Effects of background noise level on behavioral estimates of basilar-membrane compression

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Hearing-impaired (HI) listeners often show poorer performance on psychoacoustic tasks than do normal-hearing (NH) listeners. Although some such deficits may reflect changes in suprathreshold sound processing, others may be due to stimulus audibility and the elevated absolute thresholds associated with hearing loss. Masking noise can be used to raise the thresholds of NH to equal the thresholds in quiet of HI listeners. However, such noise may have other effects, including changing peripheral response characteristics, such as the compressive input-output function of the basilar membrane in the normal cochlea. This study estimated compression behaviorally across a range of background noise levels in NH listeners at a 4 kHz signal frequency, using a growth of forward masking paradigm. For signals 5 dB or more above threshold in noise, no significant effect of broadband noise level was found on estimates of compression. This finding suggests that broadband noise does not significantly alter the compressive response of the basilar membrane to sounds that are presented well above their threshold in the noise. Similarities between the performance of HI listeners and NH listeners in threshold-equalizing noise are therefore unlikely to be due to a linearization of basilar-membrane responses to suprathreshold stimuli in the NH listeners.
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I. INTRODUCTION

Cochlear hearing loss leads to a number of changes in auditory perception and performance. Most obvious is a loss of sensitivity to low-level sounds, as evidenced by the audiogram. Beyond absolute threshold, psychoacoustic studies have identified a number of tests in which hearing-impaired (HI) listeners perform differently from normal-hearing (NH) listeners. To rule out effects of signal level and audibility from true suprathreshold deficits, it is necessary to somehow provide equivalent conditions for both NH and HI listeners. Some studies have attempted to equate audibility by presenting the stimuli at the same sensation level (equal SL) for the two groups (e.g., Moore and Glasberg, 1988; Lentz and Leek, 2003). Because of the higher absolute thresholds in the HI group, this results in higher sound pressure levels (SPLs) for the HI group than for the NH group, meaning that any difference in results could potentially be due to the higher overall sound level. For instance, frequency selectivity in NH listeners becomes poorer at high levels (e.g., Moore and Glasberg, 1987; Nelson *et al.*, 1990), meaning that a difference between NH and HI listeners in frequency selectivity when measured at the same SL may have less to do with an auditory deficit than it does with a level effect that is also found in normal hearing. Other studies have equated overall sound pressure levels (equal SPL) for the two groups (e.g., Buus *et al.*, 1999; Summers, 2001). The potential problem with this approach is that the stimuli are at a lower SL for the HI group than for the NH group, making it difficult to rule out the possibility that differences in performance are due to differences in audibility, rather than any genuine suprathreshold deficit due to the hearing loss.

One way of equating both overall level and audibility has been to present the stimuli in a background of noise that elevates the thresholds of NH listeners to approximate those of HI listeners in quiet. This noise may be designed to raise thresholds in a particular frequency region (e.g., Sommers and Humes, 1993) or over a wide frequency range (e.g., Dubno and Schaefer, 1992; Bacon *et al.*, 1998). The noise may also be spectrally shaped and adjusted in level to specifically match the individual thresholds of certain HI listeners (e.g., Dubno and Schaefer, 1992) or it may be adjusted to approximate the average thresholds of a group of HI listeners (e.g., Humes, 1990). In some situations the psychoacoustic and speech perception results from HI listeners and noise-masked normal-hearing (NMNH) listeners have been comparable, as in the case of loudness recruitment (e.g., Zurek and Delhorne, 1987; Dubno and Schaefer, 1992; Hellman and Meiselman, 1993; Hall and Grose, 1997). In other situations, some HI listeners exhibit results similar to those found for NMNH listeners, whereas other HI listeners perform more poorly, such as in tasks involving speech understanding or tone detection in a modulated background (e.g., Bacon *et al.*, 1998; Oxenham and Dau, 2004). For a recent review of studies involving comparisons between HI and NMNH listeners,

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see Reed *et al.*, 2009. As pointed out by Reed *et al.* (2009), when comparing the performance of NH and HI listeners, it is also important to control for age differences, as many studies have shown that aging, independent of hearing loss, also affects many aspects of auditory processing, including temporal processing (e.g., Abel *et al.*, 1990; Moore *et al.*, 1992; Lister *et al.*, 2002; Fitzgibbons and Gordon-Salant, 2004; Lister and Roberts, 2005; Dubno *et al.*, 2008).

Aside from the issues of audibility and age, many of the deficits experienced by listeners with cochlear hearing loss are consistent with the changes in basilar-membrane mechanics that occur with outer hair cell damage or dysfunction. The physiological phenomena observed at the level of the basilar membrane (BM) include a loss of sensitivity to low-level sounds, a linearization of the normally compressive input-output function in response to tones near the characteristic frequency (CF), and a broadening of tuning (e.g., Ruggero *et al.*, 1997; Robles and Ruggero, 2001). Potential psychoacoustic correlates of these effects include higher absolute thresholds, loudness recruitment, and poorer frequency selectivity (for a review, see Oxenham and Bacon, 2003).

In general, the effect of using a background masking noise with NH listeners has been interpreted in terms of a reduction in the audibility of the stimuli. An alternative possibility is that the background noise changes the mechanical response of the BM to effectively linearize it so that it resembles that of an impaired cochlea. The particular response changes would depend on the specific underlying cochlear changes. As described in Plack *et al.* (2004), changes in cochlear compression may be manifested as a reduction in the compression exponent over the entire dynamic range, a reduced range of levels over which normal compression exponents are found, or a combination of the two. The BM response to wideband noise at a given level has been described as "quasilinear" (de Boer and Nuttall, 1997, 2000), and it is known that a low-frequency suppressor tone can linearize the response to a higher-frequency probe tone at the characteristic frequency of the point of measurement (e.g., Ruggero *et al.*, 1992). Another possible mechanism by which cochlear responses may be linearized is via efferent fibers originating in the medial olivary complex. Efferent activation is hypothesized to lead to a reduction in the gain of the cochlear amplifier, particularly in response to longer duration stimuli. It is possible that the presence of background noise may initiate gain reduction in this manner, which would result in a less compressive response (Guinan, 2006; Krull and Strickland, 2008). A recent physiological study addressed the question of whether broadband noise linearizes the BM response to simultaneously presented tones. Recio-Spinoso and Lopez-Poveda (2010) measured BM displacement in a chinchilla cochlea in response to a tone at the CF in the presence of various levels of white noise. They found that the white noise suppressed the response to the tone, especially for low tone levels and reduced the range of levels over which compression was observed.

The aim of the present study was to estimate the effects of background noise on behavioral estimates of compression, using the growth of forward masking (Oxenham and Plack, 1997) in NH listeners in the presence of various levels of threshold-equalizing noise (TEN) (Moore *et al.*, 2000). The question was whether the presence of a background noise would result in a more linear BM input-output function for tones, as estimated behaviorally. If so, then similarities between HI and NMNH listeners found in previous studies in tasks such as loudness judgments might be due to changes in BM compression, rather than audibility per se. If background noise does not make the BM input-output function more linear, then any similarities between HI and NMNH listeners are unlikely to be due to noise-induced changes in BM response for the NMNH group.

II. ESTIMATING COMPRESSION AS A FUNCTION OF BACKGROUND NOISE LEVEL

A. Listeners

Six adult listeners (all female) completed the task. The listeners had audiometric thresholds of 20 dB HL or better at octave test frequencies, as defined by ANSI S3.6-2004 (ANSI, 2004) and their ages ranged from 19 to 37. Training was provided until stable performance was achieved. No subject required more than 2 h of training. Five listeners were paid an hourly rate for their participation; S1 was the first author.

B. Procedure

Behavioral techniques that appear to provide a reasonable estimate of cochlear compression include growth of masking (GOM) (Oxenham and Plack, 1997) and temporal masking curves (TMCs) (Nelson *et al.*, 2001), both of which use forward masking to avoid the potentially confounding effects of suppression due to the masker. These behavioral estimates of compression have both been shown to provide results that are in relatively good agreement with direct physiological measurements in other species (e.g., Robles and Ruggero, 2001). Here we used the GOM method.

Forward GOM functions were measured using a three-interval three-alternative forced-choice method, with a fixed signal level and a masker level that was adaptively varied with a two-up, one-down rule to track the 70.7% correct point on the psychometric function (Levitt, 1971). The three intervals in each trial were separated by 300-ms interstimulus intervals. The pure-tone masker was presented in all three intervals, whereas the signal was presented in one, chosen at random in each trial. The listener's task was to select the interval that contained the signal. The initial step size for adaptively varying the masker level was 4 dB, which was reduced to 2 dB after the second reversal point, and was held constant for the remaining six reversals in each adaptive run. Threshold calculation for each run was based on the average masker level at the last six reversals. Subjects completed practice runs until their thresholds showed stability and the threshold for each condition and each subject was taken as the average from three subsequent runs. The presentation order of conditions was randomized within and across subjects and repetitions. Listening sessions were 2 h in length, including frequent breaks. The entire experiment took an average of 5 sessions per subject to complete.

The stimuli were generated digitally and converted to an analog signal via a 24 bit LYNX22 (LynxStudio, Costa Mesa, CA) soundcard at a sampling rate of 48 kHz. Sounds were presented to the left ear of subjects via Sennheiser HD580 earphones. The subjects were tested in a double-walled sound-attenuating booth.

C. Stimuli

The signal was a 4-ms, 4000-Hz pure tone, gated on and off with 2-ms raised-cosine ramps (no steady state). The pure-tone masker frequency was either 4000 Hz (on-frequency masker) or 1800 Hz (off-frequency masker). The masker duration was 200 ms, including 5-ms raised-cosine onset and offset ramps. The delay between the masker offset and signal onset was fixed at 0 ms. The relatively high signal frequency allowed the use of a short signal, while still ensuring that multiple cycles of the stimulus could be presented, thereby avoiding audible "spectral splatter" (e.g., Leshowitz and Wightman, 1972). Additionally, the short signal made it more likely that the off-frequency masker would provide sufficient masking even at high signal levels. With a 4-kHz signal, the response to the off-frequency masker, more than 1 octave below the signal, is thought to produce a linear response at the BM location with a CF corresponding to the signal frequency (Lopez-Poveda *et al.*, 2003; Rosengard *et al.*, 2005).

A 2/3-octave-wide Gaussian noise masker, generated and filtered in the spectral domain and centered at the signal frequency, was presented to the contralateral ear at an overall level 40 dB below that of the signal, to prevent the detection of the signal via acoustic and/or electric cross-talk. Additionally, a low-level high-pass noise masker (off-frequency condition) or spectrally notched noise masker (on-frequency condition) was presented to the test ear to reduce "off-frequency listening" (e.g., O'Loughlin and Moore, 1981). For the high-pass noise, the cut-off frequency was set to 1.117 times the signal frequency (4468 Hz). The notched noise incorporated this high-pass noise, as well as a low-pass noise with the cut-off set to 0.883 times the signal frequency (3532 Hz). The noises were generated in the spectral domain, so that only the onset and offset ramps of the noise limited the slopes of the spectral edges. To determine the appropriate levels for the notched and high-pass noise maskers, the levels of these maskers required to just mask the signal at different levels were determined during pilot testing. The notched and high-pass masker levels required to just mask the signal with a given level were obtained from a straight-line fit to these pilot data. The spectrum level of the maskers was then set 25 dB below the levels at which they would mask the signal for both the on-frequency and off-frequency conditions. No attempt was made to reduce potential "confusion" effects due to having a forward masker and signal at the same frequency (e.g., Neff, 1986). Using the TMC paradigm, Nelson *et al.* (2001) showed that confusion may result in somewhat lower masker levels, but that the derived compression exponents were essentially not affected.

Forward GOM functions were measured in quiet and in the presence of the TEN at levels of 20, 30, 40, and 50 dB SPL within the equivalent rectangular bandwidth of an auditory filter (ERB_N) centered around 1 kHz (Moore *et al.*, 2000). Because TEN is designed to produce equal masked thresholds (in dB SPL) for pure tones at all frequencies, the noise can be thought of as simulating a relatively flat hearing loss (when measured in SPL). The passband of the TEN extended from 20 to 20 000 Hz. The TEN was presented throughout each trial by gating it on 300 ms before the beginning of the first interval and gating it off 300 ms after the end of the third interval. The notched, high-pass, and contralateral maskers, when present, were gated on and off with the TEN, and all had raised-cosine onset and offset ramps of 5 ms. Signal levels ranged from 35 to 85 dB SPL (but were fixed within a given run). Only thresholds for signal levels where the tonal masker produced adequate masking (i.e., masked thresholds that were greater than 5 dB above the threshold in the TEN, as estimated from separate threshold measurements for the signal in the presence of the background TEN alone), were included in the plots.

TABLE I. Individual and average thresholds in dB SPL for the 4000 Hz signal in quiet and in various levels of TEN. Standard deviation values are given in parentheses.

	Quiet	20 TEN	30 TEN	40 TEN	50 TEN
S1	18.6 (1.6)	35.0 (1.2)	44.8 (1.3)	56.3 (0.3)	69.4 (1.3)
S2	24.7 (1.5)	34.0 (1.5)	45.8 (1.3)	56.0 (0.9)	71.9 (0.8)
S3	23.0 (1.0)	36.3 (2.3)	46.3 (0.3)	56.4 (0.8)	67.6 (0.3)
S4	17.0 (1.5)	39.2 (5.0)	47.2 (2.3)	57.9 (1.9)	71.4 (4.0)
S5	24.1 (2.1)	36.3 (1.3)	46.8 (1.4)	58.6 (1.0)	69.1 (3.1)
S6	16.6 (1.8)	36.2 (2.2)	46.6 (0.4)	59.3 (2.2)	72.6 (1.0)
Average	20.7 (3.7)	36.2 (1.7)	46.3 (0.9)	57.4 (1.4)	70.3 (1.9)

D. Results

Individual and mean thresholds for the signal measured in quiet and various levels of TEN are shown in Table I. When the TEN level was raised from 20 to 30 dB SPL/ERB_N, thresholds increased by approximately 10 dB. When the TEN level was increased from 40 to 50 dB, the thresholds increased by approximately 13 dB. The greater increase in masked threshold between and 40 and 50 dB/ERB_N may in part reflect the broadening of auditory filters at high levels, leading to greater noise power within the auditory filter. However, wider auditory filters are unlikely to account for the entire 3-dB increase in signal-to-noise ratio at threshold, as this would imply a doubling in filter bandwidth with a 10-dB increase in noise level. Individual forward GOM data for each of the six subjects are shown in Fig. 1. The masker level required to just mask the signal is plotted as a function of the signal level. Open and filled symbols represent thresholds in the presence of the on- and off-frequency pure-tone maskers, respectively. Different symbols represent thresholds in different levels of TEN, as indicated in the legend. The vertical lines represent thresholds for the signal in the different levels of TEN (from left to right, the lines represent threshold in quiet, in 20 dB TEN, in 30 dB TEN, etc.).

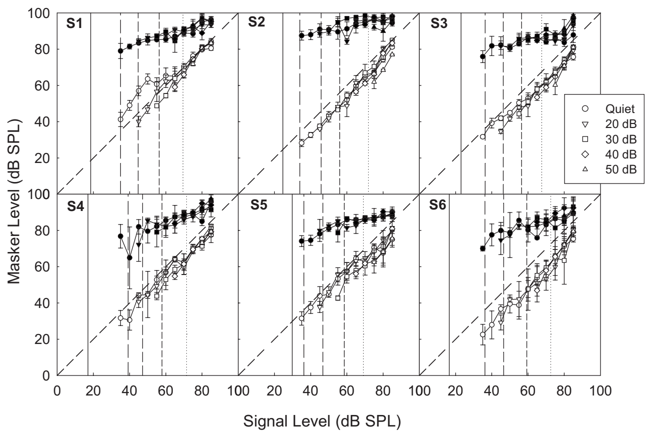

FIG. 1. Individual forward GOM functions for 6 NH listeners. Vertical lines represent signal threshold in various levels of TEN alone (from left to right: no TEN, and 20, 30, 40, and 50 dB/ERB$_N$). Each line pattern represents a given TEN level. Filled symbols represent threshold off-frequency masker levels; open symbols represent on-frequency masker levels at threshold. Error bars represent ±1 standard deviation. For reference, the dashed line on the major diagonal has a slope of 1.0, indicating linear growth of masking.

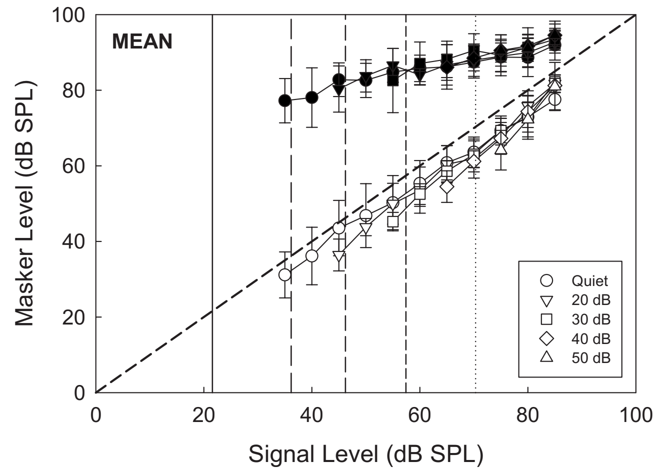

FIG. 2. As Fig. 1 but showing GOM functions averaged across 6 NH listeners. Error bars represent ±1 standard deviation.

When the masker and signal were at same frequency, and similar levels, both stimuli would presumably be subjected to the same amount of compression at the signal frequency location on the BM and the resulting GOM function would be expected to have a slope close to 1.0 (Plack and Oxenham, 1998). In the off-frequency condition, it is assumed that the masker is not subject to compression at the place with a CF corresponding to the signal frequency, while the signal continues to be compressed. Therefore the relationship between the slopes of the on- and off-frequency functions is assumed to reflect the underlying BM compression function (e.g., Oxenham and Plack, 1997). If the addition of the TEN resulted in less compression applied at the signal location on the BM, then we would expect to see the slopes of the off-frequency functions becoming gradually more linear (steeper) as the TEN level increased. We would not expect to see a change in slope for the on-frequency functions if the TEN resulted in less compression, because both the signal and the masker would be equally subjected to less compression. On the other hand, the TEN might be expected to have some effects on masker level at threshold that are not related to BM compression. For instance, when the signal is presented only a few dB above its threshold in TEN, then the TEN is likely to contribute to the masking of the signal, leading to a lower (tone) masker level at threshold. In order to reduce the effects of this “additivity of masking” (e.g., Penner, 1980; Humes and Jesteadt, 1989; Oxenham and Moore, 1995), only signal levels that were at least 5 dB above their threshold in the TEN were used in the analysis.

The data in Fig. 1 display some differences between subjects. For instance, the absolute threshold for the signal (solid vertical line in each panel) was lower for some subjects (e.g., S1) than for others (e.g., S5); however, thresholds in the presence of TEN alone (dashed or dotted vertical lines) were relatively similar for all six subjects. On-frequency masker levels at threshold (open symbols) also differ between subjects, with some subjects (e.g., S1) showing less susceptibility to masking (i.e., higher masker levels at threshold) than others (e.g., S6). Overall, though, the patterns of results are reasonably similar across subjects, with the GOM functions much shallower for the off-frequency masker than for the on-frequency masker, as found in earlier studies (e.g., Oxenham and Plack, 1997). In particular, based on the individual data, it is difficult to discern any systematic effects of TEN level on either the on- or off-frequency masker levels at threshold.

To determine whether more noticeable trends emerged for the listener group as a whole, the data from the six listeners were averaged, and are plotted in Fig. 2. For the off-frequency masker functions (filled symbols), where changes in compression would be most likely to have an effect, the data from all the functions lie essentially on top of each other, with no visible effect of TEN level. For the on-frequency functions (open symbols), the data lie close to the main diagonal, suggesting near-linear GOM. Again, for the most part the functions overlap with each other. An exception involves the leftmost data point in each function, where the masker level at threshold is typically somewhat lower than for the masker levels in the presence of lower TEN levels. This effect may involve the additivity of masking, as mentioned above, and suggests that our limit of including only signal levels that were at least 5 dB above masked threshold in the TEN may not have been stringent enough to eliminate such effects.

Plotting the off-frequency masker levels as a function of the on-frequency masker level at each signal level provides a behavioral estimate of the BM input-output function, if it is assumed that the BM response to the off-frequency masker is linear (e.g., Plack *et al.*, 2004). Figure 3 shows these derived input-output functions for the six subjects individually. The input-output functions derived from the mean data across the six subjects are shown in Fig. 4. As in Fig. 1, the different symbols represent different levels of TEN. Note that, as the TEN level increases, the total number of signal levels available decreases (due to the increase in signal threshold in TEN). In fact, the data for the 50 dB/ERB$_N$ TEN were not used to construct the I/O function in Fig. 2 because there were too few data points to permit further analysis.

To compare compression estimates across the different

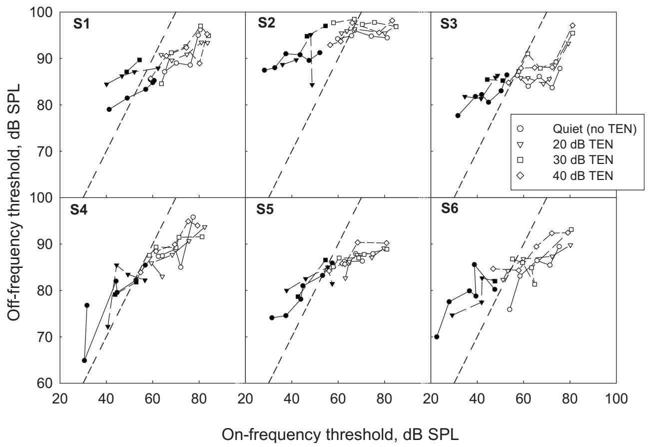

FIG. 3. Individual input-output functions derived using data from Fig. 1. Off-frequency masker levels at threshold are plotted as a function of on-frequency masker level at threshold for the same signal levels at each TEN masker level separately. The different symbols denote different TEN levels, as in Fig. 1. Only data shown as open symbols were used to calculate the function slopes shown in Table I. For reference, the dashed diagonal line in each panel has a slope of 1.0, indicating linear growth.

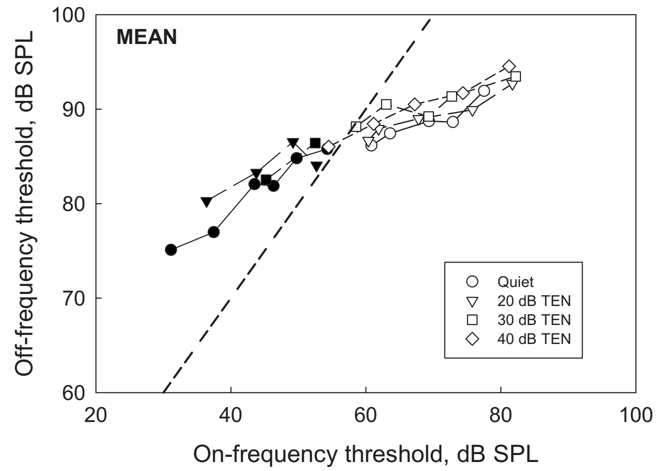

FIG. 4. As Fig. 3 but showing average input-output functions derived using data from Fig. 2.

TEN levels, a straight line was fitted to the data points for the five highest levels in each function. These points were chosen because they were measurable for all levels of TEN below 50 dB/ERB$_N$, allowing a fair comparison of slopes across different levels of TEN. The truncated functions used to obtain these slopes are shown as open symbols in Figs. 3 and 4. Bootstrapping was used to determine the individual slope values for each listener, as well as the associated variability. For each TEN level and tonal masker (i.e., on and off frequency) individual threshold estimates were selected randomly for each of the signal levels and a slope was derived using orthogonal regression. This was repeated 10 000 times for each condition and the resulting values were used to construct a histogram. The mean of the histogram was used as the slope value for that particular condition and the deviation from the mean was used to construct the 95% confidence intervals. The decision to use orthogonal regression instead of simple linear regression was based on the fact that the data to be fitted incorporated variability along both the x- and the y-axes. Linear regression assumes the data vary only in one dimension (the y-axis) and is designed is to minimize deviation between the fitted line and the data in this dimension only. Orthogonal regression minimizes the deviation between the data and the fitted line in both dimensions. Linear regression on data that have variability along both axes can be shown to underestimate the underlying slope, resulting in slight overestimates of compression. The derived individual slope values are shown in Table II, along with the 95% confidence intervals. The range of individual slope values for these six listeners is consistent with that from previous studies using similar measurement methods (e.g., Gifford and Bacon, 2005; Rosengard *et al.*, 2005). Table II also includes the slope values obtained by averaging across the slope values from the individual subjects (mean slope), as well as the slope values derived by fitting lines to the average data shown in Fig. 4 (slope of mean data). Reassuringly, these two approaches yielded very similar slope values, which are highly compressive and are broadly consistent with those found in other experiments using NH listeners tested in quiet (e.g., Oxenham and Plack, 1997).

The aim of this study was to test whether background noise affected BM compression, as estimated behaviorally. This question was addressed using a repeated-measures analysis of variance with estimated input-output slope value as the dependent variable and TEN level as the independent variable, with values of no noise, and TEN levels of 20, 30, and 40 dB SPL/ERB$_N$. Overall, no significant effect of TEN on the estimated compression exponent was observed [$F(1,3)=0.417$, $p=0.743$]. Of course, average data may ob-

TABLE II. Estimates of the slopes of the input-output functions for each subject (S1–S6) as well as for the fits to the average data, as shown in Fig. 4, and the mean slope values. The 95% confidence intervals are given in parentheses.

	Quiet	20 TEN	30 TEN	40 TEN
S1	0.597 (0.34; 0.85)	0.176 (0.07; 0.29)	0.536 (0.23; 0.84)	0.283 (0.19; 0.37)
S2	−0.008 (−0.12; 0.10)	0.032 (−0.03; 0.10)	−0.035 (−0.08; 0.01)	0.161 (0.05; 0.27)
S3	0.051 (−0.14; 0.24)	0.348 (0.18; 0.51)	0.272 (0.14; 0.41)	0.388 (0.34; 0.44)
S4	0.562 (0.14; 0.98)	0.435 (0.26; 0.61)	0.163 (−0.09; 0.41)	0.437 (0.23; 0.65)
S5	0.124 (−0.13; 0.38)	0.289 (0.03; 0.55)	0.134 (0.03; 0.23)	0.260 (0.13; 0.39)
S6	0.555 (−0.23; 0.88)	0.219 (−0.08; 0.51)	0.314 (−0.30; 0.93)	0.296 (0.13; 0.46)
Slope of mean data	0.302	0.242	0.201	0.304
Mean slope	0.313 (−0.25; 0.87)	0.250 (−0.03; 0.53)	0.231 (−0.15; 0.61)	0.304 (0.11; 0.50)

scure consistent trends within individuals. However, in each case, the confidence intervals around each individual slope estimate are large, such that they generally overlap across all TEN levels. Thus, there is no evidence of a trend toward systematic changes in slope with increasing TEN level.

In summary, aside from restricting the range of signal levels that could be tested, the presence or level of the background noise did not significantly influence the compression exponent estimates obtained in a forward GOM paradigm.

III. DISCUSSION

The results indicate that estimates of compression for NH listeners in a forward GOM paradigm are not significantly affected by background noise. The average slope values for the data in Fig. 4, obtained over the range of signal levels from 65 to 85 dB SPL, fall between 0.20 and 0.30, which is in reasonably good agreement with earlier behavioral estimates of compression in quiet from NH listeners using a variety of techniques, which are typically around 0.2 (e.g., Oxenham and Moore, 1995; Oxenham and Plack, 1997; Nelson *et al.*, 2001; Lopez-Poveda *et al.*, 2003). Thus, the results suggest that BM compression exponents are not affected by noise, at least in the conditions that were measurable here, where the probe was at least 5 dB above its threshold in the noise.

As noted in the Introduction, it has been proposed that efferent fibers may function to linearize the response of the cochlea, especially with longer duration stimuli (Guinan, 2006; Krull and Strickland, 2008). The present results do not demonstrate linearization of BM response in the presence of TEN and, therefore, do not provide any evidence for efferent activation. It is possible that either the TEN did not produce an efferent response that changed the BM response or that any efferent-driven response changes were not measurable in our data because they were restricted to lower stimulus levels than were used in the analysis.

Our conclusion can be compared with that of Recio-Spinoso and Lopez-Poveda (2010), based on direct measures of BM response in the chinchilla cochlea. They showed that the BM response to a tone was reduced (suppressed) by the presence of a broadband noise, which at first glance might appear to contradict our conclusion. However, a number of factors make a direct comparison difficult. First, their analysis of the responses involved a Fourier transform of the vibration, and the extraction of only the Fourier component corresponding to the tone's frequency. While this is common practice in BM studies, it makes a direct comparison with auditory-nerve or psychophysical suppression studies difficult: auditory-nerve studies report changes in *overall* firing rate (rather than the response locked to a particular frequency); psychophysical studies use masking, where the noise also contributes to the masking, making the outcome more comparable to the overall-response measure used in auditory-nerve studies than the frequency-specific measure used in BM studies. Second, the noise levels required to show suppression in the Recio-Spinoso and Lopez-Poveda (2010) study were much higher than were used here. Assuming the noise level was adjusted in 10 dB steps, the lowest noise level to produce measurable suppression in one animal (m31) was about 90 dB SPL. Assuming a noise bandwidth of 20 kHz, this corresponds to a level of more than 75 dB SPL within an ERB_N centered around the CF of 9.75 kHz. No suppression was observed for signal levels of 75 dB SPL or more, suggesting that the noise level within the ERB_N had to exceed the level of the signal for suppression to be observed. When viewed in this light, the results of Recio-Spinoso and Lopez-Poveda (2010) are consistent with ours in showing no suppression in conditions where the signal level exceeds the level of the background noise.

The conclusion that suppression is only observed when the noise level exceeds that of the signal may be understood in terms of the underlying mechanisms, as follows. When the signal level exceeds the noise level, it is likely that the signal, rather than the noise determines the effective gain of the cochlear amplifier in the region with a CF corresponding to the signal frequency. If the signal determines the gain, then the noise would not be expected to affect compression (see, e.g., Pang and Guinan, 1997). In contrast to studies of BM motion, it is not clear how to evaluate compression at lower signal levels psychophysically, because the signal then approaches its masked threshold in the noise alone, making it difficult to distinguish the effects of the sinusoidal masker from those of the TEN.

It therefore remains possible, indeed likely, that the noise dominates, and suppresses, the response to the signal at lower signal-to-noise ratios, where the gain is determined by the noise. Nevertheless, for the practical purposes of psychoacoustic and speech experiments, as well as for real-world applications, our results suggest that the addition of a broadband background noise does not change the underlying BM responses to sounds that are presented at positive signal-to-noise ratios measured within one ERB_N.

One potential complication in our results involves the presence of the notched or highpass noise, designed to limit the possibility of off-frequency listening. This noise was present in all our conditions, and could in principle have swamped any additional effect of the TEN noise. This seems unlikely, however, as the level of the notched or highpass noise was always much lower than that of the signal and in most cases was lower than that of the TEN. For instance, at a signal level of 55 dB SPL, the average spectrum level of the notched and highpass noise was around 0 dB (re 20 μPa). The ERB_N at 4 kHz is estimated to be around 460 Hz. Thus, the level per ERB_N of the notched or highpass noise in its passband near the signal frequency would be around 27 dB SPL, which is nearly 30 dB lower than the signal level, meaning it was unlikely to have directly affected signal thresholds. It is also lower than both the 30 and 40 dB/ERB_N TEN levels, meaning that it was unlikely to have affected, or even been audible in, the critical conditions of high TEN levels.

Overall, our results suggest that any similarities in performance between HI and NMNH listeners in most psychoacoustic and speech tasks are unlikely to be due to changes in the underlying BM compression function caused by the presence of threshold elevating background noise. Statistical analysis of the slopes derived from the individual and mean data in various levels of TEN demonstrated that the presence of the TEN masker did not significantly alter the estimates of the BM compression exponents. This conclusion leaves open the possibility that any differences observed between HI and NMNH listeners are due to differences between these two groups in terms of the underlying BM mechanics (for a review, see Oxenham and Bacon, 2003).

At least one common feature of hearing impairment that can be recreated in NMNH listeners is loudness recruitment, which has been hypothesized to be due to lack of cochlear compression in HI listeners (e.g., Moore and Glasberg, 1997; Moore *et al.*, 1999). The results from the present study suggest that if loudness recruitment in HI listeners is indeed due to loss of compression, then the mechanisms underlying loudness recruitment in NMNH (e.g., Steinberg and Gardner, 1937) and HI listeners are different. This conclusion is consistent with the way in which partial loudness is explained in the model of Moore and Glasberg (1997). It is also consistent with the physiological results of Phillips (1987). He measured neural response functions in an animal model (cat) with thresholds that were elevated either by permanent (noise-induced) cochlear hearing loss or by a simultaneously presented noise. Phillips (1987) found that the effect on the neural responses was not similar across the two groups, and concluded that loudness recruitment in cochlear hearing loss did not have the same peripheral basis as loudness recruitment produced by partial masking (Scharf, 1964). A study by Heinz *et al.* (2005), which evaluated neural responses to various stimuli in an animal model with cochlear hearing loss (due to noise trauma), has also questioned whether loudness recruitment in HI listeners is due to reduced BM compression. They found that auditory-nerve rate-intensity functions, which presumably reflect BM motion, were not consistent with expectations based on recruitment. However, the link between the physiology and human perception remains tenuous, due to species differences and uncertainty regarding how responses in the auditory nerve relate to the percept of loudness (Doucet and Relkin, 1997).

As noted in the Introduction, studies have shown mixed results when attempting to simulate the performance of HI listeners with NMNH listeners. For example, masking release in a temporally varying background, as measured by Bacon *et al.* (1998), was well simulated by NMNH listeners for approximately half of the HI listeners, while the remaining HI listeners showed deficits beyond those of their NMNH counterparts. Another study, measuring effects of masker phase curvature on signal thresholds, found substantial differences between most of the HI listeners and their NMNH counterparts (Oxenham and Dau, 2004). Earlier psychophysical results suggested that moderate-to-severe cochlear hearing loss was often sufficient to eliminate cochlear compression, as measured psychophysically (Oxenham and Moore, 1995; Oxenham and Plack, 1997; Moore *et al.*, 1999). More recent results suggest that milder hearing loss can result in normal values of maximum compression, but over a more limited range of levels than normal and that the amount of compression can vary, even for the same amount of hearing loss (e.g., Moore *et al.*, 1999; Plack *et al.*, 2004; Lopez-Poveda *et al.*, 2005). These findings suggest that the residual differences between some HI and NMNH listeners may be indicative of loss of compression for the HI ears. In Bacon *et al.* (1998), the results from the HI listeners that were accounted for by the NMNH results may have been representative of HI ears with near-normal amounts of compression while the HI results that showed additional deficits may reflect a loss of cochlear compression. Further research will be necessary to determine if degree of cochlear compression can indeed account for variation in HI listeners' performance on these types of tasks.

In summary, the results from this study indicate that the addition of masking noise to elevate thresholds in NH listeners does not alter the compressive characteristics of the BM response for tones 5 dB or more above their masked threshold in the noise, as estimated behaviorally using a forward GOM paradigm. It therefore remains possible that differences in underlying cochlear compression account for at least some of the differences in performance seen between NMNH and HI listeners.

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