A new procedure for measuring peripheral compression in normal-hearing and hearing-impaired listeners

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Forward-masking growth functions for on-frequency (6-kHz) and off-frequency (3-kHz) sinusoidal maskers were measured in quiet and in a high-pass noise just above the 6-kHz probe frequency. The data show that estimates of response-growth rates obtained from those functions in quiet, which have been used to infer cochlear compression, are strongly dependent on the spread of probe excitation toward higher frequency regions. Therefore, an alternative procedure for measuring response-growth rates was proposed, one that employs a fixed low-level probe and avoids level-dependent spread of probe excitation. Fixed-probe-level temporal masking curves (TMCs) were obtained from normal-hearing listeners at a test frequency of 1 kHz, where the short 1-kHz probe was fixed in level at about 10 dB SL. The level of the preceding forward masker was adjusted to obtain masked threshold as a function of the time delay between masker and probe. The TMCs were obtained for an on-frequency masker (1 kHz) and for other maskers with frequencies both below and above the probe frequency. From these measurements, input/output response-growth curves were derived for individual ears. Response-growth slopes varied from >1.0 at low masker levels to <0.2 at mid masker levels. In three subjects, response growth increased again at high masker levels (>80 dB SPL). For the fixed-level probe, the TMC slopes changed very little in the presence of a high-pass noise masking upward spread of probe excitation. A greater effect on the TMCs was observed when a high-frequency cueing tone was used with the masking tone. In both cases, however, the net effects on the estimated rate of response growth were minimal. *© 2001 Acoustical Society of America.* [DOI: 10.1121/1.1404439]

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I. INTRODUCTION

Several investigators have recently attempted to obtain psychophysical estimates of cochlear compression in human ears (Stelmachowicz *et al.*, 1987; Nelson and Schroder, 1997; Oxenham and Plack, 1997; Moore and Oxenham, 1998; Plack and Oxenham, 1998; Moore *et al.*, 1999; Hicks and Bacon, 1999a; Plack and Oxenham, 2000; Wojtczak *et al.*, 2001). A common procedure in many of those studies was the use of forward-masking growth functions for low off-frequency and on-frequency sinusoidal maskers to infer estimates of cochlear compression, where the *low off-frequency* masker had a frequency equal to or less than 0.6 of the probe frequency, and the *on-frequency* masker had a frequency equal to the probe frequency. That procedure is exemplified in the work of Oxenham and Plack (1997), who used forward masking from 3-kHz (low off-frequency) and 6-kHz (on-frequency) maskers to obtain estimates of response-growth rates at 6 kHz by measuring masker levels necessary to just mask a probe presented at several fixed levels. We call these functions growth-of-maskability (GMB) functions because the masker level at masked threshold is plotted on the ordinate as a function of the probe level on the abscissa. Based on data from animals indicating that the basilar-membrane response to a tone of a given frequency is linear at a place with a characteristic frequency (CF) well above the tone frequency (Yates, 1990; Yates *et al.*, 1990; Ruggero, 1992; Ruggero *et al.*, 1997; Rhode and Recio, 2000), Oxenham and Plack assumed that the response to the 3-kHz masker at the 6-kHz frequency region was linear. With this assumption, it is reasonable to interpret the slopes of their GMB functions in terms of response-growth rates at the 6-kHz place in the cochlea. For low-level and high-level probe tones the average GMB slope for three normal-hearing listeners was close to 1.0 dB/dB, suggesting linear response growth; for mid-level probe tones the average GMB slope was 0.16 dB/dB, suggesting very gradual response growth and strong peripheral compression. The GMB slope of 0.16 was similar to basilar-membrane (BM) response-growth slopes of 0.20 reported in animals for mid-level CF tones. This implies that the psychophysical measure of response-growth rate reflects BM response-growth rate, both of which are determined by cochlear compression. Where the response-growth rate is the least, cochlear compression is the strongest.

The very gradual GMB slope of 0.16 dB/dB observed by Oxenham and Plack, for a 3-kHz masker frequency (Fm) and a 6-kHz probe frequency (Fp), was obtained in the presence of a background noise intended to mask off-frequency listening at frequencies above and/or below the probe frequency. For the low off-frequency condition (3-kHz masker and 6-kHz probe) they used a high-pass noise; for their on-frequency condition (6-kHz masker and 6-kHz probe) they

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included a low-pass noise intended to mask any cues below the probe frequency. Without a background (high-pass) noise, the comparable low off-frequency GMB slope (in one listener) was not as gradual (≅0.38). This suggests that the estimate of response growth obtained from forward-masking GMB functions, for masker frequencies well below the probe frequency, is strongly dependent upon the spread of excitation from the probe, most likely an upward spread toward higher frequency regions.

Oxenham and Plack (1997) addressed this problem by specifying response-growth rate as the ratio of GMB slopes for the 3-kHz masker and the 6-kHz masker. They tested the notion, in one listener, that the effects of off-frequency listening on GMB slopes are the same for the on-frequency masker as they are for the low off-frequency masker. For that listener, the background noise reduced the GMB slope by about a factor of 2.0 for both the low off-frequency masker (with high-pass noise) and the on-frequency masker (with high-pass and low-pass noise), so the ratio of the low off-frequency and on-frequency GMB slopes and the subsequent estimate of response-growth rate remained about the same (0.17 in quiet and 0.19 in background noise). On the basis of this evidence, the ratios of GMB slopes for low off-frequency versus on-frequency maskers have been used to specify response-growth rates (and peripheral compression) from normal-hearing listeners (Moore *et al.*, 1999; Hicks and Bacon, 1999a, b), although none of the cited studies have demonstrated GMB slope ratios as small as those reported by Oxenham and Plack.

Oxenham and Plack also measured GMB functions at a 2-kHz probe frequency (using a 1-kHz masker), with and without a high-pass noise, in one of their hearing-impaired listeners who exhibited a moderate hearing loss at and above the probe frequency. That subject exhibited no significant difference in the GMB slope with the addition of the high-pass noise. This suggests that the additional high-pass noise is not necessary in hearing-impaired listeners with a hearing loss that increases markedly just above the probe frequency, probably because the hearing loss at the higher frequency regions minimizes the usefulness of upward spread of excitation from the probe toward higher frequencies as probe level increases.

The purpose of this study was twofold. First, we wanted to evaluate the effects of high-pass noise on GMB slopes and to examine more closely the notion that the ratio of GMB slopes for low off-frequency and on-frequency maskers without a background noise accurately specifies response-growth rate. Second, we wanted to explore an alternative procedure for measuring response-growth rate, one in which spread of excitation from the probe might not play such a strong role. For this procedure we made the same assumption as Oxenham and Plack about linear response growth for a low-frequency masker at a higher-frequency probe place, but we minimized spread of excitation effects by fixing the probe at a low level and varying the time delay between masker and probe. With this fixed-level probe procedure, as time delay between masker and probe is increased, a higher masker level is necessary to reach masked threshold, largely because of the increased recovery from forward masking that occurs with increased time delay. The resulting plot of masker level as a function of time delay is referred to here as a temporal masking curve (TMC). For a low off-frequency masker ($\mathrm{Fm} \leqslant 0.6\mathrm{Fp}$), the increase in masker level with time delay should only reflect recovery from forward masking. This is because the response to the low off-frequency masker at the probe-frequency place is assumed to be linear. For an on-frequency masker ($\mathrm{Fm} = \mathrm{Fp}$), the increase in masker level with time delay should reflect recovery from forward masking, just as for the low off-frequency case, but it should also reflect any cochlear compression that is applied to the masker. Assuming that recovery from forward masking is the same for low off-frequency and on-frequency maskers, response-growth rates can be estimated by computing the ratio of recovery slopes observed for a low off-frequency masker and an on-frequency masker. The computed rates of response growth can then be used to derive an input/output function. The present study estimates response-growth rates using this alternative procedure in normal-hearing and hearing-impaired listeners. The effects of off-frequency listening and temporal cueing on the estimated response-growth rates are also examined.

II. EXPERIMENT 1: GROWTH OF FORWARD MASKING IN HIGH-PASS NOISE

This experiment was a simple replication of the Oxenham and Plack (1997) forward-masking experiment that examined the effects of background noise on GMB slopes. We wanted to examine further their premise that valid estimates of response-growth rates can be obtained without a background noise by examining the ratios of GMB slopes obtained in quiet for a low off-frequency and on-frequency masker. This requires that spread of excitation above the probe frequency have the same relative effect on GMB slopes for low off-frequency and on-frequency forward maskers in quiet, thus rendering unnecessary the use of a background noise to reduce off-frequency listening.

A. Method

Forward-masking growth functions were obtained for a 6-kHz sinusoidal probe in the presence of a 3-kHz sinusoidal masker or a 6-kHz sinusoidal masker. Each point on the masking functions was obtained by fixing the level of the probe and varying the masker level to reach masked threshold. Probe levels ranged from 35 to 95 dB SPL in 5-dB steps. The resulting function is referred to as a growth-of-maskability (GMB) function to distinguish it from a growth-of-masking (GOM) function in which the masker level is fixed and the probe level is varied to reach masked threshold. This distinction is useful when referring to slopes of masking functions because some authors have reported GOM slopes (Hicks and Bacon, 1999a, b), while others have reported GMB slopes (Oxenham and Plack, 1997; Moore *et al.*, 1999). The masking tones were gated with 2-ms raised-cosine rise and decay times and were at peak amplitude for 100 ms (104-ms total duration). The probe tones were gated with 2-ms raised-cosine rise and decay times with no steady-state portion (4-ms total duration). The time delay between masker offset and probe offset was 6 ms. These parameters are the same as those used by Oxenham and Plack.

Pure-tone signals for masker and probe stimuli were produced and gated digitally by Tucker Davis Technologies (TDT) D-A converters, routed separately through programmable attenuators, added together in an active mixer, and presented monaurally through 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.

A three-interval forced-choice (3IFC) adaptive procedure was used to estimate the masker level needed to just mask the fixed-level probes and to measure absolute sensitivity thresholds. During each 3IFC trial, a subject was presented with three observation intervals demarcated by lights. The masker (or silence, for absolute thresholds) was presented in all three intervals and the probe was presented in only one, randomly selected, interval. The subject indicated which interval contained the probe stimulus by pressing one of three response buttons, after which correct answer feedback was provided.

Masked thresholds were determined using a transformed up–down adaptive procedure (Levitt, 1971). During the first four level reversals, a relatively large step size of 8 dB and a simple up–down stepping rule were used to move into the target masker-level region. Then a 2-dB step size was used for the next two reversals, again with a simple up–down stepping rule. A 2-up, 1-down, stepping rule, still with the 2-dB step size, was followed for the final six reversals to estimate the masker level corresponding to 71% correct detection of the probe. Masked threshold was estimated as the mean of the masker levels for the final six reversals. The final data points were based on the average of three or more such thresholds. Exceptions are noted in the figures for those cases where a subject could not complete at least three threshold measurements.

GMB functions were obtained in quiet and in the presence of a high-pass (HP) noise. The noise was a high-pass filtered white noise with a 3-dB cutoff frequency at 1.117Fp (6702 Hz), which was generated and filtered using TDT equipment (WG1 and PF1). Because the HP noise and the tonal signals were presented through a TDH-49 earphone, the spectrum level of the HP noise in a 6-cc coupler (measured with a Hewlett Packard 4144 1-inch microphone and a Hewlett Packard 3561A dynamic signal analyzer using a 95-Hz bandwidth filter) was relatively constant between 6702 and 9500 Hz and decreased with frequency above about 9500 Hz, such that the spectrum level was about 20 dB less at 12.5 kHz. The overall level of the HP noise was 15 dB below the level of the probe; the spectrum level between 6702 and 9500 Hz was approximately 50 dB below the probe level. At 6 kHz, the probe frequency, the spectrum level of the low-frequency skirt of the HP noise was approximately 90 dB below the probe level. The HP noise was gated on 50 ms before the onset of the masker ramp and gated off 50 ms after the offset of the probe. A GMB function was obtained in a single sitting, with probe levels always presented in ascending order to avoid obvious fatigue effects. The GMB functions were usually remeasured on different days.

In a secondary experiment, GMB functions were measured with a 1-kHz probe tone, both in quiet and in the presence of a HP noise. For those conditions, the noise was a high-pass filtered white noise with a 3-dB cutoff frequency at 1.117Fp (1117 Hz). The spectrum level of the HP noise in a 6-cc coupler was relatively constant between 1117 Hz and 6 kHz and decreased with frequency above 6 kHz, such that the spectrum level was about 10 dB less at 9.5 kHz and 20 dB less at 12.5 kHz. The overall level of the HP noise was 15 dB below the level of the 1-kHz probe tone; the spectrum level of the HP noise between 1117 Hz and 6 kHz was approximately 47 dB below the probe level. The masker-probe gating conditions were the same as those used with the 6-kHz probe.

Two normal-hearing subjects participated in the experiment. Their absolute thresholds were less than 15 dB HL (ANSI, 1989) for octave frequencies between 250 and 8000 Hz. Both subjects received several hours of practice on forward-masking tasks before data collection commenced.

B. Results and discussion

Figure 1 shows the GMB functions for the 6-kHz probe obtained in quiet (open symbols) and in the presence of the HP noise (filled symbols) from two normal-hearing listeners (ksar and yykl). The GMB functions for the 3-kHz (low off-frequency) masker are shown in Figs. 1(a) and (b) and those for the 6-kHz (on-frequency) masker are shown in Figs. 1(c) and (d) [note that the ordinates differ for panels (c) and (d) vs (a) and (b)]. Error bars represent one standard deviation above and below each mean masked threshold. Linear least-squares regression fits to the thresholds at medium probe levels (between about 40 and 80 dB SPL) are shown by the straight lines. The GMB slopes are given by $1/\beta$ (β is the GOM slope).

First notice that in the presence of the HP noise the GMB slopes were essentially identical to those obtained for the average GMB functions in background noise reported by Oxenham and Plack (1997, Fig. 2). The GMB slope of their on-frequency function was 1.0, compared to the GMB slopes of 1.0 dB/dB observed here [black diamonds, Figs. 1(c) and 1(d)]; their low off-frequency GMB slope for probe levels between 50 and 80 dB SPL was 0.16, compared to GMB slopes of 0.11 and 0.16 observed here [black diamonds, Figs. 1(a) and (b)]. Thus, their results in background noise are well replicated in these two subjects. Their ratio of low off-frequency to on-frequency GMB slopes was 0.16, while the slope ratios were 0.11 and 0.16 in the present study. Thus, estimates of response growth at the probe frequency, based on slope ratios of GMB functions that were obtained in the presence of a background noise to reduce off-frequency listening, were similar in both studies.

Oxenham and Plack's on-frequency condition actually included a low-pass noise in addition to a HP noise. Further, the levels of their two noises were not constant relative to each probe level tested. The level of their notched noise essentially increased at a rate that was about half of the rate of increase in the level of the probe. Because we replicated their

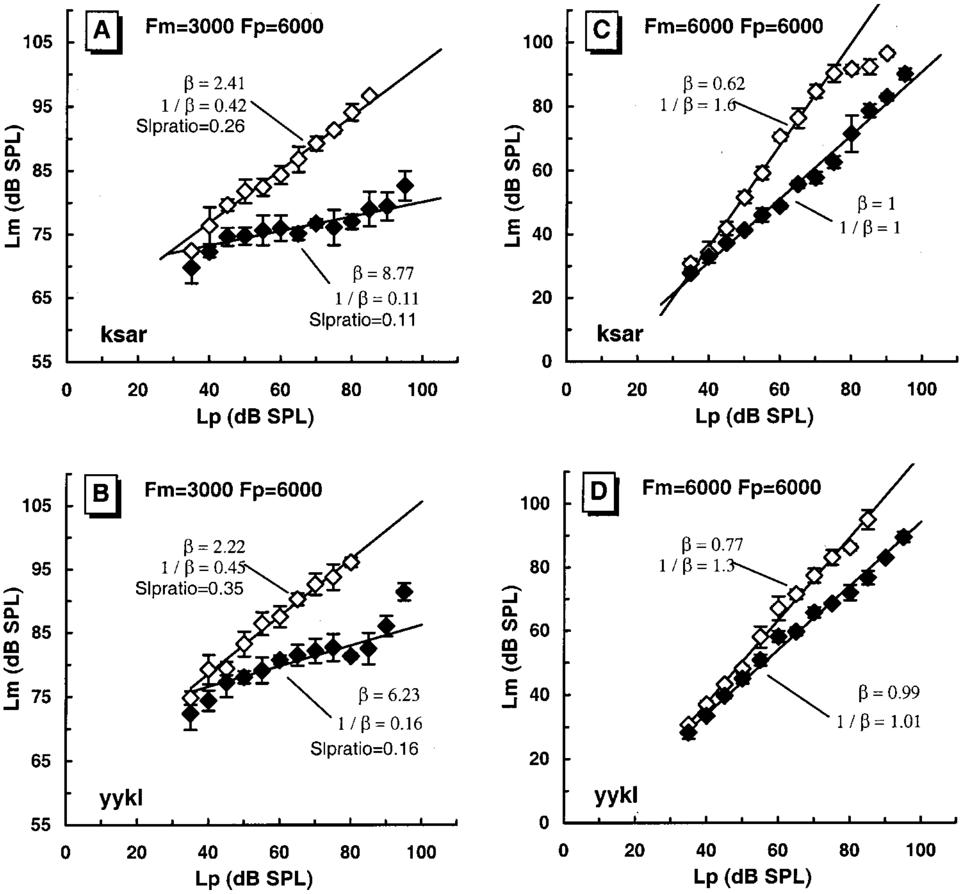

FIG. 1. Growth of maskability (GMB) functions in quiet (open symbols) and in the presence of a high-pass noise (with a low-frequency cutoff at 1.117Fp) to mask spread of excitation toward higher frequencies (closed symbols). The masker level required to mask a 6-kHz probe tone is plotted on the ordinate as a function of probe level on the abscissa. The GMB functions for an off-frequency masker (3 kHz) are shown in (a) and (b) (for normal-hearing subjects ksar and yykl, respectively), and those for an on-frequency masker (6 kHz) are shown in (c) and (d). Solid lines are linear regression fits to each function using only masker levels obtained with mid-level probe tones. The slope of each GMB function is given by $\mathbf{1/\beta}$. The growth-of-masking (GOM) slope, which describes masked threshold as a function of masker level, is given by $\boldsymbol{\beta}$. The slope ratio (Slpratio) is the GMB slope for the off-frequency condition [(a) or (b)] divided by the GMB slope for the corresponding on-frequency condition [(c) or (d)].

findings so well with only a HP noise, the addition of a low-pass noise for the on-frequency condition would seem unnecessary. Similarly, a fixed ratio between the level of the HP noise and the probe level was sufficient to replicate their findings, thus it should not be necessary to employ a varying level ratio as they did.

The GMB functions obtained without the HP noise are shown by the unfilled symbols in Fig. 1. The GMB slopes for the on-frequency condition [Figs. 1(c) and (d)] were 1.6 and 1.3 dB/dB for subject ksar and yykl, respectively, while the GMB slopes for the low off-frequency condition [Figs. 1(a) and (b)] were 0.42 and 0.45 dB/dB. The ratios of on-frequency and low off-frequency GMB slopes were 0.26 and 0.35 in quiet, which are similar to the 0.33 average GMB slope ratio reported for six normal-hearing listeners by Moore *et al.* (1999). If the GMB slope ratio is taken as an estimate of response growth at the probe frequency, then it is more than twice as steep in quiet as it is in HP noise. This result is not consistent with the result reported by Oxenham and Plack (1997). Their single subject, tested both with and without the HP noise, exhibited a GMB slope ratio of 0.17 for the HP noise condition and 0.19 dB/dB for the quiet condition, which led them to conclude that the effects of spread of excitation (as probe level was increased) was the same for low off-frequency and on-frequency maskers. While the HP noise produced about a factor of 2 reduction in GMB slope for both the low off-frequency and the on-frequency maskers in their subject, the two subjects in the present study (ksar and yykl, respectively) exhibited reductions in GMB slopes by factors of 3.8 and 2.8 for the low off-frequency condition and factors of 1.6 and 1.3 for the on-frequency condition. This indicates that, in the present study, the HP noise had a larger effect for the low off-frequency condition than for the on-frequency condition. This can be seen by examining the probe levels, in quiet versus HP noise, corresponding to a fixed masker level in Fig. 1. For example, in subject yykl, at a masker level of 85 dB SPL (Lm on ordinate), the HP noise produced a 35-dB increase in probe level at masked threshold for the low off-frequency condition [Fig. 1(b)] compared to only about a 15-dB increase in probe level for the on-frequency condition [Fig. 1(d)].

A replication of experiment 1 in the same two subjects, using a 1-kHz probe, a 0.6- or 1-kHz masker, and a HP noise with a low-frequency cut-off of 1.117Fp, yielded similar results. The reduction in GMB slope with the HP noise was not as great at 1 kHz as it was at 6 kHz. For subjects yykl and ksar, respectively, the HP noise reduced GMB slopes by factors of 1.5 and 1.4 for the low off-frequency condition and by factors of 1.2 and 1.1 for the on-frequency condition. Thus, without a background noise, upward spread of excitation from the probe still influenced GMB slopes differentially at 1 kHz, just as it did at 6 kHz, but the differential effect was not quite as great.[1]

Moore *et al.* (1999) noted that their GMB slope ratios obtained in quiet were larger than those obtained by Oxenham and Plack (1997) in background noise. They speculated that a possible factor contributing to this difference was off-frequency listening in the quiet condition. For the low-frequency masker, the signal might have been detected using a region of the basilar membrane with a CF above the signal frequency, which would be slightly less compressive than at the CF region. The present findings support their explanation.

Taken together, the present results and those of previous studies indicate that off-frequency listening to the high-frequency tail of the probe excitation pattern can strongly influence estimates of response-growth rate, and may differ widely among subjects. This is not surprising, considering that the probe level in this experiment is varied from 35 to 95 dB SPL. Spread of excitation varies substantially over such a wide range of probe levels. Thus, it seems precarious to use GMB slope ratios obtained in quiet conditions to specify response growth. The use of background noise to prevent or reduce off-frequency listening seems more prudent. At this point, the results are sufficient to question the validity of procedures for estimating response-growth rates that utilize varying probe levels without the addition of background noise. Therefore, we have examined an alternative procedure for obtaining estimates of response-growth rates, one that does not involve the large changes in spread of excitation associated with varying probe levels.

III. EXPERIMENT 2: RESPONSE GROWTH FROM TMCs

The alternative procedure estimates response-growth rates from the slopes of forward-masking recovery curves for low off-frequency and on-frequency maskers. The TMCs for a fixed-level probe define the masker levels required to just forward mask the probe as a function of the time delay between masker and probe (Nelson and Freyman, 1987). The masker level required to forward mask a probe with an on-frequency masker depends both upon the recovery from forward masking that occurs at the probe-frequency place *and* upon the cochlear compression that exists at the probe-frequency place (Oxenham and Moore, 1995, 1997; Plack and Oxenham, 1998). By way of contrast, the masker level required to forward mask a probe with a low off-frequency masker ($Fm \leq 0.6Fp$) depends *only* upon the recovery from forward masking that occurs at the probe-frequency place. This is because the low off-frequency masker that is nearly an octave below the probe frequency produces a linear response at the probe-frequency place in the cochlea (Yates, 1990; Yates *et al.*, 1990; Ruggero, 1992; Nelson and Schroder, 1997; Oxenham and Plack, 1997; Ruggero *et al.*, 1997; Moore and Oxenham, 1998; Rhode and Recio, 2000). If one assumes that the recovery time constant for forward masking at the probe-frequency place on the basilar membrane is independent of masker frequency, then the ratio of the recovery slopes for the on-frequency and the low off-frequency masker, for a given change in time delay, reflects the factor by which the masker level has to be increased in the on-frequency case to overcome cochlear compression. The reciprocal of that factor provides an estimate of response-growth rate that is determined by cochlear compression.

A critical assumption with this procedure is that the recovery time constant for low off-frequency and on-frequency maskers is the same. This assumption has been used to successfully model data for combined simultaneous and nonsimultaneous masking by on-frequency and low off-frequency maskers (Wojtczak *et al.*, 2001). Furthermore, there is evidence that the recovery process at a particular cochlear place, which proceeds exponentially (in decibels) with time delay between masker and probe (Duifhuis, 1973; Nelson and Freyman, 1987), is independent of the frequency difference between masker and probe (Nelson and Pavlov, 1989). Another critical assumption is that the exponential decay of the internal effect of a masker is the same regardless of the magnitude of the internal effect, i.e., the recovery process is well defined by an exponential decay (in decibels) with a level-independent time constant.

A. Method

The TMCs were obtained from four normal-hearing subjects for various masker frequencies surrounding a 1-kHz probe presented at a fixed low level. The fixed-probe or *iso-response* TMC requires a constant response at some central stage in the auditory system, e.g., at the output of a temporal integrator that follows peripheral filtering and compression, which then produces a constant amount of threshold shift (forward masking) at the probe frequency. The input level (masker level) is adjusted to maintain the required response at the probe-frequency place as a function of the time delay between the masker and the probe. As time delay is increased, the amount of forward masking decreases, therefore the masker level must be increased to maintain the same amount of forward masking. A plot of masker level as a function of time delay defines the iso-response TMC (Nelson and Freyman, 1987). A 1-kHz probe frequency was chosen, rather than the 6-kHz probe frequency investigated by Oxenham and Plack (1997), because 1 kHz was the frequency previously investigated by Nelson and Freyman (1987) with hearing-impaired listeners, and 1 kHz is a frequency region that is important for speech perception.

An advantage of the iso-response TMC is that the spatial region in the cochlea being assessed is held constant during an experiment. That region is defined by the excitation pattern produced by the fixed-frequency, fixed-level probe tone. That region is small when the probe is presented at a very low level. Thus, nonlinear spread of probe excitation with increasing level should not affect the estimate of response growth derived from the TMC. A further advantage of the iso-response paradigm is that nonlinearities affecting the probe are constant throughout an experiment. This allows one to infer characteristics of the nonlinearities associated with the masker, as will become apparent during the analysis of the present results.

Forward masking was produced by sinusoidal maskers that varied in frequency from well below to just above the 1-kHz probe tone. Specific masker frequencies examined were 500, 600, 700, 800, 900, 1000, 1012, 1025, 1050, 1100, 1150, and 1200 Hz, although not all masker frequencies were tested in every subject. The masker and probe durations were 200 and 20 ms at peak amplitude, respectively, with 10-ms raised-cosine rise and decay times. During each test session, delay times (between masker offset and probe offset) were tested in the following order: 42, 45, 50, 60, 70, 80, 90, 100, 110, 120, 130, and 140 ms. A minimum temporal separation between masker offset (10% of peak amplitude) and probe onset (10% of peak amplitude) of 2 ms ensured that no physical interaction occurred between masker and probe before reaching the cochlea. For each delay time, the probe level was fixed at a sound pressure level that was about 10 dB SL and the masker level was adjusted adaptively to reach masked threshold.

Pure-tone signals for masker and probe stimuli were produced by frequency synthesizers (Rockland), gated by electronic switches, 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.

The same 3IFC adaptive procedure described in experiment 1 was used to estimate the level of masker needed to just mask the fixed-level probe and to measure absolute sensitivity threshold. Four normal-hearing subjects participated in the experiment. Their absolute thresholds were less than 15 dB HL (ANSI, 1989) for octave frequencies between 250 and 8000 Hz. All subjects received several hours of practice on forward-masking tasks before data collection commenced.

B. Results and discussion

1. Iso-response TMCs

Figure 2 shows the masker levels required to mask a fixed-level 1-kHz probe, as a function of the time delay between masker offset and probe offset, for maskers varying in frequency from well below to just above the probe frequency. The TMCs are shown from four normal-hearing subjects. Dashed lines indicate three-segment exponential fits to the data.[2]

Several features of these *iso-response* TMCs are evident. The general form of the TMC shows an increase in masker level with masker-probe time delay, which reflects recovery from forward masking over time. At short delay times, considerable forward masking is evident; therefore, relatively low masker levels are required to maintain a fixed amount of forward masking. At longer time delays, more recovery from forward masking is evident; therefore, higher masker levels are required to maintain the same fixed amount of forward masking. For the on-frequency and nearly on-frequency conditions (shaded symbols), the change in masker level with time delay is steep over a range of time delays. For off-frequency maskers, both below (black symbols) and above (unfilled symbols) the probe frequency, the change in masker level with time delay is more gradual.

2. Interpretations of different TMC characteristics

Two aspects of these TMCs are particularly noteworthy: the masker level at the shortest time delay, and the relative steepness of the curve (recovery slope at different time delays). The TMCs for subject KEK are replotted in Fig. 3 to illustrate the main effects that exist, to varying extents, in the data from each of the other three subjects.

First, at the shortest time delay (42 ms), note that high levels are required for the lowest-frequency maskers [Fig. 3(a)] and progressively lower masker levels are required as the masker frequency approaches the probe frequency [Figs. 3(b)–(e)]. At any fixed time delay, masker level differences across frequency define a psychophysical tuning curve (PTC). The PTC approximates an inverted filter function describing gain across masker frequency, a gain that is relative to the gain at the probe frequency. At the shortest time delay, the difference between the level of the lowest off-frequency masker and the level of the on-frequency masker approximates the maximum gain available at and near the probe frequency [approximately 50 dB in Fig. 3(l)]. At longer time delays gain applied to the on-frequency masker decreases, which is evidenced by strong compression, and the difference in gain across masker frequencies diminishes, leading to broader tuning. For masker frequencies very close to the probe frequency, some of the subjects exhibited a large change in the masker level with only a small change in masker frequency (e.g., RXL in Fig. 2 exhibited an increase in masker level of 12 dB for only a 1.2% change in masker frequency from 1000 to 1012 Hz). Such large changes in masker level with small changes in masker frequency could be due to the improved detectability of the probe when small pitch differences exist between masker and probe (Moore, 1980a, b).

If shorter probe tones had been used, the minimum time delay between masker offset and probe offset at which forward masking was measured could have been smaller, but would likely have had little effect on the estimate of maximum gain at the probe place. In the case of shorter probe tones and shorter time delay, less recovery from forward masking may have occurred. Consequently, the masker levels required to mask the probe would have been lower. However, this would be true for both on- and off-frequency maskers. As long as the on-frequency masker falls within a linear region of response growth, the difference between the level for the lowest off-frequency masker and the on-frequency masker should remain the same irrespective of the duration of the probe. Note that for at least two of the subjects [MRM and RXL in Figs. 2(c) and (d)] the slope of the TMC over a range of short time delays, for the on-frequency masker, is approximately the same as the slope of the TMC for the low off-frequency ($Fm \leqslant 0.6Fp$) masker. Assuming the same recovery time constant for off-frequency and on-frequency forward masking, at least over a range of short time delays, the on-frequency masker produced a linear or nearly linear response. This suggests that the estimate of the maximum gain should not change with decreased probe duration, although additional research with shorter probe tones is needed to examine this premise further. For now, we use the difference between levels of the low off-frequency masker and the on-frequency masker at the shortest time delay to provide an approximation of the maximum gain at the probe frequency place. This is done so that we can express the excitation response produced at the shortest delay by the

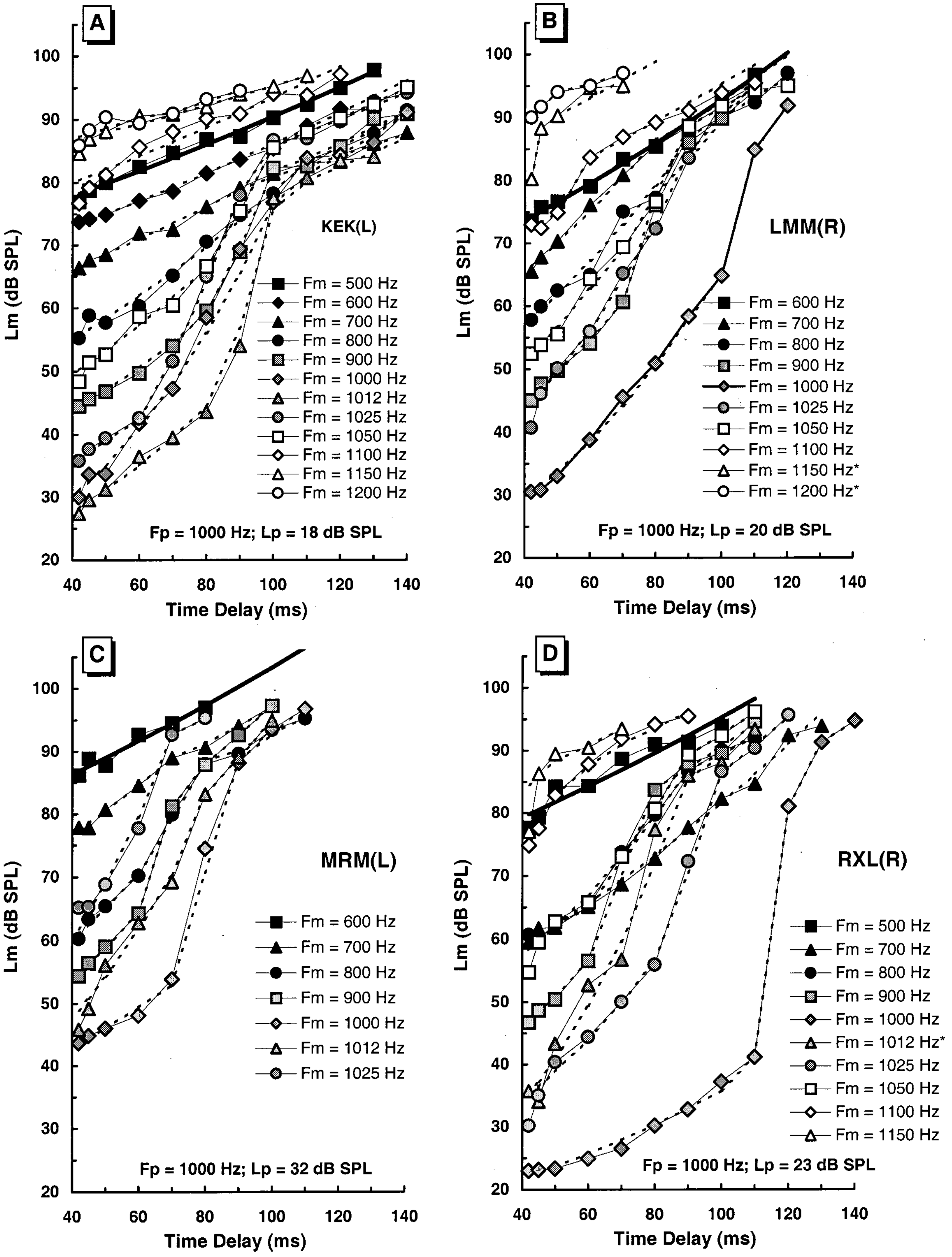

FIG. 2. Fixed-probe-level (*iso-response*) temporal masking curves from four normal-hearing subjects. Each curve shows the masker level (in dB SPL) required to forward mask a fixed-level 1-kHz probe, as a function of the time delay between masker offset and probe offset. The parameter is the frequency of the masking tone. Masker frequencies close to the probe frequency are indicated by shaded symbols, those above the probe frequency are indicated by open symbols, and those well below the probe frequency are indicated by black symbols. An asterisk next to the symbol label indicates that those data were based on only one threshold determination. Dashed lines show three-segment exponential fits to each curve. The wide curve is the single-segment exponential fit to the masker levels for the 0.5- or 0.6-kHz masker frequency.

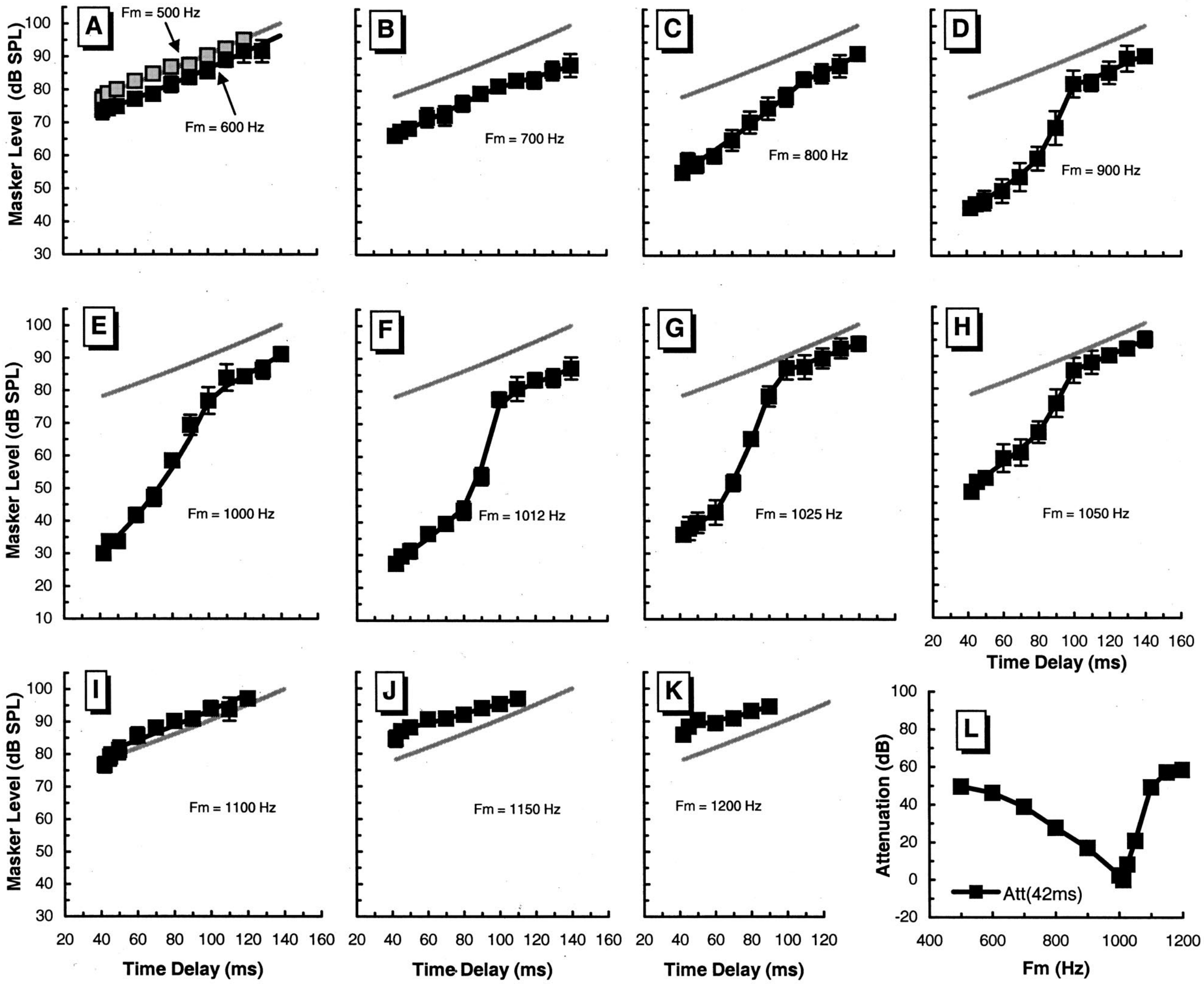

FIG. 3. Temporal masking curves (TMCs) from normal-hearing subject KEK(L), which were used to calculate response-growth slopes as a function of time delay. Each panel shows TMCs for a different masker frequency (Fm). The probe frequency was 1 kHz. Panel (a): Off-frequency TMCs for the 0.5- and 0.6-kHz maskers define the conditions in which the response growth at the 1-kHz probe frequency is linear (by assumption). The 0.5-kHz off-frequency TMC is replicated, for comparison, in (b)–(k) by the wide gray line. (e) On-frequency TMC for the 1-kHz masker. The wide black line shows the three-segment exponential fit to the on-frequency TMC. (b)–(d) and (f)–(k) make the same comparison at other masker frequencies. Panel (l): Attenuation attributed to the auditory filter, which is estimated as the difference in dB between masked thresholds at each masker frequency (Fm) and the masked threshold at 1 kHz, at the 42-ms time delay condition. Maximum gain ($\mathbf{G}_{\max}$) available in the auditory filter is approximated by the difference between the attenuation for the low off-frequency masker and the attenuation for the on-frequency masker.

different frequency maskers in terms of the input level at the probe-frequency place that, at the same time delay, produces an equivalent amount of forward masking.

Consider next the relative steepness of the TMCs at different masker frequencies. As previously proposed, the slopes of the TMCs for the lowest-frequency maskers ($\mathrm{Fm} \leqslant 0.6\mathrm{Fp}$) are determined only by the amount of recovery from forward masking existing at the probe frequency as a function of the time delay between masker and probe. Therefore, the slope of the TMC reflects the time constant of the recovery process that is represented by an exponential function with a single time constant ($\boldsymbol{\tau}$):

$$\mathbf{L}_m(\mathrm{off}) = \mathbf{L}_p \cdot e^{t/\boldsymbol{\tau}} + \mathbf{G}_{\max}, \tag{1}$$

where t is the time delay between masker and probe, $\boldsymbol{\tau}$ is the time constant for recovery from forward masking, $\mathbf{L}_p$ and $\mathbf{L}_m$ are the probe and masker levels in dB SPL, and $\mathbf{G}_{\max}$ is the maximum gain at the probe place (estimated at $t = 42\,\mathrm{ms}$). The iso-response TMC for the lowest-frequency masker is shown by the shaded squares in Fig. 3(a) (also by the black squares in each panel of Fig. 2). The exponential fit to that curve, using Eq. (1), is indicated by the wide shaded curve in Fig. 3(a) (also by the wide black curve in each panel of Fig. 2). According to our assumptions, for the low off-frequency masker, the change in masker level that occurs with increased time delay between masker and probe is determined solely by recovery from forward masking specified by the time constant, $\boldsymbol{\tau}$.

Because it is assumed that the recovery process at the probe-frequency place is independent of the relative frequencies of masker and probe (Nelson and Pavlov, 1989), then, if there is no compression, the iso-response TMCs for all of the masker frequencies should have the same slope as that shown by the wide shaded curve in Fig. 3 for the 500-Hz masker. Indeed, the recovery-curve slope for the 600-Hz masker is the same as for the 500-Hz masker [Fig. 3(a)]. At a masker frequency of 700 Hz [Fig. 3(b)], the TMC can no longer be described quite as well by a single exponential curve. And clearly, the slopes of the recovery curves for maskers between 800 and 1050 Hz [wide black curves in Figs. 3(c)–(h)] are not the same as the 500-Hz masker. As the masker frequency moves closer to the probe frequency [Figs. 3(c)–(e)], the TMCs exhibit progressively steeper recovery slopes over a range of time delays. The TMCs for these masker frequencies require three exponential segments to adequately fit the data. For the on-frequency condition, or when the masker frequency is very close to the probe frequency, a pattern emerges in which three segments of the TMC are easily distinguished by different slopes. At short time delays where low masker levels are required, the recovery slope is gradual, close to the recovery slope seen for the lowest-frequency masker. At longer time delays, where moderate masker levels are required, the recovery slopes become very steep. Then, at the longest time delays, where the highest masker levels are required, the recovery slope becomes more gradual again. For subjects LMM, MRM, and RXL, this pattern is evident for the 1000-Hz masker (Fig. 2); for subject KEK this three-segment pattern is most evident for the 1012-Hz masker [Fig. 3(f)]. When the masker frequency is moved above the probe frequency, the steep recovery slopes become progressively flatter with increased masker frequency [Figs. 3(g) and (h)], and the TMCs can again be represented by a single exponential function [Figs. 3(i)–(k)].

A single exponential function was used to fit the TMC for the low off-frequency masker because it reflects one of the traditional models used successfully in the past for quantifying recovery from forward masking (Duifhuis, 1973; Widin and Viemeister, 1979; Abbas and Gorga, 1981; Nelson and Freyman, 1987). The single exponential accounted for most of the variance in the low off-frequency TMCs from these four subjects (99%, 99%, 94% and 92%, respectively, for subjects KEK, LMM, MRM, and RXL). Exponential functions were also used for fitting the other TMCs because it was assumed that the underlying recovery process at the probe-frequency place was the same as that reflected by the low off-frequency masker (i.e., exponential with an identical time constant), regardless of masker frequency, and that compression, when present, would change the apparent slope of that exponential recovery process.[3] Three separate exponential segments were chosen for fitting the other TMCs because it was believed that compression acts differently at low, middle, and high stimulus levels. At time delays where low masker levels are required, gradual recovery slopes indicate little or no cochlear compression. At time delays where moderate-level maskers are required, steep recovery slopes suggest that strong cochlear compression is operating. At time delays where higher masker levels are required, recovery slopes are gradual again. This latter slope reduction is particularly evident for masker levels above about 80 dB for subject KEK, which can be seen in Figs. 3(c)–(h). The more gradual recovery slopes exhibited for these high-level maskers suggest that cochlear response is close to linear at higher levels. This more linear response growth at high levels is consistent with the findings of Oxenham and Plack (1997) in two of three listeners above 80 dB at 2 kHz, and in all three listeners above 80 dB at 6 kHz.

3. Deriving input/output curves from TMC curves

Input/output curves for each masker frequency can be derived from TMCs by determining the output levels for a low off-frequency masker as a function of masker/probe time delay, and then plotting those output levels as a function of input level at each masker frequency. The rationale for this process follows.

For each given time delay along a low off-frequency TMC, the level of a low off-frequency masker that produces the same amount of masking as an on-frequency masker was measured. Thus, for every time delay, it is reasonable to assume that the effective response produced by the low off-frequency masker, at the probe-frequency place, is the same as that produced by the on-frequency masker (or any other off-frequency masker). Therefore, we can express the effective level of a low off-frequency masker, at the probe-frequency place, in terms of the equivalent on-frequency masker level. To illustrate, assume that at a time delay of 42 ms a 78 dB SPL low off-frequency masker (500 Hz) is required to mask an 18 dB SPL probe tone, while a 28 dB SPL on-frequency masker is required to mask the same level probe tone. In this case the effective level for the 500-Hz masker at the probe-frequency place, after being attenuated by the auditory filter, is the same as the level required for the on-frequency masker to mask the probe, which is 28 dB. This level is used as a reference for expressing the relative output at the probe-frequency place produced by the 500-Hz masker at the shortest time delay.

According to our assumptions, any increase in the level of the low off-frequency masker (associated with an increase in time delay) results in a linear increase in the effective output level at the probe-frequency place. Therefore, the changes in masker (input) level with time delay that are observed for a low off-frequency masker will be the same as the changes in effective output level that occur at the probe frequency place. This is illustrated in Fig. 4 by curve (a). The shaded triangles show an input/output function for a 500-Hz masker at the 1-kHz place (Rm500/Lm500): the effective response of the 500-Hz masker at 1 kHz (the output level) is plotted on the ordinate versus the level of the 500-Hz masker (the input level) on the abscissa. Beginning at a low off-frequency input level of 78 dB SPL, which corresponds to an effective output level of 28 dB SPL, the effective output level increases *linearly* with increases in input level. Therefore, sequential increases in output level above 28 dB SPL are the same as the sequential increases in input level that are dictated by the different time delays tested and the time constant for recovery from forward masking.[4]

Since, for the same time delays, output levels are the same for each masker frequency used to measure TMCs, the input/output functions for each masker can be obtained by plotting the 500-Hz masker output levels against each tested masker's (input) levels. Curve (b) in Fig. 4 shows the resulting function for a 1-kHz masker.[5]

Derived input/output response-growth curves for the four normal-hearing subjects are shown in Fig. 5. Response-

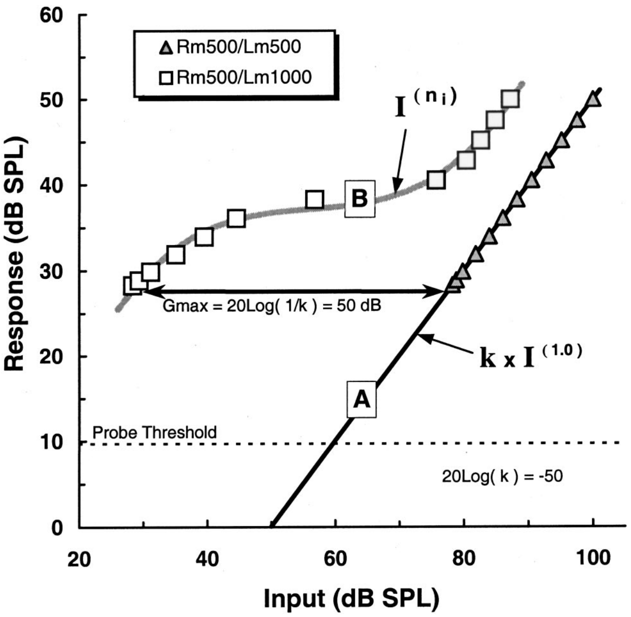

FIG. 4. Derived input/output response growth curves for a 0.5-kHz off-frequency masker [curve (a)] and a 1-kHz on-frequency masker [curve (b)]. Probe threshold is indicated by the dashed line.

growth curves for masker frequencies at and below the probe frequency are shown in the left-hand panels; those for masker frequencies above the probe frequency are shown in the right-hand panels.

4. Response-growth rates calculated from derived input/output curves

Local response-growth rates can be calculated from the derived input/output curves by taking the first derivative of third-order polynomial fits to the input/output curves. Response-growth rates calculated from the derived input/output curves are shown, as a function of input level, for the four normal-hearing listeners in Figs. 6(a)–(d). Response-growth-rate curves are shown at two or three masker frequencies that are close to or equal to the probe frequency for each subject. Typically, response-growth rate varied with input level in a U-shaped fashion, being steep at low and high input levels and gradual for moderate level inputs. The input level at which the minimum response-growth rate occurred varied across subjects, from around 55 dB SPL in subject KEK to around 70 dB in subject MRM. For subject LMM there was no obvious increase in growth rate at the higher levels for the 1000-Hz masker, but there was for the 1025-Hz masker. For subject RXL, negative response-growth rates were estimated when the masker and probe frequencies were the same, but this is an artifact of fitting the input/output curves with a third-order polynomial; none of the local slopes in the raw data in Fig. 5(g) are negative. Some of the extremely gradual growth rates for the 1-kHz masker may have been influenced by the lack of a pitch difference between masker and probe (Moore, 1980a, b), which may have made it more difficult to distinguish the probe from the end of the masker, resulting in lower masker levels at threshold for short and medium delay times. However, the very gradual response-growth rates seen here at moderate input levels are consistent with the 0.16 response-growth rate obtained by Oxenham and Plack (1997).

These computed response-growth rates tended to change with input level and masker frequency in a similar manner to BM response-growth rates. For example, for subject KEK, examination of the input/output curves for maskers with frequencies at or close to the probe frequency [900–1025 Hz in Figs. 5(a) and (b)] indicates that response-growth rates change with input level from near 1.0 at very low input levels, to <0.2 at mid levels, to near 1.0 again at high levels. BM input/output curves obtained by Ruggero *et al.* (1997) for on-frequency stimulation in the base of a chinchilla cochlea are replotted in Fig. 5(a) (a 10-kHz tone stimulating a place in the cochlea corresponding to a 10-kHz best frequency) and Fig. 5(b) (an 11-kHz tone stimulating the 10-kHz place). These functions do not provide strong evidence of a return to linearity at high input levels in healthy animal cochleae. Three subjects out of four tested in this study (KEK, MRM, and RXL) exhibit strong evidence of nearly linear growth rates at input levels above 80 or 90 dB SPL, while that behavior is not as consistent in subject LMM.

As the masker was moved further away in frequency from the probe, the general form of the input/output curve for the masker at the probe-frequency place became more linear. This tendency toward more linear response growth occurred in both frequency directions, i.e., as the masker frequency became either lower or higher than the probe frequency. This result can be seen more clearly in Fig. 7, where the smallest response-growth rate in each input/output curve is plotted against masker frequency.

As the masker frequency below probe frequency became progressively lower, input/output curves became more linear. This tendency was evident in all four subjects, although the exact frequency at which the curves became linear differed across subjects. A similar result has been reported for BM responses as the stimulating tone is lowered below the best frequency (Ruggero *et al.*, 1997; Rhode and Recio, 2000).

As the masker frequency above the probe frequency became progressively higher than the probe frequency, input/output curves also became more linear. This trend is also seen in BM responses, as shown in Fig. 5(b) by the curve for a 17-kHz tone stimulating the 10-kHz place. The separation between the probe frequency and the nearest masker frequency, for which a linear response at the probe place was observed, was smaller on the higher-frequency side of the probe than it was on the lower-frequency side as shown in Fig. 7.

From these comparisons with BM input/output curves, it is clear that the derived input/output curves generated from iso-response TMCs behave generally in the same way as BM response-growth curves in basal regions of the cochlea (Ruggero *et al.*, 1997; Rhode and Recio, 2000). Detailed characteristics of individual input/output curves, e.g., the exact input levels where response-growth rates change from linear to compressive in individual subjects, should be regarded with some caution at this stage of investigation, since subtle cues in forward masking might change them slightly.

The input/output curves derived here are similar to those

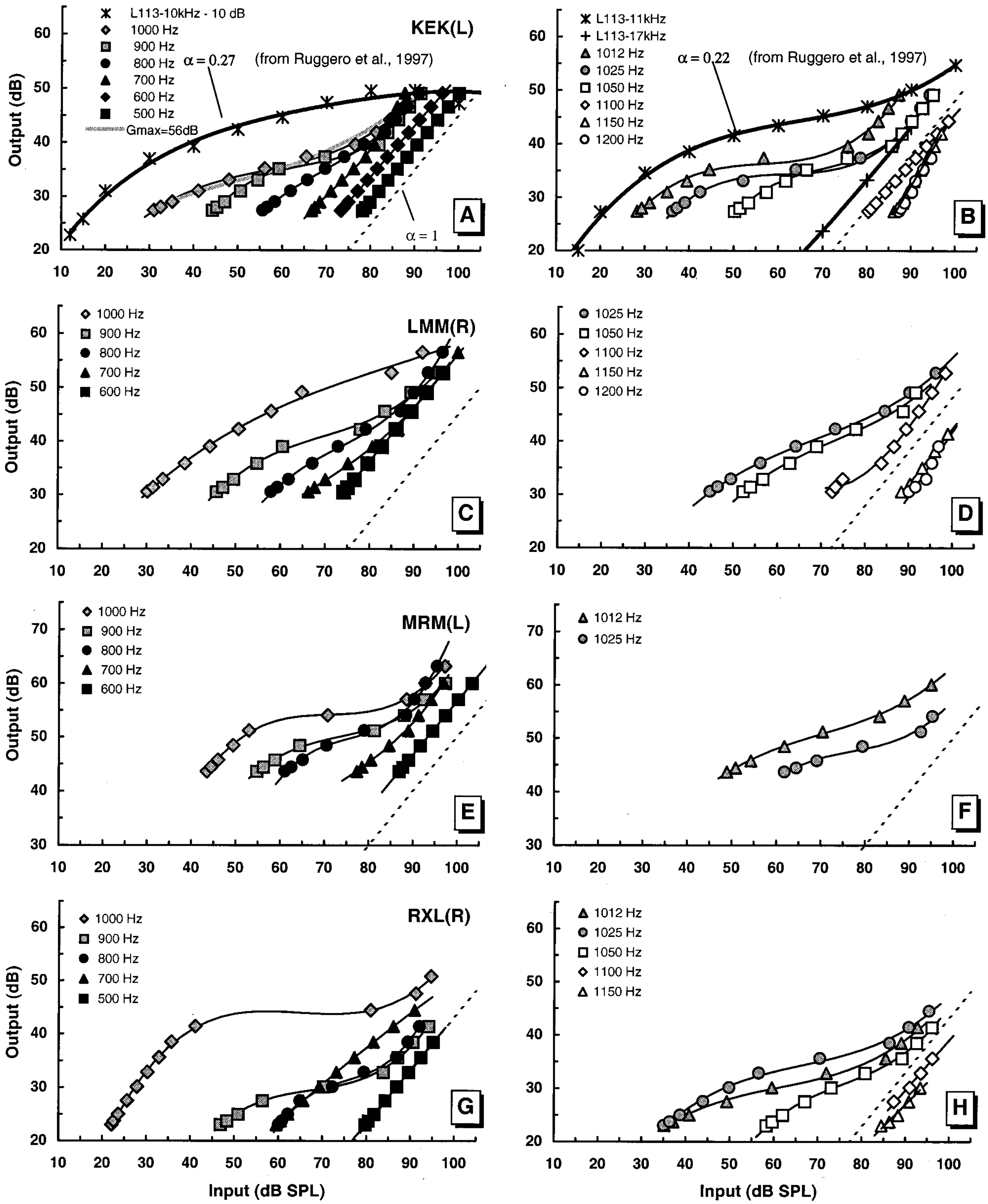

FIG. 5. Derived input/output response-growth curves from four normal-hearing listeners. Response-growth curves for maskers at and below the probe frequency are shown in the left-hand column of panels; those for maskers above the probe frequency are shown in the right-hand column of panels. Solid curves are third-order polynomial fits to the individual input/output curves (linear fits are used for the low- and high-frequency off-frequency curves). Input/output curves from a chinchilla are replotted from Ruggero *et al.* (1997) for comparison. Output for BM curves is velocity (μm/s) less a scaling factor for comparison with psychophysical data. Response-growth slopes at mid levels are indicated by α for Ruggero's near CF curves. A linear growth curve, with α=1.0, is shown for reference by the dashed line in each panel. The wide gray curve in (a) is the 1-kHz input/output function predicted by an equation proposed by Glasberg and Moore (2000).

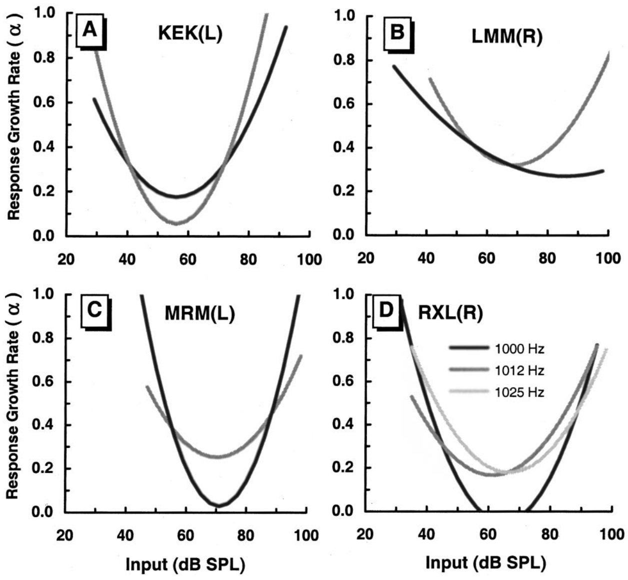

FIG. 6. Response-growth rates estimated from derived input/output curves are shown as a function of input level (masker SPL). The parameter is masker frequency as labeled. Several curves are shown for each subject, one for a masker frequency at the probe frequency and one or two for masker frequencies slightly higher in frequency. For subject RXL(R), the 1000-Hz growth curve exhibited negative growth rates, which was an artifact of the third-order polynomial fitting function.

predicted by an equation published recently by Glasberg and Moore (2000). Their equation (1) describes the gain in dB, for the average normal-hearing listener, that exists at a particular place in the cochlea, as a function of input level (in dB SPL). The free parameter in that equation is $\mathbf{G}_{\max}$, the maximum gain provided by the cochlear amplifier at low input levels. By way of comparison, the input/output function at 1 kHz predicted by their equation, for a $\mathbf{G}_{\max}$ value of 56 dB, is shown by the wide gray curve in Fig. 5(a). For subject KEK the Glasberg and Moore input/output function describes the derived input/output values (shaded diamonds) quite well. A good linear prediction was also achieved for the 0.5-kHz data with a $\mathbf{G}_{\max}$ value of 0.8 dB. However, with only $\mathbf{G}_{\max}$ as a free parameter, the Glasberg and Moore equation did not do a good job of describing the 1-kHz input/output curves derived for the other three subjects. In order to achieve good fits for those subjects, the various parameters in the Glasberg and Moore equation that control the width and center of gravity of the compression region (across input level) would have to be adjusted in addition to the $\mathbf{G}_{\max}$ value.

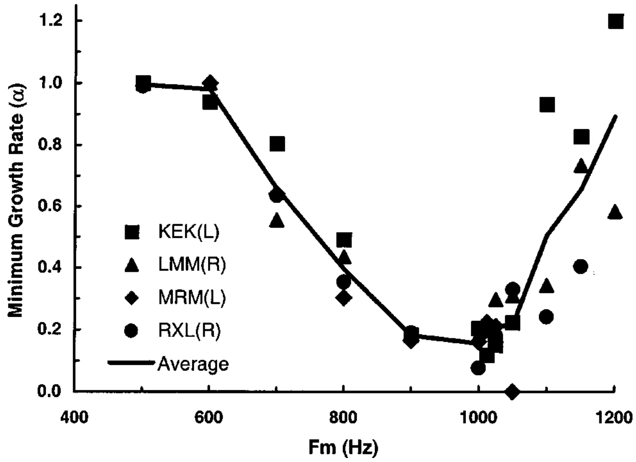

FIG. 7. Minimum response growth rates at 1 kHz as a function of masker frequency, which were taken from the third-order polynomial fits to the derived input/output curves at each masker frequency.

5. Deriving response-growth rates from TMC slope ratios

The response-growth rates calculated from the slopes of derived input/output curves are conceptually equivalent to response-growth rates calculated directly from TMC slope ratios. In the latter case, response-growth rate at any input level is determined by the ratio between the recovery slope for the low off-frequency masker and the recovery slope for any other masker closer in frequency to the probe frequency. Based on Eq. (1), for the lowest off-frequency masker, the change in masker level, $\Delta\mathbf{L}_m(\mathrm{off})$, corresponding to a change in time delay between $t1$ and $t2$ is determined solely by the forward-masking recovery process as described by

$$\Delta\mathbf{L}_m(\mathrm{off}) = (\mathbf{L}_p)e^{t2/\tau} - (\mathbf{L}_p)e^{t1/\tau}, \tag{2}$$

where $t1$ and $t2$ are any consecutive time delays along the TMC.

By assumption, the change in masker level with time delay for an on-frequency masker is controlled by the same recovery process as that operating for a low off-frequency masker, but in addition it is influenced by cochlear compression, which affects the response growth rate with level ($\boldsymbol{\alpha}$) for the masker at the probe-frequency place. Thus, $\boldsymbol{\alpha}$ is a continuously varying function of masker level, which is an exponential function of time delay. Conceptually, for the same two consecutive time delays, $t1$ and $t2$, along the TMC, response growth associated with the on-frequency masker levels at those time delays can be represented by a single exponential and a multiplicative constant as in

$$\boldsymbol{\alpha}\cdot\Delta\mathbf{L}_m(\mathrm{on}) = (\mathbf{L}_p)e^{t2/\tau} - (\mathbf{L}_p)e^{t1/\tau}, \tag{3}$$

From Eqs. (2) and (3), the response-growth rate for the on-frequency masker resulting from a change of $\Delta\mathbf{L}_m$ in masker level can be expressed by

$$\boldsymbol{\alpha} = \Delta\mathbf{L}_m(\mathrm{off})/\Delta\mathbf{L}_m(\mathrm{on}). \tag{4}$$

Thus, for any change to the *input* masker level, $\Delta\mathbf{L}_{mj}$, which corresponds to a change in time delay from t_j and $t_{j'}$, with j and j' corresponding to consecutive time delays along the TMC, there exists a response-growth rate ($\boldsymbol{\alpha}_j$) associated with that change. Response-growth rates calculated in this way are the same as those determined directly from the raw data used to fit the third-order polynomial representing the smoothed input/output curve in the previous section.

6. Response growth and cochlear hearing loss

An important application of the TMC procedure for estimating compression is to evaluate response-growth rates in ears with cochlear hearing loss. This was done by reanalyzing the TMCs from two subjects, EP(R) and RA(R), previously tested by Nelson and Pavlov (1989) in a similar ex-

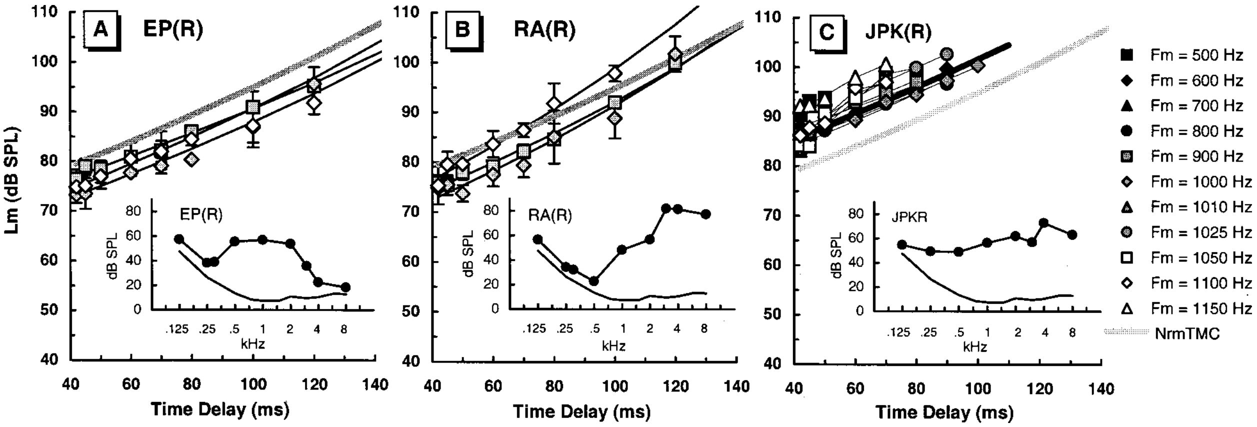

FIG. 8. Results for hearing-impaired listeners. (a) and (b) Fixed-probe-level TMCs for a 1-kHz probe from two hearing-impaired subjects who were previously tested by Nelson and Pavlov (1989) at masker frequencies of 0.9, 1.0, and 1.1 kHz. The parameter is masker frequency, with the on-frequency masker (1 kHz) represented by shaded diamonds. Each curve is fitted with a single-segment exponential, shown by the solid curves. Absolute thresholds for 200-ms tones are plotted as a function of frequency within the inserts. The solid line represents 0 dB HL (ANSI, 1989). The average TMC for low-frequency (0.5–0.6 kHz) maskers in normal-hearing ears (wide shaded curve) is also shown for reference. (c) TMCs for 1-kHz probe tones from a third hearing-impaired listener who was recently tested over a broader range of masker frequencies (0.5–1.15 kHz).

periment using a 4IFC procedure, but at only three masker frequencies (900, 1000, and 1100 Hz). A third subject with cochlear hearing loss, JPK(R), was tested using the same procedure as described for experiment 2, but using the instrumentation from experiment 1. For JPK, the same range of masker frequencies was employed as for the normal-hearing listeners. All three subjects were experienced with forward-masking tasks. Iso-response TMCs obtained from the two previously tested subjects are replotted in Figs. 8(a) and (b); those obtained recently from the third subject using a broader range of masker frequencies are plotted in Fig. 8(c). The average iso-response TMC for the lowest-frequency masker (500 or 600 Hz) from the four normal-hearing listeners is shown, for comparison, by the wide gray curve (labeled NrmTMC).[6] Nearly all of the TMCs from the hearing-impaired listeners are as gradual as those from normal-hearing listeners for a *low off-frequency* masker. The exceptions are the TMCs for maskers above the probe frequency in subjects RA(R) and JPK(R), which exhibited slightly steeper slopes than those exhibited by maskers at and below the probe frequency.

Since the normal-hearing low off-frequency TMC is assumed to reveal linear response growth at the probe frequency, these data suggest that the hearing-impaired listeners also exhibited linear response growth for maskers at and below the probe frequency. In fact, response-growth rate curves derived for all three subjects (not shown) using the methods described for normal-hearing listeners were linear ($\boldsymbol{\alpha}$ close to 1.0) for masker frequencies at and below the probe frequency (the normal-hearing 0.6-kHz frequency curve was used to derive response growth for the two subjects who were not tested at such a low masker frequency). The observed linear response growth at the probe frequency in listeners with cochlear hearing loss is consistent with conclusions reached by other investigators about response growth in cochlear-impaired ears (Stelmachowicz *et al.*, 1987; Oxenham and Moore, 1995; Nelson and Schroder, 1997; Oxenham and Moore, 1997; Moore, 1998; Moore *et al.*, 1999; Hicks and Bacon, 1999b; Wojtczak *et al.*, 2000, 2001).

7. Characterizing compression in the auditory system

Historically, compression effects in the auditory system have been characterized by a compression ratio, which has been defined as the ratio between the change in the input stimulus level and the corresponding change in the output level. For example, a change in the input from 75 to 80 dB SPL that produces a change in the output level from 39 to 40 dB would be defined as a compression ratio of 5:1. This type of relation between input and output has often been described by a power function as in $\mathbf{I}_{\text{out}}=k\mathbf{I}_{\text{in}}^{p}$, where $\mathbf{I}_{\text{out}}$ is output intensity, $\mathbf{I}_{\text{in}}$ is input intensity, and k and p are constants, the former describing the intercept and the latter describing the slope of the input–output function in log–log coordinates (with $0<p<1$). The inverse of the exponent, p, defines the compression ratio.

The use of a power function to describe or simulate the effects of cochlear compression has a rich history (Penner, 1978; Humes and Jesteadt, 1989, 1991; Oxenham and Moore, 1995; Nelson and Schroder, 1996, 1997). In all of these studies a fractional intensity exponent ($\mathbf{I}_{\text{in}}^{p}$, with $0<p<1$) was used to characterize a nonlinearity; usually the exponent was adjusted in order to reduce input intensities sufficiently to account for psychophysical data. Because a single exponent was used, the exponent acted as a constant slope of the input/output function plotted in log–log coordinates.

However, we know from the physiological data that the slope of the BM input/output function is not constant (Yates, 1990; Yates *et al.*, 1990; Ruggero, 1992; Ruggero *et al.*, 1997; Rhode and Recio, 2000); it changes with input level, being linear at low input levels, compressive at mid levels, and perhaps linear again at high input levels. The results of the present study confirm the level dependence of response-growth slopes. Therefore, the use of a power function with a constant exponent, p, independent of input level, cannot accurately characterize compression in the auditory system over a wide range of levels. In order to describe any given output accurately, the slope and the intercept need to change with input level. Therefore, the output $\mathbf{I}_{\mathrm{out}}$ has to be described by

$$\mathbf{I}_{\mathrm{out}}=k(\mathbf{I}_{\mathrm{in}})\mathbf{I}_{\mathrm{in}}^{p(\mathbf{I}_{\mathrm{in}})}, \tag{5}$$

where $p(\mathbf{I}_{\mathrm{in}})$ is an array of local slopes, and $k(\mathbf{I}_{\mathrm{in}})$ is an array of local intercepts in log–log coordinates, which vary with input intensity. It should be noted that by using Eq. (5), we effectively approximate the input/output function by a set of straight lines (in log–log coordinates) defined by local slopes and intercepts.

For the purpose of modeling the effects of compression, it seems more convenient to use one of the following approaches, where compression is level dependent. One is based on a gain function, e.g., similar to the one that was proposed by Glasberg and Moore (2000). Using their equation describing gain in dB for each input level, $\mathbf{L}_{\mathrm{in}}$ (expressed in dB SPL), it is possible to compute the corresponding output level, $\mathbf{L}_{\mathrm{out}}$ (in dB) by adding gain to the input level. This would be equivalent to expressing the output intensity as

$$\mathbf{I}_{\mathrm{out}}=\mathbf{g}(\mathbf{I}_{\mathrm{in}})\cdot\mathbf{I}_{\mathrm{in}}, \tag{6}$$

where $\mathbf{g}(\mathbf{I}_{\mathrm{in}})$ is obtained by converting gain in dB into linear units.

The exact shape, and thus the local slopes and intercepts of the output function computed with Glasberg and Moore's formula depend on the maximum gain ($\mathbf{G}_{\max}$), which is applied to a stimulus of 0 dB SPL. By subtracting the maximum gain (in dB) from each output level, a compressive function will be obtained, in which each output will be equal to (linear response growth) or smaller than the input. In this case, the compressive function could be described by a series of fractions, $n(\mathbf{I}_{\mathrm{in}})$, by which the change in the output response relative to the response corresponding to 0 dB output (after subtracting maximum gain) is smaller than the respective change in the input relative to the input of 0 dB SPL. By subtracting the maximum gain from each point on the input/output function, the different intercepts in log–log units corresponding to different values of maximum gain are eliminated and the normalized output intensity can be expressed as

$$\mathbf{I}_{\mathrm{out}}/\mathbf{g}_{\max}=(\mathbf{I}_{\mathrm{in}})^{n(\mathbf{I}_{\mathrm{in}})}, \tag{7}$$

where $\mathbf{I}_{\mathrm{in}}$ is effectively the intensity obtained by converting the input level from dB SPL into linear intensity units, and $\mathbf{g}_{\max}$ is the maximum gain in linear units. Expressed in terms of levels

$$n(\mathbf{L}_{\mathrm{in}})=(\mathbf{L}_{\mathrm{out}}-\mathbf{G}_{\max})/\mathbf{L}_{\mathrm{in}}. \tag{8}$$

Since exponent $n(\mathbf{I}_{\mathrm{in}})$ only takes on values between 0 and 1, and it effectively "compresses" a change in input level (*re*: 0 dB SPL) into an equal or smaller change at the output (*re*: the output corresponding to the input of 0 dB SPL normalized by $\mathbf{G}_{\max}$), it can be called a compression exponent. This exponent, however, is *not* equivalent to the slope of the input/output function, and, therefore, is *not* equivalent to the reciprocal of the commonly used compression ratio. The only case where this exponent would describe the slope would be if the input/output function had a constant slope for all input levels, as was often assumed in some previous studies. This assumption is not correct given both physiological and psychophysical data. Input/output functions obtained from Eq. (6) normalized by maximum gain, i.e., $\mathbf{I}_{\mathrm{out}}=(\mathbf{g}(\mathbf{I}_{\mathrm{in}})/\mathbf{g}_{\max})\mathbf{I}_{\mathrm{in}}$, and those obtained from Eq. (7) for $n(\mathbf{L}_{\mathrm{in}})=(\mathbf{L}_{\mathrm{out}}-\mathbf{G}_{\max})/\mathbf{L}_{\mathrm{in}}$, are identical.

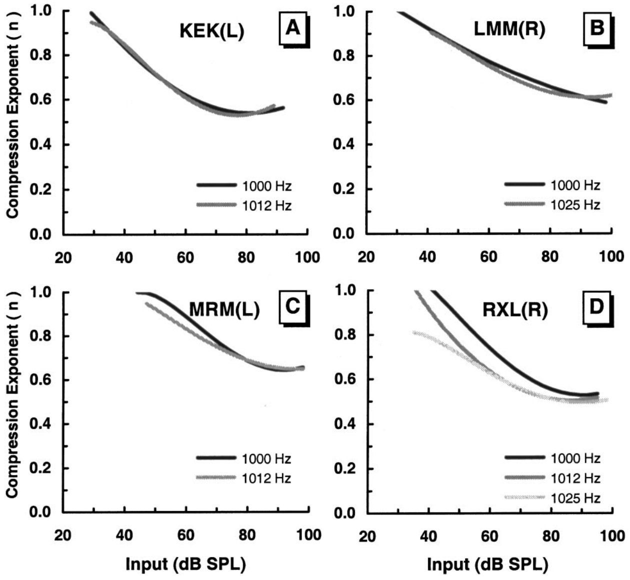

FIG. 9. Compression exponents calculated from the derived input/output curves are shown as a function of input level (masker SPL). The parameter is masker frequency as labeled. Several curves are shown for each subject, one for a masker frequency at the probe frequency and one or two for masker frequencies slightly higher in frequency.

Thus, all three ways of describing the input/output function with a varying slope across levels, presented above [in Eqs. (5)–(7)], are equivalent, and each one of them can be used to make predictions about outputs for different input levels.

Equation (7) characterizes compression as the ratio between output level, normalized by maximum gain, and input level. This is exemplified by curve (b) in Fig. 4. At the input level of 28 dB, the output is equal to the input (by assumption that the response is linear for input levels up to 28 dB SPL), so the compression exponent is 1.0. At 60 dB the output is 38 dB, so the compression exponent is 0.63. At 80 dB the output is about 40 dB, so the compression exponent is 0.50. At 90 dB the output is about 45 dB, so the compression exponent is 0.50. This way of expressing compression, as an exponent applied to input intensity, is consistent with previous descriptions of compression in the auditory system that used a power function with an exponent, *p*, and ignored intercept *k*, to predict the output *at only a single input level* (or only a very restricted range of input levels) (Penner, 1978; Humes and Jesteadt, 1989, 1991; Nelson and Schroder, 1996, 1997).

Figure 9 shows compression exponents (output/input ratios) calculated from third-order polynomial fits to the derived input/output curves, plotted as a function of the input level, for two or three masker frequencies at or near the probe frequency. Compression exponents are large, near 1.0, at low input levels between 25 and 40 dB SPL. As input level rises above about 40 dB SPL, compression exponents decrease with input level and gradually saturate at input levels above about 80 dB SPL. The smallest compression exponents were seen for input levels above 80 dB SPL, where the minimum exponents ranged between 0.5 (KEK) and 0.62 (MRM).

IV. EXPERIMENT 3: HIGH-PASS NOISE AND RESPONSE GROWTH

Experiment 1 demonstrated how GMB functions, where forward masker level is varied to reach masked threshold for a range of fixed probe levels, are strongly influenced by spread of excitation from the probe toward higher frequency regions. Consequently, it was concluded that a HP noise is necessary to obtain valid indices of cochlear compression with that procedure. Because probe level is fixed at a relatively low sensation level in the new iso-response temporal masking procedure proposed here for measuring cochlear compression (experiment 2), it was hypothesized that spread of excitation toward higher frequency regions should not be an important factor affecting estimates of cochlear compression. To confirm this hypothesis, normal-hearing subjects were tested in the presence of a HP noise.

A. Method

Three additional normal-hearing subjects participated in the experiment. TMCs were obtained for a 1-kHz probe in quiet, and in the presence of a HP noise with a high-pass cutoff at 1.117 kHz. Masker, probe, and ramp durations were the same as those used to obtain the TMCs in experiment 2. The HP noise was turned on 20 ms before the onset of the masker ramp and was turned off 20 ms after the offset of the probe ramp. The noise was gated with 10-ms raised-cosine ramps. The spectrum level of the HP noise in a 6-cc coupler was relatively constant between 1117 Hz and 6 kHz and decreased with frequency above 6 kHz, so that the spectrum level was about 10 dB less at 9.5 kHz and 20 dB less at 12.5 kHz. Because the probe sensation level was low (10 dB), and the edge of the HP noise was close to the probe frequency, we wanted to ensure that, for each subject, the HP noise would just partially mask the probe, but not completely mask it. Therefore, for each subject, a complete simultaneous growth-of-masking function was measured for the 1-kHz probe in the presence of the HP noise, and then one of two fixed noise levels (25 or 30 dB SPL) was chosen that would produce less than 5 dB of masking. The noise levels used for each subject produced 3.3, 2.6, and 1.7 dB of masking at 1 kHz, respectively, for subjects DYS, KJB, and KSA.

Psychophysical procedures were the same as those described earlier for experiment 2. The instrumentation system was the same as that used in experiment 1. Three TMCs were obtained in each subject: one for a 0.6-kHz (low off-frequency) masker in quiet, one for a 1-kHz (on-frequency) masker in quiet, and one for the 1-kHz masker in the presence of the HP noise.

An obvious control experiment was the measurement of the low off-frequency iso-response TMC in the presence of the HP noise. However, given the large level difference between the 0.6-kHz masker and the 1-kHz probe at masked threshold, the upward spread of excitation above 1 kHz produced by the 0.6-kHz masker was likely to be much greater than any upward spread of excitation produced by the 10-dB SL 1-kHz probe (Kidd and Feth, 1981; Zwicker and Jaroszewski, 1982). The HP noise might partially mask the probe and result in slightly lower 0.6-kHz masker levels, but the likelihood that off-frequency listening might change the slope of the 0.6-kHz TMC is small. Therefore, the HP noise condition with the 0.6-kHz masker was not included in the main experiment.[7]

B. Results and discussion

Figure 10 shows the iso-response TMCs obtained in quiet and HP noise, along with the input/output curves derived from those TMCs, and the response-growth rates calculated from those derived curves. The results in quiet (Q) were similar to those reported above for the other four normal-hearing listeners that were tested in experiment 2. The low off-frequency TMCs obtained in quiet [shaded squares in Figs. 10(a)–(c)] were gradual, presumably because they only reflect recovery from forward masking without any effects of compression. The on-frequency TMCs [black squares and triangles in Figs. 10(a)–(c)] exhibited three segments, reflecting the effects of compression in addition to recovery from forward masking for both the quiet and noise cases. The corresponding derived input/output curves in Figs. 10(d)–(f), exhibit linear response growth for the low off-frequency masker and nonlinear response growth for the on-frequency conditions.

If detection of the probe in quiet involves listening at higher-frequency regions, then the HP noise should mask those frequency regions, and as a result the probe should be more difficult to detect. Consequently, introduction of the noise should result in lower level masking tones to forward mask the probe than during the quiet condition. Except at very short time delays for two of the subjects (DYS and KSA), this was not the case. Masker levels were generally the same or higher in the presence of the HP noise [black triangles in Figs. 10(a)–(c)]. The most consistent effect of the noise was to require higher masker levels in the steeply sloped region of the TMCs (e.g., at a time delay of 80 ms). This could have been due to learning effects, since most of the noise conditions were obtained during later testing sessions, although the subjects were highly practiced at forward masking tasks before beginning the experiments.

Figures 10(g)–(i) show response-growth rates calculated from the derived input/output curves in Figs. 10(d)–(f). Response growth was curvilinear (U-shaped): steep at low and high levels, and very gradual at mid levels (just as in experiment 2). The background noise (N) decreased the minimum growth rate slightly in two of the subjects, but the net effect on response-growth functions was minimal.

From these results it is apparent that the iso-response temporal masking procedure for estimating cochlear compression is relatively free from contamination by the upward spread of excitation from the probe. Thus, it does not appear to be necessary to employ HP noise to obtain valid measures of response growth with this procedure.

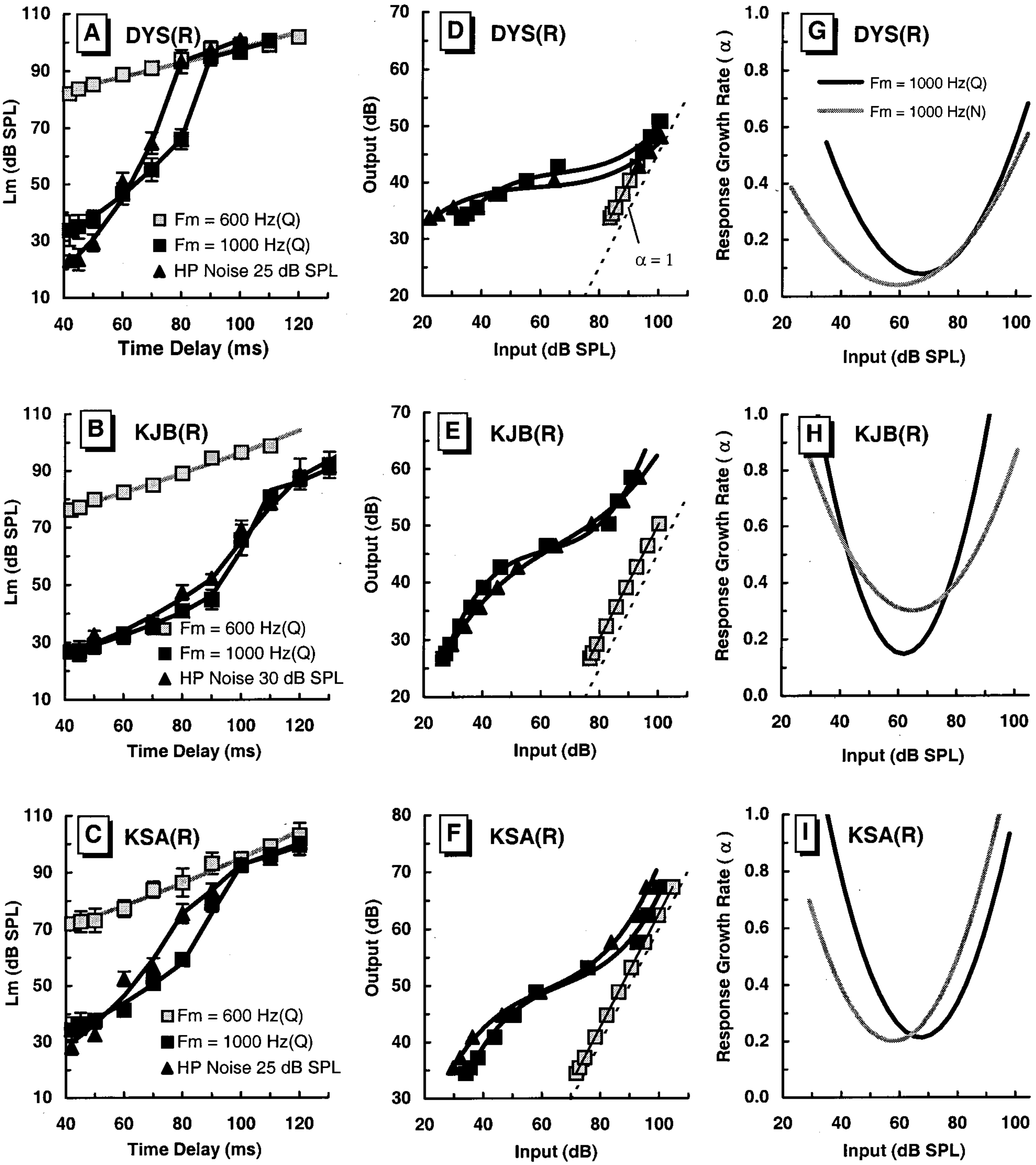

FIG. 10. Effects of high-pass noise on TMCs, derived input/output curves, and response-growth rates, in three normal-hearing listeners. Each row shows results for a different subject. (a)–(c) Fixed-probe-level TMCs at 1 kHz for a low off-frequency masker condition (0.6 kHz) in quiet (shaded squares), an on-frequency masker condition (1 kHz) in quiet (black squares), and an on-frequency masker condition in high-pass noise (black triangles) that was introduced to mask the spread of excitation toward higher frequency regions. (d)–(f) Derived input/output curves for each of the masker conditions. The dashed lines represent linear response growth. (g)–(i) Response growth-rate curves calculated from the derived input/output curves. Black curves are for data obtained in quiet (Q), shaded curves are for data obtained in the high-pass noise (N).

V. EXPERIMENT 4: CUEING TONES AND RESPONSE GROWTH

In forward-masking tasks, when a masker and a subsequent probe are at the same frequency, and consequently have nearly the same pitch, it is often difficult to detect the presence of a short probe immediately following the masker (Terry and Moore, 1977; Moore, 1980a, b; 1981). When the masker and probe are at different frequencies they no longer have similar pitches; therefore, it is easier to detect the presence of the probe tone. Moore (1980a) demonstrated improvements in masked threshold that were as large as 20 dB in some subjects, for maskers at the probe frequency, when a high-frequency cueing tone was gated synchronously with the masker to mark the masker duration, particularly the end of the masker, by introducing a pitch-difference cue. When masking tones were more than 50 Hz below the probe tone, cueing tones had no effect (Terry and Moore, 1977). Thus, in the present study, the lack of pitch differences between masker and probe for the on-frequency condition could have made it more difficult to hear the probe than in those conditions in which the masker frequency was either below or above the probe frequency, where pitch differences were available.

In experiment 2, the lack of a pitch difference between masker and probe in the on-frequency condition may have made it easier to mask the probe tone. Consequently, adding a pitch-difference cue to an on-frequency masker should raise the masker levels required to mask the probe. Furthermore, it is possible that the lack of pitch differences in experiment 2 may have influenced forward-masked thresholds more at short time delays than at longer time delays. At short time delays the masker and probe are closer together, thus a greater possibility exists for a lack of a temporal distinction between masker and probe. If the lack of pitch differences for on-frequency forward-masking conditions differentially affects masked thresholds at different time delays, then it could influence measurements of response-growth rate. To determine whether or not the lack of pitch difference cues in on-frequency masking influences response-growth rates obtained from iso-response TMCs, the on-frequency masking conditions were tested in the presence of a higher-frequency cueing tone and the results were compared with those obtained earlier without a cueing tone.

A. Method

The three normal-hearing subjects from experiment 3 participated in this experiment. The TMCs were obtained in the presence of a cueing tone. The cueing tone was gated with the masker and on each trial was presented at the same level as the masker. This is slightly different from other experiments with cueing tones because the masker level is varied to reach masked threshold in this experiment. Thus, the level of the cueing tone was also varied with masker level. This method ensured that the cueing tone was always audible. Psychophysical procedures were the same as those described earlier for experiment 2. The instrumentation system was the same as that used in experiment 1. Two TMCs were obtained from each subject for the 1-kHz masker and the 1-kHz probe: one with a 2-kHz cue and one with a 2.5-kHz cue. The 2-kHz cue was an octave above the masker frequency, where suppression of the 1-kHz masker should have been minimal. However, if suppression were involved, the effectiveness of the cue should depend on its proximity in frequency to the main masker and signal. Therefore, moving the cue toward a higher frequency should maintain the cueing effect but reduce any suppression effect. Therefore, a 2.5-kHz cue condition was included.

B. Results and discussion

Figures 11(a)–(c) show the iso-response TMCs obtained in quiet (from experiment 3) and those obtained in the presence of a cueing tone at 2.0 or 2.5 kHz. As noted previously, the TMCs for the 0.6-kHz masker exhibited gradual slopes, reflecting the recovery from forward masking without the influence of cochlear compression. The TMCs for the on-frequency 1-kHz masker, with and without a cue, exhibited the three-sloped characteristics that reflect gradual response growth at short and very long delays and strong compression at mid delays. Presentation of the cueing tones had similar effects across subjects. In general, higher masker levels were required with the cueing tones present than without them, more so at middle time delays than at short time delays.

These effects are shown more clearly in Fig. 12, where the differences between the masker levels obtained with and without a cueing tone are plotted against time delay. At short time delays (<60 ms) the 2.0-kHz cueing tones increased masker levels at threshold by about 4–6 dB [Fig. 12(a)]. The 2.5-kHz cueing tones also raised masker levels at threshold at short delays, but by a smaller amount [Fig. 12(b)]. This increase in masker level at threshold for short time delays, in the presence of a cueing tone, was seen in all three subjects.

It might be argued that the effects of the cueing tones could originate from one of two possible sources: pitch difference cues or suppression. However, several factors argue against the suppression explanation. The cueing tones and the masking tones were always at the same overall SPL, a condition for which suppression is typically not observed, except for very small frequency ratios between suppressor and suppressee (Sachs and Kiang, 1967; Geisler *et al.*, 1990). The nearest cueing tone was an octave above the masking tone, which is a fairly wide frequency separation that is unlikely to produce any significant suppression (Houtgast, 1974; Shannon, 1976; Javel *et al.*, 1983; Delgutte, 1990). Increasing the cueing tone frequency to 2.5 kHz only reduced the required masker levels slightly [Fig. 12(b)]. There were still significant effects of the high-frequency cueing tone in all three subjects, despite the additional 500-Hz frequency separation between masker and cueing tone. Significant increases in masker thresholds occurred at short time delays where the masker levels, and therefore the cueing tones, were at low SPLs where the existence region for suppression is even more restricted. Therefore, it seems most likely that the increased masker levels at threshold were caused by improved information about the exact end of the masker.

At middle time delays (60–100 ms), the effects of the cueing tones were considerably larger than at the short time delays (Fig. 12). An increase in masker level as large as 28 dB was required in some subjects to maintain a constant amount of forward masking when the cueing tone was present. The large effects of the cueing tones were then reduced again at still longer time delays (>80–100 ms). Notice that the steeply sloped portions of the TMCs [Figs. 11(a)–(c)], and the largest effects of the cueing tones (Fig. 12), occurred over the same range of time delays. In accordance with our earlier reasoning, the steep portion of the TMC is associated with gradual response growth and strong

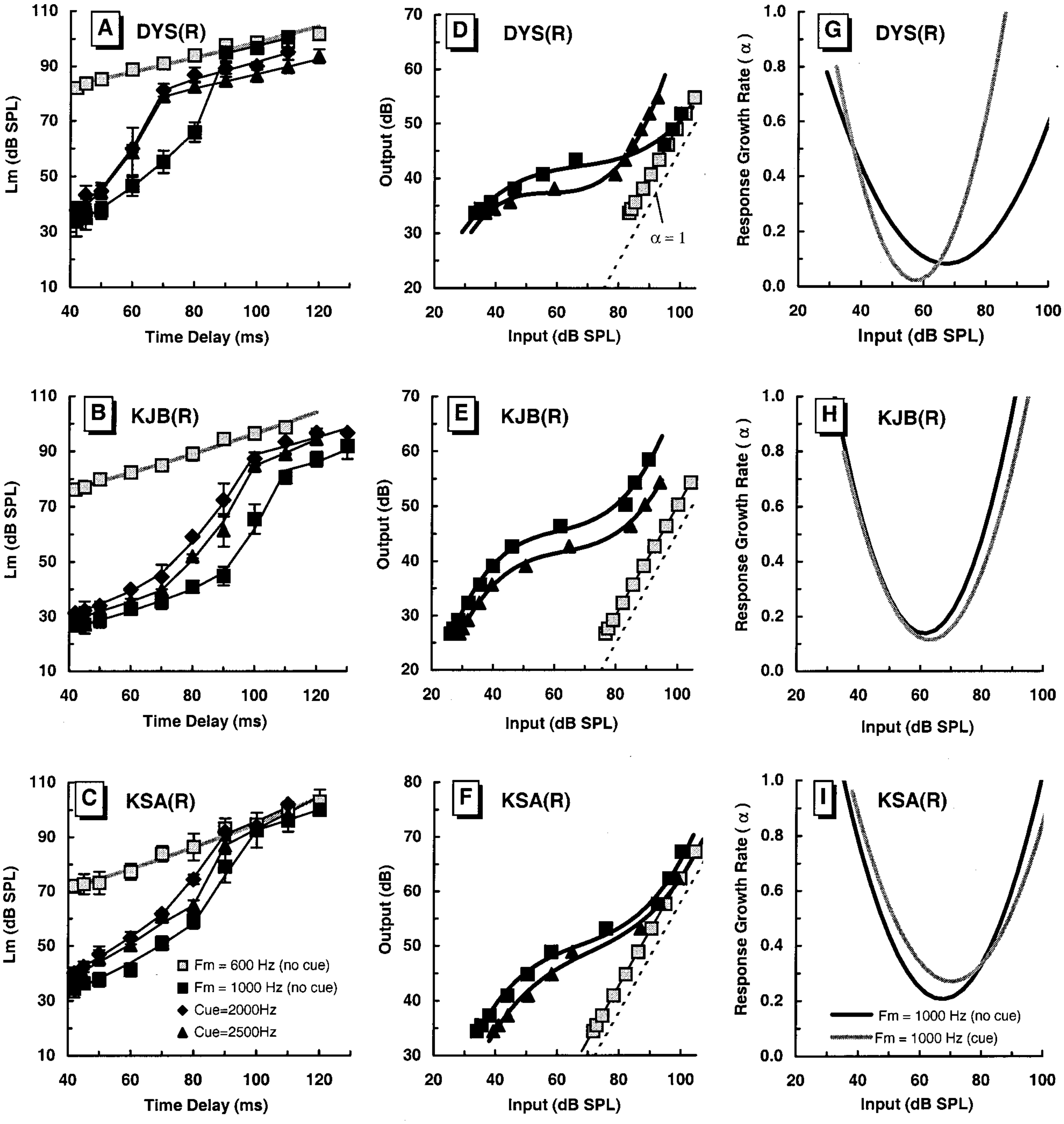

FIG. 11. Effects of cueing tones on TMCs, derived input/output curves, and response growth-rate curves, in three normal-hearing listeners. Each row shows results for a different subject. (a)–(c) Fixed-probe-level TMCs at 1 kHz for a low off-frequency masker condition (0.6 kHz) without any cueing tone (shaded squares), an on-frequency masker condition (1 kHz) with no cueing tone (black squares), an on-frequency masker condition with an additional 2-kHz cueing tone (black diamonds), and an on-frequency masker condition with a 2.5-kHz cueing tone (black triangles). The cueing tones were gated with the masker to introduce a defined pitch cue for the termination of the on-frequency masker. (d)–(f) Derived input/output curves for the masker conditions in quiet and with the 2.5-kHz cueing tone. The dashed lines represent linear response growth. (g)–(i) Response growth rates estimated from the derived input/output curves, as a function of input level (masker SPL). Black curves are for data obtained in quiet, shaded curves are for data obtained in the presence of the 2.5 kHz cueing tone.

cochlear compression. It appears that the small effects of the cueing tones seen at short time delays, where input levels are low, were magnified at the middle time delays where masker levels were higher. At short time delays, where response growth is steep and compression is minimal, only a small increase in masker level was required to maintain constant masking with the addition of a cueing tone. At middle time delays, where compression acting on the masker is strong, a larger increase in masker level was required to maintain the same amount of masking.

The effects of the 2.5-kHz cueing tones on derived input/output curves are shown in Figs. 11(d)–(f) (the results were similar for the 2.0-kHz condition). The general shapes of the fitted input/output curves were not dramatically affected by the cueing tones, although there was a tendency for the input/output curves to be slightly more compressive in

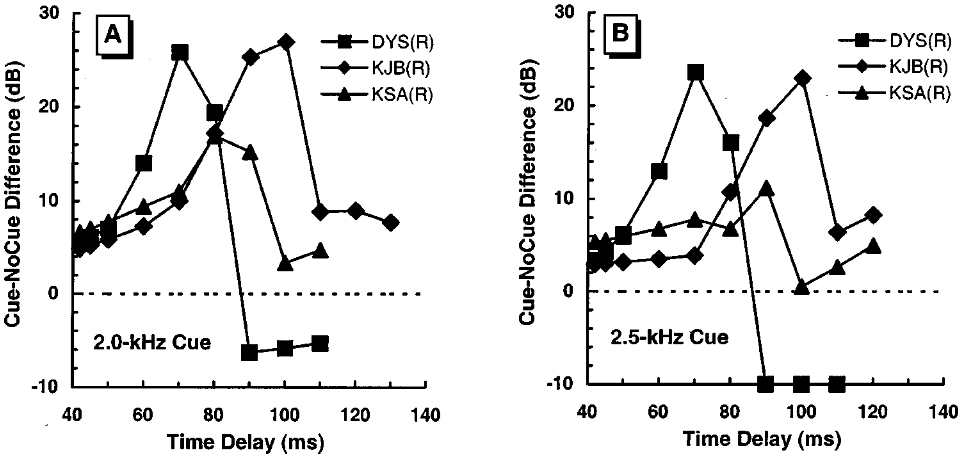

FIG. 12. Effects of cueing tones expressed as masker-level differences. (a) 2.0-kHz cue. (b) 2.5-kHz cue. The differences (in dB) between masker levels, with and without a cueing tone gated with the masker, required to produce a constant amount of forward masking, are plotted on the ordinate as a function of the delay time between masker and probe. The differences are small at short time delays, where masker levels are low and the system is linear. The differences are larger at longer time delays where masker levels are higher and the system is nonlinear.

the presence of the cueing tones for two of the subjects (DYS and KJB). Figures 11(g)–(i) show response-growth rate curves calculated for the quiet and the 2.5-kHz cueing conditions (curves for the 2.0-kHz cueing condition behaved similarly). Response-growth rates changed little in the cueing condition for two subjects (KJB and KSA). For subject DYS, the 2.5-kHz cueing tone made the response-growth curve more compressive and the high-level linearity began at lower input levels.

VI. SUMMARY AND CONCLUSIONS

The GMB forward-masking functions measured in quiet and in the presence of a HP noise, using a 3- or 6-kHz forward masker and a 6-kHz probe, indicated that GMB slope ratios for low off-frequency and on-frequency maskers obtained in quiet do not reflect the same response-growth rates as those obtained in the presence of a HP noise. The estimates of response-growth rate obtained from GMB slope ratios in quiet were at least twice those obtained with a HP noise. Estimates of response-growth rates at 6 kHz obtained in the HP noise are consistent with those observed in animals from basal regions of the cochlea.

An alternative procedure for measuring response-growth rates was presented. That procedure used iso-response TMCs for different masker frequencies around 1 kHz to specify response-growth rates at the 1-kHz place in the cochlea. Input/output curves were derived from the TMCs, and fitted with a polynomial. The first derivative of the fitted input/output curves specified response-growth rate as a function of input level. Response-growth rate varied with input level in a U-shaped fashion, with linear growth at low levels, gradual growth at mid levels, and linear growth again at higher levels. Iso-response TMCs obtained from three subjects with cochlear hearing loss revealed linear response growth throughout the entire range of input levels for on-frequency maskers, indicating the absence of cochlear compression.

Iso-response TMCs obtained in HP noise yielded response-growth rates similar to those obtained in quiet; thus, upward spread of excitation from the probe has little effect on measures of compression with this procedure. Iso-response TMCs obtained in the presence of cueing tones were elevated, more so at time delays where compression existed, which is consistent with the cueing tones facilitating detection of the probe following a masker of the same or nearly the same frequency. However, for two out of three listeners, response-growth rates derived from those curves were similar to those obtained from the TMCs obtained without the cueing tones. Thus, the availability of pitch-difference cues between masker and probe had little effect on measures of response growth obtained with this procedure. From these results we conclude that the iso-response TMC provides a valid psychophysical description of peripheral compression in human subjects.

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[1] The effects of the high-pass noise at 1 kHz should be considered with some caution, because off-frequency listening to splatter below the probe frequency, due to the 2-ms ramp on the probe (4-ms total probe duration), could have affected the measured growth-of-masking slopes. Moore *et al.* (1999) found obvious slope changes in only two out of six subjects when a 5-ms ramp (10-ms total probe duration) was compared with a 2-ms ramp (4-ms total probe duration) on a 2-kHz probe tone. However, at 1 kHz the splatter effects might have been greater for a 2-ms ramp condition.

[2] To facilitate calculation of recovery slopes, from which response-growth slopes were estimated, three different curve segments were used to describe the entire temporal masking curve. An exponential function was fit using least-squares procedures for each segment, in which the masker level decayed exponentially with time delay as in $\ln(\mathrm{Lm})=b+a(\mathrm{Lp})$. The limits for the fits were adjusted manually until the excellent fits shown in Fig. 2 were achieved. It should be noted that any curve-fitting procedure that fits the data well could have been used.

[3] Any hypothetical function could have been used to fit the low off-frequency and on-frequency TMCs, as long as the fit was excellent, since the ratios of the slopes of the two functions define response growth slopes.

[4] Changes in input level used to calculate associated changes in effective output level were based on the exponential fit TMCs curves rather than the raw data. This was done to smooth the TMCs in order to minimize variability in local slopes.

[5] This procedure for deriving input/output curves is similar to plotting the input level for the low off-frequency masker, on the ordinate, against the input level for the on-frequency masker, on the abscissa. The low off-

frequency masker input levels are then normalized to effective output levels at the probe frequency place by subtracting the maximum gain in the auditory filter estimated at 42 ms, given by $\mathbf{G}_{\max}=20\ \mathrm{Log}(1/\mathbf{k})$, which results in the same values as those shown by the open squares in curve b of Fig. 4.

[6] The "average TMC" was obtained by fitting each of the normal-hearing curves with a single exponential and then averaging the fitting parameters for that exponential across subjects. Then the average TMC was calculated from those average fitting parameters.

[7] Comments from one of the reviewers led us to verify our reasoning. We obtained iso-response temporal masking curves for 0.6-kHz maskers from three additional normal-hearing subjects, both in quiet and in the presence of the high-pass noise (the original subjects were no longer available for testing at the time). The slope of the 0.6-kHz iso-response TMC did not change in any of the subjects.

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