

Effects of peripheral nonlinearity on psychometric functions for forward-masked tones^{a)}

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Psychometric functions (PFs) for forward-masked tones were obtained for conditions in which signal level was varied to estimate threshold at several masker levels (variable-signal condition), and in which masker level was varied to estimate threshold at several signal levels (variable-masker condition). The changes in PF slope across combinations of masker frequency, masker level, and signal delay were explored in three experiments. In experiment 1, a 2-kHz, 10-ms tone was masked by a 50, 70 or 90 dB SPL, 20-ms on-frequency forward masker, with signal delays of 2, 20, or 40 ms, in a variable-signal condition. PF slopes decreased in conditions where signal threshold was high. In experiments 2 and 3, the signal was a 4-kHz, 10-ms tone, and the masker was either a 4- or 2.4-kHz, 200-ms tone. In experiment 2, on-frequency maskers were presented at 30 to 90 dB SPL in 10-dB steps and off-frequency maskers were presented at 60 to 90 dB SPL in 10-dB steps, with signal delays of 0, 10, or 30 ms, in a variable-signal condition. PF slopes decreased as signal level increased, and this trend was similar for on- and off-frequency maskers. In experiment 3, variable-masker conditions with on- and off-frequency maskers and 0-ms signal delay were presented. In general, the results were consistent with the hypothesis that peripheral nonlinearity is reflected in the PF slopes. The data also indicate that masker level plays a role independent of signal level, an effect that could be accounted for by assuming greater internal noise at higher stimulus levels. © 2003 Acoustical Society of America. [DOI: 10.1121/1.1543933]

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I. INTRODUCTION

Forward masking occurs when the threshold for detection of a brief tone or signal is elevated in the presence of a preceding stimulus or masker. Forward masking data have been obtained in conditions in which signal level is varied to estimate threshold at fixed masker levels (*variable-signal condition*), or conditions in which masker level is varied to estimate threshold at fixed signal levels (*variable-masker condition*). The function describing the relation between masker level and signal level at threshold is referred to as growth of masking (GOM). These patterns have been described in detail for variable-signal (e.g., Jesteadt *et al.*, 1982) and variable-masker conditions (e.g., Nelson and Freyman, 1987), and will not be reviewed here. A recent model of forward masking (Oxenham and Plack, 2000; Plack and Oxenham, 1998) accounts for GOM results by assuming a peripheral nonlinearity with a specific form that is consistent with direct basilar membrane (BM) input-output (I/O)

recordings (Rhode, 1971; Robles *et al.*, 1986; Ruggero *et al.*, 1997) and with estimates from auditory nerve rate-intensity functions (Yates *et al.*, 1990). The BM I/O function is described as having a compressive, nonlinear growth when the signal frequency is equal to the characteristic frequency (CF), which is analogous to the case in which the masker and signal are the same frequency (on-frequency masker), and more linear growth when the signal frequency is different from CF, which is analogous to the case in which the masker is a different frequency than the signal (off-frequency masker). The nonlinearity at CF can be characterized by two straight lines in log-log coordinates, with a low-level linear region (i.e., slope of 1.0), and a moderate-level compressive region with a slope of around 0.2 above some breakpoint (Yates *et al.*, 1990).

The Plack and Oxenham (1998) model assumes that a sliding temporal integration window receives the output of the peripheral nonlinearity, and serves to overlap the masker and signal. In a two-interval forced choice task (2IFC), the output of the temporal window is compared for the two intervals, and the subject is assumed to vote for the interval with the greater output. Multiplicative internal noise limits performance and is assumed to be uniform across all conditions. The current paper is concerned only with the peripheral nonlinearity component of the model. Therefore, the remaining components of the model and their underlying processes will not be discussed further here.

The Plack and Oxenham (1998) model describes the relationship between signal level and masker level when both of these quantities are changing, as in GOM functions. The

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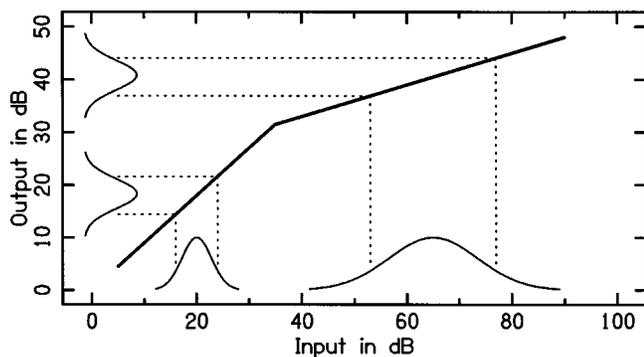


FIG. 1. Example of a compressive nonlinearity similar to the nonlinearity assumed in the model of forward masking. For conditions that produce low signal level at masked threshold, the signal passes through the more linear portion of the function as its level varies during the threshold estimation procedure. Changes in signal level at the input of the function will result in similar changes in signal level at the output of the function, and a smaller range of input levels will be presented in establishing threshold. The underlying distribution of input signal levels in this case is represented by the probability density function (PDF) on the left along the X axis, and the corresponding distribution for signal levels at the output is represented by the lower PDF on the Y axis. PF slopes, which reflect the standard deviation of these underlying PDFs, would be steep for low-threshold conditions because the standard deviation of the distribution on the X axis would be small. 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 (PDF on the right along the X axis) to produce the same change in signal level at the output of the nonlinearity (upper PDF along the Y axis). In this case, the PF slope would be more shallow (i.e., the underlying PDF would have a larger standard deviation). Internal noise is assumed to be uniform across conditions, and is reflected in this figure by similar standard deviations for the upper and lower PDFs on the Y axis.

dynamic nature of this relationship has tended to obscure the role of the peripheral nonlinearity and the model has provided valuable insights concerning the effects of specific changes in stimulus parameters or of changes in the nonlinearity itself (e.g., Oxenham and Plack, 1997). Psychometric functions (PFs), which describe the relationship between stimulus level and percent correct in a given condition, may provide a means of exploring the effect of the nonlinearity in a simpler framework in which only one quantity, either signal or masker level, is varied. In particular, the slope of the PF might be expected to provide a direct measure of the degree of nonlinearity at the signal place on the BM in the range of intensities traversed by the signal or masker.

For example, in variable-signal conditions, the combination of a moderate masker level and a longer signal delay produces a low signal level at masked threshold. In this case, the signal passes through the more linear portion of the BM I/O function as its level varies. Thus, changes in signal level at the input of the cochlear nonlinearity will result in similar changes in signal level at the output of the nonlinearity, and a smaller range of input signal levels will be presented in establishing threshold (Fig. 1). The underlying distribution of input signal levels in this case is represented by the probability density function (PDF) on the left along the X axis, and the corresponding distribution for signal levels at the output of the nonlinearity is represented by the lower PDF on the Y axis. PF slope is related to the PDF width such that the wider the PDF (i.e., the greater the standard deviation of the under-

lying distribution), the shallower the PF slope. Thus, associated PFs for low masked-threshold conditions would be steep because the standard deviation of the distribution on the X axis would be small. In conditions that produce higher signal levels at masked threshold, such as with shorter signal delay and/or higher masker level, the signal will pass through the more compressive region of the BM I/O function. The signal level at the input of the nonlinearity will have to change by a greater amount to produce the same change in signal level at the output of the nonlinearity, thus the PF slope would be more shallow. This relationship is illustrated by the wider PDF on the right along the X axis, and the corresponding upper PDF on the Y axis. Note that the range of the PF at the output of the nonlinearity is specified by internal noise, which is assumed to be uniform across conditions (Plack and Oxenham, 1998). This is illustrated by similar standard deviations for the upper and lower PDFs on the Y axis. We also would predict that PF slopes should be similar for on- and off-frequency maskers in the variable-signal case if the signal levels at threshold are similar for the two conditions. When signal level is varied in order to determine threshold at a fixed masker level, the effect of the nonlinearity should be independent of the properties of the masker.

In the current experiments 1 and 2, variable-signal conditions were presented that produced a range of signal levels at masked threshold for on- and off-frequency maskers. Mean thresholds from the on-frequency masker case in experiment 2 were used to estimate the parameters of the nonlinearity as described by Plack and Oxenham (1998) using data analysis software provided by Plack. The purpose was to demonstrate the ability of the Plack and Oxenham model to predict our own masked thresholds before extrapolating the model predictions to PFs. Next, PF slopes were estimated and compared across conditions. It was hypothesized that PF slope would decrease as a function of signal level, and that this trend would be similar for on- and off-frequency masker cases.

Although variable-masker conditions have been used frequently in forward masking studies (Nelson *et al.*, 2001, 1990; Nelson and Freyman, 1987, 1984; Oxenham and Plack, 1997), PFs have not been reported for those conditions. When the masker level is varied to determine threshold at a fixed signal level, the masker travels through the nonlinearity at the place of the signal, but the growth of the masker at the place of the signal is different for on- and off-frequency maskers. This is because the growth of the on-frequency masker will be influenced by the compressive nonlinearity at the place of the signal, whereas the growth of the off-frequency masker will be linear at the place of the signal. Thus, we predicted that PF slopes should be different for on- and off-frequency maskers in variable-masker conditions. Masker levels were varied to find threshold at several fixed signal levels for on- and off-frequency maskers in experiment 3 and PFs were fitted to those data.

It should be emphasized that the purpose of the current paper is to demonstrate that the peripheral nonlinearity has an effect on PF slopes, and not to identify a specific form of the underlying nonlinear function. More recent models that

incorporate a compressive nonlinearity have assumed a continuously level-dependent function, such as that employed in Glasberg and Moore (2000), rather than the two-straight-line approximation assumed in the Plack and Oxenham (1998) model. We focus on the latter model because its properties allow for specific predictions about forward-masked thresholds and associated PFs, and because we have used select conditions from Plack and Oxenham (1998) and Oxenham and Plack (2000) in our experiments 1 and 2.

All of the PFs reported here have been reconstructed from trial-by-trial data obtained with an adaptive procedure using data collection and analysis procedures described and tested by Dai (1995). These procedures provided an efficient method of obtaining PFs, while allowing us to obtain threshold estimates using a procedure comparable to that used by Plack and Oxenham (1998). As a result of using an adaptive procedure and then fitting a PF to the data, there are two “threshold” estimations described in the Results section for each experiment. The thresholds estimated from the adaptive procedures are presented first (i.e., the GOM functions), then the PF data are presented, which include slope and threshold from the PF fitting procedures. Where PF slopes are compared to threshold, “threshold” in this case refers to the values obtained from the PF fitting procedure, although the good agreement between these measures makes them interchangeable.

II. EXPERIMENT 1

Variable-signal conditions were presented for combinations of three on-frequency masker levels and three signal delays. PFs were reconstructed for each subject in each condition. If PF slope is determined by the degree of peripheral nonlinearity, and only by the degree of peripheral nonlinearity, then slopes should decrease as masked threshold for the signal increases.

A. Subjects

Three subjects, ages 20 to 41, participated in experiment 1 (S1–S3). Two of the subjects were the first and second authors. The other subject was a college student from a local university who was paid for his participation. This subject was informed of the procedures and purpose of the study, and signed a consent form prior to participation. Hearing for the authors was screened at 0.5, 1.0, 2.0, and 4.0 kHz in both ears, using laboratory stimulus generation and threshold measures as described in the following sections. Thresholds were at or better than 20 dB SPL at each test frequency, bilaterally. Hearing for the third subject was screened using standard clinical procedures as part of a research project for another laboratory at this facility. Results from that test indicated thresholds were at or better than 15 dB HL at octave and interoctave test frequencies from 0.25 to 8.0 kHz, bilaterally.

B. Stimuli

The variable-signal conditions in the current experiment 1 were a subset of the conditions used by Plack and Oxenham (1998) in their experiment 1. The signal was a 2-kHz,

10-ms tone (5-ms rise/fall) shaped with a cosine-squared envelope. The forward masker was a 2-kHz, 20-ms tone (2-ms rise/fall) shaped with a cosine-squared envelope, presented at 50, 70, or 90 dB SPL. Each masker level was presented in conditions in which the signal delay (measured at 0-voltage points) was 2, 20, or 40 ms. Threshold for the signal in quiet also was determined for each subject.

The masker and signal were generated digitally at 50 kHz (TDT AP2), and routed through separate 16-bit D/A converters (TDT DD1), then to an anti-aliasing filter (FT6) with a 20-kHz low-pass cutoff. The filtered stimuli were routed to programmable attenuators (PA4), mixed (SM3), then presented through headphone buffers (HB6) to the left ear of each participant through circumaural headphones (Sennheiser HD 250 II). Additional attenuation of up to 30 dB was available from resistor pads located in each booth. The headphones were plugged directly into boxes that contained these resistor pads.

C. Threshold determination

Thresholds for the signal in quiet and in the various experimental conditions were obtained using a 2IFC adaptive procedure, in which the level of the signal was decreased after two correct responses and increased after one incorrect response (Levitt, 1971). The step size was 8 dB until the fourth reversal, after which the step size was 4 dB. The step sizes were selected to reduce the number of levels visited by the adaptive procedure and increase the number of trials per level, an approach that Dai (1995) found to result in more stable estimates of PF parameters. Subjects responded using hand-held microterminals (Intelligent Instrumentation CTM280B). A trial consisted of a 500-ms warning interval (indicated by a “*” on the microterminal), two observation intervals (indicated by a “1” and “2”) separated by 500 ms, an answer interval (indicated by a “?”), and a 300-ms feedback interval in which the correct answer was displayed. There was a 500-ms interval between the trials, and 50 trials were presented in each block. Threshold for a block was calculated as the mean of the signal levels of all reversals after the fourth reversal. Conditions were presented in counterbalanced order. Subjects completed a minimum of 13 50-trial blocks for each of the nine conditions (three signal levels \times three masker levels). Data were collected in 2-h sessions, and subjects were given breaks periodically during the sessions. Mean threshold for each subject in each condition was calculated using thresholds from the last 12 blocks of trials.

D. Psychometric functions

PFs have been analyzed in many different coordinates, particularly in the literature on intensity discrimination (e.g., Buus and Florentine, 1991; Moore *et al.*, 1999). In the literature on detection, the most common approach is to assume that the PF can be described by

$$d' = m(I)^k,$$

where the special cases of amplitude detection and energy detection are represented by $k=0.5$ and $k=1$, respectively

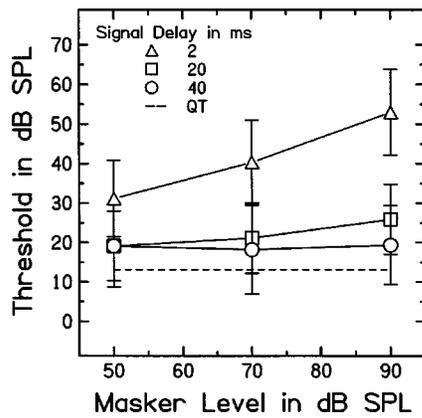


FIG. 2. Signal levels at masked threshold as a function of masker level, with signal delay as the parameter, for the mean across subjects for experiment 1. The forward masker was a 2-kHz, 20-ms tone presented at 50, 70, or 90 dB SPL and the signal was a 2-kHz, 10-ms tone presented at 2- (triangles), 20- (squares), or 40-ms (circles) signal delay in a variable-signal condition. Error bars represent plus and minus one standard deviation. The dashed line represents mean threshold for the signal in quiet (QT). Thresholds are low and slopes of GOM for the 20- and 40-ms delay conditions are shallow. Thresholds are higher in the 2-ms delay condition, and the slope of GOM is steeper for all subjects.

(Egan *et al.*, 1969). Other authors have assumed an underlying function of this form when simulating recovery of PF parameters from adaptive-tracking data (Dai, 1995; Leek *et al.*, 1992). Dai (1995) used a modified form of the equation

$$d' = (I/I_o)^k$$

where $I_o = (I/m)^k$ in the Egan *et al.* equation. In Dai's version, $10 \log(I_o)$ represents the level required for $d' = 1$, whereas values of m in the original equation have no meaning independent of k . In Dai's approach, I_o and k are varied to minimize the weighted squared deviation between obtained and estimated values of percent correct, a χ^2 measure. Weights reflect the standard errors associated with the estimated percent correct values. The exponent k can be treated as a measure of the slope of the PF, given that $10 \log d' = k * 10 \log(I/I_o)$. We have used Dai's version of the formula in the data analyses reported here.

The trial-by-trial data were pooled across the last 12 blocks to obtain estimates of percent correct as a function of signal level for each subject in each condition. Signal levels that were presented on 30 trials or less and/or produced less

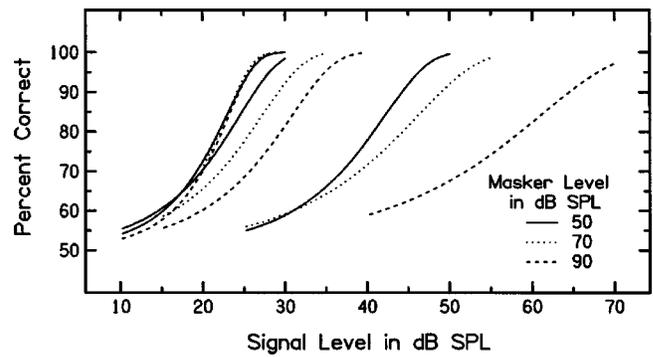


FIG. 3. Mean PFs for all nine conditions in experiment 1. The 50-dB masker conditions are represented by the solid lines, 70-dB maskers by dotted lines, and 90-dB maskers by dashed lines. Signal delay is not directly identified in this figure. As the signal levels increase, the slopes of the PFs decrease, indicating that presentation of a wider range of signal levels was required to determine threshold at higher levels.

than 50% correct were not included in the fits.¹ The Dai fitting procedure provided the threshold and the slope of the PF for each condition for each subject. These parameters were averaged across the three subjects to obtain grand average PFs in each condition. The average across subjects included only those PF fits that had an r^2 of 0.50 or greater.

E. Results

Mean signal levels at threshold across subjects as a function of masker level, with signal delay as the parameter, are displayed in Fig. 2. Error bars represent the standard deviation of thresholds across subjects. Masked thresholds for the 20- and 40-ms delay conditions are low, slopes of GOM (i.e., the rate at which masked threshold increases as a function of masker level) are shallow, and the two functions are similar. Masked thresholds are much higher in the 2-ms delay condition, and the slope of GOM is much steeper.

Although Dai's maximum-likelihood procedure for fitting PFs minimizes χ^2 , unweighted r^2 values provide a more interpretable measure of goodness of fit. Table I provides a summary of the PF thresholds and slopes, and r^2 values for the individual PF fits. All but one fit met the criteria of $r^2 > 0.50$ for inclusion in the mean data (S1, 50-dB masker, 2-ms signal delay). Mean PFs for all nine conditions are shown in Fig. 3. Overall, as the signal levels increase, the slopes of the PFs decrease. Thus, presentation of a wider

TABLE I. PF thresholds and slopes, and r^2 values for PF fits for each subject in each condition in experiment 1.

Subject	Masker level	2-ms signal delay			20-ms signal delay			40-ms signal delay		
		Threshold	Slope	r^2	Threshold	Slope	r^2	Threshold	Slope	r^2
S1	50	17.98	0.10	0.40	12.24	0.65	0.97	9.63	0.84	0.95
	70	30.46	0.36	0.94	13.67	0.37	0.92	8.99	0.60	0.96
	90	45.96	0.28	0.76	19.16	0.39	0.89	9.16	0.65	0.88
S2	50	39.30	0.67	0.96	29.44	0.58	0.95	30.79	0.56	0.90
	70	48.06	0.60	0.97	32.27	0.54	0.88	31.33	1.11	0.99
	90	56.72	0.36	0.92	32.59	0.69	0.99	28.71	1.03	0.99
S3	50	39.45	0.39	0.93	24.38	0.58	0.93	22.45	0.92	0.99
	70	48.65	0.20	0.83	27.54	0.74	0.80	23.21	0.90	0.89
	90	65.84	0.28	0.82	32.54	0.54	0.94	26.50	0.94	0.96

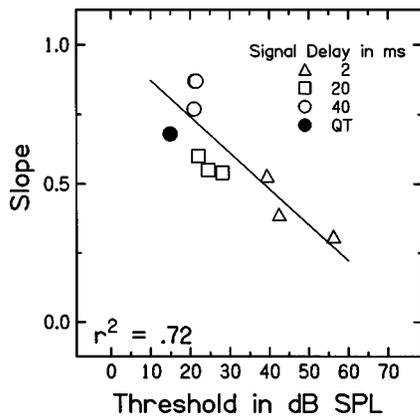


FIG. 4. Mean slopes of PFs as a function of mean threshold in dB SPL across subjects for all masker levels and signal delays in experiment 1. The filled circle represents the PF threshold and slope for the quiet threshold condition (QT). The r^2 value of 0.72 is from the linear regression fit. Note that this r^2 is associated with the regression line for slope versus threshold, not individual PF fits.

range of signal levels is required to determine threshold at higher levels. In Fig. 4, the mean slope of PFs across subjects is shown as a function of mean threshold for the nine masker level and signal delay combinations. PF slope decreases as masked threshold increases, and the relation is well described by a straight line. However, the data points for the two longer signal delays are not well separated, either in terms of slope or threshold. Shorter signal delays may have produced a better spread of masked thresholds and a more appropriate set of data for regression analysis.

Individual PF fits to the data for three of the nine conditions are shown in Fig. 5. As stated previously, the two longer signal delays produced mean masked thresholds that were very close together (see Fig. 2), and this is reflected in the PFs in the lower signal level range for individual subjects. The data points, particularly in the middle of the percent correct range, are well represented by the fits. However, values closer to 50% correct are weighted less in the fitting procedure, and sometimes are not well represented by the fitted line.

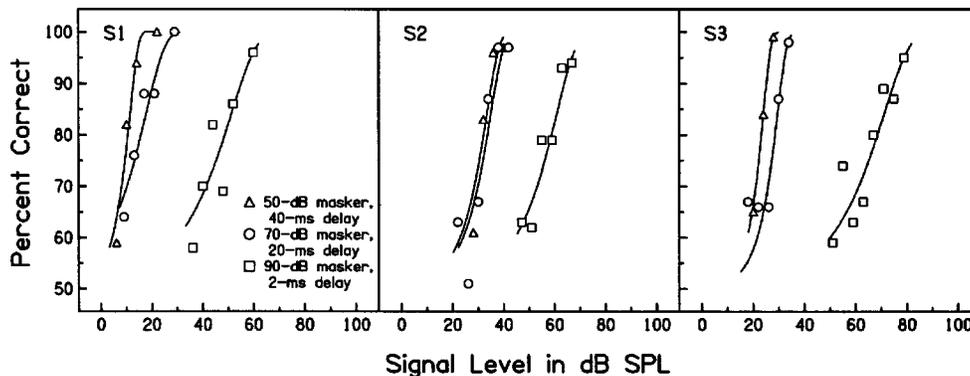


FIG. 5. Individual PF fits for select variable-signal conditions for experiment 1. The open symbols represent the actual data points, and the solid lines represent the fits to the points. The parameter and r^2 values are listed in Table I. Figure 2 shows that the two longer signal delays produced mean masked thresholds that were very close together, and this is reflected in the PFs for individual subjects. The fits to the data points are good, particularly in the middle of the percent correct range. Values at the lower end of the percent correct scale tend to be weighted less in the fitting procedure, and sometimes are not well represented by the fitted line. In these individual fits, particularly for S3, it can be seen that PF slopes tend to decrease as signal level increases.

III. EXPERIMENT 2

Variable-signal conditions were presented using three shorter signal delays and a longer duration masker to produce more masking than in experiment 1. Off-frequency forward maskers also were included. The stimuli and signal delays were the same as those in experiment 1 of Oxenham and Plack (2000). Software supplied by Plack was used to estimate the nonlinearity parameters from the mean data from on-frequency masker conditions. It was predicted that PF slopes would decrease as a function of signal level at masked threshold, and that this trend would be similar for on- and off-frequency masker conditions.

A. Subjects

Three males and four females from 19 to 35 years of age participated in experiment 2 (S4–S10). Two of the males and one of the females were tested simultaneously in one group, and the remaining subjects were tested together in a second group. Each participant was informed of the procedures and purpose of the study, and signed a consent form prior to participation. All participants were college students from a local university, and none had previous experience with the task. They were paid for their participation. Hearing was screened at 0.5, 2.0, and 4.0 kHz in both ears using the same procedures as described for the authors in experiment 1. Thresholds for all participants were at or better than 20 dB SPL at each test frequency, bilaterally.

B. Stimuli

The signal was a 4-kHz, 10-ms tone (5-ms rise/fall) shaped with a cosine-squared envelope, and presented at delays of 0, 10, or 30 ms. The on-frequency forward masker was a 200-ms tone, presented at 30 to 90 dB SPL in 10-dB steps in different blocks. The off-frequency forward masker was a 2.4-kHz, 200-ms tone presented at 60 to 90 dB SPL in 10-dB steps in different blocks. Both maskers were shaped with 2-ms cosine-squared rise/fall envelopes. Stimulus generation and delivery was the same as for experiment 1, with

the exception that multiple sets of attenuators, mixers, and headphone buffers were used to enable simultaneous testing of up to four subjects.

C. Threshold determination

Thresholds were determined using the same procedures as experiment 1, with the exception that step sizes were all 4 dB. The first group (S5, S7, and S9) completed 12 50-trial blocks of each condition; the second group (S4, S6, S8, S10) completed eight blocks per condition. Data from all subjects were combined and treated as one group for subsequent analyses.

D. Data analysis

Plack and Oxenham (1998) used temporal window parameters established by Oxenham and Moore (1994) and nonlinearity parameters established by Oxenham and Plack (1997) to fit their data. After adjusting the breakpoint of the nonlinearity from 45 dB (used by Oxenham and Plack, 1997) to 35 dB, they varied only the efficiency parameter, k , the threshold-level difference at the output of the temporal window required for detection of the signal (Plack and Oxenham, 1998). The model assumes that k is constant across conditions. In a later study, Oxenham (2001) varied the lower (more linear) and upper (more compressive) slope of the nonlinearity as well as window parameters to obtain an optimum fit, but allowed only a few parameters to vary at once. In fitting the current data, we have taken a similar approach. Using the standard window parameters, two successive iterations were performed to arrive at best estimates of the nonlinearity parameters based on the group mean adaptive thresholds in the on-frequency conditions.² First, lower slope was fixed at 0.78 and k , breakpoint, and upper slope were allowed to vary until a least squares fit was obtained. The resultant values for k , breakpoint, and upper slope were then fixed, and lower slope was allowed to vary until a least squares fit was obtained.

PFs were calculated for each subject in each condition using the Dai (1995) procedure. Signal levels with 30 trials or less and/or less than 50% correct were excluded from the fits. Of the 231 PFs (excluding those for quiet threshold) for seven listeners and 33 conditions, 218 were used in further analyses. Twelve PFs were excluded because of poor fits ($r^2 < 0.50$), and one was excluded because only one signal level remained after the trim procedure. Poor fits typically resulted from nonmonotonic functions. Correlations were calculated using SPSS to examine the relationship between mean PF slope and mean threshold from the PF fits, masker level, signal delay, and masker frequency.

E. Results

Mean signal levels at masked threshold (across replications, then across subjects) are shown as a function of masker level with signal delay as the parameter in Fig. 6. In the on-frequency masker conditions, the shorter signal delays and longer masker duration used in experiment 2 produced higher signal levels at masked threshold in comparison to experiment 1. In both the on- and off-frequency conditions,

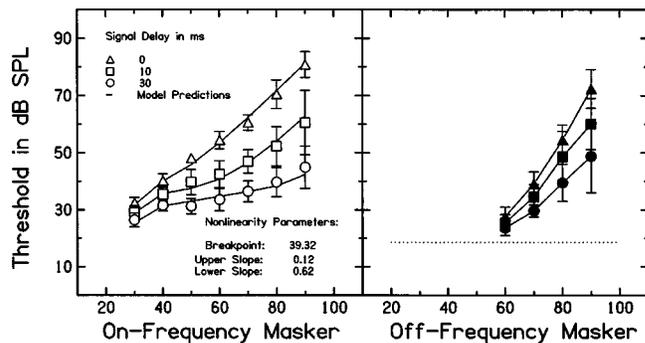


FIG. 6. Mean signal levels at threshold as a function of masker level with signal delay as the parameter for on-frequency (left panel) and off-frequency (right panel) masker conditions for experiment 2. The on-frequency forward masker was a 4-kHz, 200-ms tone presented at 30 to 90 dB SPL in 10-dB steps, and the off-frequency forward masker was a 2.4-kHz tone presented at 60 to 90 dB SPL in 10-dB steps. The signal was a 4-kHz, 10-ms tone presented at 0- (triangles), 10- (squares), or 30-ms (circles) signal delay in a variable-signal condition. Error bars represent plus and minus one standard deviation across subjects. The solid lines in the left panel for the on-frequency masker conditions represent the model fit to the mean data obtained with the specified parameters. The dotted line in the right panel represents threshold for the signal in quiet.

signal level at masked threshold increases with increases in masker level. However, the slopes of GOM are much steeper for the off-frequency maskers, and remain steep as the delay increases, whereas the slopes of GOM tend to decrease with an increase in signal delay for the on-frequency masker case.

The final fits of the Plack and Oxenham model to the mean on-frequency masking data also are shown in the left panel of Fig. 6. The rms error was 1.30 dB. The lower slope that produced the best fit was 0.62 dB/dB. This value is lower than the 0.78 dB/dB slope that Plack and Oxenham use, and physiological data suggest a value closer to 1.0. The upper slope of 0.12 dB/dB and breakpoint of 39 dB agree more closely with the values of 0.16 dB/dB and 35 dB assumed by Plack and Oxenham. The efficiency factor, k , was 2.58 dB.

The PF thresholds and slopes estimated from the Dai procedure and the corresponding r^2 values for a subset of the conditions are summarized in Table II. Because there is a large amount of data, only the on-frequency, 30-, 60-, and 90-dB masker conditions, and the off-frequency 60- and 90-dB masker conditions for each signal delay are presented to demonstrate the range of parameters and goodness of fit to individual subject data. PF fits to the individual data for a sample of low and high masked threshold conditions are presented in Fig. 7. PF fits whose parameters are included in Fig. 8 and in other summaries are shown by solid lines, and PF fits that are excluded are shown by dotted lines. These excluded conditions are the on-frequency, 60-dB masker, 30-ms signal delay condition for subject S7, and the on-frequency, 90-dB masker, 0-ms signal delay condition for subjects S6, S8, and S10.

Figure 8 shows the PF slopes plotted as a function of the PF thresholds for individual subjects, and the mean PF slope as a function of mean PF threshold across subjects. Note that subject S8 has extreme slope values (i.e., greater than 3.00) in six conditions, and they are not plotted here in order to keep the Y-axis scale in a range that is appropriate for the

TABLE II. PF thresholds and slopes, and r^2 values for PF fits for each subject for select conditions in experiment 2.

Subject	Masker frequency	Masker level	0-ms signal delay			10-ms signal delay			30-ms signal delay		
			Threshold	Slope	r^2	Threshold	Slope	r^2	Threshold	Slope	r^2
S4	On	30	34.60	0.97	0.86	29.84	0.82	0.90	24.76	1.41	0.99
		60	54.33	0.88	0.97	41.08	0.65	0.99	30.22	0.75	0.93
		90	82.76	0.24	0.64	63.28	0.24	0.80	49.76	0.38	0.46
	Off	60	25.12	0.91	0.99	23.19	1.10	0.85	20.85	1.33	0.98
		90	81.79	0.48	0.82	63.10	0.35	0.92	43.37	0.29	0.98
S5	On	30	34.68	0.91	0.75	32.92	1.30	1.00	30.67	0.49	0.54
		60	56.14	1.19	0.97	47.62	0.92	0.99	36.41	1.13	1.00
		90	85.80	0.47	0.83	58.02	0.22	0.80	44.82	0.96	0.96
	Off	60	27.50	1.06	0.98	29.08	1.45	1.00	28.99	1.17	0.98
		90	69.06	0.38	0.93	57.45	0.33	0.81	44.39	0.61	0.83
S6	On	30	34.68	0.98	0.93	31.34	0.98	0.92	30.20	0.76	0.91
		60	54.22	0.60	0.89	42.00	0.33	0.97	34.98	1.03	0.95
		90	76.30	0.10	0.37	50.42	0.64	0.97	41.45	0.64	0.87
	Off	60	29.65	1.47	0.99	26.96	2.12	0.99	24.57	0.99	0.92
		90	64.84	0.53	0.95	52.31	1.04	0.99	One-point	function	
S7	On	30	21.41	0.16	0.21	28.05	2.23	0.99	29.32	0.28	0.58
		60	57.19	0.35	0.53	36.83	0.79	0.91	30.05	0.08	-0.13
		90	88.17	0.30	0.96	49.23	0.13	0.61	36.55	0.70	0.89
	Off	60	34.16	0.29	0.52	29.91	0.35	0.85	26.15	0.72	0.94
		90	77.57	0.26	0.62	54.54	0.43	0.83	45.03	0.30	0.70
S8	On	30	31.20	2.23	0.98	29.56	4.19	1.00	27.15	4.20	0.98
		60	58.72	2.02	0.97	44.66	0.75	0.86	34.06	1.72	1.00
		90	86.33	0.24	0.41	66.60	0.25	0.95	44.52	0.23	0.74
	Off	60	29.57	0.66	0.86	29.57	1.29	1.00	27.59	1.19	0.95
		90	78.63	0.94	0.96	71.34	0.27	0.66	54.12	0.45	0.68
S9	On	30	27.80	0.26	0.99	33.77	0.88	0.89	31.27	0.61	0.87
		60	61.39	0.66	0.85	50.07	0.57	0.96	39.27	0.51	0.92
		90	83.73	0.25	0.68	69.65	0.19	0.84	55.83	0.27	0.88
	Off	60	28.82	1.07	0.95	28.04	0.66	0.88	27.23	1.02	0.69
		90	76.65	0.38	0.88	67.67	0.30	0.89	51.82	0.26	0.69
S10	On	30	37.53	0.62	0.98	33.73	0.54	0.93	29.06	0.33	0.94
		60	58.61	0.45	0.99	52.53	0.40	0.88	42.27	0.28	0.91
		90	85.52	0.06	0.18	87.78	0.24	0.66	60.08	0.42	0.83
	Off	60	34.66	0.35	0.79	25.33	0.48	0.98	25.35	0.53	0.91
		90	81.94	0.63	0.92	80.14	0.33	0.83	81.11	0.56	0.98

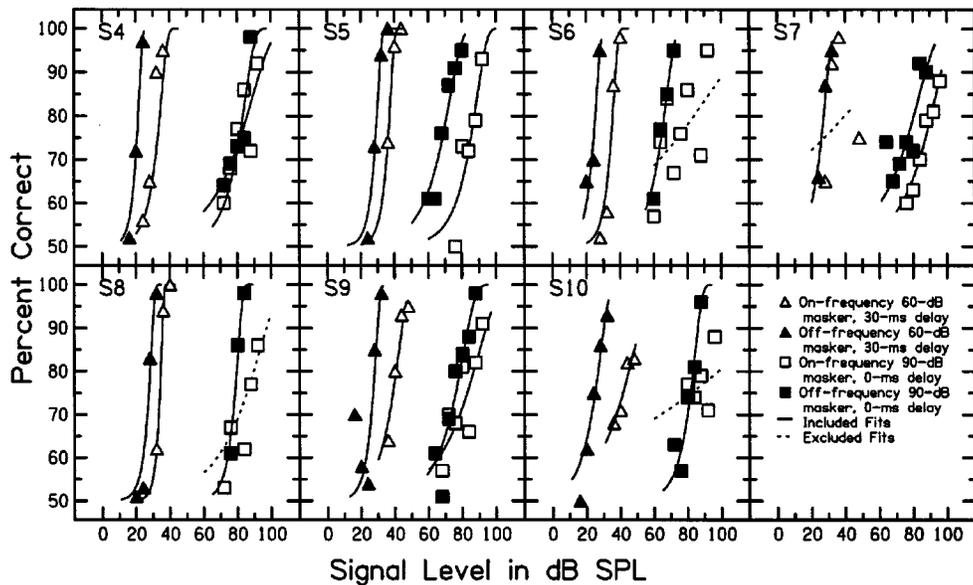


FIG. 7. PF fits to the individual data for a sample of low threshold (60-dB masker, 30-ms signal delay, represented by triangles) and high threshold conditions (90-dB masker, 0-ms signal delay, represented by squares) for on-frequency (open symbols) and off-frequency masker cases (filled symbols) for experiment 2. PF fits that were excluded from summaries due to $r^2 < 0.50$ are shown by dotted lines.

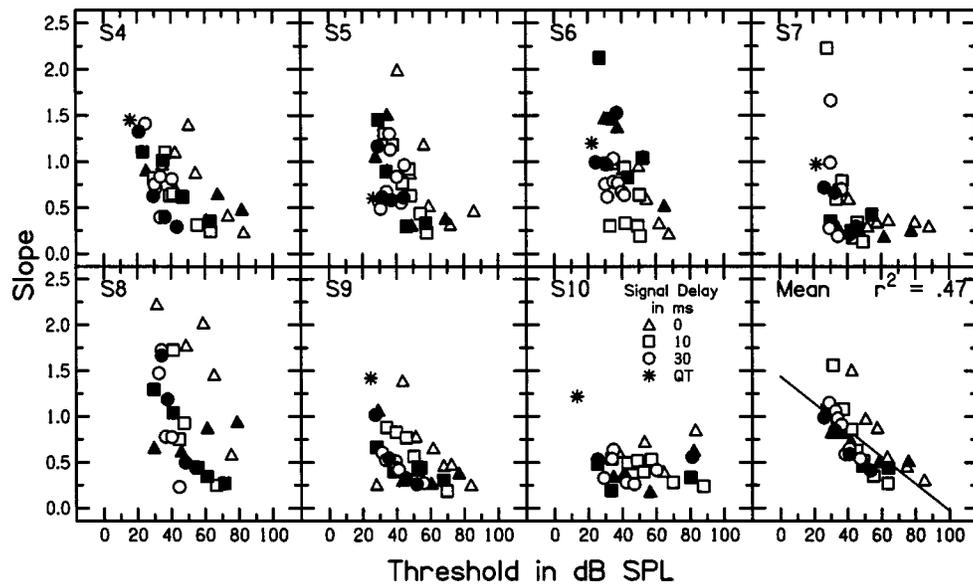


FIG. 8. Slopes of PFs plotted as a function of threshold for individual subjects, and the mean PF slope as a function of mean threshold for experiment 2. On- and off-frequency masker conditions are represented by open and closed symbols, respectively. The 0-ms signal delay conditions are represented by triangles, 10-ms delay by squares, and 30-ms delay by circles. Masker level is not directly identified in this plot. Threshold for the signal in quiet is represented by the star. Slopes of PFs decrease as signal threshold increases, and there does not appear to be a systematic difference between masker frequency conditions. However, there does appear to be a large amount of variability across subjects. Subject S10 has relatively uniform PF slopes across conditions. Also, subjects S4, S5, and S8 have higher signal thresholds in the on-frequency, 0-ms condition (open triangles) without a corresponding decrease in the slopes of the PFs. It should be noted that subject S8 has extreme slope values (i.e., >3.00) for five of the low-level, on-frequency masker conditions, and for the threshold in quiet condition. These data points are not plotted because the Y axis would have to be expanded to accommodate them, making the trends in the data for other subjects difficult to distinguish.

remaining subjects. For this subject, the slope values in the 40-dB, on-frequency masker conditions are 4.13, 3.06, and 3.55 in the 0-, 10-, and 30-ms signal delay conditions, respectively. Slope values in the 30-dB, on-frequency masker condition are 4.19 and 4.20 for the 10- and 30-ms signal delay conditions, respectively, and the slope value for threshold for the signal in quiet is 3.02. All of these conditions have associated PF thresholds that are below 41 dB SPL. In general, PF slopes decrease as signal level at threshold increases as observed in experiment 1. Further, there does not appear to be a systematic difference between on- and off-frequency masker conditions. However, there does appear to be a large amount of variability across subjects. Subject S10, for example, has relatively uniform PF slopes across conditions. Also, although the mean data do not indicate a systematic difference among signal delays and masker frequencies, subjects S4, S5, and S8 have higher masked thresholds in the on-frequency, 0-ms condition (open triangles) without a corresponding decrease in the slopes of the PFs.

The correlation of mean PF slope with mean PF threshold in Fig. 8 is -0.69 . We also evaluated the correlation of mean PF slope with the stimulus parameters. The correlation is -0.89 with masker level, 0.06 with signal delay, and 0.18 with masker frequency. Only the correlations between PF slope and PF threshold and between PF slope and masker level are significant ($p < 0.05$). PF threshold also is significantly correlated with masker level (0.66) and with signal delay (-0.49). The higher correlation of PF slope with masker level than with signal level is unexpected, and may be due in part to results obtained for the 0-ms signal delay, on-frequency masker condition. When subjects S4, S5, and S8 are excluded from the mean data for the 0-ms signal

delay, on-frequency masker condition, the correlation of mean PF slope is -0.77 with mean PF threshold, -0.78 with masker level, 0.28 with signal delay, and 0.49 with masker frequency.

Given the form of the nonlinearity assumed by Plack and Oxenham (1998), described by two straight lines in dB coordinates, all PFs with signal levels falling only on the lower slope should be uniformly steep, while all PFs with signal levels falling only on the upper slope should be uniformly shallow. The pattern of results in Fig. 8 suggests a smooth nonlinearity that is continuously decreasing in slope and is consistent with recent models that incorporate smooth nonlinear functions (e.g., Glasberg and Moore, 2000) and with data that provide independent support for those models (e.g., Nelson *et al.*, 2001).

IV. EXPERIMENT 3

Variable-masker conditions were presented for on- and off-frequency maskers at one signal delay. In this case, it was predicted that the slopes of PFs for the on-frequency maskers would be shallow at higher masker levels, and that slopes of PFs for the off-frequency maskers would be steep across masker levels.

A. Subjects and procedures

Three females and one male from experiment 2 participated in experiment 3 (S4, S6, S8, and S10). The signal was a 4-kHz, 10-ms tone (5-ms rise/fall) shaped with a cosine-squared envelope, presented 0 ms after the offset of the masker. The on-frequency forward masker was a 4-kHz, 200-ms tone. The off-frequency forward masker was at 2.4

kHz. Maskers were shaped with 2-ms rise/fall cosine-squared envelopes. Stimulus generation and delivery were the same as for experiments 1 and 2.

Initially, signal levels were fixed at 30 and 50 dB SPL for both on- and off-frequency maskers. Thresholds were obtained using a 2IFC adaptive procedure in which the level of the masker was decreased after two correct responses and increased after one incorrect response. Step sizes were 4 dB. Threshold for a block was calculated as the mean of the masker levels of all reversals after the fourth reversal. Sixteen blocks of each condition were presented in a counter-balanced order. There was an extended break after completing data collection for these four conditions. In the process of data analysis, an error in the stimulus file was discovered for the off-frequency masker, 30-dB SPL signal level condition. All blocks in this condition were repeated for all subjects, along with four more blocks of the other three conditions as a check for consistent thresholds. The first four blocks that were collected previously in these conditions were excluded from further analysis.

The initial data for masker levels at threshold for fixed signal-level conditions of 30 and 50 dB were used to select signal levels that would produce an overlap in the range of masker levels at threshold for on- and off-frequency conditions. The final data set included threshold for the signal in quiet, and masked thresholds for fixed signal levels of 30, 50, 57, and 63 dB SPL for the on-frequency masker case, and 25, 30, 40, and 50 dB SPL for the off-frequency masker case. Twelve 50-trial blocks were completed for threshold in quiet, and 16 50-trial blocks were completed in the remaining conditions, with the exception of the off-frequency masker in the 25-dB SPL signal level condition. S6's threshold for the signal in quiet was 24.9 dB SPL, and she reported difficulty hearing the signal and masker in the 25-dB SPL fixed-signal condition. The condition was terminated after eight blocks for all subjects.

Subjects occasionally produced masked thresholds that clearly deviated (e.g., by more than 8 dB) from the rest of their masked thresholds in a particular condition. These data were excluded, and runs for the corresponding conditions were repeated. In one instance, a subject produced unusually variable thresholds for the 63-dB SPL fixed-signal, on-frequency masker condition (8.95 dB standard deviation across the 16 thresholds), which were all collected during one test session. These initial thresholds were discarded, and 16 more repetitions were collected. This second set of thresholds had a lower standard deviation, and were used for further data analysis.

PFs were calculated using the Dai (1995) method. However, because PFs in this case described percent correct as a function of masker level, percent correct increased as masker level decreased. PFs were fitted for individual subjects, and only those fits that produced r^2 values of >0.50 were included in further analyses. With this criterion, PFs were excluded for the off-frequency masker, 25 dB SPL signal condition for subjects S6 and S10. Correlations were calculated for mean PF slope as a function of mean PF threshold for on- and off-frequency masker conditions.

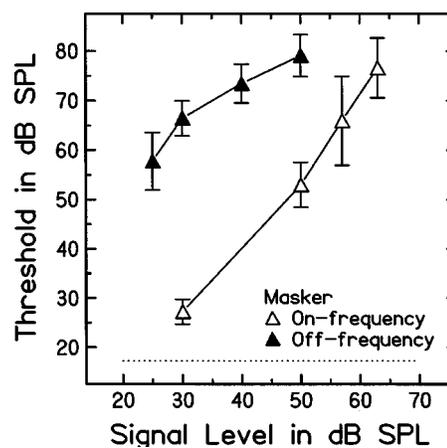


FIG. 9. Mean masker levels at threshold across subjects as a function of signal level for experiment 3. The on-frequency forward masker (open symbols) was a 4-kHz, 200-ms tone and the off-frequency forward masker (filled symbols) was a 2.4-kHz tone presented in a variable-masker condition. The signal was a 4-kHz, 10-ms tone presented at 0-ms signal delay. Mean threshold for the signal in quiet is represented by the dotted line. The signal was fixed in different conditions at 30, 50, 57, and 63 dB SPL for the on-frequency masker case, and at 25, 30, 40, and 50 dB SPL for the off-frequency masker case. Masker level at threshold is much higher in the off-frequency masker case than for the on-frequency case, particularly for the lower signal levels. The slope of GOM is more shallow for the off-frequency case. These trends agree with the literature.

B. Results

Mean growth of masking (GOM) functions in the variable-masker conditions are shown in Fig. 9. The GOM in the variable-masker conditions was steeper for on-frequency maskers than for off-frequency maskers. The PF thresholds, slopes, and r^2 values for each subject in each condition are summarized in Table III. The correlation of mean PF slope and mean PF masker level at masked threshold was -0.88 for the on-frequency masker case and -0.87 for the off-frequency masker case. Given the small number of data points, neither of the correlations was significantly different from zero. The negative correlation in the on-frequency case was expected, but the correlation was expected to be near 0 for the off-frequency case.

PF fits to the individual data for select conditions are shown in Fig. 10. As noted in experiments 1 and 2, there is variability in PF slopes among the subjects. For example, PFs for subjects S4 and S6 reflect the expected trends, that is, PFs are steeper in the off-frequency masker conditions across masker level in comparison to the shallower PFs in the on-frequency masker conditions. However, subject S8's PFs are of similar slope across all conditions. Subject S10's PFs are shallow across conditions, which is similar to experiment 2 in which the PFs for the same subject were shallow regardless of masker frequency, masker level, or signal delay (see Fig. 8). There are also concerns regarding individual fits. Although the PF fit for the off-frequency masker, 50-dB fixed-signal level condition for S10 met the criteria for inclusion in data analysis, for example, the line appears to approximate only one or two data points. Alternative fits with higher values of r^2 and better visual properties are available, but the values of χ^2 associated with those fits are much greater.

TABLE III. PF thresholds and slopes, and r^2 values for PF fits for each subject in each condition in experiment 3.

Subject	Masker frequency	Signal level	Threshold	Slope	r^2
S4	On	30	27.32	1.00	1.00
		50	54.53	0.55	0.99
		57	75.77	0.32	0.94
	Off	63	79.33	0.51	0.89
		25	61.71	1.75	1.00
		30	65.93	1.15	0.99
S6	On	40	72.79	1.51	1.00
		50	77.78	0.99	0.96
		30	26.42	0.62	0.97
	Off	50	51.42	0.33	0.85
		57	60.96	0.26	0.88
		63	77.33	0.26	0.82
S8	On	25	32.88	0.11	0.28
		30	64.39	1.38	0.98
		40	72.70	0.51	0.71
	Off	50	80.41	1.13	0.99
		30	26.89	0.74	0.90
		50	50.97	1.18	0.90
S10	On	57	58.44	0.46	0.91
		63	67.86	0.45	0.81
		25	53.33	0.55	0.82
	Off	30	59.60	0.64	0.89
		40	65.84	1.09	0.97
		50	71.88	0.92	0.99
S10	On	30	21.69	0.52	0.90
		50	43.65	0.40	0.84
		57	59.20	0.20	0.90
	Off	63	68.83	0.41	0.99
		25	58.45	0.08	0.27
		30	67.40	0.33	0.86
Off	40	73.97	0.19	0.77	
	50	77.93	0.27	0.80	

V. DISCUSSION

A. Methodological issues

Our confidence in the interpretation of the current PF data is limited by several issues that are ongoing topics of

debate in the literature. The first is the use of adaptive-procedure data to estimate PF parameters. Simulation studies suggest that procedures with more than two intervals, combined with a decision rule that estimates a higher point on the PF, provide more efficient and more accurate estimates of the PF slope (e.g., Leek *et al.*, 1992; Leek, 2001). Dai (1995), using a similar approach based on extensive simulations, found that estimates of PF parameters were unbiased when obtained using the data collection and analysis procedures we have used, although he did not explore the alternative decision rules tested by Leek *et al.* (1992). While Dai (1995) evaluated the accuracy of both the PF slope and the PF threshold estimate, only the accuracy of the slope estimate is of any concern here. The PF threshold estimates are highly correlated with the estimates obtained by taking the mean of the reversal points in the adaptive procedure ($r=0.99$ for the 231 thresholds in experiment 2), a widely used threshold measure.

The second issue is the choice of equation used to fit the PFs and to estimate the slope parameter. The estimates of PF slope reflect the representation of the stimuli used in fitting the PFs, as well as the assumed form of the PF. Any of the approaches used in the detection literature would show shallower slopes at higher signal levels, but the outcome of a statistical analysis could be somewhat dependent on the measure of slope that was used. We converted signal levels to power and fitted the data using the same equation used to fit PFs for absolute thresholds (e.g., Watson *et al.*, 1972). This approach seemed most consistent with the literature, given that the data were obtained in a masking procedure where we had no valid measure of the effective level of the masker at the time the signal was presented. The Plack and Oxenham (1998) model assumes, however, that the task is equivalent to intensity discrimination where the decision variable is an internal representation of $\Delta I/I$ or $(I + \Delta I)/I$. Those two quantities produce identical threshold predictions when using the model, but they do not result in identical PFs. Use of $\Delta I/I$,

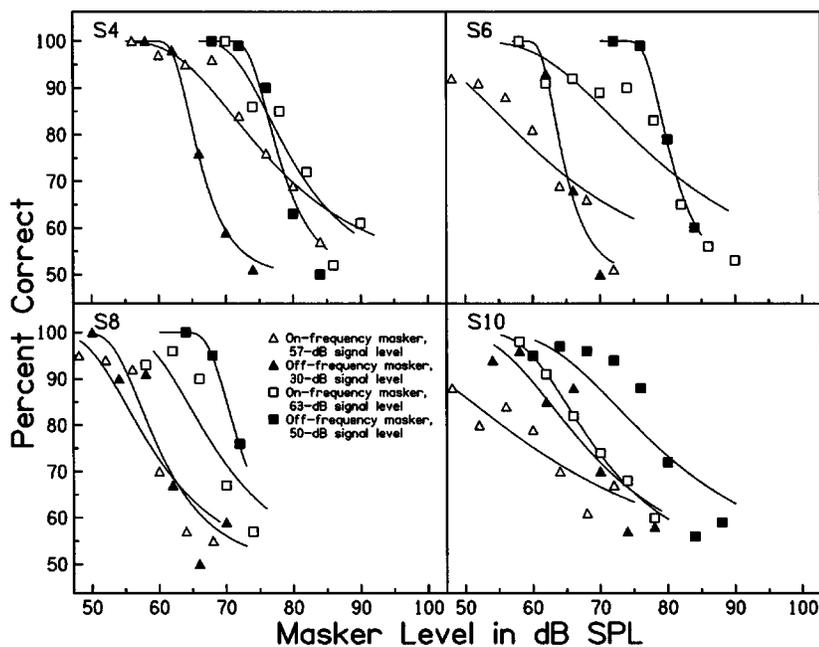


FIG. 10. Example PF fits to the individual data for variable-masker conditions in experiment 3. Data for the on-frequency masker, 57- and 63-dB fixed-signal-level conditions are represented by open triangles and squares, respectively. Data for the off-frequency masker, 30- and 50-dB fixed-signal-level conditions are represented by filled triangles and squares, respectively. PF fits to the data are represented by solid lines. PFs for subjects S4 and S6 demonstrate steeper PFs in the off-frequency masker conditions across masker level, and shallower PFs in the on-frequency masker conditions. However, PF slopes are similar across conditions for subjects S8 and S10s. For S10, PFs are shallow across conditions for variable-masker conditions (this figure) and variable-signal conditions (see Fig. 8).

where I was a constant dependent on masker level, would rescale all points on the function leaving the slope unchanged and thus would produce slope estimates identical to those we have obtained. Conversion to $(I + \Delta I)/I$ would be a nonlinear transform, with unclear results, but it seems unlikely that the differences in the fits would be large. We assumed a form of the PF (e.g., Egan *et al.*, 1969) that has been widely used in the detection literature, but many alternatives have been proposed. There are only two other studies in the literature that we are aware of that have reported PFs for forward masking conditions. Werner (1999) plotted PFs in percent yes votes versus signal level in dB, but did not fit an equation to the data. Nizami and Schneider (1999) used probit analysis to fit PFs as normal ogives in percent correct versus signal level in dB. Their PFs were similar in form to those generated with the Egan *et al.* equation.

The quality of some of the individual PF fits also is an issue. In order to avoid ambiguity in the analyses and the potential for selective data trimming when fitting a large number of PFs, we adopted strict rules for removing data points before fits were done and for excluding unreliable fits when computing mean slope values. The criterion of $r^2 > 0.50$ used for inclusion of the PF slope in summary data was somewhat arbitrary, but use of other criterion points did not have a strong effect on the correlation of slope with signal level or masker level. Some fits appeared to be less than optimal when the PFs were plotted with the actual data points (e.g., Fig. 10, S10, off-frequency masker, 50-dB signal level data) because the maximum likelihood procedure (Dai, 1995) assigned more weight to points higher on the PF.

Finally, it is a concern that the individual data were highly variable across subjects and conditions. For example, subject S10 demonstrated shallow PFs as a function of signal level, regardless of masker frequency, masker level, signal delay, or varied parameter (see Fig. 8 and Fig. 10). We do not have an explanation for this trend. One possibility is that this subject has greater internal noise in comparison to the other subjects. If this is the case, the difference in internal noise did not extend to detection of the signal in quiet, where results are in line with the remaining subjects (see the data points represented by stars in Fig. 8). Another example of individual variability is that a few of the subjects demonstrated higher PF slopes than would have been expected, given the associated signal levels, in the on-frequency masker, 0-ms signal delay, variable-signal condition (see S4, S5, and S8 in Fig. 8). There is not sufficient information to determine whether the slopes or the thresholds were unusually high. It also cannot be determined at this point whether this threshold/slope effect is one that should be taken into account in a model of forward masking, or could be attributed to a phenomenon such as confusion (Neff, 1985, 1986) that is outside the framework of the model. A confusion effect seems unlikely given that such effects are not generally found for sinusoidal maskers and signals, and tend to be associated with nonmonotonic PFs, with sharp decreases in percent correct in regions where the signal and masker levels are nearly equal. Of the individual PFs that met the criteria for inclusion in the mean, only one function (subject S4, 90-dB masker condition, see Fig. 7) displayed this trend.

B. Effects of the peripheral nonlinearity

Despite the methodological considerations discussed in the previous section, the peripheral nonlinearity is clearly reflected in both the GOM and PF data. In general, GOM functions for on- and off-frequency maskers and with various signal delays were consistent with previous reports in the literature for variable-signal conditions (Fastl, 1979; Jesteadt *et al.*, 1982; Kidd and Feth, 1981; Luscher and Zwislocki, 1947; Munson and Gardner, 1950; Oxenham and Plack, 2000; Plack and Oxenham, 1998; Widin and Viemeister, 1979; Zwislocki *et al.*, 1959) and variable-masker conditions (Nelson *et al.*, 2001, 1990; Nelson and Freyman, 1987, 1984; Oxenham and Plack, 1997). The Plack and Oxenham (1998) model, which includes peripheral nonlinearity as a first stage, provides an excellent account of the present GOM data for on-frequency maskers (see the left panel of Fig. 6). The current data for off-frequency maskers show a larger effect of signal delay on GOM functions than observed by Oxenham and Plack (2000), but the effect was still smaller than that observed with on-frequency maskers, in agreement with their model.

Plack and Oxenham (1998) make no specific predictions concerning PFs, but the assumptions of the model suggest that PF slopes should reflect the nonlinearity, and the model and supporting data specify the degree of nonlinearity expected for the on- and off-frequency maskers used here. The model assumes that internal noise is Gaussian in power with a standard deviation that is proportional to the mean (i.e., constant in dB), except in conditions where the masked threshold is near quiet threshold. Given that internal noise is constant, the slope or exponent of the PF should be proportional to the degree of nonlinearity. To a first approximation, the results of the present experiments were consistent with this prediction. In the variable-signal conditions of experiments 1 and 2, PF slopes decreased as a function of signal level for on- and off-frequency maskers. This was expected because in variable-signal conditions, the signal passes through a range of input levels to the nonlinearity at the place of the signal during threshold estimation. Thus, the associated PF slopes should be influenced by the nonlinearity at the place of the signal, regardless of masker frequency. Given this trend, it also was expected in experiment 2 that PF slope would be more highly correlated with signal level at threshold than with the other variables (i.e., masker level, signal delay, and masker frequency). However, the correlation of PF slope with masker level was greater than the correlation with signal level. This relationship is explored further in the following section.

In the variable-masker conditions of experiment 3, it was expected that PF slope would be shallower at higher masker levels for the on-frequency masker case, and that PF slope would remain steep across all masker levels for the off-frequency masker case. This is because in the variable-masker condition, masker level passes through a range of input levels to the nonlinearity at the place of the signal as the PF is obtained for any given condition. Thus, the on-frequency masker will be influenced by the nonlinearity at the place of the signal, and the associated PF slopes will reflect the amount of compression, whereas the off-frequency

masker will grow linearly at the place of the signal, and the associated PF slopes should be similar over the entire range of masker levels. Only two of the four subjects demonstrated this trend. Because on- and off-frequency masker cases were examined separately, there were fewer data points available for the correlation in experiment 3 in comparison to experiment 2 in which on- and off-frequency data were combined. Given the small number of data points, we cannot draw any meaningful conclusions from the correlation coefficients for experiment 3.

Both of the previous studies that describe PFs for forward-masked conditions used variable-signal procedures. Werner (1999) used a 65-dB SPL broadband noise to mask a 1-kHz tone with signal delays varying from 5 to 200 ms in normal-hearing adults and infants 3 to 6 months of age. The PFs for the adult group were steep and parallel across signal delay, and all PFs were restricted to signal levels below approximately 40 dB SPL. Thus, the PFs for the adult group in the Werner study were not in a signal-level range that would have reflected the effects of the nonlinearity as in the current study. Even if the PFs had extended into a higher signal range, it is not clear that the effects of the nonlinearity should be evident in conditions using a broadband masker rather than a pure tone masker. Nizami and Schneider (1999) obtained their data using a 97-dB, on-frequency, 2-kHz tone to mask a Gaussian-shaped signal, and manipulating signal delay in very small steps. While we found a large effect of masker level on PF slope in experiment 2, in the Nizami and Schneider study, masker level was constant. Their data point to a strong effect of signal level. They also observed fine structure and nonmonotonicity in their PF parameters, characterized by sharp increases in masked threshold and slope with successive increases in signal delay. This fine structure was not observable in the current data because of the large differences in signal delays (2, 20, and 40 ms in experiment 1, and 0, 10, and 30 ms in experiment 2 in the current study, as opposed to 0.5-ms steps in some cases in the Nizami and Schneider study). The general trend in their data was for masked threshold to decrease and PF slope to increase as signal delay increased. This is consistent with the current data (experiments 1 and 2, on-frequency masker) and with the interpretation that signal level at threshold determines the slope of the PF.

The Plack and Oxenham (1998) model can be extended to make specific quantitative predictions about PF slope ratios, in addition to the qualitative predictions reviewed above. If the slope or exponent of the PF is truly proportional to the degree of nonlinearity, then the compression ratio assumed in the model should be reflected in the slopes estimated from the data. Plack and Oxenham (1998) assumed a compressive nonlinearity with a lower slope of 0.78 dB/dB and an upper slope of 0.16 dB/dB, a ratio of 4.9 to 1 in the model fits to their on-frequency masker data. This is similar to the ratio of 5.2 to 1 that was obtained with the parameters estimated from the current GOM data (see Fig. 6, lower slope of 0.62 and upper slope of 0.12) and predicts a ratio of 5 to 1 in the slopes of the PFs. The observed ratio of the mean PF slope at 25.8 dB (slope=0.99), the lowest signal level in the mean data panel of Fig. 7, to the mean slope at

85.1 dB (slope=0.31), the highest signal level, was 3.2 to 1. The smaller ratio may reflect errors in fitting the PFs.

Finally, regardless of the strength of the relationship between signal level and PF slope, the pattern of PF slopes across conditions should predict the general form of the nonlinearity. The assumption in the Plack and Oxenham (1998) model that the nonlinearity can be approximated by a two-part function defined by two straight lines predicts two groups or clusters of data points in Figs. 4 and 8, one at high PF slope values (i.e., to reflect the linear portion of the function) and the other at low slope values (to reflect the compressive portion of the function). The PF slope data suggest a nonlinearity with a continuously decreasing slope or a very gradual transition, consistent with more recent models that include a peripheral nonlinearity (e.g., Glasberg and Moore, 2000).

The degree of peripheral nonlinearity has been estimated from masking data using the comparison of slopes of GOM for on- and off-frequency maskers in variable-masker conditions (Oxenham and Plack, 1997), from the ratio of temporal-masking-curve slopes for on- and off-frequency maskers (Nelson *et al.*, 2001), and from behavioral thresholds in on-frequency masking conditions with a range of signal delays and masker levels, such as those shown in Fig. 6. The current data suggest that measures based on slopes of PFs might offer another alternative that, with use of optimum procedures for measurement of PFs, could be both efficient and broadly applicable. The ratio of slopes of GOM functions for on- and off-frequency maskers only provides an estimate of the compressive portion of the nonlinearity, not of the transition or the lower, steeper portion of the function. In contrast, the ratio of fixed-probe temporal-masking-curve slopes for on- and off-frequency maskers provides an estimate of the transfer function for a larger range of input levels, including the lower levels (Nelson *et al.*, 2001). However, collection of a full set of data for a range of masker levels and signal delays is time consuming and recovery of nonlinearity parameters for either method requires a specific model with numerous assumptions. The range of PF slopes from a carefully selected set of conditions could be used to provide a more complete estimate of the nonlinearity, with fewer *a priori* assumptions concerning its form.

C. Exploring the masker level effect on PF slope

By far the biggest issue in the interpretation of the current data is the strong effect of masker level on the slope of the PF. The original hypothesis was that PF slope would have a higher correlation with signal level than with the other variables in experiment 2 because the signal level was varied in the adaptive procedure to reconstruct the individual PFs within conditions. However, it was found that PF slope was more highly correlated with masker level than with signal level. Interpreting the relationship between PF slope and signal level, and between PF slope and masker level, is complicated by the fact that masker level and signal level are highly correlated with each other. We examined these relationships further using partial correlations to obtain a measure of the relation between PF slope and each variable, with all other

variables held constant. The partial correlation of PF slope with threshold was -0.06 , with masker level was -0.71 , with signal delay was 0.05 , and with masker frequency was 0.28 . Thus, signal level at threshold had no almost relationship to PF slope once the remaining variables were accounted for in the comparison. Masker level had the strongest relationship with PF slope, indicating that as masker level increased, PF slope decreased with signal level held constant. This effect is not predicted by the model described in Fig. 1. When the data from the three subjects (S4, S5, and S8) in the 0-ms signal delay conditions were excluded from the analysis, the overall correlation of PF slope decreased with masker level (from -0.89 to -0.78) and increased with signal level (from -0.69 to -0.77). A similar trend was noted in the partial correlations of PF slope with masker level (a decrease from -0.71 to -0.61) and with signal level (an increase from -0.06 to -0.10). Partial correlations of PF slope increased with signal delay to 0.29 and with masker frequency to 0.34 . This shift in the zeroth order and partial correlations cannot account for the masker level effect, and it does not change the conclusion that masker level has a strong, independent contribution to PF slope.

Three factors might contribute to the strong effect of masker level in experiment 2. First, the relationship between signal level at threshold and PF slope is not linear, and therefore would be poorly represented by a correlation that assumes a linear relationship between variables. The mean data panel in Fig. 7 could be viewed as nonlinear, particularly if the 0-ms signal delay conditions are disregarded, and the model described in Fig. 1 predicts a nonlinear effect. We do not have enough data points to support a nonlinear regression analysis. Second, the correlation of PF slope with signal level at threshold is attenuated by the measurement error associated with the latter variable. Masker level, masker frequency, and signal delay are all independent variables whose values are not subject to measurement error. We do not have an appropriate measure of the reliability of the estimates of signal level at threshold that could be used to correct for attenuation (e.g., Guilford, 1965, p. 487). Data from experiment 3, where masker level was the dependent variable, are too limited to provide a valid comparison.

Third, the strong effect of masker level might reflect an increase in internal noise with an increase in overall level. In the example provided in Fig. 1, the internal noise is assumed to be the same across conditions as represented by lower and upper PDFs with similar standard deviations on the Y axis. An increase in internal noise with increases in level, corresponding to the more compressive region of the function, would be represented by an upper PDF with a larger standard deviation. This would result in a stronger effect of masker level than of signal level because masker levels vary over a wider range than signal levels. We would also predict an effect of masker level with signal level held constant. Of the factors considered here, the assumption that internal noise is greater at higher levels seems best able to account for the observed pattern of results. This assumption would have a significant impact on procedures for fitting threshold data. It may be possible to test the assumption by measuring the amount of internal noise (e.g., Spiegel and Green, 1981).

VI. CONCLUSIONS

Growth of masking results for on- and off-frequency forward-masker cases, in variable-masker and variable-signal conditions, were consistent with the literature. The mean on-frequency masker data from experiment 2 were well represented by a model described by Plack and Oxenham (1998) that incorporates a peripheral nonlinearity as its first stage. The model assumptions suggest that this nonlinearity also should be reflected in the PF slopes. Mean PF slopes decreased with increases in mean signal level at threshold for on- and off-frequency masker cases in the variable-signal conditions of experiments 1 and 2. PF slopes were shallow for on-frequency maskers and steep for off-frequency maskers at high thresholds for two of the four subjects in the variable-masker conditions of experiment 3. These results are consistent with the hypothesis that the peripheral nonlinearity is reflected in PF slopes, particularly for experiments 1 and 2. Further data collection would be necessary to make stronger statements about the influence of the peripheral nonlinearity on PF slopes for variable-masker conditions. PF slopes from select conditions could be used to produce more direct estimates of the specific form of the nonlinearity than can be obtained by fitting current models to threshold data. An unexpected result was the strong relationship of masker level with PF slope, independent of signal level. This finding might be explained by assuming that internal noise increases with increasing stimulus level. Greater internal noise would result in shallower PFs. Given that masker levels are higher than the corresponding signal levels at threshold in forward masking and that the range of masker levels is greater than the range of signal levels, an internal noise that increased with stimulus level would result in a correlation between PF slope and masker level that was higher than the correlation between PF slope and signal level. Further work will be required to determine the cause of the masker level effect.

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¹The number of signal levels excluded during the PF fitting procedure varied among subjects, and depended, for example, upon the starting level of the signal at the beginning of each adaptive track. Because we collected data from three to four subjects simultaneously in experiments 2 and 3, the starting level was the same for all subjects. A greater number of signal levels were trimmed due to rare occurrence for subjects who had lower thresholds because they produced correct responses at a larger number of the initial signal levels in comparison to subjects with higher thresholds. As threshold was approached, many of these initial signal levels were not presented again for those with lower thresholds, but were presented repeatedly for those with higher thresholds. We counted the number of signal levels that remained after trimming the levels that were associated with low occurrence or less than 50% correct, and averaged these value across conditions and subjects for experiments 1 and 2. The mean number of signal

- levels left after the trim was 5.1 (sd=1.3) for experiment 1, and 4.5 (sd = 1.5) for experiment 2.
- ²The temporal window parameters used in fitting the current data were fixed at $Tb1=4.00$, $Tb2=29.00$, $w=0.16$, and $Ta=3.50$. $Tb1$, $Tb2$, and Ta were the same values Plack and Oxenham (1998) used to fit their data. Although Plack and Oxenham (1998) used a different value for w in the 1998 study, and Oxenham (2001) found better fits after allowing $Tb1$, $Tb2$, and w to vary, we felt the fit to our data was adequate using the original temporal window parameters listed above.
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