

A behavioral measure of basilar-membrane nonlinearity in listeners with normal and impaired hearing

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This paper examines the possibility of estimating basilar-membrane (BM) nonlinearity using a psychophysical technique. The level of a forward masker required to mask a brief signal was measured for conditions where the masker was either at, or one octave below, the signal frequency. The level of the forward masker at masked threshold provided an indirect measure of the BM response to the signal, as follows. Consistent with physiological studies, it was assumed that the BM responds linearly to frequencies well below the characteristic frequency (CF). Thus the ratio of the slopes of the masking functions between a masker at the signal frequency and a masker well below the signal frequency should provide an estimate of BM compression at CF. Results obtained from normally hearing listeners were in quantitative agreement with physiological estimates of BM compression. Furthermore, differences between normally hearing listeners and listeners with cochlear hearing impairment were consistent with the physiological effects of damage to the cochlea. The results support the hypothesis that BM nonlinearity governs the nonlinear growth of the upward spread of masking, and suggest that this technique provides a straightforward method for estimating BM nonlinearity in humans. © 1997 Acoustical Society of America.

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INTRODUCTION

Physiological studies of cochlear mechanics have established that the response of the basilar membrane (BM) to tones at characteristic frequency (CF) is generally nonlinear and compressive (Rhode, 1971; Sellick *et al.*, 1982; Robles *et al.*, 1986; Ruggero, 1992). Damage to the cochlea, and in particular the outer hair cells (OHCs), results in a reduction in sensitivity and a loss of compression at CF (Ruggero and Rich, 1991; Ruggero *et al.*, 1993, 1995). Many of the difficulties experienced by people with sensorineural hearing loss may be explained in terms of the physiological changes associated with damage to the cochlea. For instance, the effect of abnormal growth of loudness, or "loudness recruitment" (Fowler, 1936), may be due to a loss of compression in the cochlea (Yates, 1990; Glasberg and Moore, 1992). Similarly, the deterioration of performance in some measures of temporal resolution, such as gap detection in narrow-band noise (Glasberg and Moore, 1992) and the decay of forward masking (Oxenham and Moore, 1997), can also be explained in terms of loss of BM compression. Finally, a reduction in BM sensitivity to stimuli at CF results in reduced frequency selectivity, which is also a common symptom of cochlear hearing loss (e.g., Glasberg and Moore, 1986).

Given its likely influence on perception, a measure of cochlear compression in human hearing would be of considerable value. The aim of the research reported in this paper is therefore to provide a behavioral measure of BM nonlinearity in humans. The method applied here relates to the nonlinear growth of masking (GOM) observed when a masker is

well below the signal in frequency (e.g., Wegel and Lane, 1924; Egan and Hake, 1950).

One explanation for the nonlinear GOM when the masker is well below the signal in frequency is as follows. The BM responds linearly to tones with a frequency well below CF (e.g., Sellick *et al.*, 1982). A given increase in masker level will therefore be reflected by a proportional increase in BM motion at the place with a CF corresponding to the signal frequency. In contrast, the BM response to the signal at CF is compressive, and so the signal level must be increased by more than the masker level in order to produce the same change in response at the relevant place along the BM (Oxenham and Moore, 1995). Essentially the same argument has also been applied to differences in the rate-intensity functions of auditory-nerve fibers between stimuli at CF and those well below CF (Stelmachowicz *et al.*, 1987). Accordingly, a loss of compression due to cochlear hearing loss should produce a more linear GOM function. Psychoacoustic measurements using hearing-impaired listeners support this prediction (Stelmachowicz *et al.*, 1987; Murnane and Turner, 1991; Dubno and Ahlstrom, 1995; Nelson and Schroder, 1996, 1997).

While the above theory can qualitatively account for the nonlinear growth of the upward spread of masking, there is a discrepancy between the slope of the predicted GOM function, based on physiological measurements of BM nonlinearity, and that actually observed. For instance, most recent studies of BM motion have observed growth in the response to a tone at CF of around 0.2 dB/dB or less for levels above about 40 dB SPL (Sellick *et al.*, 1982; Yates *et al.*, 1990; Ruggero, 1992; Murugasu and Russell, 1995). This leads to

the prediction that the slope of a GOM function for a masker well below the signal frequency should be five or more times steeper than the GOM slope for an on-frequency masker. For simultaneous masking, a 1-dB increase in masker level should therefore produce a 5-dB increase in signal level. Instead, a survey of previous studies by Stelmachowicz *et al.* (1987) showed that, even when the masker was an octave or more below the signal frequency, the slope of the GOM function rarely exceeded 2. The slope appears to be steepest for tone-on-tone masking (van der Heijden and Kohlrausch, 1995), but even here maximum estimates range from between 2 (Schöne, 1979) and 2.5 (van der Heijden and Kohlrausch, 1995).

The discrepancy between the physiological predictions and the psychophysical results may be related to differences in the method of stimulus presentation. In the physiological studies, the response to a single tone is measured over a range of levels. In most psychophysical masking experiments, the masker and signal are presented simultaneously. The presence of the masker, by suppressing the signal, may reduce the slope of the GOM function. Ruggero *et al.* (1992) have shown not only that the BM response to a tone at CF is reduced in the presence of a low-frequency suppressor, but also that the growth of response becomes more linear. Thus, in simultaneous masking experiments, we may be measuring the more linear response to the signal in the presence of the masker, rather than the desired response of the signal alone. This would lead to an underestimate of BM compression. The possible role of suppression has also been pointed out by Nelson and Schroder (1997).

Another factor which may lead to an underestimate of compression is the possibility that listeners combine information over a number of frequency channels when detecting a signal (e.g., Zwicker, 1970). High-level signals would stimulate a greater number of frequency channels, and so enhance detection. This in turn would produce a shallower GOM slope than would otherwise be measured. The benefit of such a cue can be reduced by adding background noise to the stimuli.

In order to avoid the problems associated with suppression, we have employed a forward-masking paradigm to study the on-frequency compression of the BM. A number of previous studies have also used forward masking, including conditions where the masker was below the signal in frequency (e.g. Kidd and Feth, 1981; Nelson and Freyman, 1984; Nelson *et al.*, 1990). However, in these and other studies, the level of the signal was rarely above 40 dB SPL. It is thought that the response of the BM is more linear at lower levels, below about 30–40 dB SPL (Sellick *et al.*, 1982; Yates *et al.*, 1990; Murugasu and Russell, 1995), and so the signal levels used in previous forward-masking studies may not have been sufficiently high to measure maximum BM compression. The experiments described below employed a very brief signal, presented close to the offset of the masker, in order to measure thresholds over a wide range of signal levels. Masker, rather than signal, level was chosen as the dependent variable, as is the case in the measurement of psychophysical tuning curves.

A similar method of using the difference in response to

an on-frequency and a low-frequency stimulus to derive the amount of BM compression has been employed by Yates *et al.* (1990) in order to transform auditory-nerve rate-intensity functions into BM input-output functions. The argument that the ratio of on-frequency to off-frequency GOM slopes provides a measure of physiological response has also been used by Stelmachowicz *et al.* (1987).

I. EXPERIMENT 1. FORWARD MASKING WITH A 6-KHz SIGNAL

A. Stimuli and procedure

The level of a sinusoidal forward masker needed to mask a 6-kHz sinusoidal signal was measured for a wide range of signal levels. The masker frequency was either 3 kHz (off-frequency condition) or 6 kHz (on-frequency condition), and had a total duration of 104 ms, including 2-ms raised-cosine onset and offset ramps. The signal was also gated with 2-ms raised-cosine ramps and had no steady-state portion, giving it a total duration of 4 ms. The silent interval between the masker offset and signal onset was 2 ms (defined in terms of the zero-points in the envelope). A high signal frequency was chosen so that the signal could be made very brief while ensuring that the 3-dB bandwidth of the signal (360 Hz) fell well within the estimated equivalent rectangular bandwidth (ERB) of an auditory filter centered at 6 kHz (approximately 675 Hz; see Glasberg and Moore, 1990). This reduces the possibility of signal detection in the presence of the on-frequency (6-kHz) masker being mediated by off-frequency components of the signal, or “spectral splatter.” Also, a brief (2-ms) masker-signal interval could be employed without the response to the masker and signal temporally overlapping in the auditory periphery near the signal place, due to ringing in the auditory filters (Duifhuis, 1973). The on-frequency masker was used in order to check, and if necessary calibrate, for any nonlinear effects of forward masking *per se*. If a linear response to the 3-kHz masker at the BM place with a CF of 6 kHz is assumed, then the ratio of the slopes of the two masking functions (on-frequency and off-frequency conditions) provides an estimate of on-frequency compression.

For the normally hearing listeners, a background noise was simultaneously presented in order to restrict “off-frequency listening” (Johnson-Davies and Patterson, 1979). The background noise may also restrict “off-time listening” (Robinson and Pollack, 1973; Oxenham and Moore, 1994): It has been suggested that neural activity due to the signal may persist after the signal’s offset, and that this activity could aid detection in the presence of a forward masker. If this were the case, then a simultaneous masker which continues beyond the offset of the signal should reduce the “audibility” of this cue. For an illustration of this hypothesis, see Oxenham and Moore (1994).

For the off-frequency condition, the white, random background noise was digitally high-pass filtered (180 dB/oct slope) with a cutoff frequency of $1.117f_s$, where f_s is the signal frequency. In this case, the spectrum level of the noise in its passband was 55 dB below the level of the signal. This resulted in high-level signals being presented at least 25 dB,

TABLE I. Spectrum level of the notched noise used in experiment 1 with a 6-kHz masker and 6-kHz signal.

Signal level (dB SPL)	Noise spectrum level (dB SPL)
40	-17.0
45	-11.5
50	-6.0
55	-2.5
60	1.0
65	3.5
70	6.0
75	8.5
80	11.0
85	13.5

and more typically 35 dB, above the simultaneous masked threshold of the signal in the background noise alone. For the on-frequency condition, a low-pass noise (cutoff frequency $0.883f_s$, 180 dB/oct filter slope) was added to the high-pass noise. The spectrum level of the resulting notched noise was set so that it was always 30 dB below the spectrum level needed to simultaneously mask the signal alone for author/listener CP. The notched-noise spectrum level used in experiment 1 at each signal level is given in Table I. The spectrum level of the notched noise was generally lower than that of the high-pass noise, as the notched noise was a more effective masker, especially at higher levels. The background noise was gated on 50 ms before the masker onset and gated off 50 ms after the signal offset, giving it a total duration of 210 ms. Due to the limited dynamic range and the probable reduced frequency selectivity of the hearing-impaired listeners, it was not thought necessary to add background noise to their stimuli. A schematic diagram of the stimulus configuration is given in Fig. 1.

All stimuli (signals, maskers, and background noise) were generated and controlled digitally on Silicon Graphics

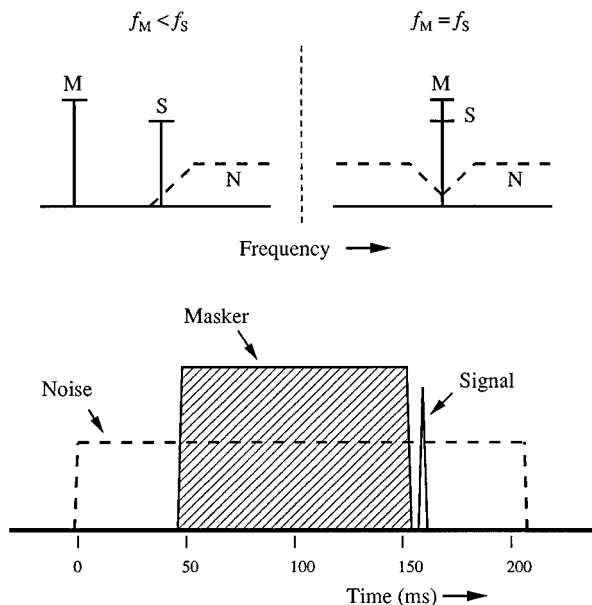


FIG. 1. Schematic diagram of the stimuli used in the experiments. The upper and lower panels show the spectral and temporal characteristics of the stimuli, respectively.

workstations using a 32-kHz sampling rate, and analog waveforms were created using the built-in 16-bit DACs. A trial consisted of two observation intervals, marked by lights and separated by an interstimulus interval of 500 ms. The masker was presented in both intervals, and the signal was presented randomly in either the first or second interval. Thresholds were estimated using a two-alternative forced-choice paradigm with a two-up one-down adaptive procedure that estimates the masker level at the 70.7% correct point on the psychometric function (Levitt, 1971). Each reported threshold is the mean of four estimates. Listeners sat in an IAC sound-attenuating booth. The normally hearing listeners were tested at the University of Sussex, while the hearing-impaired listeners were tested at the Institute for Perception Research (IPO). Differences in setup are described below.

1. Sussex setup (normally hearing listeners)

Thresholds were measured for signal levels between 40 and 90 dB SPL in 5-dB steps. Stimuli were presented to the right ear of the listeners via a Sony MDRV6 headset, with the headset input taken directly from the output of the computer's DAC. An earplug was inserted into the left ear to prevent the detection of the signal in that ear via acoustic (or electric) crosstalk. Responses were made via a computer keyboard and feedback was provided by a graphical display on the computer monitor. In the adaptive procedure, the masker level was initially varied with a step size of 4 dB, which was reduced to 2 dB after the first four turnpoints. The threshold estimate was taken as the mean masker level at the last 12 turnpoints.

2. IPO setup (hearing-impaired listeners)

Thresholds were measured for signal levels from about 5 dB above threshold in quiet for each listener up to a maximum of about 95 dB SPL, in 5-dB steps. Stimuli were presented to the ear with the lower threshold in quiet for the brief signal at 6 kHz. For all three listeners in this study this was the left ear. Stimuli were passed from the Silicon Graphics DAC through a programmable attenuator and a headphone buffer (Tucker Davies Technologies PA4 and HB6, respectively) and were presented via a Beyer DT990 headset. No earplug was required in the opposite ear, as any crosstalk would have been well below absolute threshold in that ear. Responses were given via a response box and feedback was provided by lights on the response box. The initial step size for the adaptive procedure was 4 dB. This value was halved after every two turnpoints until a value of 1 dB was reached, and then remained constant. A run was terminated after ten reversals with a step size of 1 dB. Threshold was defined as the median masker level at the last ten turnpoints.

Both headsets (Sony MDRV6 and Beyer DT990) were calibrated with respect to their acoustic output at 1 kHz. Responses for both headsets at 2, 3, and 6 kHz (the other frequencies used in this study) were within -1 and $+2.5$ dB of the response at 1 kHz. Differences in the frequency response between the headphones used in the two test centers

TABLE II. Pure-tone thresholds (dB HL) for the three listeners with cochlear hearing loss.

Listener	Ear	Frequency (Hz)					
		250	500	1000	2000	4000	8000
AR	L	10	5	10	25	60	60
	R	15	25	35	65	80	>90
JK	L	20	20	35	45	50	65
	R	20	25	50	60	60	70
MV	L	10	10	10	30	45	35
	R	15	15	15	40	50	50

may have affected the absolute values of masked thresholds, but should not have affected the slopes of the masking functions.

B. Listeners

Three normally hearing listeners, aged between 28 and 32, participated. One was the author CP and the others were paid an hourly wage for their services. All listeners had absolute thresholds of no more than 15 dB HL, measured at octave frequencies between 250 and 8000 Hz. Thresholds in quiet for the 4-ms signal were 28.6, 29.1, and 31.2 dB SPL for listeners CP, JB, and SD, respectively. Listeners were given at least 20 h practice before data collection began.

The three hearing-impaired listeners, MV, AR, and JK, were aged 48, 60, and 69, respectively, and were all diagnosed as having bilateral cochlear hearing loss, based on the following information: air-bone gaps were no more than 5 dB at any of the audiometric frequencies, and all three listeners had normal tympanograms and acoustic reflexes, indicating no conductive element. The normal acoustic reflexes, and the fact that speech recognition thresholds in each ear were consistent with the respective pure-tone audiometric thresholds, were interpreted as evidence against a retro-cochlear component to the hearing losses. Nothing definite

was known about the respective etiologies, but the hearing losses of AR and JK were thought to be presbycusis.

Pure-tone audiometric thresholds, measured using an Interacoustics AC-5 audiometer, are given in Table II. These thresholds were measured using long-duration tones, a modified method of limits, and a fixed step size of 5 dB. As mentioned above, the left ears of all three listeners were tested. Thresholds for the 4-ms signal, using the 2IFC adaptive procedure, were 65, 73, and 77 dB SPL for MV, AR, and JK, respectively. All three were paid for their participation and were given at least 2 h practice before data were recorded. The total practice time for the hearing-impaired listeners was therefore much less than for the normally hearing group. However, no consistent changes in the performance of the hearing-impaired listeners were noted during the course of the experiment, which lasted for a period of five weeks, with two 2-h sessions per week. This suggests that results would probably not have been different if the hearing-impaired listeners had been given more practice.

C. Results

Results are shown in Fig. 2, where masker level at threshold is plotted as a function of signal level. Note that the slope of this masking function is the reciprocal of the more usual GOM function.

Consider first the data from the normally hearing listeners (left-hand panel). Individual thresholds for the three listeners are plotted, with the error bars denoting \pm one standard deviation of the four estimates. With the masker at the same frequency as the signal (on-frequency condition; filled symbols), there are fairly large differences in threshold values for a given signal level across listeners. However, for all three listeners the masker level grows approximately linearly with signal level across the range of levels studied (cf. dashed line); the slopes of the lines fitted to the individual data are very similar, ranging from 0.96 to 1.08. Linear

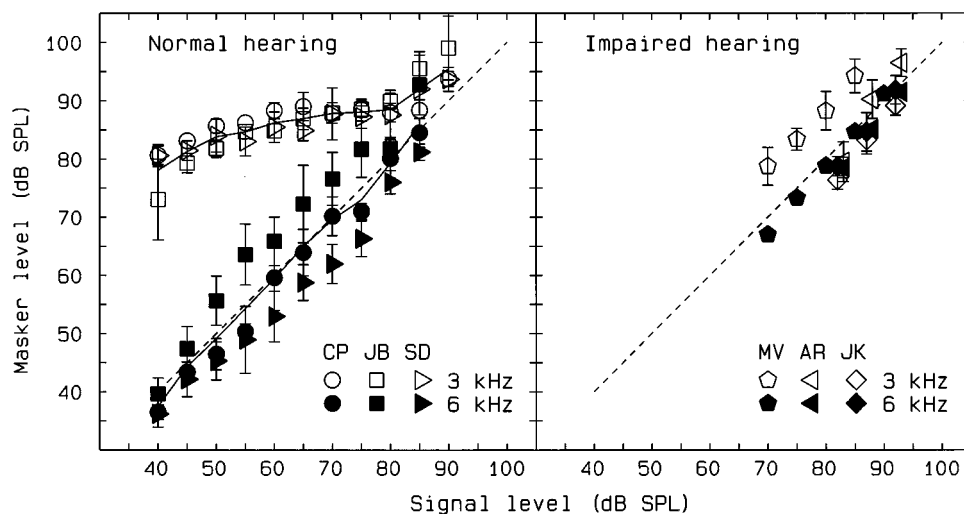


FIG. 2. The level of a masker required to mask the 6-kHz signal, as a function of signal level. Data from the three normally hearing listeners are shown in the left-hand panel and data from the three hearing-impaired listeners are shown in the right-hand panel. Error bars represent \pm one standard deviation, and are omitted if they are smaller than the respective symbol. Solid curves denote the mean thresholds of the listeners in the normally hearing group, and the dashed lines denote linear growth of masking.

growth is not usually found in forward masking (e.g., Jesteadt *et al.*, 1982); typically masker level grows more rapidly than signal level, which would lead to a steeper slope on these coordinates. However, the growth of forward masking, using a broadband forward masker and a sinusoidal signal is known to become more linear for brief signals at short masker-signal intervals (Oxenham and Moore, 1995), and the results are also consistent with a recent theory of forward masking (Oxenham and Moore, 1995, 1997).¹ In contrast to the linear masking function observed with the on-frequency masker, the results using the 3-kHz masker (open symbols) indicate highly compressive growth. For instance, increasing the signal level from 50 to 70 dB SPL results in only a 4-dB mean increase in masker level, from 83.8 to 87.8 dB SPL, across the three listeners. The slope for the mean data between signal levels of 50 and 80 dB SPL, inclusive, is 0.16. At the highest signal levels (80–90 dB SPL), growth becomes more linear for all three listeners, with individual regression lines of 0.58, 0.61, and 0.91 for listeners CP, JB, and SD, respectively. At the lowest signal levels, the masking function also seems to become more linear; individual regression lines between 40 and 50 dB, inclusive, are 0.50, 0.88, and 0.34 for listeners CP, JB, and SD, respectively.

The right-hand panel of Fig. 2 shows the individual results from the three hearing-impaired listeners.² Again, the masking function for the on-frequency masker (filled symbols) is approximately linear. This is consistent with a previous study of forward masking in hearing-impaired listeners (Oxenham and Moore, 1995). However, in contrast to the results from normally hearing listeners, masker level also grows approximately linearly with signal level in the off-frequency condition (open symbols), implying an absence of BM compression.

For two of the three hearing-impaired listeners, thresholds could only be measured for signal levels at which the masking function for the normally hearing listeners was also becoming more linear. This may mean that some of the apparent difference between the normally hearing and hearing-impaired listeners in the off-frequency condition is simply due to the exclusively high signal levels used for the hearing-impaired listeners. However, listener MV continues to show a linear masking function down to signal levels of 70 dB SPL, where the masking function for the normally hearing listeners is most compressive. Furthermore, an analysis of variance of linear regressions including only signal levels of 80 dB or more, indicated a significant difference in slope between the two groups for the off-frequency condition [$F(1,9) = 25.73$; $p < 0.001$], but not for the on-frequency condition [$F(1,7) = 0.11$; $p > 0.5$]. This implies that the difference between the normally hearing and hearing-impaired listeners in the slope of the off-frequency masking function is probably not due to the different range of signal levels used.

D. Discussion

The compression observed in the normally hearing listeners for the 3-kHz masker is, to our knowledge, greater than any previously reported in a similar task. As mentioned above, the best-fitting line for our data between signal levels

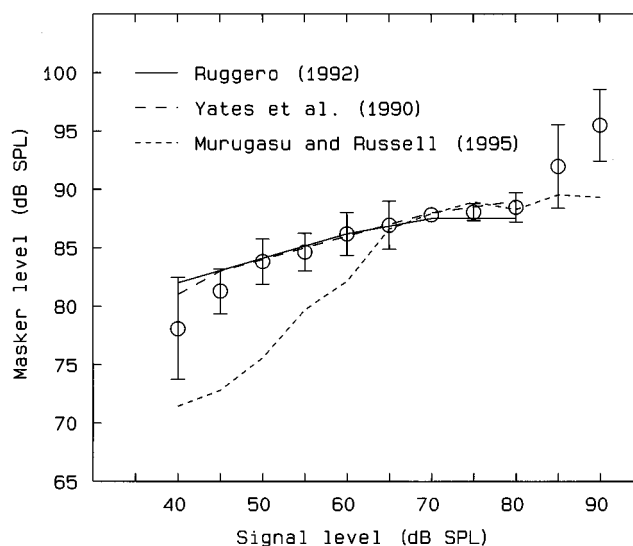


FIG. 3. A comparison of the mean 3-kHz masker data from the normally hearing listeners in Fig. 2 with physiological data of BM nonlinearity from three studies. Error bars represent \pm one standard deviation across listeners, and are omitted if smaller than the symbol. The units of dB SPL on the ordinate refer only to the psychophysical data; the absolute dB values of the physiological data are arbitrary. The characteristic frequencies in the physiological measurements were 9 kHz (Ruggero, 1992), 17.5 kHz (Yates *et al.*, 1990), and 16 kHz (Murugasu and Russell, 1995).

of 50 and 80 dB SPL, inclusive, has a slope of 0.16. In terms of GOM (signal threshold as a function of masker level), this corresponds to a slope of 6.25, which contrasts strongly with previous estimates of around 2 (e.g., Stelmachowicz *et al.*, 1987). We attribute this difference to our use of forward masking, which eliminates the effects of suppression, and the use of a very brief signal, positioned close to the masker, which allowed us to measure thresholds for signal levels higher than 50 dB SPL.

Our results may appear in conflict with those from a physiological study of Delgutte (1990). He concluded that the upward spread of masking was primarily due to the effects of suppression, while our results suggest that suppression may in fact reduce the nonlinear growth of the upward spread of masking. These apparently conflicting conclusions can, however, be reconciled if the signal levels are compared: In Delgutte's study, signal thresholds in nonsimultaneous masking conditions were rarely above 50 dB SPL, while our data show most compression above about 50 dB SPL. Thus, his conclusions may apply for low, but not high, signal levels.

Due to the linear relationship between signal level and the level of the on-frequency masker at threshold, the slope of the function for the off-frequency condition provides a direct estimate of BM compression at CF. Our estimate of 0.16 dB/dB between 50 and 80 dB SPL is in quantitative agreement with recent physiological estimates of BM compression. To illustrate this, the mean data from the normally hearing listeners in the off-frequency condition are replotted in Fig. 3, together with a sample of BM data from the chinchilla (Ruggero, 1992, Fig. 1a) and the guinea pig (Murugasu and Russell, 1995, Fig. 1b), and an estimate of BM response, derived from auditory-nerve rate-intensity func-

tions, also from the guinea pig (Yates *et al.*, 1990, Fig. 8). The BM data have been transformed from their original units (BM velocity and BM displacement) into dB and have been displaced vertically to provide easier comparison with our own data. The agreement between our data and those of Ruggero (1992) and Yates (1990) is very good. The maximum compression measured by Murugasu and Russell (1995) is similar to that of our data and the other studies, but the compression only becomes pronounced above levels of 60 dB SPL. This apparent shift of the point between more linear and more compressive response may be due to differences in the middle-ear transfer function. For instance, a horizontal shift of the function to the right, as is seen in the Murugasu and Russell data, would be the predicted result of linear attenuation due, perhaps, to a mild conductive loss in that guinea pig.

At the highest signal levels, the masking function for the off-frequency condition seems to become more linear. While some BM data show more linear growth at high levels (Ruggero and Rich, 1991), others do not (Murugasu and Russell, 1995). Unfortunately, our data cannot distinguish between these two alternatives for the following reason. If the response at CF remains compressive at high levels (beyond, say, 80 dB SPL), places along the BM with higher CFs will show a greater response to the signal than the nominal CF, in what is observed as a shift in the peak of excitation along the BM. Despite the use of background noise, we cannot rule out the possibility that, at the highest signal levels, the signal was detected at a place with a higher nominal CF and hence a more linear response to a 6-kHz tone. Another possible explanation for the apparently more linear function at high levels is that the middle-ear reflex selectively attenuates the high-level masker but not the signal, as the signal is beyond the frequency at which the reflex is effective. However, the fact that the 3-kHz masker is also probably too high in frequency for the middle-ear reflex to have any significant effect renders this explanation less likely.

At the lowest levels, the interpretation of the more linear response is also not clear-cut. Again, it is not clear from the physiological data whether, at what level, and to what extent the BM input-output function becomes more linear. In the case of our data, the steepening of the masking slope at the lowest levels does not necessarily reflect less compression. Instead, the change in slope may be due to the approach of absolute threshold. If threshold in quiet is treated as being due to a constant "internal masker," a steeper masking function is predicted as the signal approaches absolute threshold, even if the compression remains constant (Humes and Jesteadt, 1989).

In order to test whether the change in slope at low levels was due to a change in BM nonlinearity or simply the approach of absolute threshold, a further experiment using a 3-kHz masker and a 6-kHz signal was carried out with a somewhat longer signal. Increasing the duration of the signal generally increases its sensation level. Thus, at equal signal levels, the longer signal was at a higher sensation level, and so should be less influenced by the effects of absolute threshold. Second, the experiment provides a test of the generality of our hypothesis. If the shape of the masking function is

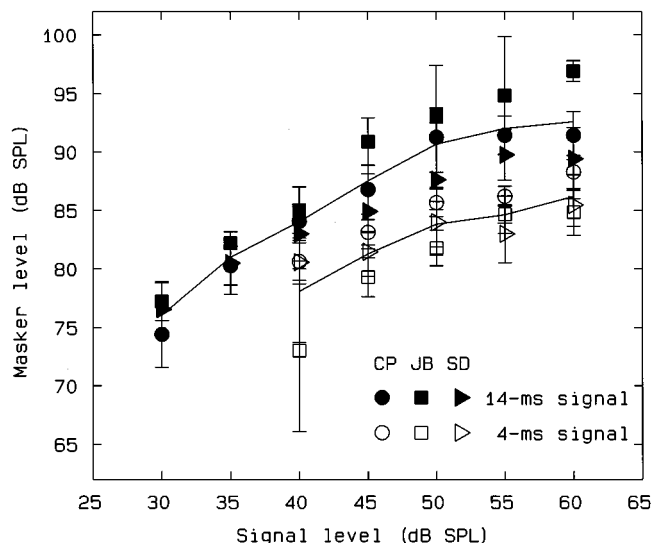


FIG. 4. Masker level at threshold as a function of signal level using a 14-ms 6-kHz signal and a 3-kHz masker for three normally hearing listeners (filled symbols). For comparison, data from Fig. 2 using a 4-ms signal are replotted as open symbols. Mean data are shown by the solid curves.

determined by BM nonlinearity, using a longer signal should result in an upwards shift of the function, but the function should be parallel to that measured with the shorter signal.

E. Experiment 1a. Effect of a longer signal

1. Method

The level of a 3-kHz masker required to mask a 6-kHz signal was measured for the three normally hearing listeners for signal levels between 30 and 60 dB SPL. The signal had a steady-state duration of 10 ms and was gated with 2-ms raised-cosine ramps. All other parameters were as described above. Thresholds in quiet for the longer signal were approximately 12 dB lower than for the original 4-ms signal.

2. Results

The results from the three normally hearing listeners are plotted as solid symbols in Fig. 4. For comparison, the data using the 4-ms signal, taken from Fig. 2, are shown as open symbols. As expected, the masker level needed to mask the longer signal is higher than for the shorter signal for a given signal level. The shape of the function matches the original function rather well. This shows first that the more linear growth below 50 dB is probably not due solely to the approach of absolute threshold and, second, that the more linear slope continues down to signal levels of 30 dB SPL.

II. EXPERIMENT 2. MEASURING COMPRESSION AT 2 kHz

The first experiment showed that normally hearing listeners exhibit strong compression at a frequency of 6 kHz. Moderate to severe (60–70 dB) cochlear hearing loss seems to eliminate the compression completely. In this experiment, we repeated part of experiment 1 at a lower frequency in order to examine whether compression varies with CF. Studies of BM nonlinearity have generally been limited to the

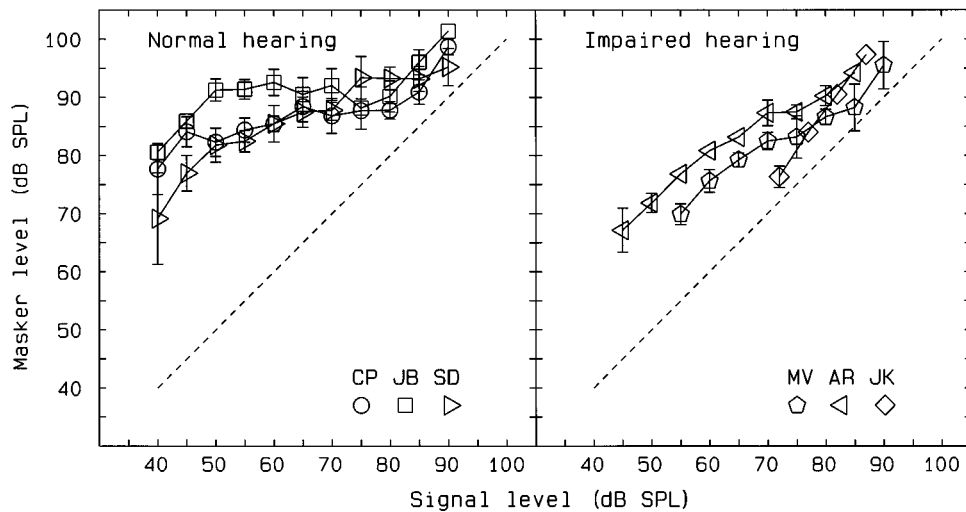


FIG. 5. Masker level at threshold as a function of signal level using a 2-kHz signal and a 1-kHz masker. Individual results from the normally hearing and hearing-impaired listeners are shown in the left- and right-hand panels, respectively. Error bars represent \pm one standard deviation, and are omitted if they are smaller than the respective symbol.

basal turn of the cochlea (highest CFs) for logistical reasons, meaning that there are essentially no reliable direct studies of BM nonlinearity at places corresponding to lower CFs. However, Cooper and Yates (1994) have derived BM input-output functions at lower frequencies from auditory-nerve rate-intensity functions in the guinea pig. They found that for fibers with CFs between 1.5 and 3.6 kHz, the derived input-output functions were more than three times steeper, and hence less compressive, than for fibers with CFs above 4 kHz.

Using the stimulus parameters as before was somewhat more problematic at 2 kHz. First, the signal bandwidth of 360 Hz is greater than that of the ERB at 2 kHz. For a masker at the signal frequency, it is difficult to rule out the detection of off-frequency components of the signal, or “spectral splatter.” This is less of a problem when the masker is below the signal in frequency, as the high-frequency slope of the masker excitation is probably shallower than that due to the splatter of the signal. Even with a masker below the signal frequency, the narrower bandwidth of the auditory filter at 2 kHz means that there is an increased chance of the masker and signal interacting on the BM, due to ringing in the filter. However, in pilot experiments, it was found that increasing the duration of the signal, or the ramps, resulted in too great a reduction in the level range over which thresholds could be measured. For this reason the temporal parameters of the stimuli were retained. The probable effect of stimulus overlap on the BM is the introduction of some suppression effects. According to our reasoning this should result in, if anything, a steepening of the slope of the masking function, and so a reduction in the apparent compression. Another possible confounding factor at 2 kHz is the influence of the middle-ear reflex. This may attenuate the 1-kHz masker more than the 2-kHz signal at high masker levels. The effect of this would again be a steeper slope and an underestimate of compression at the highest levels.

A. Method

Due to the problems of using a masker at the signal frequency, discussed above, thresholds were only measured for a 2-kHz signal and a 1-kHz masker. All other parameters were as described in experiment 1.

B. Listeners

The six listeners of experiment 1 also participated in this experiment. Thresholds in quiet for the 2-kHz, 4-ms signal were 28.3, 27.9, and 32.9 dB SPL for the normally hearing listeners CP, JB, and SD, respectively, and 44, 37, and 67 dB SPL for the hearing-impaired listeners, MV, AR, and JK.

C. Results and discussion

Figure 5 shows the results using a 2-kHz signal and a 1-kHz masker. Consider first the data from the normally hearing listeners. It can be seen that, despite the large inter-subject differences in masker level of as much as 10 dB, the slopes for all three listeners are rather flat between 50 and 80 dB SPL. We could not reliably measure masking functions for the on-frequency condition, and so it is not possible to calculate the ratio of the off-frequency slope to the on-frequency slope, as we did for the mean data at 6 kHz. For the purposes of this analysis, however, we assume that the mechanisms underlying forward masking do not change with CF and so the slope of the masking function is again interpreted as a direct measure of BM nonlinearity at 2 kHz.

The slope of the mean data from the normally hearing listeners between 50 and 80 dB is 0.17. This compares well with the slope of 0.16 for the same level range at 6 kHz. Thus, for normally hearing listeners, unlike the physiological data from the guinea pig (Cooper and Yates, 1994), our data provide no evidence for a difference in compression between CFs of 2 and 6 kHz. Again, the functions seem to become more linear at the lowest and highest signal levels.

Results from the hearing-impaired listeners are shown in the right-hand panel of Fig. 5. It was possible to measure thresholds over a much wider range of signal levels than at 6 kHz for two of the three hearing-impaired listeners (AR and MV), due to their lower absolute thresholds at 2 kHz. Again, the hearing-impaired listeners show much less compressive masking functions. For instance, between signal levels of 55 and 70 dB SPL, the slope of the mean data for listeners AR and MV is 0.75. However, the two listeners (AR and MV) with less hearing loss at 2 kHz seem to show some “residual” compression between 70 and 80 dB SPL. It seems that limited cochlear hearing loss may not necessarily result in a uniform reduction of BM compression over the entire level range, but may instead reduce the range of levels over which “normal” compression is observed. However, a larger number of listeners would be necessary to confirm this observation.

III. CONCLUDING REMARKS

The results from both experiments suggest that it is possible to derive a behavioral measure of BM nonlinearity which is in quantitative agreement with physiological measurements. We attribute the difference between these data and previous GOM data to our use of forward masking, which eliminates the effects of suppression. Another difference in stimuli between these experiments and most previous studies is the use of background noise for the normally hearing listeners. The presence of the noise may have limited the use of off-frequency and off-time listening at high signal levels, and so may have made the masking functions shallower. Cues associated with off-time listening would be the same for both on-frequency and off-frequency maskers. Also, detection of the signal’s upward spread of excitation would probably not be affected by the masker frequency. The background noise should therefore not affect the ratio between the slopes of the on- and off-frequency conditions. Thus, if our hypothesis is correct, the removal of the background noise may increase the slope of both masking functions, but the ratio, and hence the estimate of BM nonlinearity, should remain approximately constant. The background noise was not used for the hearing-impaired listeners, as in most cases the noise would have fallen below absolute threshold. However, it is possible that some of the difference observed between the two groups is due to the difference in conditions. This possibility is tested in the Appendix, using one normally hearing and one hearing-impaired listener. It is concluded there that the results cannot be accounted for by the presence or absence of the background noise.

In due course it may be possible to apply a measure similar to that used here to the diagnosis of hearing impairment. A given hearing loss may have a number of causes. For instance, selective damage to the inner hair cells (IHCs) may produce the same elevation in absolute threshold as damage to the OHCs, but may have a rather different effect on loudness perception and frequency selectivity. Patuzzi (1993) has argued that while OHC damage reduces the “active” mechanism (and hence the amplification, compression, and frequency selectivity around CF), IHC damage may produce an effect similar to a simple linear attenuation, thus

retaining compression and reasonably normal frequency selectivity. The possible perceptual consequences of such a two-component scheme are discussed in detail by Moore and Glasberg (1997), who use this approach in a model of abnormal loudness perception.

A reliable measure of BM compression may complement more traditional tests, such as loudness judgments and measures of frequency selectivity, in determining whether such a two-component approach can help account for the variability observed in hearing-impaired listeners with the same absolute hearing loss. Results from this and other studies (Oxenham and Moore, 1995; Oxenham *et al.*, 1997) indicate that compression is probably absent for hearing losses of 60 dB or more. For less severe hearing losses, however, it may be possible to test the two-component hypothesis, based on the presence and the amount of residual compression.

Some problems remain in the implementation of such tests. As discussed above, the method employed in this study is not suited to testing frequencies below about 2 kHz, which limits its use in an audiological setting. Also, the variability across the normally hearing listeners, especially in the on-frequency condition at 6 kHz (see Fig. 2), may cast doubt on the interpretation of individual data. However, the estimate of BM nonlinearity relies on the slopes of the masking functions, which were much more similar across listeners. Absolute differences in masked thresholds may not therefore play an important role. Finally the presence of the background noise had a large effect on masked thresholds, as discussed in the Appendix, although the resulting estimate of BM nonlinearity was not dependent on the presence or absence of the noise. A similarly large effect of background noise on forward-masked thresholds has been reported by Jesteadt *et al.* (1997). While the effects of noise may be accounted for by the loss of cues such as off-frequency and off-time listening, the underlying mechanisms are not quantitatively understood. An understanding of the effects of the background noise may shed light on the mechanisms involved in forward masking, and so may lead to improved techniques for measuring BM nonlinearity over a wider range of frequencies.

IV. SUMMARY

A comparison of the effects of an on-frequency forward masker with those of a forward masker well below the signal frequency provides an estimate of BM compression which is in quantitative agreement with physiological measurements. The loss of compression inferred from the results of three hearing-impaired listeners is also consistent with the physiological effects of damage to the cochlea.

The highly compressive function, derived using forward masking, suggests that suppression is not necessary for the nonlinear growth in upward spread of masking at signal levels above about 40 dB SPL. In fact, at higher signal levels, suppression may produce a more linear masking function. This may be why previous studies using simultaneous masking have found much less compression than is reported here.

If the results are accepted as providing a reasonable estimate of basilar-membrane compression, then a modified

version of the experiment may eventually be of use in the clinical diagnosis of hearing impairment.

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APPENDIX: EFFECTS OF BACKGROUND NOISE

For the normally hearing listeners, background noise was used to reduce the possibility of performance being improved at high signal levels by off-frequency and off-time listening. The background noise was not used for the hearing-impaired listeners because of their generally reduced dynamic range of hearing, meaning that the noise would, in most cases, have been below absolute threshold. However, to ensure that the absence of background noise was not in part responsible for the more linear masking functions found for the hearing-impaired listeners, one of the two listeners with lower thresholds at 2 kHz (listener MV) repeated some of the conditions from experiment 2 in the presence of a background noise with the same characteristics as that used for the normally hearing listeners. These results are shown in the right-hand column of Table AI, and are compared with the data from experiment 2, collected in the absence of noise. It can be seen that the presence of the noise has very little effect on performance. Thus, it is unlikely that the absence of the background noise was responsible for the more linear functions of the hearing-impaired listeners.

While the addition of the noise may reduce the slope of the masking function for normally hearing listeners, there is no *a priori* reason why the slopes from the on-frequency and off-frequency conditions should be affected differently. Therefore, while removing the noise may produce an increase in the slope of the functions, the ratio of the two slopes, and hence the estimate of BM compression, should remain roughly constant. This was tested using one normally hearing listener, CP, at the 6-kHz signal frequency. The methods and stimuli were identical to those used in experiment 1, except that the background noise was not present. The masker level necessary to mask the signal was measured for signal levels between 45 and 75 dB SPL, in steps of 10 dB.

TABLE AI. Comparison of masker levels at threshold (dB SPL) with and without background noise for hearing-impaired listener MV at masker and signal frequencies of 1 and 2 kHz, respectively. Standard deviations are shown in parentheses.

Signal level	No noise	Noise
55	69.9 (1.8)	70.0 (2.0)
65	79.3 (1.2)	79.1 (0.3)
75	83.2 (3.6)	85.6 (0.9)
85	88.3 (4.0)	91.5 (4.6)

TABLE AII. Comparison of results with and without background noise for listener CP. Levels are given in dB SPL. Standard deviations of the threshold estimates are shown in parentheses. An asterisk indicates that the masker level necessary was too high to be measured. The final row gives the ratio of the slopes of the off-frequency to the on-frequency regression lines.

Condition	Signal level	Masker level	
		No noise	Added noise
Off-frequency (3-kHz masker)	45	84.1 (2.1)	83.1 (1.1)
	55	90.0 (1.2)	86.2 (0.8)
	65	91.8 (0.7)	89.0 (2.4)
	75	95.5 (0.3)	88.4 (1.9)
On-frequency (6-kHz masker)	45	43.4 (2.2)	43.4 (1.7)
	55	63.9 (7.3)	50.3 (1.3)
	65	87.1 (7.0)	63.9 (4.0)
	75	*	71.0 (1.3)
Ratio of slopes		0.17	0.19

Results are shown in Table AII, and are compared with the results from experiment 1, where noise was present. For both the on- and off-frequency conditions, the absence of noise resulted in markedly higher masker levels for a given signal level, especially at the higher signal levels. This is consistent with the idea that the background noise prevents off-frequency and off-time listening. However, a linear-regression analysis of these data showed that the ratio of the on- and off-frequency slopes remains similar both with and without noise, being slightly smaller for the no-noise condition than for the original condition, as shown in the last column of Table AII. This provides support for the idea that the ratio of the on- and off-frequency slopes can be used to estimate the amount of BM nonlinearity. The results also indicate that the strong compression observed in the experiments was probably not due to the presence of background noise.

¹Briefly, the theory postulates that the mechanisms underlying the decay of forward masking are essentially linear, but that the combination of changes in BM compression with level and the approach to absolute threshold produces a nonlinear effect overall. This scheme has been shown to be able to account for the nonlinear growth of forward masking over a wide range of masker levels, for masker-signal intervals of between 5 and 25 ms (Oxenham and Moore, 1997). The model has, however, not yet been tested on a full range of forward-masking conditions.

²For listeners MV and JK (pentagons and diamonds, respectively), the lowest signal levels measured represent 5 dB SL. For listener AR (triangles) thresholds with a 5 dB SL signal could not be measured reliably; he sometimes reported that the signal was not audible, even when the masker itself was below threshold. Repeated measures of the signal threshold in quiet indicated considerable variability. Thus, it seems likely that the 5-dB signal fell below AR's threshold in quiet at times. For this reason, only data for signal levels at 10 dB SL and above are plotted for AR.

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