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Use of Psychometric-function Slopes for Forward-masked Tones to Investigate Cochlear Nonlinearity

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Use of psychometric-function slopes for forward-masked tones to investigate cochlear nonlinearity[a)]

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Schairer *et al.* [(2003). "Effects of peripheral nonlinearity on psychometric functions for forward-masked tones," J. Acoust. Soc. Am. **133**, 1560–1573] demonstrated that cochlear nonlinearity is reflected in psychometric-function (PF) slopes for 4 kHz forward-masked tones. The goals of the current study were to use PF slopes to compare the degree of compression between signal frequencies of 0.25 and 4 kHz in listeners with normal hearing (LNH), and between LNH and listeners with cochlear hearing loss (LHL). Forward-masked thresholds were estimated in LNH and LHL using on- and off-frequency maskers and 0.25 and 4 kHz signals in three experiments. PFs were reconstructed from adaptive-procedure data for each subject in each condition. Trends in PF slopes across conditions suggest comparable compression at 0.25 and 4 kHz, and potentially a wider bandwidth of compression in relative frequency at 0.25 kHz. This is consistent with other recent behavioral studies that revise earlier estimates of less compression at lower frequencies. The preliminary results in LHL demonstrate that PF slopes are abnormally steep at frequencies with HL, but are similar to those for LNH at frequencies with NH. Overall, the results are consistent with the notion that PF slopes reflect degree of cochlear nonlinearity and can be used as an additional measure of compression across frequency. © *2008 Acoustical Society of America.*
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I. INTRODUCTION

The overall goal of the current set of experiments was to expand the results of Schairer *et al.* (2003b), which demonstrated that cochlear nonlinearity is reflected in slopes of psychometric functions (PFs) for forward-masked, 4 kHz tones. PF slopes are used here to investigate cochlear nonlinearity at 0.25 kHz in comparison to 4 kHz in listeners with normal hearing (LNH) and in listeners with cochlear hearing loss (LHL). Sections I A–I D describe how cochlear nonlinearity is reflected in forward masking, how cochlear nonlinearity is reflected in PF slopes, and how PF slopes can be used to investigate compression at low frequencies and in ears with HL.

A. Forward masking and cochlear nonlinearity

Forward masking refers to the condition in which the threshold for a short-duration signal is elevated in the presence of a preceding masker. Forward-masked thresholds have been used to estimate frequency selectivity (see, e.g., Nelson and Freyman, 1984) as well as auditory time constants or temporal resolution (see, e.g., Nelson and Pavlov, 1989; Nelson and Freyman, 1987; and Jesteadt *et al.*, 1982). Many recent studies have used forward masking to assess the amount of cochlear compression or nonlinear basilar-membrane (BM) response growth (see, e.g., Lopez-Poveda *et al.*, 2003; Nelson *et al.*, 2001; Nelson and Schroder, 2004; Oxenham and Plack, 1997; Plack and Oxenham, 1998; Rosengard *et al.*, 2005; Schairer *et al.*, 2003b; and Williams and Bacon, 2005).

Forward masking is thought to reflect either temporal integration or adaptation, or some combination of both processes (Chatterjee, 1999; Oxenham, 2001; Plack and Oxenham, 1998). Temporal integration is conceptualized as an overlap of the internal representations of the signal and the masker that occurs centrally; it can also be thought of as "persistence" of neural activity after the masker offset. Adaptation is the reduction of activity or response to a signal after presentation of a masker. It may occur at different places in the auditory periphery, such as the synapse between the inner hair cells (IHCs) and the eighth nerve, and the involvement of neural adaptation is supported by a recent computer modeling study (Meddis and O'Mard, 2005). Peripheral adaptation cannot entirely account for the observed threshold shift, however, because forward masking can be obtained in individuals with cochlear implants in whom stimulation bypasses the cochlea and IHC-eighth nerve synapse (Chatterjee *et al.*, 2006; Chatterjee, 1999; Shannon, 1990). Thus, forward masking is due not only to peripheral adaptation, but is almost certainly influenced by a retrocochlear process.

[a)] Portions of this work were presented in Schairer, K. S., Messersmith, J., and Jesteadt, W. (2005). "Psychometric-function slopes for forward-masked tones in listeners with cochlear hearing loss," J. Acoust. Soc. Am. **117**, 2599 (Abstract) and Schairer, K. S, and Jesteadt, W. (2003). Evidence of peripheral nonlinearity in psychometric function slopes of forward-masked tones at 250 and 4000 Hz," J. Acoust. Soc. Am. **113**, 2226 (Abstract).

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For sinusoidal forward maskers and signals, the amount of forward masking is greater when the masker and signal are at the same frequency (on frequency) than when the masker is at a different typically lower frequency (off frequency). Slopes of growth of masking (GOM), or the change in signal level at threshold for a given change in masker level, can be obtained in conditions in which the signal level is varied to estimate threshold in different fixed masker-level conditions [variable signal (VS)] or conditions in which the masker level is varied in different fixed signal level conditions [variable masker (VM)]. In VS conditions, slopes of GOM are less than 1 dB/dB in on-frequency conditions and are similar at low and high frequencies in LNH (see, e.g., Jesteadt *et al.*, 1982). Signal level at threshold increases at a faster rate for off-frequency than for on-frequency conditions at moderate masker levels (see, e.g., Luscher and Zwislocki, 1949 and Plack and Drga, 2003). Comparable effects can be observed by fixing the signal at a low level in a VM paradigm with different signal delays in different conditions using on- and off-frequency maskers (Nelson and Schroder, 2004; Nelson *et al.*, 2001). The resulting temporal masking curves (TMCs) show the effects of both signal delay and masker frequency. GOM functions obtained with VS procedures are used in the current set of experiments.

BM response growth is nonlinear at characteristic frequency (CF) (see, e.g., Ruggero *et al.*, 1997 and Yates *et al.*, 1990). That is, if a tone with a frequency equal to CF is presented, the amount of BM deflection as a function of stimulus level is linear at low levels and gradually becomes compressive as stimulus level increases. If the recording is made from the same place on the BM, but a lower or higher frequency is presented, the response growth becomes more linear. Response growth also becomes more linear in ears with HL, presumably due to the loss of outer hair cell (OHC) function.

Although forward masking almost certainly has a retrocochlear contribution, it is thought that cochlear nonlinearity is reflected in slopes of GOM and TMC in on-frequency and off-frequency masker conditions. In a VS paradigm in LNH, the shallow GOM in the moderate masker-level range in on-frequency masker conditions is thought to be due to compression of the on-frequency masker (Plack and Oxenham, 1998). In a VM paradigm, the off-frequency masker condition has been used as a linear reference in a ratio of slopes of GOM for on- and off-frequency masker conditions to estimate the degree of compression in LNH and reduced compression in LHL (Oxenham and Plack, 1997). On-frequency TMCs are steeper and off-frequency TMCs are shallower in LNH, whereas the differences in TMC slopes decrease and functions become more parallel across masker frequencies in LHL (Nelson *et al.*, 2001; Plack *et al.*, 2004; Rosengard *et al.*, 2005).

A three-stage model described by Plack and Oxenham (1998) can be used to predict the pattern of thresholds in a VS paradigm at various signal delays and masker levels. The model has a compressive nonlinearity as its first stage, followed by a sliding temporal integration window, and a decision process that compares the level at the output of the window to determine which interval contained the signal.

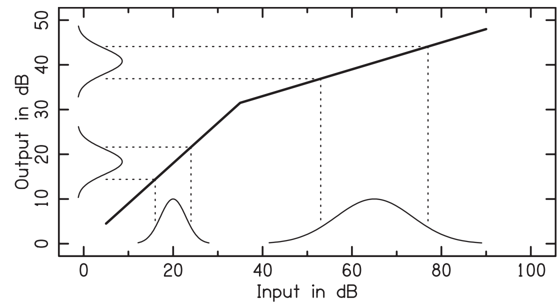

FIG. 1. Relationship between compressive nonlinearity and psychometric-function (PF) slope (from Schairer *et al.*, 2003b). In a forward-masking condition that produces a low signal level at threshold, the signal will pass through the more linear portion of the nonlinearity during threshold estimation. Changes in signal level at the input and output of the function will be similar, the standard deviation of the underlying distributions will be small, and the corresponding PF slope will be steep. In conditions that produce higher masked thresholds, the signal will pass through the more compressive region of the function. The signal level will have to change by a greater amount to produce the same change in signal level at the output of the nonlinearity, the underlying standard deviation will be larger, and the PF slopes will be shallower.

The model uses a two-line approximation to the function representing compression, with linear growth of response at the signal frequency for low-level on-frequency maskers and constant compression above some breakpoint. The amount of compression can be determined by fitting a two-line function to the data.

There is a consensus in literature that the difference in on- and off-frequency GOM or TMC functions can be used to estimate compression at signal frequencies of 1 kHz or higher, although Wojtczak and Oxenham (2007) recently have questioned the necessary assumption that the rate of recovery is the same for on- and off-frequency forward maskers. The literature on compression at lower frequencies, reviewed here in a later section, suggests that the comparison of on- and off-frequency masking may be problematic because the assumption of linearity in the off-frequency reference condition may not be valid. Estimates of compression based on PF slopes for forward-masked tones do not require comparison of results obtained in on- and off-frequency conditions.

B. Cochlear nonlinearity reflected in PF slopes

PFs showing percent correct (PC) as a function of the level of the variable stimulus take different forms and have different meanings in VS and VM paradigms. In the VS paradigm, PC increases as the signal level increases. In a VM paradigm, PC decreases as the masker level increases, but the data can be fitted using the same equations and procedures. Schairer *et al.* (2003b) demonstrated that PFs obtained in a VS paradigm in LNH, with either on- or off-frequency forward maskers, have shallower slopes under conditions that result in large amounts of forward masking and interpreted the change in slope as a measure of compression. The rationale for this argument is shown in Fig. 1 (from Schairer *et al.*, 2003b). In a VS paradigm, conditions that produce low signal levels at masked threshold will result in the signal passing through the more linear portion of the peripheral nonlinearity as the signal level varies during the threshold estimation procedure. PF slopes would be steep in this case because a small range of signal levels would be necessary to establish threshold. In conditions that produce higher signal levels at masked threshold, the signal will pass through the more compressive region of the function and will have to change by a greater amount to produce the same change at the output of the nonlinearity. In this case, the PF slope would be shallower. The nonlinearity is depicted in Fig. 1 as a two-line approximation, as represented in the Plack and Oxenham (1998) model. It is assumed that the true underlying nonlinearity has a more gradual transition into the compressive region (see, e.g., Neely and Jesteadt, 2005). The decrease in PF slope as a function of signal level at threshold should be the same for the on-frequency and off-frequency masker conditions in a VS paradigm, because for any given PF, signal level is the only varying parameter. The signal is "on frequency" by definition and will be affected by the nonlinearity at its place regardless of the masker frequency.

In a VM paradigm, however, PF slopes for on- and off-frequency conditions should be different because in this case, the varied parameter is the masker level, and the masker response growth will be different at the place of the signal depending on the relation between the masker and the signal frequency. In on-frequency conditions, results should be similar to the VS case because the masker will be compressed just as the signal is compressed. In off-frequency masker conditions, however, the masker response growth will be linear at the place of the signal and PF slopes should be steep and parallel, regardless of the masker level at the threshold. Schairer *et al.* (2003b) provided evidence to support these predictions in LNH using a 4 kHz signal and on- and off-frequency maskers.

C. Use of PF slopes to investigate compression at low frequencies

Behavioral studies have demonstrated a significant amount of compression at signal frequencies of 1 kHz and above (see, e.g., Nelson *et al.*, 2001 and Oxenham and Plack, 1997), but earlier studies showed less compression at lower frequencies (see, e.g., Hicks and Bacon, 1999 and Plack and Oxenham, 2000). These studies relied on the assumption that response growth at the place of the signal is linear for off-frequency maskers. Several authors [Lopez-Poveda *et al.* (2003), Plack and Drga (2003), Plack *et al.* (2004), and Plack and O'Hanlon (2003)] have pointed out that if compression affects a wider range of frequencies relative to CF (Rhode and Cooper, 1996), then response growth of on-frequency and off-frequency maskers at the place of the signal would be similar and would confound methods that rely on the linearity of the off-frequency response. TMC and GOM methods that do not rely on the assumption of linear growth at the signal place for off-frequency maskers, or that use off-frequency growth at higher frequencies as a linear reference, have demonstrated low-frequency compression that is greater than in previous studies and is comparable to compression estimates for higher-frequency signals (see, e.g., Lopez-Poveda and Alves-Pinto, 2008; Lopez-Poveda *et al.*, 2003; Plack and Drga, 2003; and Williams and Bacon, 2005). A recent report (Stainsby and Moore, 2006) suggests, however, that decay of forward masking is not independent of signal frequency and that it may not be appropriate to use a high-frequency reference to estimate compression at low frequencies. Additivity of masking (Plack and O'Hanlon, 2003; Plack *et al.*, 2005) methods do not depend on an off-frequency masker condition or on uniform decay of forward masking across frequency and can be used to directly compare compression at low and high frequencies. In addition, Lopez-Poveda and Alves-Pinto (2008) described a method of using TMCs to estimate compression that does not require the assumption of uniform decay of forward masking across frequencies. In their new method, the comparison is made between TMC slopes obtained at two different probe levels within masker-frequency conditions. PF slopes are another measure of cochlear compression that requires no assumptions regarding the decay of forward masking or the degree of off-frequency compression and could provide an independent measure of the frequency range of compression at low frequencies.

D. Use of PF slopes to investigate compression in ears with hearing loss

There are few studies that address PFs for detection of tones in quiet in LHL. Marshall and Jesteadt (1986) obtained PFs for LHL and LNH for 0.5 and 4 kHz tones. PFs were estimated by straight-line least-squares fits weighted by number of trials for d' as a function of level. They reported no differences in PF slopes between the two groups. In contrast, Arehart *et al.* (1990) estimated PF slopes using linear regression and probit analysis for 0.5, 2, 4, and 8 kHz tones in quiet in groups of LHL and LNH. The slopes of the two groups overlapped, but the LHL had significantly steeper slopes in the 2 kHz condition and some LHL had abnormally high slopes across frequencies.

Thresholds for forward-masked tones under a number of different conditions have been reported for LHL due to OHC dysfunction. However, PFs for those conditions have not been reported. Following the logic described for LNH (Fig. 1), it is predicted that PF slopes for forward-masked tones in a VS condition should be steeper for LHL than for LNH. This is because LHL presumably lack the nonlinearity that is hypothesized to be responsible for the decrease in PF slope with masked threshold in the LNH. The function in Fig. 1 would be a straight line with a slope near 1.0, rather than a two-part function with a compressive region. Thus, any changes in the external signal across the range would be represented by the same amount of change internally, similar to conditions that would produce thresholds in the lower-level (linear) portion of the function for LNH. PFs should remain steep and parallel across the masker frequency and the threshold level.

II. EXPERIMENT 1: PSYCHOMETRIC FUNCTIONS FOR FORWARD-MASKED, LOW- AND HIGH-FREQUENCY TONES IN A VARIABLE-SIGNAL PARADIGM IN LISTENERS WITH NORMAL HEARING

The purpose of experiment 1 was to use PF slopes to test the hypothesis that compression is comparable at low- and high-signal frequencies. Note that the purpose is to compare relative compression between frequencies and not to estimate specific parameter or compression values. This method has the benefit that it does not rely on a comparison of off- and on-frequency conditions. Because both types of maskers should have a similar effect on the PF slope, based on the argument in the Introduction and in Schairer *et al.* (2003b), only on-frequency conditions were included. Forward masking was measured in on-frequency VS conditions at both 0.25 and 4 kHz in a group of LNH. It was predicted that PF slopes would decrease similarly as a function of signal threshold in both the 0.25 and 4 kHz conditions, suggesting comparable cochlear compression at these frequencies.

A. Subjects

Five paid adults, two males and three females, ages 19–32 years (mean=25.2, standard deviation [SD]=6.3) served as subjects. Three were college students, one was the first author, and one was a research associate from another laboratory. Hearing for the three college students had been screened at 0.5, 1, 2, and 4 kHz within the past year using the same two-interval forced-choice (2IFC) adaptive procedure used in the experiment. Thresholds were at or better than 15 dB sound pressure level (SPL) for all test frequencies, bilaterally, for each subject. Hearing for the other two subjects had been tested, using clinical procedures, as part of a research protocol for another laboratory. Hearing thresholds were at or better than 15 dB hearing level (dBHL), bilaterally, at the same frequencies for both subjects.

B. Stimuli and apparatus

Signals and maskers were all pure tones. Signal frequencies were 0.25 or 4 kHz, signal duration was 10 ms (5 ms rise/fall), and signal delay was 10 ms (from offset of masker to onset of signal). A 10 ms delay was selected in order to provide a sufficient amount of masking (in comparison to decreased masking at longer delays) and to avoid abnormally steep PFs observed in some listeners in very short (e.g., 0 ms) signal delay conditions (as observed in Schairer *et al.*, 2003b). The on-frequency forward masker duration was 200 ms (2 ms rise/fall) and the maskers were presented at levels of 30, 50, 70, and 90 dB SPL in separate conditions. All stimuli were generated with ramps that were shaped using a half-cycle of a raised-cosine function. Thresholds for each signal in quiet also were obtained.

Stimuli were generated digitally at a sampling rate of 50 kHz using a Tucker-Davis Technologies (TDT) array processor (TDT AP2) and 16 bit digital-to-analog converters (TDT DD1). The forward masker was generated on one channel of the DD1, while the signal was generated on the other. The output of each channel was low-pass filtered at 20 kHz (TDT FT6) and attenuated (TDT PA4), then the outputs of the two channels were combined (TDT SM3) and presented monaurally to the left ear through a headphone buffer (TDT HB6), a remote passive attenuator in the sound treated room, and a Sennheiser HD 250 Linear II headphone. Parallel use of multiple attenuators, summers, and headphone buffers made it possible to simultaneously test up to four listeners. Subjects 078 and 175 were tested individually. Subjects 100, 102, and 108 were tested as a group.

C. Adaptive-procedure thresholds

Thresholds were obtained in a VS paradigm using a two-track 2IFC adaptive procedure with decision rules to estimate 71 PC (two-down, one-up) on one track and 87 PC (five-down, one-up) on the other track (Levitt, 1971), with a 4 dB step size. Two tracks with different decision rules were used to obtain a larger range of PCs for the PF fits. Threshold for each track was calculated as the mean of the reversal levels after the fourth reversal. Five 200-trial repetitions were obtained in each condition. The first repetition was excluded as practice. A total of 800 trials, or 400 trials per track, were available for further analysis. There were two exceptions. Four repetitions were obtained in the 0.25 kHz quiet-threshold condition for subject 102. After excluding the first repetition as practice, a total of 600 trials remained for this subject in this condition. For subject 175, one repetition in the 4 kHz, 90 dB masker condition yielded only one reversal after the fourth with which to calculate the threshold. This repetition was discarded and an extra repetition was obtained. Mean thresholds were calculated across repetitions for each track, and then the mean across the two tracks was calculated as the adaptive-procedure threshold for each subject in each condition. This threshold was an estimate of the level required for 79 PC.

D. Psychometric-function fits

All trials from both tracks were combined to fit PFs. The combined data were trimmed such that signal levels that were presented on <30 trials across both tracks and/or associated with <50 PCs were excluded. As the signal level increased, subsequent signal levels were deleted after the first occurrence of 100 PC. The purpose was to remove multiple levels with associated PCs of 100 that would skew the fits to be shallower than they probably were, and to avoid nonmonotonic functions. PFs were fitted for each condition using Dai's (1995) modification of the equation proposed by Egan *et al.* (1969), in which $d'=(I/a)^b$, where I is signal power, 10 $\log(a)$ is the signal level required for $d'=1$, and b is the slope of a line in $\log d'$ versus signal level. Dai's (1995) fitting procedure minimizes the deviation between expected and obtained proportion correct, expressed in units of χ^2. To provide a more familiar measure of goodness of fit in terms of variance accounted for, an r^2 was calculated for each PF. For a total of 50 PF fits, including the quiet-threshold conditions, the r^2 values ranged from 0.79 to 1.00 (mean=0.95). Note that the fitting procedure yields a measure of the threshold, 10 $\log(a)$, that is computed very differently than the adaptive threshold described above. The correlation between the two threshold types across frequency, masker level, and subject (not including quiet thresholds, but including all masked thresholds regardless of associated slopes) was 0.998.

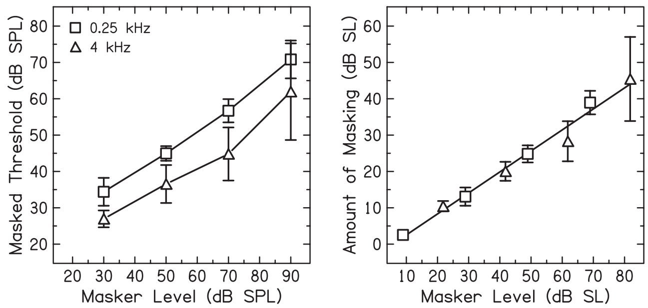

FIG. 2. Mean masked adaptive threshold in dB SPL across listeners with normal hearing (LNH) as a function of masker dB SPL (left panel) and mean amount of masking (i.e., signal dB SL) as a function of masker dB SL (right panel) for 0.25 kHz (squares) and 4 kHz (triangles) signal conditions in experiment 1. The mean masker thresholds in quiet for the LNH in experiment 2 were used to estimate masker dB SL in experiment 1. The error bars represent +/−1 standard deviation. The on-frequency forward masker duration was 200 ms, and maskers were presented at 30, 50, 70, and 90 dB SPL in separate conditions. Signal duration was 10 ms and signal delay was 10 ms, presented in a variable signal (VS) paradigm. The amount of masking increases as a function of masker level at a similar rate for both frequencies. The line in the right panel is fitted with all data points (across frequency) and has a slope of 0.58 dB/dB.

E. Results and discussion

1. Adaptive-procedure thresholds

Jesteadt *et al.* (1982) noted that forward masking appears more uniform across frequency conditions when thresholds are plotted in units of sensation level (SL). Figure 2 shows mean masked threshold across subjects as a function of masker dB SPL in the left panel and mean amount of masking as a function of dB SL in the right panel. Amount of masking was calculated for each subject in each condition by subtracting the signal threshold in quiet from the masked thresholds. Thresholds for the masker in quiet were not obtained for this group and some members of the group were not available to return to run those conditions. The mean masker thresholds in quiet for the LNH in experiment 2 were therefore used to estimate masker levels in dB SL in experiment 1.Threshold increases as a function of masker level at a similar rate for both frequencies, but appears to be consistently greater in the 0.25 kHz condition when expressed in terms of masker dB SPL (left panel). However, when corrected by masker threshold in quiet, the amount of masking is similar across signal-frequency conditions (right panel) and is well described by a single line with a slope of 0.58 dB/dB.

2. Psychometric-function fits

Figure 3 shows fits to the individual data points for the 30 dB (low threshold) and 90 dB (high threshold) masker conditions for both signal frequencies for each subject. There does not appear to be a difference in the goodness of fit to the data points as a function of frequency or masker level. Thus, the trend of shallower slopes as a function of signal level cannot be accounted for by poorer PF fits at higher levels. Table I provides a summary of the PF parameters and r^2 values for each subject in each condition. Figure 4 shows PF slope as a function of PF threshold in dB SL for each subject and for the geometric mean across subjects (geometric mean slope as a function of arithmetic mean PF threshold). One data point from the 4 kHz, 30 dB masker condition is missing from the panel for subject 175 because the slope is excessive (5.6). Despite the variability across subjects, on average PF slope decreases as a function of threshold at a similar rate for both frequencies. The pattern of slope change

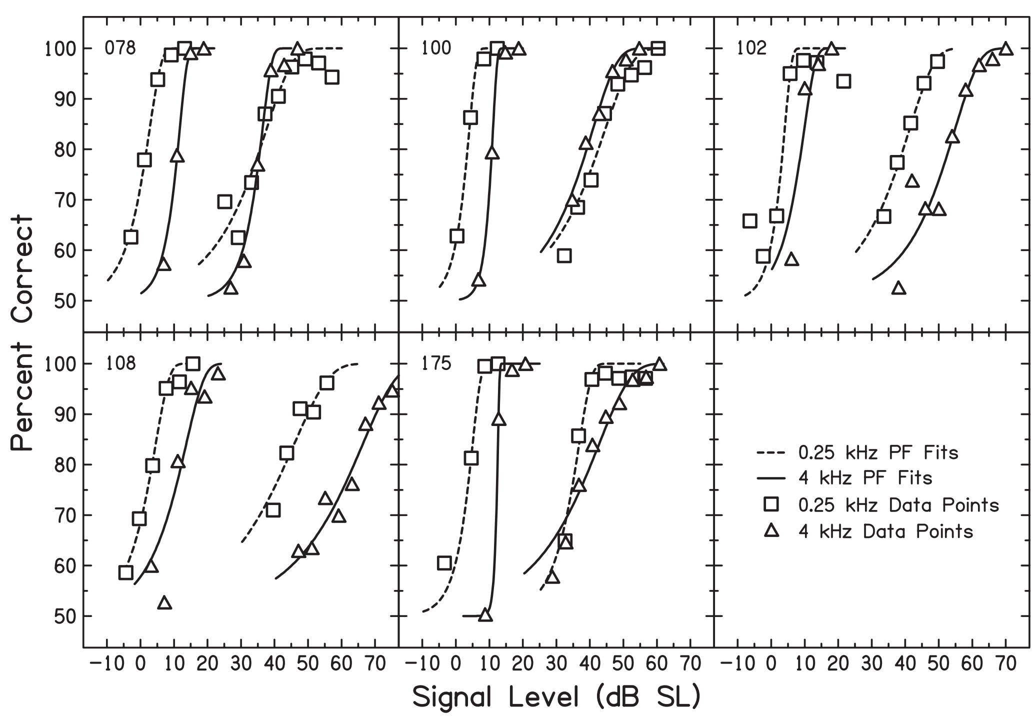

FIG. 3. Psychometric-function (PF) fits to the data points in the lowest (30 dB SPL) and highest (90 dB SPL) masker-level conditions for each subject in experiment 1. Data points are represented as in Fig. 2. The dashed and solid lines represent PFs in the 0.25 and 4 kHz signal conditions, respectively. PF threshold, slope, and goodness of fit (r^2) parameters for all subjects and conditions (including those not shown here) are listed in Table I.

TABLE I. Experiment 1 psychometric function (PF) parameters for listeners with normal hearing (LNH) in variable signal (VS), on-frequency forward-masking conditions [QT=quiet threshold; SD =standard deviation].

Signal frequency	Masker level	Parameter	078	100	102	108	175	Mean(SD)
0.25 kHz	QT	Threshold	30.84	27.64	38.37	32.36	31.39	32.12 (3.92)
		Slope	1.79	0.99	0.74	0.63	2.04	1.11
		r^2	0.99	0.98	0.88	0.92	0.95	
	30	Threshold	31.72	30.55	41.29	34.74	35.07	34.67 (4.17)
		Slope	0.80	1.31	1.34	0.69	1.13	1.02
		r^2	0.99	0.99	0.87	0.99	0.96	
	50	Threshold	43.14	45.33	48.51	44.34	45.09	45.28 (2.0)
		Slope	0.72	0.57	1.10	0.37	1.25	0.73
		r^2	0.98	0.98	0.97	0.94	1.0	
	70	Threshold	53.20	56.42	59.29	57.74	55.14	56.36 (2.34)
		Slope	0.48	0.47	0.50	0.28	0.73	0.47
		r^2	0.96	0.89	0.93	0.82	0.92	
	90	Threshold	64.40	68.00	75.77	72.74	66.24	69.43 (4.71)
		Slope	0.37	0.35	0.38	0.27	0.76	0.40
		r^2	0.93	0.96	0.98	0.89	0.98	
4 kHz	QT	Threshold	17.15	13.28	22.01	16.91	15.27	16.93 (3.24)
		Slope	1.05	1.93	1.16	2.42	1.36	1.58
		r^2	0.98	1.00	0.98	0.99	1.00	
	30	Threshold	27.68	23.71	30.10	27.67	27.57	27.35 (2.30)
		Slope	1.24	2.23	0.83	0.52	5.57	1.46
		r^2	0.99	0.99	0.85	0.84	1.00	
	50	Threshold	36.16	30.66	43.39	37.32	33.04	36.11 (4.84)
		Slope	1.11	0.73	0.78	0.30	0.91	0.71
		r^2	0.99	0.92	0.97	0.86	0.95	
	70	Threshold	40.94	38.86	51.49	50.56	39.08	44.18
		Slope	1.07	0.52	0.53	0.20	0.83	0.55
		r^2	0.99	0.96	0.93	0.79	0.95	
	90	Threshold	52.09	50.42	73.14	77.92	53.04	61.32 (13.11)
		Slope	1.00	0.39	0.40	0.28	0.30	0.42
		r^2	0.99	0.98	0.90	0.95	0.95	

with level is related to the form of the compressive nonlinearity. The function fitted to the mean data in Fig. 4 is the reciprocal of a quadratic compression function, as described by Neely and Jesteadt (2005).

In summary, thresholds in on-frequency VS conditions increased as a function of masker level and PF slopes decreased as a function of signal threshold similarly for both the 0.25 and 4 kHz signals. Results suggest comparable cochlear on-frequency compression at these two frequencies.

III. EXPERIMENT 2: PSYCHOMETRIC FUNCTIONS FOR FORWARD-MASKED, LOW- AND HIGH-FREQUENCY TONES IN A VARIABLE-MASKER PARADIGM IN LISTENERS WITH NORMAL HEARING

The purpose of experiment 2 was to test the hypothesis that the bandwidth of compression at 0.25 Hz is wider than at 4 kHz. VS conditions do not provide information about the range of frequencies that are compressed at each CF because on- and off-frequency conditions produce similar PF slopes. However, for any given PF in a VM condition, the varied parameter is the masker level, which will grow compressively at the place of the signal in the on-frequency condition, and linearly or less compressively at the place of the signal for the off-frequency condition. If the bandwidth of compression at 0.25 kHz is wider than at 4 kHz signal, then PF slopes might decrease as a function of threshold in both on-frequency and off-frequency conditions, because the off-frequency masker may grow compressively at the place of the signal, just as the on-frequency masker does. Thus, the prediction is that in the 4 kHz signal condition, PF slopes will decrease as a function of masker threshold for the on-frequency conditions and will remain steep for off-frequency conditions; in the 0.25 kHz signal condition, PF slopes will decrease as a function of threshold similarly in on- and off-frequency conditions.

A. Subjects

Four paid adults, one male and three females, ages 19–23 years (mean=20.5, SD=1.7) served as subjects. Three were college students; and one was the second author, who was a graduate research assistant in the laboratory. Subjects had hearing thresholds less than 20 dB SPL at 0.5, 1, 2, and 4 kHz, bilaterally.

B. Stimuli and apparatus

The stimuli were delivered through the same equipment as experiment 1. Signal frequencies were 0.25 or 4 kHz, signal duration was 10 ms (5 ms rise/fall), and signal delay was 5 or 10 ms. Forward masker duration was 200 ms (5 ms

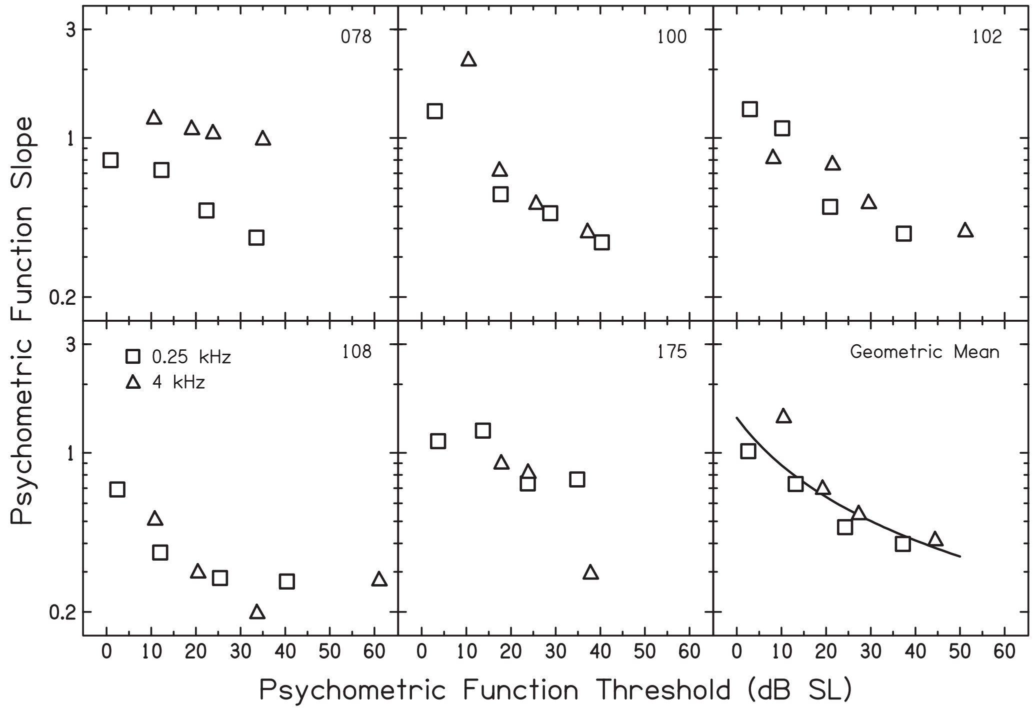

FIG. 4. Psychometric-function (PF) slope as a function of PF threshold in dB SL for each subject and the geometric mean across subjects for experiment 1. Frequencies are represented as in Fig. 2. On average, although there is variability across subjects, PF slope decreases as a function of masked threshold for both frequencies at approximately the same rate. The function fitted to the geometric mean data is the reciprocal of the quadratic compression function described by Neely and Jesteadt (2005).

rise/fall) and masker frequencies were 0.15 and 2.4 kHz in the off-frequency conditions. The off-frequency maskers were selected such that the ratios between the masker and the signal frequencies were identical for 0.25 and 4 kHz signals. Fixed signal levels were selected to produce masker levels at threshold that were in the moderate (i.e., compressive) range. Signal levels were restricted to a range in which masker levels did not consistently exceed 90 dB SPL during the adaptive procedure for any subject. Different delays were used in an attempt to produce masker levels at threshold that covered overlapping ranges for the on- and off-frequency conditions. For the 0.25 kHz signal condition, signal levels in the off-frequency conditions were fixed at 45, 50, and 55 dB SPL; signal levels in the on-frequency conditions were fixed at 50, 55, and 57 dB SPL. All signal delays were 10 ms except for the 50 dB on-frequency condition in which signal delay was 5 ms. Signal levels in the off-frequency, 4 kHz signal condition were fixed at 30, 40, and 50 dB SPL; in the on-frequency condition, signal levels were fixed at 30, 40, and 45 dB SPL. All signal delays were 5 ms, except for the 50 dB off-frequency condition in which signal delay was 10 ms. Thresholds also were obtained for each signal and masker in quiet.

C. Adaptive-procedure thresholds

Thresholds were obtained in a VM paradigm using the same two-track procedure used in experiment 1 with the exception that the step size was initially 4 dB until after the fourth reversal, and then step size was 2 dB. Six to eight 200-trial repetitions were obtained in each condition. The last six repetitions were included in the analyses. There were 1200 trials, or 600 trials per track, available for further analysis. Mean adaptive thresholds were calculated as described in experiment 1.

D. Psychometric-function fits

All trials from both tracks were combined to fit PFs. PF threshold and slope were estimated as in experiment 1. Because VM PFs are "backwards" from VS PFs, the software routine and the rules used to fit PFs could not handle the data as extracted from the original data files. To obtain slopes following the VS procedure as closely as possible, masker levels were transformed by subtracting each from 100 before the PFs were fitted. There was a total of 72 PF fits, including the quiet-threshold conditions. The correlation between the masked adaptive and PF thresholds (excluding quiet-threshold conditions) across signal frequency, signal level, masker frequency, and subject was 0.988.

E. Results and discussion

1. Adaptive-procedure thresholds

Figure 5 shows mean threshold as a function of signal dB SPL in the left panel and as a function of dB SL (with regard to mean signal threshold in quiet) in the right panel. Thresholds increase as a function of signal level, and the level of the masker at threshold is higher in the off-frequency masker condition than in the on-frequency masker condition for both signal frequencies. For the 4 kHz signal condition, the rate of growth, estimated using slopes of linear regression line fits, is shallower for the off-frequency masker (0.78 dB/dB) than for the on-frequency masker (1.81 dB/dB). This

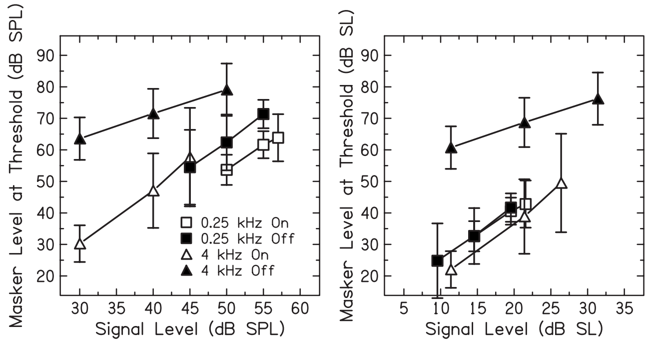

FIG. 5. Mean masker level at threshold across listeners with normal hearing (LNH) as a function of signal dB SPL (left panel) and dB SL (with regard to mean signal threshold in quiet, right panel) for 0.25 and 4 kHz signal (squares and triangles, respectively), on- and off-frequency masker conditions (open and filled, respectively) in experiment 2. The error bars represent +/−1 standard deviation. The forward masker duration was 200 ms and the masker levels were varied to estimate the level required to just mask the fixed signal. Signal duration was 10 ms and the signal delay was 5 or 10 ms. The rate of growth is shallower for the off-frequency than for the on-frequency case for the 4 kHz signal condition. Growth for the on- and off-frequency, 0.25 kHz signal conditions was similar to each other and to the on-frequency, 4 kHz signal condition.

difference in the slope of growth of maskability (Nelson *et al.*, 2001), which is another term for GOM functions obtained using a VM paradigm, can be used to estimate cochlear compression. If the off-frequency condition is assumed to be a linear reference, the slope ratio indicates on-frequency compression by a factor of 2.32. For the 0.25 kHz condition, however, the slopes of the off-frequency (1.69) and on-frequency (1.48) functions are similar. At first glance, this might suggest that there is little compression at 0.25 kHz, but both functions are similar to the on-frequency function at 4 kHz rather than to the off-frequency function. This is particularly clear in the right-hand panel. This suggests that the off-frequency function at 0.25 kHz cannot be used as a linear reference and that both functions reflect the effects of compression that is similar to the amount of compression observed at 4 kHz.

2. Psychometric-function fits

The interpretation of the thresholds obtained in on- and off-frequency conditions at 0.25 kHz is supported by the PFs. Figure 6 shows fits to the individual data points for the lowest and highest signal level conditions. The data appear to be more nonmonotonic in this experiment than in experiment 1, probably because the smaller step size (2 dB in this experiment and 4 dB in experiment 1) resulted in fewer trials per point. In general, the fits appear to be acceptable, with the exception of subject 231. It is unclear why this subject had a difficult time with this paradigm, considering all these subjects participated in VS conditions in experiment 3, where subject 231's fits appear to be more orderly (see Fig. 12). As in all regression analyses, poor fits result in shallower slopes. Table II provides a summary of the PF parameters and r^2 values for each subject in each condition.

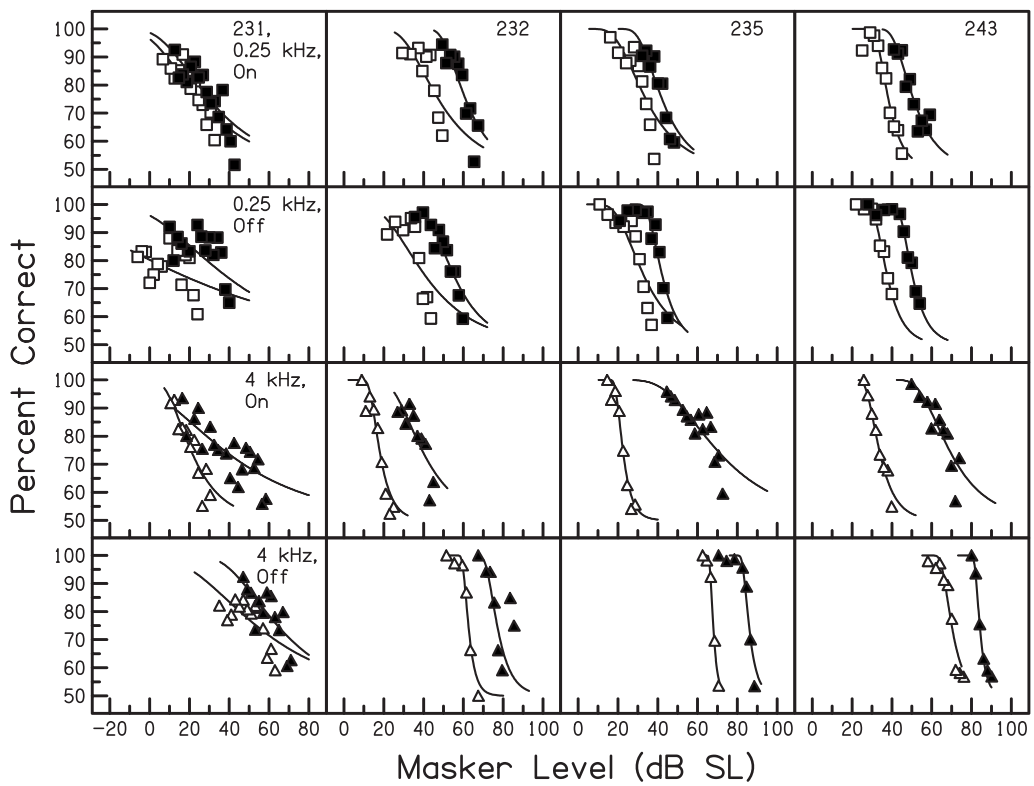

FIG. 6. Psychometric-function (PF) fits to the individual data points for the lowest (open) and highest (filled) signal level conditions, for on-frequency and off-frequency maskers, in 0.25 and 4 kHz variable masker (VM) conditions, for listeners with normal hearing (LNH) in experiment 2. The associated PF parameters (slope and threshold) and goodness of fit (r^2) are shown in Table II for each subject in each condition. Subject 231 stands out as having widely varying data and poor fits in comparison to the other subjects. This is not the case in the variable signal (VS) conditions of experiment 3, for which 231's data are more orderly (see Fig. 12).

TABLE II. Experiment 2 psychometric function (PF) parameters for listeners with normal hearing (LNH) in variable masker (VM), on- and off-frequency forward-masking conditions [QT=quiet threshold; SD =standard deviation].

Signal frequency	Masker frequency	Signal level	Parameter	231	232	235	243	Mean (SD)
0.25 kHz	None	QT	Threshold	38.455	22.228	36.208	34.228	32.78(7.24)
			Slope	0.433	0.132	0.283	1.124	0.37
			r^2	0.804	0.523	0.775	0.969	
None	0.15 kHz	QT	Threshold	33.969	18.314	33.143	26.020	27.86(7.30)
			Slope	0.433	0.446	0.166	1.094	0.43
			r^2	0.902	0.833	0.601	0.978	
None	0.25 kHz	QT	Threshold	25.334	10.617	23.834	18.979	19.69(6.63)
			Slope	0.916	0.908	0.286	0.290	0.51
			r^2	0.952	0.824	0.849	0.807	
0.25 kHz	0.25 kHz	50	Threshold	49.050	57.184	57.135	56.926	55.07(4.02)
			Slope	0.171	0.237	0.280	0.701	0.30
			r^2	0.756	0.623	0.724	0.970	
		55	Threshold	57.437	66.579	62.831	65.395	63.06(4.06)
			Slope	0.240	0.237	0.434	0.529	0.34
			r^2	0.595	0.634	0.839	0.940	
		57	Threshold	54.115	71.138	65.431	69.298	65.00(7.63)
			Slope	0.172	0.361	0.365	0.414	0.31
			r^2	0.711	0.778	0.838	0.867	
0.25 kHz	0.15 kHz	45	Threshold	46.564	57.730	65.279	63.241	58.20(8.39)
			Slope	0.064	0.200	0.311	0.647	0.23
			r^2	0.190	0.559	0.802	0.982	
		50	Threshold	58.510	65.224	70.962	70.927	66.41(5.91)
			Slope	0.112	0.213	0.183	0.406	0.21
			r^2	0.524	0.704	0.580	0.916	
		55	Threshold	30.383	72.707	74.951	75.929	73.30(2.80)
			Slope	0.111	0.314	0.597	0.672	0.34
			r^2	0.207	0.872	0.885	0.985	
4 kHz	None	QT	Threshold	17.031	18.076	20.662	16.233	18.00(1.93)
			Slope	1.366	0.389	0.879	1.053	0.84
			r^2	0.973	0.806	0.965	0.989	
None	2.4 kHz	QT	Threshold	7.046	6.594	−0.491	−3.996	2.29(5.43)
			Slope	1.098	0.743	0.515	0.747	0.75
			r^2	0.983	0.928	0.943	0.977	
None	4 kHz	QT	Threshold	3.622	11.118	9.444	4.202	7.10(3.75)
			Slope	0.963	0.306	0.386	1.154	0.60
			r^2	0.921	0.795	0.728	0.993	
4 kHz	4 kHz	30	Threshold	23.725	28.716	31.739	37.526	30.43(5.77)
			Slope	0.335	0.838	1.141	0.643	0.67
			r^2	0.839	0.928	0.972	0.965	
		40	Threshold	32.955	44.780	57.980	59.299	48.75(12.41)
			Slope	0.089	0.378	0.225	0.377	0.23
			r^2	0.620	0.883	0.850	0.954	
		45	Threshold	39.055	49.613	77.917	72.308	59.72(18.43)
			Slope	0.111	0.287	0.161	0.277	0.19
			r^2	0.644	0.706	0.722	0.768	
4 kHz	2.4 kHz	30	Threshold	58.890	68.980	67.294	65.810	65.24(4.43)
			Slope	0.117	1.451	2.364	0.817	0.76
			r^2	0.465	0.974	0.992	0.942	
		40	Threshold	66.719	74.881	77.347	74.687	73.41(4.62)
			Slope	0.165	1.187	2.357	0.648	0.74
			r^2	0.654	0.973	0.986	0.876	
		50	Threshold	70.056	83.310	85.199	80.024	79.65(6.74)
			Slope	0.163	0.743	1.309	1.630	0.71
			r^2	0.572	0.192	0.949	0.985	

Figure 7 shows PF slope as a function of PF threshold for each subject and for the geometric mean across subjects. If the PF slope in a VM paradigm reflects compression of the masker at the signal place, we would expect steep slopes in the off-frequency conditions regardless of the masker level and shallower slopes at high masker levels in the on-

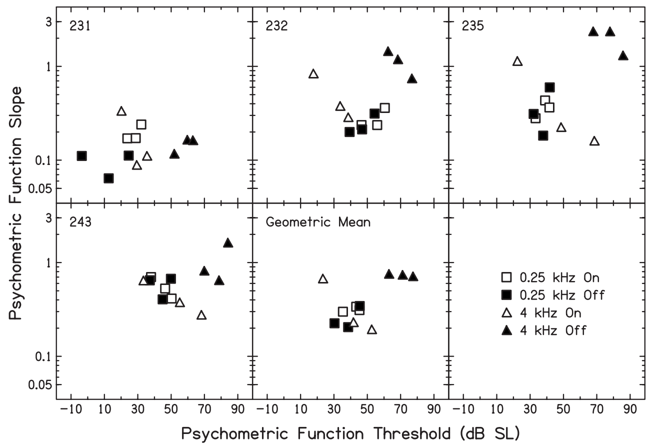

FIG. 7. Psychometric-function (PF) slope as a function of PF threshold for each subject and the geometric mean across subjects in experiment 2. Signal frequencies are represented as in Fig. 5. The trend for shallow slopes in all conditions for 231 is evident in this plot. On average the PF slopes in the off-frequency masker, 4 kHz signal conditions are steeper than the other conditions, including the off-frequency, 0.25 kHz signal conditions. On average, these results are consistent with comparable compression, but a wider bandwidth of compression at 0.25 in comparison to 4 kHz.

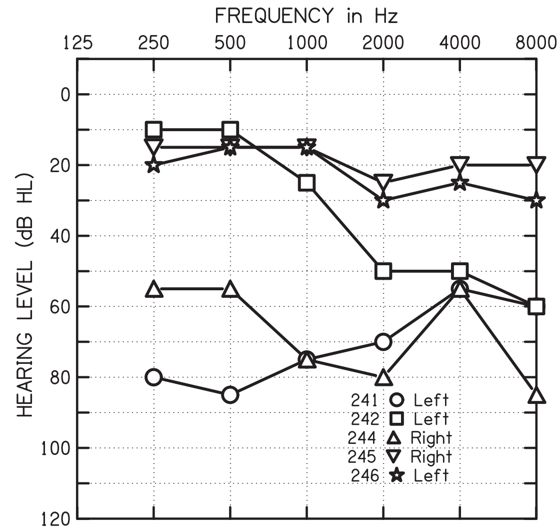

FIG. 8. Audiometric hearing thresholds for listeners with hearing impairment for experiment 3. The better ear is shown in this plot for each subject, and it is also the test ear in the experiment.

frequency conditions. With the exception of subject 231, all of the subjects had steeper PFs in the off-frequency condition at 4 kHz than in the on-frequency conditions, and slopes in the on-frequency condition became shallower as the masker level increased. The pattern is clear in the mean data, where the off-frequency PF slopes for the 4 kHz signal conditions remain constant at a value that is observed for the on-frequency conditions only at the lowest level. For the 0.25 kHz signal conditions, however, PF slopes are shallower for both the off-frequency and on-frequency masker conditions. The overlap of these slopes with those observed in on-frequency masker, 4 kHz signal conditions suggests compression in both the off-frequency and on-frequency conditions at the lower frequency. On average, these results are consistent with comparable compression with a wider bandwidth of compression at 0.25 in comparison to 4 kHz.

IV. EXPERIMENT 3: PSYCHOMETRIC FUNCTIONS FOR FORWARD-MASKED, LOW- AND HIGH-FREQUENCY TONES IN A VARIABLE-SIGNAL PARADIGM IN LISTENERS WITH NORMAL HEARING AND WITH HEARING LOSS

The purpose of experiment 3 was to test the hypothesis that PF slopes reflect reduced compression in LHL in comparison to LNH. As in experiment 1, the purpose is to compare relative compression between frequencies and groups of LNH and LHL, and not to estimate specific parameter or compression values. Off-frequency maskers were included in this experiment to provide a more complete set of data. Although the off-frequency masker, 4 kHz signal condition was used in Schairer *et al.* (2003b), the off-frequency masker, 0.25 kHz signal condition has yet to be reported in this context. In addition, results in LHL using this PF slope method have not been reported for any of the conditions, and thus, it was deemed appropriate to collect data in the full complement of conditions (low- and high-signal frequency conditions and on- and off-masker conditions) for comparison with the LNH. It was predicted that (1) in LNH, PF slopes will decrease as a function of threshold for both on- and off-frequency masker conditions, for both 0.25 and 4 kHz signal conditions, further supporting the hypothesis that there is comparable cochlear compression at these two frequencies, and (2) PF slopes in LHL will be steeper at frequencies with HL than for the LNH, and they will decrease less (or not at all) as a function of threshold.

A. Subjects

The group of LNH included the same subjects as in experiment 2. The group of LHL included four females and one male, ages 24–43 years (mean=31.2, SD=7.5). One other LHL was enrolled in the study but did not complete the data collection. Her data were not included. Audiometric hearing thresholds in the test ear for the group of LHL are shown in Fig. 8. In the experiment, left ears were tested in the group of LNH, and the better ear was tested in the group of LHL (as specified in Fig. 8). All five LHL were tested in the 0.25 and 4 kHz signal conditions, with the exception of subject 241, who was not tested in the 0.25 kHz signal conditions due to the degree of HL at that frequency.

B. Otoacoustic emission stimuli and apparatus

Distortion-product otoacoustic emission (DPOAE) input-output (I/O) functions at f_2=4 kHz were obtained in all test ears in order to demonstrate the presence of cochlear nonlinearity in the LNH and decreased or absent cochlear nonlinearity in the LHL. DPOAEs were not collected at f_2 =0.25 kHz because biological noise obscures the responses at low frequencies. Data were obtained as described in Schairer *et al.* (2003a) using a double-evoked technique (Keefe, 1998). DPOAEs are elicited by presenting two tones or primaries, and recording the emission at the distortion product frequency of $2f_1-f_2$. In the double-evoked technique, the SPL in the ear canal is recorded across three intervals: one primary presented alone ($p1$), the second primary presented alone ($p2$), and both primaries presented together ($p12$). The DPOAE is calculated as $(p1+p2)-p12$. In this manner, the linear distortion of the system is presumably canceled and the residual is the nonlinear emission.

DPOAEs were elicited with an f_2/f_1 of 1.21. L_2 levels for the DPOAE conditions were presented in descending 5 dB steps from 85 dB SPL down to 0 dB SPL. For L_2 levels of 65 dB SPL and above, $L_1=L_2$. At each L_2 below 65 dB SPL, $L_1=0.4L_2+39$ dB SPL, as proposed by Kummer *et al.* (1998). The current data were compared to the 25th and 75th percentile values from 15 left ears with NH from the study of Schairer *et al.* (2003a).

C. Forward masking stimuli and apparatus

The stimuli were delivered through the same equipment as experiments 1 and 2. Signal and masker frequencies were the same as for experiment 2, and a VS instead of a VM paradigm was used. Signal delays were 10 ms, as in experiment 1. Thresholds in quiet were obtained for each signal and masker (thresholds for LNH were presented in Table II as part of the experiment 2 results). In the masked conditions, masker levels were fixed at 50, 70, or 90 dB SPL for both on- and off-frequency conditions for the LNH. An additional set of conditions was added in order to obtain masked thresholds in the group of LNH that were similar to the highest masked thresholds of the listeners with the greatest HL. In this set of conditions, on- and off-frequency maskers were 90 dB SPL, for both signal frequencies, but the signal delay was shortened to 5 ms. Schairer *et al.* (2003b) did not find a significant independent effect of signal delay on PF slopes. Thus combining the 10 and 5 ms delay conditions for the current purposes was deemed appropriate.

For the LHL, in general, masker levels were selected individually based on thresholds in quiet for the maskers. The lowest masker level was selected such that it was estimated to produce at least 5–10 dB of masking (based on a comparison of masked thresholds after one to two practice repetitions with the average quiet threshold of the signal). The highest masker level was selected such that it would not require a signal level to exceed 90 dB SPL during the adaptive procedure. The exceptions were as follows. For listener 244 in two conditions, and listeners 241 and 242 in one condition each, the starting signal level was 94 dB SPL. This is because we attempted to use starting levels that were 14–20 dB above the estimated threshold for all conditions, and levels above 90 dB SPL were required to meet that target in these cases. The goal was to obtain data for three masker levels for each masker-frequency/signal-frequency combination. This was not possible for listeners 244 and 245 due to time and dynamic range constraints. In some cases, the same masker levels were used with the LHL that were used with the LNH. This occurred when a LHL had a normal or near-normal threshold at the signal frequency. Listener 246 was tested at the same masker levels for both signal frequencies as the group of LNH, and listener 242 was tested at the same masker levels as the group of LNH for the 0.25 kHz signal condition.

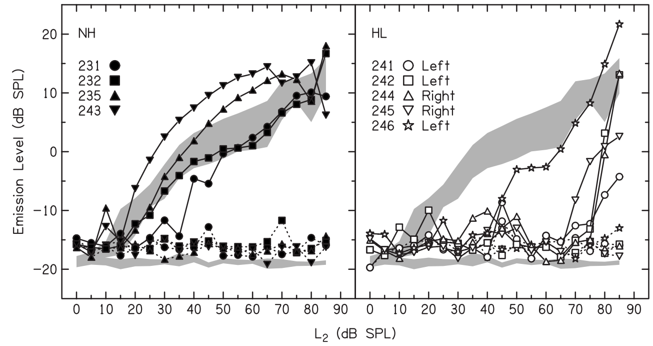

FIG. 9. Distortion-product otoacoustic emission (DPOAE) input-output (I/O) functions with $f_2=4$ kHz for ears with normal hearing (NH) (left panel) and ears with hearing loss (HL) (right panel) for experiment 3. The symbols represent individual subjects. The symbols connected by solid lines represent the DPOAE levels, and the symbols connected by dashed lines represent the noise levels. The shaded areas represent the 25th to 75th percentile of responses from left ears with NH from Schairer *et al.* (2003a). DPOAEs were not obtained for $f_2=0.25$ kHz (the other signal frequency in the behavioral tests) because biological noise at low frequencies obscures the responses. The results suggest normal cochlear nonlinearity in ears with NH and reduced or absent nonlinearity in ears with HL.

D. Adaptive-procedure thresholds

Thresholds were obtained in a VS paradigm using a two-track 2IFC adaptive procedure with decision rules to estimate 71 PC on one track and 87 PC on the other track (Levitt, 1971). The initial and final step sizes (after four reversals) were 4 and 2 dB, respectively. The threshold for each track was calculated as the mean of the reversal levels after the fourth reversal. Eight 200-trial repetitions were obtained in each condition. The first two repetitions were excluded as practice. A total of 1200 trials, or 600 trials per track, were available for further analysis. The exception was for subject 245 for whom only six repetitions of each condition were obtained due to time constraints. Mean thresholds were calculated across repetitions for each track, and then the mean across the two tracks was calculated as the adaptive-procedure threshold for each subject in each condition. Mean thresholds across LNH were calculated for comparison with individual LHL.

E. Psychometric-function fits

PFs were fitted as for experiments 1 and 2. All trials from both tracks were combined to fit the PFs. There was a total of 144 PFs to fit (64 for LNH, 80 for LHL, but two could not be fitted). This total includes the quiet thresholds for the LHL but excludes the quiet thresholds for the LNH because they were already presented in experiment 2. The correlation between the masked adaptive and PF thresholds (not including quiet thresholds) across signal frequency, masker level, masker frequency, and subject was 0.995.

F. Results

1. DPOAE I/O functions

Figure 9 shows the DPOAE I/O functions obtained in individual ears with NH (left panel) and with HL (right panel) compared to the 25th to 75th percentile responses (shaded areas) recorded in a group of left ears with NH

(Schairer *et al.*, 2003a). The responses in ears with NH in the current study exceed the 25th percentile of the normal range with the exception of listener 231 at L_2's below 50 dB SPL. The responses from ears with HL do not reach the 25th percentile of the normal range except at the highest L_2 levels. This suggests normal cochlear nonlinearity for the ears with NH and decreased or absent nonlinearity in ears with HL. Note that despite the fact that subjects 245 and 246 have near-normal audiometric thresholds at 4 kHz (Fig. 8), their DPOAE I/O functions suggest loss of OHC function and, presumably, loss of cochlear nonlinearity. Further, the thresholds in quiet for the 4 kHz signal obtained in the laboratory were higher for subjects 245 and 246 (39.5 and 40.6 dB SPL, respectively) than for the LNH (16.3–21.0 dB SPL) For these reasons, it was deemed appropriate to include them in the group of LHL for the 4 kHz signal conditions.

DPOAEs were not obtained in the f_2=0.25 kHz case because biological and environmental noise make it difficult to measure reliable robust responses in a reasonable amount of time. Thus, DPOAEs cannot be used to compare the degree of cochlear nonlinearity between the two subject groups at that signal frequency. Subjects 242, 245, and 246 (of the group of LHL) had audiometric thresholds within normal limits at 0.25 kHz (Fig. 8) despite having HL (or borderline HL) at 4 kHz. They also had thresholds for the 0.25 kHz signal in quiet (39.7, 33.3, and 35.9 dB SPL) that were comparable to the LNH (in the range 30.9–39.4 dB SPL). These three subjects in the group of LHL were therefore considered to have NH at 0.25 kHz. They could in a sense serve as their own controls (NH at 0.25 kHz and HL at 4 kHz). It was demonstrated in experiment 1 that in LNH, on-frequency masking produces similar PF slope results at 0.25 and 4 kHz (and presumably reflects cochlear nonlinearity). It follows that any difference in PF slope between the 0.25 and 4 kHz signal conditions in these three individuals with presumably normal function at 0.25 kHz and impaired function at 4 kHz is likely due to loss of cochlear nonlinearity.

2. Adaptive forward-masked thresholds

Figure 10 shows mean adaptive threshold across LNH as a function of masker dB SPL in the left panel and mean amount of masking as a function of masker dB SL in the right panel. All signal- and masker-frequency conditions are represented in each panel. Slopes of GOM (fit without the 5 ms duration condition) are similar for on-frequency (0.57) and off-frequency (0.66) conditions in the 0.25 kHz signal case and for the on-frequency (0.48) condition in the 4 kHz signal case. The slope is steeper in the off-frequency masker condition in the 4 kHz case (0.97) than for the other three conditions. This result is consistent with the data shown in Fig. 5 that were obtained using a VM paradigm.

Figure 11 shows the means across LNH (filled squares in all panels) along with the individual thresholds for each LHL (open symbols, as in Fig. 8), with different signal and masker frequencies represented in different rows. In the 4 kHz signal conditions, the masked thresholds for the LHL are generally higher than those for LNH (left panels), with the exception of subjects 245 and 246 in the highest masker-level condition. In the 0.25 kHz signal conditions, responses

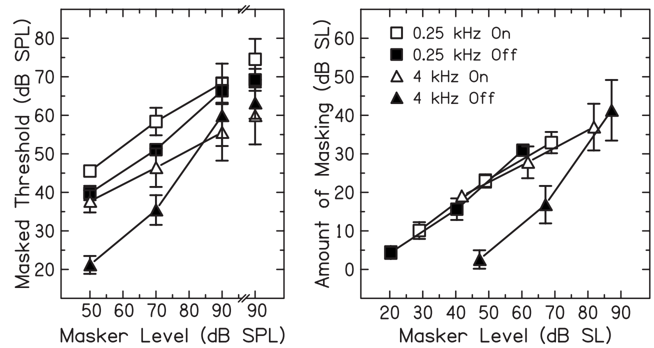

FIG. 10. Mean masked threshold across listeners with normal hearing (LNH) as a function of masker dB SPL (left panel) and mean amount of masking as a function of masker dB SL (with regard to mean masker thresholds in quiet; right panel) for 0.25 and 4 kHz signal conditions (squares and triangles, respectively) and on- and off-frequency masker conditions (open and filled, respectively) in experiment 3. The error bars represent +/−1 standard deviation. Masker duration was 200 ms with a 10 ms signal delay. Maskers were presented at 50, 70, and 90 dB SPL in different conditions. Another condition with a masker level of 90 dB SPL and a 5 ms signal delay (disconnected symbols in left panel) was also presented. Signal duration was 10 ms and signals were presented in a variable signal (VS) paradigm. The amount of masking increases as a function of masker level at a similar rate for all but the 4 kHz, off-frequency condition (see Table III for slopes).

were not obtained in subject 241 due to degree of HL. Subjects 242, 245, and 246 had normal thresholds. Subject 244 was the only listener who had HL at 0.25 kHz but was still able to perform the task over a range of masker levels. Slopes of GOM for the LHL are similar in most cases to those for the LNH (see Table III for specific values).

3. Psychometric-function fits

The threshold, slope, and r^2 values for each condition for LNH and LHL are shown in Tables IV and V, respectively. Examples of PF fits to individual data points for the lowest and highest masker-level conditions for LNH and LHL are shown in Figs. 12 and 13, respectively. Figure 14 shows the PF slope as a function of the PF threshold for the individual LNH along with the mean results across subjects (geometric mean slope as a function of arithmetic mean PF threshold). Because the PFs in a VS paradigm provide a measure of compression at the signal frequency, no difference is expected between PF slopes in on-frequency and off-frequency conditions. If there were markedly less compression at 0.25 kHz, slopes would not be expected to decline with increasing threshold in those conditions. Although the slope estimates vary widely for individual subjects, in general, slopes decrease as a function of threshold and the decrease is similar for on-frequency and off-frequency maskers and for 0.25 and 4 kHz signal conditions. As in Fig. 4, the function fitted to the mean data in Fig. 14 is the reciprocal of a quadratic compression function, as described by Neely and Jesteadt (2005).

The mean data points and line fitted to the mean data from Fig. 14 are replotted in Fig. 15, along with the individual data for the LHL. Note that the scale is larger in Fig. 15 than in Fig. 14 to accommodate the larger slopes in the LHL. In the 4 kHz signal conditions, although there appears to be some decrease in PF slope as a function of threshold,

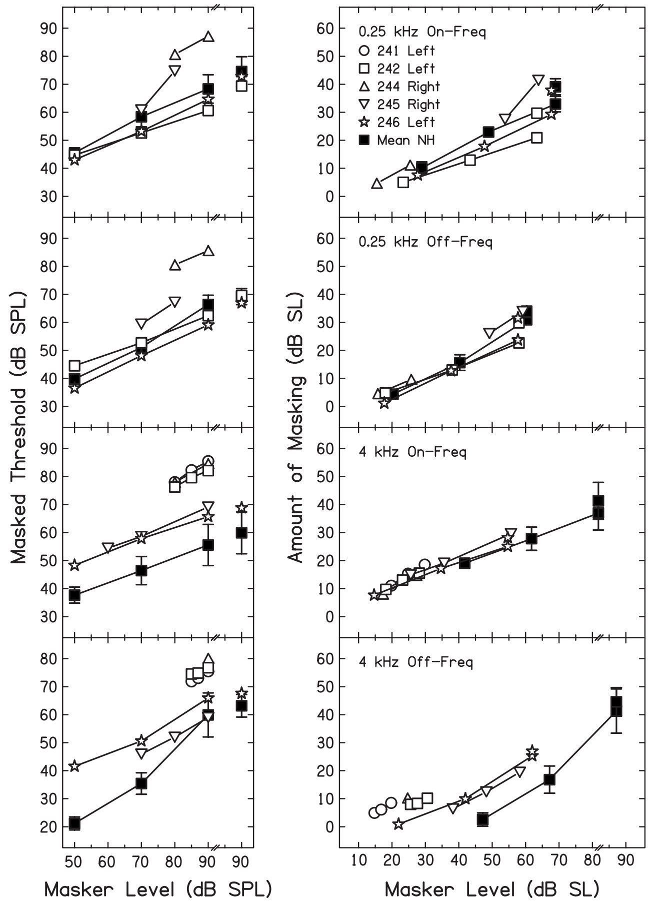

FIG. 11. Mean data across listeners with normal hearing (LNH; mean NH) from Fig. 10 are reproduced here (filled squares) along with individual data from listeners with hearing loss (LHL; symbols as in Fig. 8) from experiment 3. Signal and masker-frequency conditions are represented in rows, with adaptive threshold as a function of masker dB SPL in the left column and amount of masking as a function masker dB SL in the right column. Although it appears that more masking was produced in general in LNH (left panel), when masker levels are expressed in dB SL (with regard to masker thresholds in quiet), there is actually a comparable amount of masking across subjects except in the 4 kHz signal, off-frequency masker condition.

the slopes are steeper in all cases (except for one data point for subject 245 in the on-frequency masker case) than the fit to the data from the LNH. In the 0.25 kHz signal conditions, subject 244, who has HL at 0.25 kHz, has steeper slopes than the LNH except for one on-frequency condition. Subjects 242, 245, and 246 served as their own controls because they have NH at 0.25 kHz and impaired hearing at 4 kHz. Subject 246 has slightly steeper PF slopes in comparison to LNH in the 0.25 kHz signal conditions. In general, subjects 242 and 245 have PF slopes that are comparable or lower than LNH in the 0.25 kHz signal conditions. The very shallow slopes in these conditions may be due to poor goodness of PF fits rather than perceptual variability. For subject 242, the two conditions that have slopes that are out of line with the rest of the data have associated r^2 values of 0.597 and 0.443 (see Table V for the 50 and 70 dB off-frequency masker, 0.25 kHz signal conditions). The r^2 values for all other masked conditions are >0.60 for these two subjects and the other subjects. For subject 245, the r^2 for the 70 dB on-frequency masker condition was 0.453. As stated in experiment 2, poor PF fits can be associated with PF slopes that are shallower than expected.

In summary, the on-frequency results in LNH are in agreement with experiment 1. PF slopes decreased as a function of threshold for both on- and off-frequency masker conditions, for both 0.25 and 4 kHz signal conditions. In addition, preliminary results in LHL demonstrated that PF slopes were steeper at frequencies with HL. The PF slopes demonstrated differences in compression between the groups that were not obvious in the GOM functions, because slopes of GOM were similar between the LNH and the LHL (see Fig. 11 and Table III).

V. DISCUSSION

A. Summary of experiments

The goals of the current set of experiments were to use trends in PF slopes across conditions to compare compression and bandwidth of compression at low- and high-signal frequencies, and to compare degree of compression in LNH and LHL. For LNH, PF slopes decreased as a function of signal threshold for VS, 4 kHz, on-frequency conditions (experiments 1 and 3) and at a similar rate for off-frequency conditions (experiment 3), consistent with Schairer *et al.* (2003b). In addition, PF slopes decreased as a function of signal threshold for VM, 4 kHz, on-frequency but not off-frequency conditions (experiment 2), also consistent with Schairer *et al.* (2003b). These results suggest that PF slopes reflect the compressive nonlinearity at the place of the signal.

The current results extend this conclusion to the 0.25 kHz signal condition and suggest comparable compression in the 0.25 and 4 kHz conditions (experiments 1 and 3). The finding of comparable compression at the low- and high-signal frequencies is consistent with recent behavioral data (see, e.g., Lopez-Poveda and Alves-Pinto, 2008; Lopez-Poveda *et al.*, 2003; Plack and Drga, 2003; and Williams and Bacon, 2005) and DPOAE data in LNH (Gorga *et al.*, 2007). Gorga *et al.* (2007) reported that although the I/O functions

TABLE III. Slope of linear regression line fits to growth of amount of masking as a function of masker dB SL for experiment 3: Means across listeners with normal hearing (NH) and individual listeners with hearing impairment.

Signal frequency	Masker frequency	241	242	244	245	246	NH
0.25 kHz	On		0.40	0.65	1.39	0.54	0.57
0.25 kHz	Off		0.45	0.51	0.78	0.56	0.66
4 kHz	On	0.75	0.58	0.67	0.50	0.44	0.48
4 kHz	Off	0.72	0.45		0.65	0.61	0.97

TABLE IV. Experiment 3 psychometirc function (PF) parameters for listeners with normal hearing (LNH) in variable signal (VS), on- and off-frequency forward-masking conditions [SD=standard deviation].

Signal frequency	Masker frequency	Masker level	Parameter	231	232	235	243	Mean (SD)
0.25 kHz	0.25 kHz	50	Threshold	45.535	43.274	45.436	45.288	44.88(1.08)
			Slope	0.510	0.576	0.451	1.469	0.66
			r^2	0.717	0.877	0.730	0.980	
		70	Threshold	58.840	51.398	61.243	56.340	56.96(4.21)
			Slope	0.379	0.444	0.360	0.734	0.46
			r^2	0.806	0.775	0.940	0.913	
		90	Threshold	69.756	63.140	72.836	62.723	67.11(4.99)
			Slope	0.368	0.312	0.231	0.712	0.37
			r^2	0.785	0.860	0.862	0.958	
		90, 5 ms delay	Threshold	78.031	70.993	77.174	66.855	73.26(5.30)
			Slope	0.313	0.398	0.425	0.484	0.40
			r^2	0.725	0.851	0.937	0.956	
0.25 kHz	0.15 kHz	50	Threshold	41.198	37.269	37.856	38.891	38.80(1.73)
			Slope	0.851	0.476	0.171	1.112	0.53
			r^2	0.823	0.759	0.537	0.958	
		70	Threshold	50.665	49.148	50.133	49.493	49.86(0.68)
			Slope	0.458	0.333	0.466	0.753	0.48
			r^2	0.938	0.824	0.951	0.960	
		90	Threshold	65.966	62.810	66.138	62.388	64.33(2.00)
			Slope	0.189	0.380	0.419	0.407	0.33
			r^2	0.612	0.760	0.533	0.832	
		90, 5 ms delay	Threshold	72.137	67.238	69.105	65.809	68.57(2.73)
			Slope	0.567	0.544	0.388	0.707	0.54
			r^2	0.904	0.907	0.910	0.909	
4 kHz	4 kHz	50	Threshold	34.399	38.942	39.050	33.846	36.56(2.82)
			Slope	0.266	0.422	0.748	1.179	0.56
			r^2	0.735	0.916	0.927	0.982	
		70	Threshold	44.047	49.478	43.455	39.533	44.13(4.09)
			Slope	0.167	0.263	0.369	0.628	0.32
			r^2	0.650	0.767	0.749	0.936	
		90	Threshold	53.778	59.283	46.405	46.781	51.56(6.16)
			Slope	0.140	0.186	0.160	0.829	0.24
			r^2	0.676	0.826	0.593	0.918	
		90, 5 ms delay	Threshold	53.392	67.762	51.891	55.337	57.10(7.25)
			Slope	0.152	0.243	0.554	0.337	0.29
			r^2	0.663	0.719	0.905	0.946	
4 kHz	2.4 kHz	50	Threshold	22.003	17.794	21.254	18.162	19.81(2.14)
			Slope	0.534	0.717	1.384	1.154	0.88
			r^2	0.796	0.937	0.986	0.947	
		70	Threshold	39.370	31.387	32.362	34.533	34.41(3.56)
			Slope	0.504	1.196	1.268	0.288	0.69
			r^2	0.925	0.982	0.990	0.496	
		90	Threshold	67.912	59.204	51.551	55.297	58.49(7.02)
			Slope	0.198	0.165	0.911	0.446	0.34
			r^2	0.673	0.547	0.969	0.952	
		90, 5 ms delay	Threshold	64.035	63.494	56.626	63.266	61.86(3.50)
			Slope	0.405	0.236	0.525	0.318	0.36
			r^2	0.899	0.678	0.840	0.915	

differed across f_2 frequencies of 0.5 and 4 kHz overall, the maximum compression ratios were comparable (approximately 4:1). The fact that there is evidence from behavioral and nonbehavioral studies strengthens the argument that compression is comparable at low and high frequencies.

The fact that PF slopes in the 0.25 kHz signal, on- and off-frequency masker conditions decreased at a similar rate in the VM conditions (experiment 2) provides support for the conclusion of Lopez-Poveda *et al.* (2003) and Plack and Drga (2003) that the bandwidth of compression is wider at lower frequencies. PF slopes provide a uniform measure of compression that can be used in all conditions, allowing a direct assessment of the range of frequencies around CF that have compressive response growth at CF. Another benefit of the current approach is that it does not require assumptions about the rate of recovery from forward masking for either on-frequency or off-frequency maskers, or across signal frequency, thus avoiding issues raised by Stainsby and Moore

TABLE V. Experiment 3 psychometric function (PF) parameters for listeners with hearing loss (LHL) in variable signal (VS), on- and off-frequency forward-masking conditions [QT=quiet threshold].

Signal frequency	Masker frequency	Masker level	Parameter	241	242	244	245	246
0.25 kHz	None	QT	Threshold		39.260	74.781	32.871	35.308
			Slope		0.633	0.438	0.641	1.182
			r^2		0.953	0.762	0.969	0.948
None	0.15 kHz	QT	Threshold		31.222	64.298	20.276	29.507
			Slope		0.447	1.099	0.677	0.198
			r^2		0.980	0.983	0.894	0.634
None	0.25 kHz	QT	Threshold		25.516	64.491	15.666	19.392
			Slope		0.445	0.931	0.833	0.290
			r^2		0.861	0.989	0.980	0.841
0.25 kHz	0.25 kHz	50	Threshold		44.062			42.840
			Slope		0.733			1.127
			r^2		0.939			0.915
		70	Threshold		52.654		57.881	52.987
			Slope		1.314		0.145	1.199
			r^2		0.950		0.450	0.936
		80	Threshold			80.594	71.934	
			Slope			2.010	0.253	
			r^2			0.975	0.661	
		90	Threshold		59.595	85.297		64.055
			Slope		0.449	0.495		0.551
			r^2		0.814	0.717		0.883
		90, 5 ms delay	Threshold		68.462			72.055
			Slope		0.439			0.683
			r^2		0.928			0.958
0.25 kHz	0.15 kHz	50	Threshold		42.448			36.197
			Slope		0.227			0.836
			r^2		0.597			0.976
		70	Threshold		47.479		56.340	48.034
			Slope		0.159		0.220	0.850
			r^2		0.443		0.691	0.894
		80	Threshold			80.780	60.782	
			Slope			1.529	0.214	
			r^2			0.997	0.811	
		90	Threshold		62.058	85.728		58.338
			Slope		0.397	1.399		0.594
			r^2		0.917	0.972		0.947
		90, 5 ms delay	Threshold		68.603			66.600
			Slope		0.315			0.531
			r^2		0.885			0.911
4 kHz	None	QT	Threshold	65.300	66.782	70.216	39.651	40.030
			Slope	0.392	1.235	1.415	1.798	0.614
			r^2	0.468	0.985	0.976	0.980	0.738
None	2.4 kHz	QT	Threshold	70.295	59.353	65.495	31.104	27.903
			Slope	1.022	0.965	1.117	1.225	1.139
			r^2	0.993	0.882	0.979	0.884	0.989
None	4 kHz	QT	Threshold	60.418	61.971	62.756	34.148	35.203
			Slope	1.577	1.521	0.913	1.085	1.597
			r^2	0.997	0.988	0.956	0.938	0.953
4 kHz	4 kHz	50	Threshold					CNF
			Slope					
			r^2					
		60	Threshold				54.457	
			Slope				2.192	
			r^2				0.987	
		70	Threshold				58.997	57.986
			Slope				2.508	1.775
			r^2				0.977	0.992
		80	Threshold	78.829	76.619	78.017		
			Slope	3.723	3.553	2.394		

TABLE V. (*Continued.*)

Signal frequency	Masker frequency	Masker level	Parameter	241	242	244	245	246
			r^2	0.947	0.987	0.926		
		85	Threshold	82.369	79.662			
			Slope	2.341	1.902			
			r^2	0.988	0.967			
		90	Threshold	85.160	81.975	85.247	63.492	64.927
			Slope	1.415	1.131	4.857	0.216	0.830
			r^2	0.956	0.907	0.971	0.778	0.912
		90, 5 ms delay	Threshold					69.071
			Slope					1.246
			r^2					0.980
4 kHz	2.4 kHz	50	Threshold					41.536
			Slope					1.372
			r^2					0.958
		70	Threshold				45.845	51.306
			Slope				1.925	1.632
			r^2				0.991	0.887
		80	Threshold				52.281	
			Slope				2.179	
			r^2				0.988	
		85	Threshold	71.887	74.564			
			Slope	2.024	1.292			
			r^2	0.916	0.971			
		87	Threshold	73.532	75.100			
			Slope	7.500	1.157			
			r^2	0.996	0.965			
		90	Threshold	75.478	CNF	80.166	58.894	65.578
			Slope	1.725		2.115	0.943	0.982
			r^2	0.818		0.964	0.964	0.922
		90, 5 ms delay	Threshold					67.214
			Slope					0.984
			r^2					0.982

(2006) and Wojtczak and Oxenham (2007). Finally, preliminary results in LHL suggest that the decrease in compression at frequencies with HL is reflected in steeper PF slopes. Because the PF slope can be measured in on-frequency conditions independent of the recovery function, this measure is less likely to be confounded by differences in frequency or temporal analysis between LNH and LHL.

B. Methodological issues

Schairer *et al.* (2003b) noted a number of methodological issues related to the procedures for fitting PFs and the assumed form of the PF that also apply to the current study. In both studies, PFs were reconstructed from adaptive-procedure data and fitted using procedures described by Dai (1995). The current study used two interleaved adaptive tracks with different decision rules, as suggested by Dai (1995), in an effort to sample the range of the PF more evenly. The use of two tracks also makes it possible to estimate the slope of the PF from the two adaptive thresholds by computing the slope of the line connecting the 71- and 87-PC points on the PF. We compared the two measures using the data obtained in experiment 1. Slope estimates obtained by connecting the two points were shallower on average than those obtained by fitting reconstructed PFs, but showed a similar pattern as a function of level. Both measures yielded one extreme slope estimate out of a total of 40 estimates (5 subjects $\times$ 8 conditions). In both cases, the estimate obtained with the other measure fell well within the range of slopes observed across subjects and conditions. Additional work will be required to simulate the two estimation approaches and to obtain estimates of the stability of the two measures. A simplified method for estimating the PF slope would facilitate use of slopes as a measure of compression.

Based on simulations, Dai (1995) recommended use of a 4 dB final step size when reconstructing PFs rather than the typical 2 dB value, because the larger step size would concentrate more trials on a smaller number of levels, resulting in better estimates of the proportions correct at those levels. It is worth noting that a 4 dB step size was used in experiment 1, but a 2 dB step size was used in the later experiments. PF fits were generally poorer in those experiments, consistent with Dai's (1995) simulations.

The off-frequency maskers were selected such that the ratios between the masker and the signal frequencies were identical for 0.25 and 4 kHz signals. However, it is possible that the off-frequency maskers were not low enough. Lopez-Poveda and Alves-Pinto (2008) found evidence of compression using a 2.2 kHz off-frequency masker in their 4 kHz signal conditions and suggested that studies that used $\geq$2.2 kHz tones as off-frequency maskers may not have

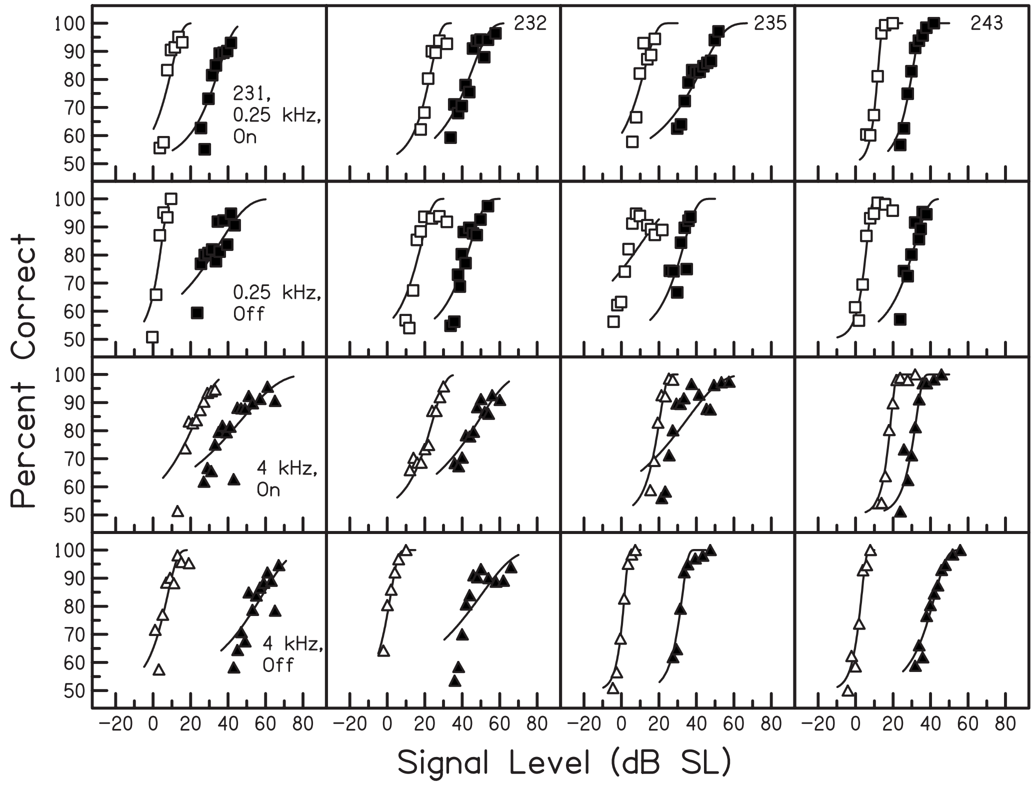

FIG. 12. Psychometric-function (PF) fits to the individual data points for the 50-(open) and 90-(filled) dB SPL on-frequency and off-frequency maskers in 0.25 and 4 kHz signal conditions for listeners with normal hearing (LNH) in experiment 3. The PF thresholds, slopes, and goodness of fit measures (r^2) for all conditions and subjects are listed in Table IV.

been purely linear reference conditions. Compression was not evident in their 1.6 kHz off-frequency masker conditions. The 4 kHz off-frequency masker conditions of the current experiment 2 are relevant to this issue. The theory is that in the VM conditions, PF slope should become shallow as a function of masker threshold for on-frequency masker conditions but remain steep in the off-frequency masker conditions. The on-frequency masker should be compressed be-

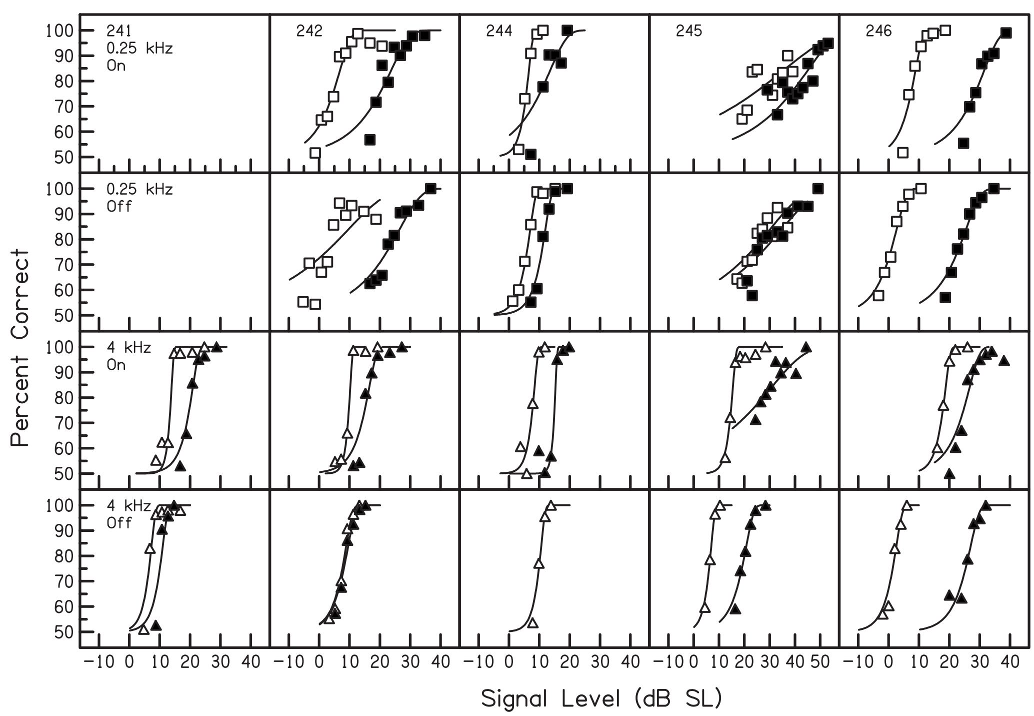

FIG. 13. Psychometric-function (PF) fits to individual data points for the lowest (open) and highest (filled) masker-level conditions (varied by subject, see Table V) for listeners with hearing loss (LHL) in experiment 3. Conditions are represented as in Fig. 12. The PF thresholds, slopes, and goodness of fit measures (r^2) for all conditions and subjects are listed in Table V.

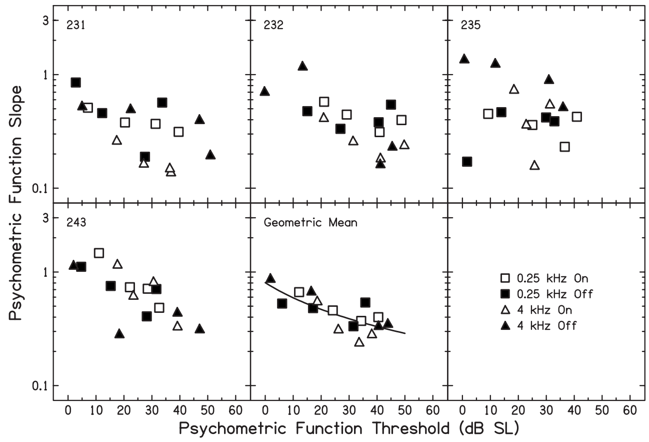

FIG. 14. Psychometric-function (PF) slope as a function of PF threshold for on-frequency (open symbols) and off-frequency (filled symbol) masker conditions for 0.25 (squares) and 4 kHz (triangles) signal conditions in listeners with normal hearing (LNH) in experiment 3. In general, slopes decrease as a function of threshold similarly for on- and off-frequency maskers, and for 0.25 and 4 kHz signal conditions. The function fitted to the geometric mean data is the reciprocal of the quadratic compression function described by Neely and Jesteadt (2005).

cause its traveling wave should peak at the place of signal but the off-frequency masker should not be compressed because its traveling wave peaks at a lower frequency, presumably out of the range of compression around the signal frequency. If compression had influenced the results in the off-frequency masker condition, the slopes should have become shallow as a function of masker level at threshold. In Fig. 7, there may be a slight decrease in slopes in subjects 232, 235, and 243, but slopes in the 4 kHz off-frequency condition were still much steeper than in the remaining conditions. The data for subject 231 may agree with the results of Lopez-Poveda and Alves-Pinto (2008), although caution should be taken when making this comparison due to the relatively poorer r^2 values (i.e., PF fits) for this subject in several conditions. If the data are taken at face value regardless of PF fit, slopes for the 4 kHz signal, off-frequency masker condition were similar to the remaining conditions, suggesting comparable compression in the on- and off-frequency conditions and a wider range of compression around 4 kHz for this subject than for the other three subjects.

A 10 ms, 0.25 kHz signal was used in the current study in order to achieve the range of masker and signal thresholds that were necessary to test the hypotheses across experiments. In particular, a longer duration signal would have required excessive masker levels in experiment 2. Spectral splatter from the short-duration signal may have affected the results, but only for the off-frequency masker conditions for which there may have been unintended overlap in the spectra of the signal and the masker. This potential confounding factor would not affect the conclusions drawn from the PF slopes for experiments 1 and 3 for three reasons: (1) off-frequency maskers were not used in experiment 1, (2) the comparison of compression at 0.25 and 4 kHz requires only the on-frequency conditions, and (3) the comparison of compression between LHL and LNH requires only the on-frequency conditions. However, spectral splatter from the short-duration 0.25 kHz signal may confound conclusions drawn from the results of experiment 2. The off-frequency masker in the 0.25 kHz signal condition produced higher masker levels at threshold than the on-frequency masker (see left-hand panel of Fig. 5), which suggests enough separation in the off-frequency masker and signal spectra that a higher masker level was necessary to just mask the signal than in the on-frequency masker conditions. Overlapping spectra of the masker and signal may have influenced the trends in PF slopes. PF slopes for on- and off-frequency maskers were similar to each other and to the slopes for the 4 kHz signal, on-frequency condition. This may be due to a wider range of compression around the 0.25 kHz signal, to spectral splatter from the short-duration signal that overlapped the spectrum of the off-frequency masker, or to a combination of both.

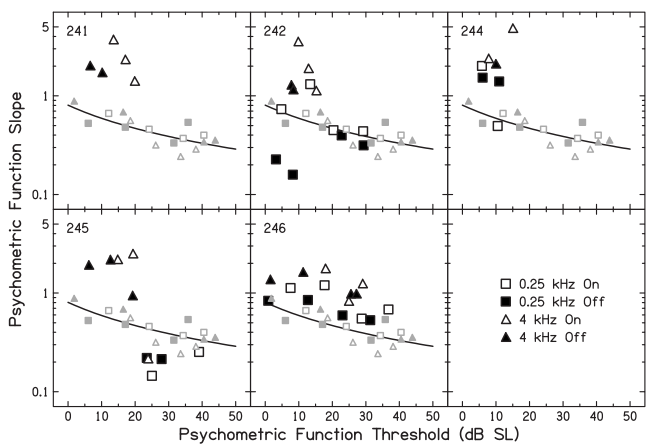

FIG. 15. Psychometric-function (PF) slope as a function of PF threshold for the individual listeners with hearing loss (LHL; dark symbols, as in Fig. 14) in experiment 3. The line fit to the geometric mean across listeners with normal hearing (LNH) is replotted from Fig. 14 along with the mean data points (small, gray symbols). Note that the axes are on a different scale than in Fig. 14 in order to accommodate the wider range of values in the LHL. In the 4 kHz signal conditions, although there appears to be some decrease in PF slope as a function of threshold, in general the slopes are steeper than the data from the LNH. In the 0.25 kHz signal conditions, subject 244, who has impaired hearing at 0.25 kHz, has steeper slopes than the LNH except for one on-frequency condition. Subjects 242, 245, and 246 have normal or near NH at 0.25 kHz (see Fig. 8). Subjects 242 and 245 have PF slopes that are comparable or lower than LNH in the 0.25 kHz conditions, although the shallowest slopes may be related to poorer PF fits in those conditions (see text for explanation and Table V for PF fit parameters). Subject 246 has slightly steeper PF slopes in comparison to LNH in the 0.25 kHz conditions.

C. Results for listeners with hearing loss

PF slopes in LHL were consistent with reduced compression at frequencies at which there was hearing impairment, and with compression that was comparable to LNH at frequencies at which hearing was normal. Having some frequencies of NH and some frequencies with impaired hearing allows subjects to serve as their own "controls." The need to measure PF slope over a range of threshold levels required LHL to have mild or moderate losses at the test frequencies. The use of an independent DPOAE measure of compression strengthened the interpretation of the data. It might be feasible to compare the PF slope and the DPOAE measures in a larger group of LHL tested only at high levels.

It should be noted that a slight decrease in PF slope as a function of PF threshold was observed in LHL despite the fact that slopes remained steep in comparison to LNH. Given the mild and moderate HLs in this group, the decrease in PF slope may reflect varying degrees of residual compression. This is consistent with the VS results from Lopez-Poveda *et al.* (2005) in which nearly normal compression was observed in two ears with sensorineural HL, but reduced compression in a third ear with HL, and with VM results from Oxenham and Plack (1997) in which some residual compression was evident in two of their LHL.

In some cases, the steepness of the PF slope may be due to a reduced dynamic range, as a result of loss of amplification and compression mechanisms in the inner ear. A shallow PF slope implies a large range over which signal levels are detected, from just audible to 100% audible. Ears with HL have reduced ranges in comparison to ears with NH, and therefore PF slopes could be steeper simply due to the restricted range.

D. Cochlear nonlinearity as a function of level

In principle, PF slopes can be used to estimate the form of the function describing cochlear nonlinearity as a function of level. To accept one proposed nonlinearity function and reject the others, or to obtain reliable estimates of parameter values for individual subjects, would require a larger number of more stable PF slope estimates than were obtained in the present experiments. Geometric mean slopes across subjects in Figs. 4 and 14 were fitted with quadratic compression functions described by Neely and Jesteadt (2005). The parameters were estimated by iterative fits of the equation: $1/\text{slope}=a+bT+cT^2$, where T is the PF threshold, the signal level in dB SL required for $d'=1$, a specifies the compression at absolute threshold, and b describes the rate at which compression increases with level. The best fitting value of c was zero and it can be ignored for purposes of the current discussion. The functions account for the general form of the data and suggest that compression is comparable at the two signal frequencies, but the parameter values differ from those used by Neely and Jesteadt (2005) and differ from one set of data to the next. Neely and Jesteadt (2005) assumed $a=0.6$ and $b=0.1$. In Fig. 4, $a=0.7$ and $b=0.04$. In Fig. 14, $a=1.2$ and $b=0.04$. Differences among conditions in experiments 1 and 3 may have influenced the parameter estimates. The largest difference was the inclusion of off-frequency masker conditions in experiment 3. Fitting a quadratic compression function to the slopes obtained in only the on-frequency conditions yielded parameter estimates of $a=0.9$ and $b=0.06$. We have no reason to believe, however, that the relation between the PF slope and the signal level should vary for on- and off-frequency maskers.

Schairer *et al.* (2003b) noted that the PF slope appeared to be more highly correlated with the masker level than with the signal level. The high correlation observed between the masker level and the signal level made it difficult to separate the two effects, but partial correlation of the PF slope was much lower with the signal threshold (−0.06) than with the masker level (−0.71). In the current experiments 1 and 3, masker level and PF threshold were significantly correlated with each other and with PF slope. Because the range of signal delays was limited, it was not possible to separate the masker and signal level effects on the PF slope in the data reported here. The assumption that the signal level is the critical factor governing changes in the PF slope leads to the most straightforward interpretation of the data, but the relative contributions of the signal and the masker level have yet to be thoroughly explored.

VI. CONCLUSIONS

The trends in the PF slopes across conditions suggest comparable compression at 0.25 and 4 kHz, and potentially a wider bandwidth of compression in relative frequency at 0.25 kHz. This is consistent with other recent behavioral studies that have revised earlier estimates of less compression at lower frequencies. The preliminary results in LHL demonstrate that PF slopes are abnormally steep at frequencies with HL, but are similar to those for LNH at frequencies with NH. Overall, the results are consistent with the notion that PF slopes reflect degree of cochlear nonlinearity, and can be used as an additional measure of compression across frequency. More data are required in VM conditions in LNH to investigate bandwidth of compression and in VS conditions in LHL, particularly in the lower frequency signal condition.

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