractive because, as we will show later, the compression is consistent with more gradual growth-of-masking slopes in regions of hearing loss (Smits and Duifhuis, 1982; Stelmachowicz *et al.*, 1987; Murnane and Turner, 1991) and with more linear basilar membrane response characteristics in animals with damaged cochleas (Ruggero and Rich, 1991; Ruggero *et al.*, 1993).

Figure 1 demonstrates how well masked thresholds can be predicted with the MPL model for the QFM and SAM maskers used here. Masked thresholds predicted with the MPL model are shown by the heavy solid curves, along with the values of the exponents required to achieve those predictions (insets). The predictions are fairly good for subject EIP [Fig. 1(c)], who exhibited the least amount of high-frequency hearing loss. The difference between QFM and SAM masked thresholds for EIP, the masking release, was maintained over a wide frequency region and was reduced in frequency regions where absolute thresholds were higher than about 40 dB SPL. The exponent required for the SAM masker was considerably smaller than for the QFM masker. The predictions for QFM in subject CLK [Fig. 1(d)] were poor because masked thresholds were better than normal in the region of rising absolute threshold. For the two subjects with precipitous high-frequency losses [Fig. 1(e) and (f)], the model approximated the higher than normal masked thresholds and the fitting exponents were smaller for the SAM than for the QFM masker. Although the MPL model does a fair job of predicting both QFM and SAM masked thresholds, it applies a single exponent to the amount of masking at each probe frequency, regardless of the amount of hearing loss that might exist at each frequency. As will become apparent later in this discussion, the physiological basis for a single exponent in situations where the degree (amount) of hearing loss

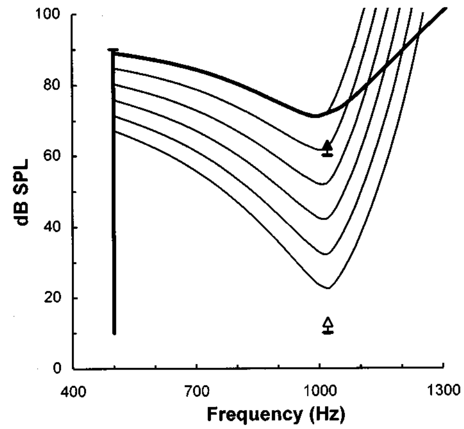

FIG. 3. A probe-level series of tuning curves for normal hearing at the probe frequency, and a single tuning curve for a hearing-impaired ear with an elevated probe threshold and abnormal frequency selectivity. Tuning curves calculated with Eq. (A4) from Nelson and Freyman (1984) show masker levels required to mask a 1020-Hz probe tone as a function of masker frequency. The probe-level series of tuning curves for normal hearing (thin solid curves) is shown for probe tones ranging from 13 dB SPL (unfilled arrow) to 63 dB SPL in steps of 10 dB, where absolute threshold at 1020 Hz is at 10 dB SPL (base of unfilled arrow). A tuning curve for a hearing-impaired ear with abnormal frequency selectivity (wide solid curve) is shown for a probe at 63 dB SPL (filled arrow) and a probe threshold at 60 dB (base of filled arrow). A 90-dB SPL masker at 500 Hz is represented by the bar-topped vertical line.

changes with frequency is not well supported. Furthermore, the reason why a different exponent is required for QFM and SAM maskers is not clear.

B. Relevant model parameters and hearing loss

The relative success of the MPL model suggests that some reduced version of the normal masking effect can be added to an internal noise representing elevated threshold to achieve fairly accurate predictions of upward spread of masking. With this class of model the effects of a low-frequency masker on masked thresholds in high-frequency channels are determined by three major factors: (1) absolute threshold at the probe frequency, (2) a reduction in the normal masking effect, and (3) a frequency weighting by auditory filters tuned to the probe frequency. For our purposes here, absolute threshold is easily measured and, so far, well modeled by an internal noise. Thus it needs little discussion here. We will focus on the remaining two factors.

1. Frequency weighting function

Nelson and Freyman (1984) have shown that the frequency weighting function, W_F, for the upward spread of masking is primarily determined by the output level of the auditory filter, which is determined in large part by elevated absolute threshold. Their findings are illustrated in Fig. 3, which shows theoretical tuning curves derived from forward masking data in normal-hearing and hearing-impaired listeners.[2] These tuning curves illustrate the masker levels required to mask probe tones at 1020 Hz, as a function of masker frequency. A series of tuning curves is shown for probe levels varying in 10 dB steps from 13 dB SPL to 63 dB SPL, which is representative of the tuning curves Nelson and Freyman obtained from normal-hearing ears by varying probe level. The low-frequency sides of these tuning curves, which reflect upward spread of masking, become more gradual with increased probe level primarily because of a frequency dependent slope to the growth of masking. The underlying frequency weighting function, W_F, used to calculate these tuning curves was a rounded exponential function of the frequency difference in Barks between the masker and probe. This function is independent of probe level. The fact that a constant W_F can generate level dependent tuning-curve shapes is particularly important. The change in tuning-curve shape with level occurs because W_F operates on the nonlinear growth of masking with intensity, which varies with frequency distance between masker and probe. For the range of stimuli shown here, the slope of the growth of masking varied between 1.0 for a masking tone at 1020 Hz and 2.2 for a masking tone at 500 Hz. From this illustration, in which W_F is held constant, it is apparent that masked thresholds for a fixed frequency distance between masker and probe are primarily dependent upon the overall level of the masker and the *slopes of the growth of masking*.

Figure 3 also illustrates a tuning curve for an ear with an elevated absolute threshold at the probe frequency and with abnormal frequency selectivity. Nelson (1991) found that the low-frequency sides of forward-masked tuning curves from listeners with different amounts of hearing loss were essentially the same as those from normal-hearing listeners, when the tuning curves were compared at the same filter output levels, i.e., when masker levels near the tuning-curve tips were the same. Abnormal frequency selectivity, in some listeners with elevated thresholds above about 60 dB SPL, was exhibited as a more gradual slope on the high-frequency side of the tuning curve. This is illustrated in Fig. 3 by the tuning curve for a 63-dB SPL probe and 60-dB SPL probe threshold (wide dark curve). The low-frequency side of this tuning curve is identical to that from a normal ear at the same output level. Therefore, it is not necessary to make an independent estimate of W_F, because it is implicit in the measurement of I_N from a normal-hearing ear, and the W_F for spread of masking from low to high frequencies is largely unaffected by cochlear damage (Nelson, 1991).

2. Slopes of the growth of masking

Thus knowledge about slopes of the growth of masking seems to be the one unknown factor that precludes good predictions of upward spread of masking in hearing-impaired ears. It has been well documented that growth-of-masking slopes in subjects with hearing loss tend to be more gradual than in normal-hearing subjects (Smits and Duifhuis, 1982; Stelmachowicz *et al.*, 1987; Murnane and Turner, 1991; Dubno and Ahlstrom, 1995; Oxenham and Moore, 1995). Growth of masking at probe frequencies above the masker was not measured in this study, so we have no direct indication of growth-of-masking slopes in regions of hearing loss. However, one can estimate the reduction in slope that would be needed to obtain a good prediction of masked thresholds in individual subjects with hearing loss. We call this a slope reduction factor (α) because it represents the factor by which the normal slope of the growth of masking must be modified to yield the masked thresholds that were observed in hearing-impaired ears. Slope reduction factors are calculated by assuming that the intensity at masked threshold for a probe in a region of hearing loss, I_P, is determined by a reduced (compressed) version of the normal masking effect $(1 + I_M/I_0)^{\beta_{nrm}}$, which is multiplied by an internal noise representing elevated absolute threshold (I_{th}) in an ear with hearing loss, as in

$$I_P = (1 + I_M/I_0)^{\alpha\beta_{nrm}} I_{\text{th}}, \tag{1}$$

with the exponent β_{nrm} representing the slope of the growth of masking in a normal-hearing ear at a particular probe frequency.[3] In this case, I_M is the physical intensity of the masker and I_0 is an internal noise representing absolute threshold at the probe frequency in a normal-hearing ear. The frequency weighting function for upward spread of masking, W_F, is implicit in the measurement of masked threshold at each probe frequency in normal-hearing ears and is not different for upward spread of masking in hearing-impaired ears (Nelson, 1991). Thus, one can solve for the reduction factor, α, at each probe frequency to see how much normal masking must be reduced to predict masked thresholds in the presence of hearing loss. Since masking is determined by the slope of the growth of masking at the probe frequency in a normal ear (β_{nrm}), which changes with frequency distance between masker and probe, α can also be considered the normalized growth-of-masking slope irrespective of probe frequency as in

$$\alpha = \beta_{hls}/\beta_{nrm}. \tag{2}$$

The results of this procedure for masked thresholds below 70 dB SPL in the four hearing-impaired subjects of the present study are shown in Fig. 4. Normalized slopes for the QFM masker are shown in Fig. 4(a) as a function of probe frequency. For subject EIP, the normalized slope is near 1.0 at 650 Hz, which means that the growth-of-masking slope for this subject was the same as in normal ears at this frequency. At higher probe frequencies (1020 Hz) the normalized slope decreased to around 0.8 and remained there until it decreased further to around 0.2 for probe frequencies above 2400 Hz, indicating that the growth-of-masking slopes in these frequency regions were less than they were in normal-hearing ears. In the other subjects, normalized slopes decreased from near 1.0 to around 0.2 over a smaller frequency range. The same trends can be seen in Fig. 4(b) for the SAM masker, except normalized slopes for EIP remain near, or slightly above 1.0, over much of the frequency range.

Figure 4(c) and (d) show normalized growth-of-masking slopes for the QFM and SAM maskers, respectively, as a function of the amount of hearing loss at the probe frequency. In Fig. 4(c), the orderly decrease in normalized slope with amount of hearing loss for the QFM masker suggests that the change in slope across probe frequency is primarily due to an increase in the amount of hearing loss at the probe frequency. The decrease in normalized slope with hearing loss is less orderly for the SAM masker [Fig. 4(d)], especially for subject EIP who shows little effect of degree of hearing loss below 50 dB. This suggests some additional

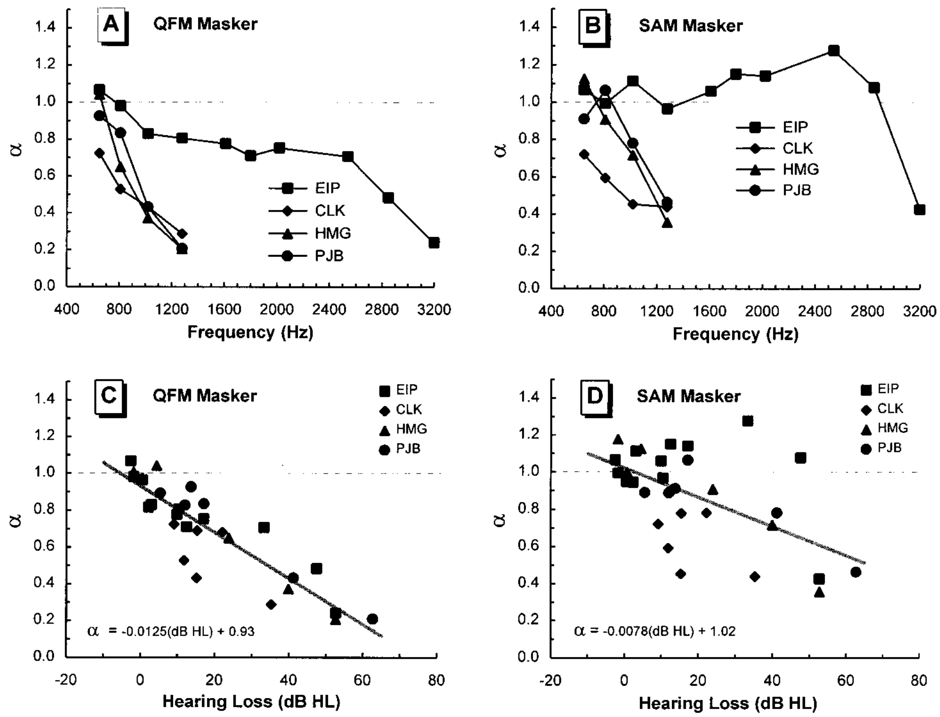

FIG. 4. Estimates of the slope reduction factor (α), or normalized growth-of-masking slope, required to sufficiently reduce the masking effect (amount of masking) in normal ears to predict individual masked thresholds in hearing-impaired ears. Normalized slopes for QFM and SAM maskers are shown as a function of probe frequency in the top two panels and as a function of hearing loss in the bottom two panels. Normalized slopes as a function of amount of hearing loss are described by the least-squares linear regression shown in each panel. A dashed line is shown at 1.0, which indicates no reduction in the amount of masking was needed to predict masked thresholds.

factors other than amount of hearing loss may be involved for the SAM masker. For example, nonsimultaneous masking involves an additional nonlinearity that results in more gradual growth-of-masking slopes (Jesteadt *et al.*, 1982). Additional research with nonsimultaneous maskers may help understand such factors and the large differences among subjects. Nevertheless, the trend for the SAM masker is similar to that seen for the QFM masker. The normalized slope (α) is a decreasing function of the amount of hearing loss as in

$$\alpha = \mathbf{m}(\mathrm{dbHL}) + \mathbf{n}, \tag{3}$$

with **m** negative in the range of -0.01 and **n** close to 1.0 to represent normal growth-of-masking slopes. Equation (3) implies that the reduction factor α, and by inference the slope of the growth of masking, β_{hls} from Eq. (2), decreases by about 0.01 units relative to that in normal-hearing ears for every decibel of hearing loss.

This analysis demonstrates how masked thresholds in regions of high-frequency hearing loss can be predicted by a reduction in masking measured from normal-hearing ears. Furthermore, it suggests that the reduction factors are directly related to growth-of-masking slopes in regions of hearing loss, and that growth-of-masking slopes should be inversely proportional to the amount of hearing loss. General support for this can be found in previously published data (Smits and Duifhuis, 1982; Murnane and Turner, 1991). Specifically, Murnane and Turner (1991) found that slopes of the growth of masking above a 3rd-oct band of noise centered at 1000 Hz decreased proportionately with amount of hearing loss. Additional research is required to determine the exact form of the relationship between slopes of the growth of masking and hearing loss, i.e., whether the slope reduction with hearing loss follows Eq. (3) or some other form, but the implication is that the physiological mechanisms underlying slopes of the growth of masking in hearing-impaired ears may be responsible for reduced release from upward spread of masking.

C. A linearized response growth (LRG) model of masking

Evidence from animal studies suggests that the physiological mechanisms underlying growth-of-masking slopes in subjects with hearing loss involve changes in the basilar membrane (BM) transfer function associated with cochlear damage. Both BM studies (Yates *et al.*, 1990; Ruggero and Rich, 1991; Ruggero *et al.*, 1993) and neurophysiological studies (Sachs and Abbas, 1974; Harrison, 1981; Gorga and Abbas, 1981a, b) report results consistent with the idea that, in normal-hearing ears, excitation by a tone at the probe frequency involves a relatively *nonlinear* (compressed) BM transfer characteristic (exponent$<$1); whereas, excitation by a masker much lower in frequency involves a more *linear* basilar membrane transfer characteristic (exponent $\cong$1). In ears with cochlear damage due to ototoxic drugs or acoustic trauma, threshold is elevated and the BM transfer characteristic is ''linearized,'' presumably because the active gain mechanism is affected (Ruggero and Rich, 1991; Ruggero *et al.*, 1993). This suggests that excitation by a probe in a region of hearing loss is subject to a more *linear* BM transfer characteristic (Stelmachowicz *et al.*, 1987; Oxenham and Moore, 1995).

This ''linearized response growth'' (LRG) associated with cochlear damage should lead to steeper than normal growth of excitation for a probe tone in the region of hearing loss, which 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 fixed ratio (κ), as in

$$\kappa = R_P / R_M, \tag{4}$$

then it can be shown that the reduction factor (α) reflects the LRG characteristic of cochlear damage. Response growth to a probe tone or a masker can be represented as a simple power function of stimulus intensity relative to absolute threshold as

$$R_P = (1 + I_P/I_0)^p \quad \text{and} \quad R_M = (1 + I_M/I_0)^q, \tag{5}$$

with exponents, **p** and **q**, reflecting 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

$$I_P = [\kappa(1 + I_M/I_0)^q)^{1/p} - 1] I_0, \tag{6a}$$

or

$$I_P = [\kappa(1 + I_M/I_0)^{\beta} - 1] I_0, \quad \text{with } \beta = \mathbf{q}/\mathbf{p}. \tag{6b}$$

Since the BM transfer function for a low-frequency masker at a higher-frequency place is relatively linear, one can assume $\mathbf{q} \cong 1$. Then β becomes proportional to $1/\mathbf{p}$. 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 hearing loss affecting 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 (close to 1). Since, with these assumptions, $\beta \cong 1/\mathbf{p}$, and α is proportional to β, the decrease in the slope reduction factor α with hearing loss given by Eq. (3) should reflect an increase in **p** associated with cochlear hearing loss. Thus it appears that the LRG associated with cochlear hearing loss may increase the slope of the growth of response to the probe tone (**p**), but not the slope of growth of response to the masker (**q**); consequently, the slope of the growth of masking (β_{hls}) is reduced, effectively reducing the masking effect from the normal ear by the factor α.

D. Predicting masking release from linearized response growth

One consequence of the reduction in growth-of-masking slopes predicted by this LRG model is that *masking release will decrease with increased hearing loss*. This is illustrated in Fig. 5 for QFM and SAM maskers that produce masked thresholds at 55 and 30 dB SPL in a normal-hearing ear, i.e., a masking release of 25 dB. Notice that as hearing loss in-

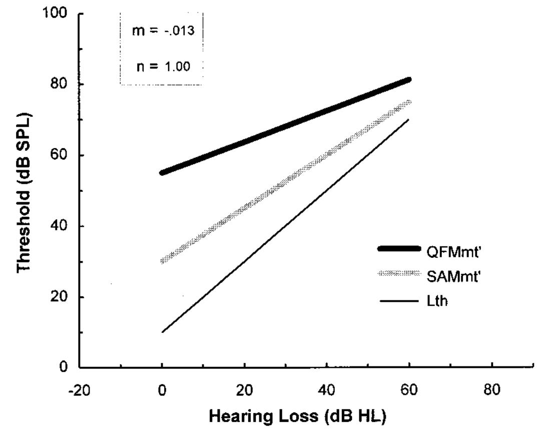

FIG. 5. Masked thresholds predicted by the LRG model as a function of hearing loss, to illustrate the reduced masking release that results from more gradual growth-of-masking slopes in the presence of hearing loss. Predicted masked thresholds are shown for QFM and SAM maskers (top and middle curves, respectively) that produce masked thresholds at 55 and 30 dB SPL in normal-hearing ears (at 0 dB HL). Elevated probe threshold is shown by the bottom curve (Lth). The normal masking effect, or amount of masking, is reduced by the reduction factor, α, which decreases with hearing loss. Consequently, the QFM-SAM masked-threshold difference, or masking release, is progressively reduced from 25 to 6 dB as hearing loss increases from 0 to 60 dB. Masked thresholds were predicted from Eq. (1) and Eq. (3) using the parameter values for **m** and **n** indicated within the inset.

creases to 60 dB, the amount of masking release is progressively reduced to 6 dB. The reduction factor α reduces normal masking from QFM and SAM maskers. Since α is inversely proportional to amount of hearing loss, the reduction is greater where hearing loss is larger. Because the reduction factor operates on the slope of the growth of masking, the masker that produces the largest amount of masking is reduced more (in this case QFM). Consequently, the difference between masked thresholds for the QFM and SAM maskers, the masking release, is reduced. Thus a large part of the reduced masking release in regions of hearing loss can be explained by the LRG associated with cochlear hearing loss.

From Fig. 5, it does not appear that the normalized slope α accounts for the entire reduction in masking release seen in the present data. With a 60-dB hearing loss 6 dB of masking release still remains, while it is apparent from Fig. 2 that subjects with 60 dB of hearing loss revealed little or no masking release. The simulation in Fig. 5, however, does not take into consideration the reduced masking associated with increased frequency distance between masker and probe. As probe frequency increases masking decreases, largely because of the frequency weighting (W_F) of the auditory filter. Thus the reduced masking release exhibited by subjects in the present study (Fig. 2) is confounded by changes in both α and W_F.

Figure 6 shows that as α operates on the reduced masking associated with higher probe frequencies, masking release is completely eliminated. Each panel in Fig. 6 shows amount of masking for QFM and SAM maskers in individual subjects (symbols) as a function of probe frequency, along with amount of masking in the normal ears (dashed lines). The amount of masking predicted by the LRG model is also shown (wide curves), along with the fitting parameters for

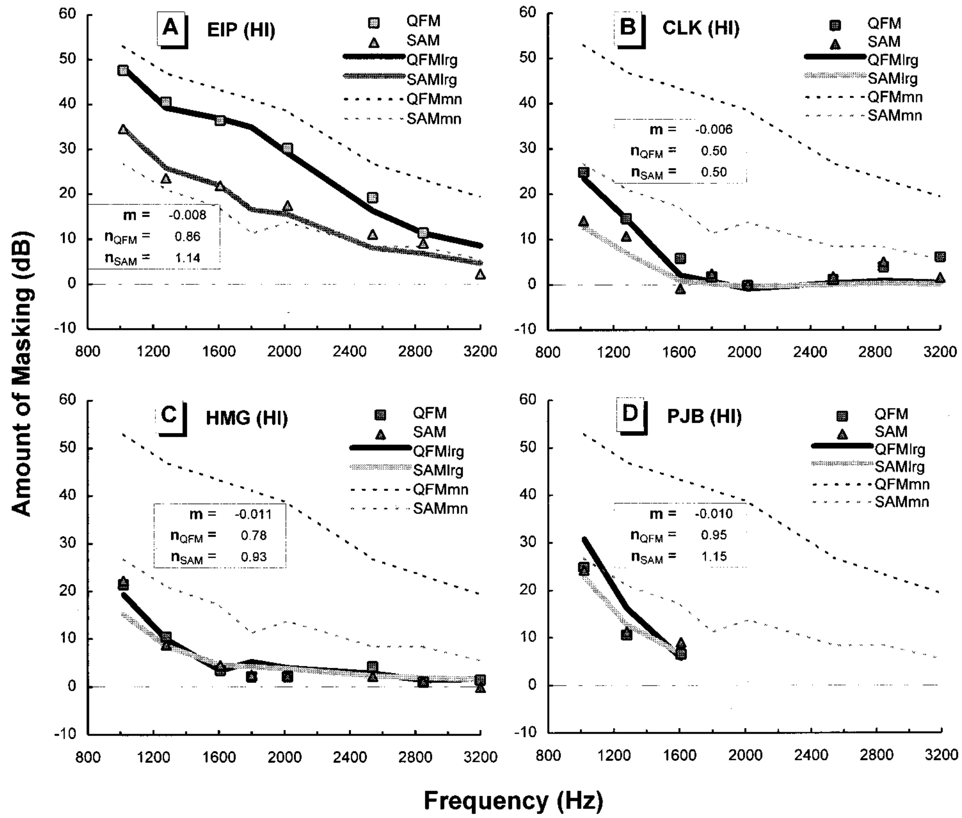

FIG. 6. Amount of masking predicted by the LRG model as a function of probe frequency for the QFM masker (QFMlrg) and SAM masker (SAMlrg), along with the amount of masking obtained from each of four hearing-impaired subjects (symbols) and the average amount of masking obtained from two normal-hearing subjects (dashed curves). A reduction in masking release can be seen as a reduced difference between the predicted masking curves for QFM (wide dark curve) and SAM (wide shaded curve) maskers. Masking was predicted from Eq. (1) and Eq. (3) using the parameter values for **m** and **n** indicated within the insets.

the model (insets). Masking release can be seen as the difference between QFM and SAM masking curves. Notice that the LRG model predicts the general trends in the masking curves, and consequently the masking release, with a fair degree of accuracy, especially for subject EIP who exhibited the most gradual increase in hearing loss with frequency. For subjects HMG and PJB, who exhibited steeply sloping high-frequency hearing losses, the LRG model predicted very little masking and consequently little or no masking release.[4] For these three subjects, the values of **m** were around -0.01 and the values of **n** were less for the QFM than the SAM masker. For subject CLK, the values of **n** were 0.5 for both QFM and SAM maskers and the slope reduction with hearing loss given by **m** was slightly less than -0.01, which suggests that CLK's hearing loss may reflect different physiological mechanisms than the other three subjects. Rather than interpret CLK's results entirely as a much steeper underlying growth of response at the probe frequency (**p**), one might attribute some of the reduced masking to a more gradual masker growth (**q**) due to the presence of a mild hearing loss at the masker frequency. Also, one must keep in mind that the masking predicted here does not include spatial integration of excitation along the basilar membrane, which is certainly limited by the steeply sloping high-frequency hearing loss exhibited by CLK.

E. Other factors

Finally, as promising as the LRG model is for explaining reduced upward spread of masking in hearing impaired ears, one must not overlook the possible contribution of suppression. The values of **n** that were derived here were typically smaller for the QFM masker than for the SAM masker. This indicates that the reduction factor α was smaller for QFM than SAM, which means that normal masking had to be reduced more for the QFM masker than the SAM masker to predict masked thresholds in hearing-impaired ears. The larger reduction in masking slopes implied by a smaller **n** value for QFM than SAM maskers could involve reduced suppression in regions of hearing loss. Animal research has shown that reduced or absent neural rate suppression is commonly associated with the loss in sensitivity and broader tuning that accompanies outer-hair-cell dysfunction (Evans, 1975; Robertson, 1976; Harrison and Evans, 1979; Schmiedt and Zwislocki, 1980; Schmiedt *et al.*, 1980; Javel *et al.*, 1983; Liberman, 1984; Pickles, 1984a; Pickles, 1984b; Smoorenburg and Kloppenburg, 1986; Delgutte, 1990; Ruggero and Rich, 1990; Ruggero and Rich, 1991; Ruggero *et al.*, 1996). Loss of suppression is also consistent with interpretations posited in other psychoacoustic studies of cochlear hearing loss in humans (Leshowitz and Lindstrom, 1977; Wightman *et al.*, 1977). Thus to the extent that suppression involves different physiological mechanisms than linearized response growth of the BM, it should not be dismissed as a contributing factor to reduced release from upward spread of masking in impaired ears.

Clearly more research is needed to separate the contribution of these additional factors to upward spread of masking from the linearized response growth associated with cochlear damage. It is likely that the details of upward spread of masking in individual subjects are more complex than implied by the LRG model, but the general trends in the data are remarkably well predicted by it. Reduced masking release in regions of high-frequency hearing loss appears to be largely explained by the loss in basilar membrane nonlinearity associated with cochlear damage.

IV. CONCLUSIONS

Masking patterns for fluctuating-envelope and flat-envelope maskers revealed a release from upward spread of masking that implies an ability to utilize short moments of lower masker energy to improve masked threshold. This masking release can exceed 30 dB when envelope fluctuations are regular, as with pure-tone SAM maskers, and when signals are at higher frequencies than the masker. Masking release obtained from ears with high-frequency sensorineural hearing loss was reduced or completely absent in regions of hearing loss. Evaluation of a linearized response growth model of masking, which relies upon a linearization of basilar membrane transfer functions in the presence of cochlear damage, indicates that the reduced masking release can be attributed largely to steeper response growth at the probe frequency associated with cochlear hearing loss. Any higher-level process that utilizes across-channel response envelope cues to derive masking release in the presence of cochlear hearing loss clearly must deal with effectively smaller response fluctuations than those that exist in regions of normal hearing.

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[1]Predictions for the power summation model can be seen in Fig. 1(c)–(f) as whichever of the following is greater: (1) the masked threshold for normal ears (dashed curve), or (2) the absolute threshold for the hearing-impaired ear (solid curve). At the frequency where the two curves cross, predicted masked threshold would be 3 dB higher. Masked thresholds at hearing-loss frequencies are higher than predicted with this model except for QFM conditions in subject CLK and where elevated thresholds at frequencies above 1600 Hz exceed about 60 dB SPL.

[2]The tuning curves shown here were derived from an excitation pattern equation [Eq. (A4)] published by Nelson and Freyman (1984), with parameter values similar to those given in Table A1 for their Fig. 5. For this illustration, the value of t was 0.001 ms to represent simultaneous masking conditions. These curves are not intended to reflect all of the details of psychophysical tuning curves, only the most prominent features.

[3]Notice that Eq. (1) expresses the masking effect as a compressed ratio of intensities rather than as a difference between compressed intensities as in the MPL model. The constant 1 makes the internal noise additive to the masking effect and also precludes negative masking when the masker intensity I_M is less than the internal noise I_0 representing normal absolute threshold. This equation accurately describes growth-of-masking functions in both normal-hearing and hearing-impaired ears (Nelson and Swain, 1996; Nelson and Schroder, 1997).

[4]The reduced amount of masking in regions of hearing loss shown in Fig. 6 is consistent with findings from six previous studies of the upward spread of simultaneous masking, in which the amount of masking in hearing-impaired ears was consistently less than the amount of masking in normal-hearing ears (Martin and Pickett, 1970; Smits and Duifhuis, 1982; Gagne, 1983; Trees and Turner, 1986; Klein *et al.*, 1990; Dubno and Schaefer, 1992).

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