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## Influence of primary-level and primary-frequency ratios on human distortion product otoacoustic emissions<sup>a)</sup>

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### Abstract

The combined influence of primary-level differences ( $L_1-L_2$ ) and primary-frequency ratio ( $f_2/f_1$ ) on distortion product otoacoustic emission (DPOAE) level was investigated in 20 normal-hearing subjects. DPOAEs were recorded with continuously varying stimulus levels for the following stimulus conditions:  $f_2 = 1, 2, 4,$  and  $8$  kHz and  $f_2/f_1 = 1.05$  to  $1.4$ ; various  $L_1-L_2$ , including one individually optimized to produce the largest DPOAE. For broadly spaced primary frequencies at low  $L_2$  levels, the largest DPOAEs were recorded when  $L_1$  was much higher than  $L_2$ , with  $L_1$  remaining relatively constant as  $L_2$  increased. As  $f_2/f_1$  decreased, the largest DPOAEs were observed when  $L_1$  was closer to  $L_2$  and increased as  $L_2$  increased. Optimal values for  $L_1-L_2$  and  $f_2/f_1$  were derived from these data. In general, average DPOAE levels for the new  $L_1-L_2$  and  $f_2/f_1$  were equivalent to or larger than those observed for other stimulus combinations, including the  $L_1-L_2$  described by Kummer et al. (1998) and those defined by Neely et al. (2005) in which  $L_1-L_2$  was evaluated, but  $f_2/f_1$  was fixed at 1.2.

### I. INTRODUCTION

Distortion product otoacoustic emissions (DPOAEs) have been used to assess normal and impaired cochlear function in humans (e.g., Stover et al., 1996; Janssen et al., 1998; Kummer et al., 1998; Abdala 2000, 2003; Dorn et al., 2001; Gorga et al., 1993, 2002, 2003; Abdala and Fitzgerald, 2003; Neely et al., 2003) and are commonly used as a clinical tool for the objective prediction of auditory status (e.g., Gorga et al., 1997; Norton et al., 2000). The level of the DPOAE recorded in the ear canal depends on the frequency and level characteristics of the stimuli used to elicit the DPOAE. The choice of stimulus parameters, therefore, may influence the success with which DPOAEs can be used to assess cochlear function and predict auditory status. It may be more important to focus on maximizing DPOAE level rather than other DPOAE measures such as signal-to-noise ratio (SNR) on the assumption that DPOAE level is correlated with cochlear function. Additionally, while DPOAE phase may be important for basic research applications (e.g., Shera and Guinan, 1999), current clinical applications of DPOAE measures depend on DPOAE level (or SNR), but largely ignore phase measurements.

A number of previous investigations have examined the influence of stimulus parameters on the DPOAE (e.g., Harris et al., 1989; Brown and Gaskell, 1990; Gaskell and Brown, 1990; Hauser and Probst, 1991; Whitehead et al., 1995a, c) resulting in recommendations for stimulus conditions likely to yield robust emissions in human ears. A constant level relation of  $L_1-L_2 = 10$  or  $15$  dB has been used in some cases (Gorga et al., 1993; 1997), although recent work

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reported by Kummer et al. (1998) suggests that setting  $L_1 = 0.4 \cdot L_2 + 39$  results in the largest DPOAE level at each  $L_2$ , independent of frequency (Kummer et al., 2000). A primary-frequency ratio of 1.22 has been recommended as optimal (Harris et al., 1989; Gaskill and Brown, 1990; Brown et al., 1994), although variability in the frequency ratio producing the largest DPOAE across stimulus frequency has been reported (Harris et al., 1989).

The majority of previous parametric investigations of the DPOAE stimulus space, especially those involving humans, have focused on a restricted region of the level and/or frequency space. Although Mills (2002) described a comprehensive investigation of the four-dimensional stimulus space in gerbil, similar investigations have not been completed in humans. This is due, in part, to the time involved in recording DPOAEs in response to a large number of stimulus combinations.

Neely et al. (2005) described a novel method of recording DPOAE responses using continuously varying stimulus levels, which was validated by comparing results with it to more traditional measurements in which  $L_1$  and  $L_2$  were set to discrete values. Using this new method, Neely et al. were able to more fully explore the two-dimensional  $L_1, L_2$  space in a group of normal-hearing subjects and were able to determine an individually optimized primary-level difference ( $L_1-L_2$ ). Larger DPOAE levels were recorded when the individually optimized  $L_1-L_2$  was used, as compared to DPOAE levels obtained with the relation recommended by Kummer et al. (1998). Furthermore, in contrast to the findings reported by Kummer et al. (2000), where the optimal  $L_1-L_2$  was found to be independent of  $f_2$ , Neely et al. found a systematic effect of  $f_2$  on the optimal  $L_1-L_2$ . Specifically, the optimal  $L_1-L_2$  for low-level stimuli increased with  $f_2$ . When  $f_2 = 8$  kHz, the optimal  $L_1-L_2$  resulted in DPOAE levels that were approximately 10-dB higher than those observed with the approach to setting stimulus level recommended by Kummer et al. (1998). These differences decreased as  $f_2$  decreased and, on average, were only 2 dB when  $f_2 = 1$  kHz.

Although the reason for the discrepancy between the Neely et al. (2005) results and the results reported by Kummer et al. (1998, 2000) is not clear (it may be due, in part, to differences in recording paradigms), a question arising from the Neely et al. data is whether the variation in optimal  $L_1-L_2$  with  $f_2$  can be attributed to differences in cochlear frequency selectivity along the length of the basilar membrane. Direct observation of basilar-membrane motion in lower animals suggests that the spatial distribution of excitation patterns is more localized at the base of the cochlea than at the apex (e.g., Robles and Ruggero, 2001). The observation in Neely et al. (2005) that the  $L_1-L_2$  for maximum DPOAE level is larger for  $f_2 = 8$  kHz than for  $f_2 = 1$  kHz is consistent with the idea that excitation patterns for the eliciting stimuli (i.e., the two primaries) are more spatially separated when  $f_2 = 8$  kHz than when  $f_2 = 1$  kHz, requiring an increase in the level of  $f_1$  in order to generate “optimized” overlap at the  $f_2$  place.

The purpose of the present study was to provide a more complete investigation of the stimulus parametric space in humans and to further investigate the trends observed by Neely et al. (2005). We hypothesized that differences in frequency resolution as a function of  $f_2$  might underlie the effect of  $f_2$  on the primary-level difference producing the largest DPOAE. Stated another way, more sharply defined representation of high-frequency primaries at the cochlear base might result in less effective overlap between  $f_2$  and  $f_1$ , requiring an increase in  $L_1$  relative to  $L_2$  in order to maximize the interaction between primaries and the generation of distortion. In contrast, broader cochlear representation for lower frequencies might result in greater overlap (for the same  $f_2/f_1$ ); under these conditions, maximum distortion might be produced when there was less difference between  $L_1$  and  $L_2$ , compared to high-frequency conditions. Furthermore, we predicted that, for any stimulus frequency, a broader cochlear representation would occur as level increased; thus, we hypothesized that an interaction might occur among  $f_2/f_1$ ,  $L_1 - L_2$ , and  $L_2$ . A related goal was to determine the stimulus parameters producing the

largest DPOAE levels in a group of normal-hearing subjects, with the expectation that those conditions might have use in the clinical application of DPOAEs.

## II. METHODS

### A. Subjects

Twenty normal-hearing subjects participated in this project. Normal hearing was defined as thresholds  $\leq 10$  dB HL (ANSI, 1996) for the octave frequencies from 0.25 through 8 kHz. Normal 226-Hz tympanograms were required just prior to each session in which DPOAE data were collected.

### B. Procedures

All DPOAE data were collected using custom-designed software (SYSRES, Neely and Stevenson, 2002) that controlled a 24-bit soundcard (CardDeluxe, Digital Audio Labs) housed in a PC. An ER-10C probe-microphone system was used to present stimuli and record DPOAE responses. Stimuli were calibrated in-situ in sound pressure level at the plane of the probe. While concerns exist for pressure calibrations in the ear canal (Siegel, 1994; Siegel and Hirohata, 1994; Neely and Gorga, 1998), those same concerns apply for other approaches to selecting stimulus conditions for DPOAE measurements. In-situ pressure calibration represents one of the sources of variability in our DPOAE measurements. The variability associated with in-situ pressure calibration is acknowledged and accepted as inherent in current standard calibration methods. This variability is addressed in our study by including subjects ( $N = 20$ ) with a range of different ear canal dimensions.

DPOAEs were recorded in response to pairs of primary tones ( $f_1, f_2$ ) whose levels ( $L_1, L_2$ ) varied continuously. The frequency of  $f_2$  varied in octave steps from 1 to 8 kHz. Responses for a total of 8 primary-frequency ratios ( $f_2/f_1$ ), ranging from 1.05 to 1.40 in steps of 0.05, were recorded for each subject. The continuous-level method has been described previously (Neely et al., 2005). Briefly, the levels of  $f_1$  and  $f_2$  are continuously amplitude modulated in dB. The DPOAE level is extracted using a frequency-domain, heterodyne technique (Kim et al., 2001). As in our previous work with the continuous-level method (e.g., Neely et al., 2005), DPOAE responses were recorded using two different stimulus paths, a Lissajous path and a linear path, each of which is described below.

In the Lissajous-path condition, the levels of the primary stimuli were continuously amplitude modulated over a 33-s time course, which was repeated.  $L_2$  ranged from 17 to 69 dB SPL and  $L_1$  ranged from 43 to 76 dB SPL. In each half of the 66-s stimulus buffer, 23 cycles of  $L_1$  modulation and 17 cycles of  $L_2$  modulation were presented. Stimulus and DPOAE levels were determined by summing the two halves of the buffer. Noise levels (at the  $2f_1-f_2$  frequency) were determined by subtracting the halves. These stimulus conditions allowed us to rapidly record DPOAE responses for stimulus conditions representing a broad  $L_1, L_2$  space. The rapid collection of data for the Lissajous-path stimulus results in a smoothing of the DPOAE response levels. As a consequence, the DPOAE levels obtained with this stimulus can be compared in relative terms across  $L_1, L_2$  combinations; however, as will be seen below, DPOAE levels obtained with this stimulus cannot be compared to those obtained with more traditional stimulus and recording parameters. The reader is referred to Neely et al. (2005) for more information regarding the Lissajous-path stimuli.

The responses to the Lissajous-path stimuli were used to determine the optimal, linear  $L_1, L_2$  relationship for each subject and each  $f_2/f_1$  combination (as described below). The DPOAE levels recorded for the Lissajous-path stimuli also were used to compare the responses obtained

for a variety of linear  $L_1, L_2$  paths, including the frequency-independent relation recommended by Kummer et al. (1998) and the frequency-dependent paths described in Neely et al. (2005).

Each individual's optimal path was determined from the response to Lissajous-path stimuli by identifying the  $L_1$  producing the largest DPOAE for each  $L_2$ . A linear function was fit to the subset of these  $L_1, L_2$  values producing responses with a signal-to-noise ratio (SNR)  $\geq 12$  dB. Pilot data suggested that a 12-dB SNR represented a reasonable compromise between the need to fit a function over a range of  $L_2$  levels and the desire to minimize the influence of noise on the line fits. The resulting equation describes the optimal, linear path through  $L_1, L_2$  space. This procedure was repeated for each  $f_2$  and  $f_2/f_1$  combination, resulting in a total of 32 optimal linear paths for each subject ( $4 f_2 \times 8 f_2/f_1$ ).

For each subject, DPOAE I/O functions were recorded along these 32 optimal linear  $L_1, L_2$  paths. The optimal linear-path I/O functions were recorded using continuously varying stimulus levels, in a manner similar to that used to record responses to the Lissajous-path stimuli. However, these I/O functions were obtained with more slowly varying stimulus levels such that only one cycle of  $L_1$  and  $L_2$  modulation was presented in each half of the 66-s stimulus buffer. As for the Lissajous-path stimuli, the stimulus and DPOAE levels were obtained by summing the two halves of the buffer and the noise was obtained from the difference.  $L_2$  varied continuously from -20 to 80 dB SPL and  $L_1$  varied according to each individual's optimal linear path. For certain conditions (typically the smallest and largest frequency ratios) in several subjects, we were unable to determine an optimal  $L_1, L_2$  relationship because the DPOAE levels were too small to fit a valid linear function to the Lissajous-path responses (i.e., points with  $\geq -12$  dB SNR extended over less than a 10-dB  $L_2$  range). For these conditions in these subjects, the optimal linear  $L_1, L_2$  path condition was not tested.

All data were collected in a sound-treated room. During data collection, subjects relaxed or slept in a reclining chair. They were asked to remain quiet throughout the test session and breaks were provided as needed. These data were typically collected in three test sessions, with each session lasting two hours.

### III. RESULTS

#### A. Responses to Lissajous-path stimuli

DPOAE levels in  $L_1, L_2$  stimulus space for each  $f_2$  and  $f_2/f_1$  are shown as contour plots in Fig. 1. These data represent the DPOAE levels obtained for the Lissajous-path stimuli averaged across all 20 subjects. Each column represents data for a different  $f_2$ , from  $f_2 = 1$  kHz (left column) to  $f_2 = 8$  kHz (right column). Each row represents data for a different  $f_2/f_1$ , with  $f_2/f_1 = 1.40$  in the top row, decreasing to  $f_2/f_1 = 1.05$  in the bottom row. The contours are spaced in 2-dB increments of DPOAE level, with the maximum DPOAE level represented by the contours in the upper right portion of each panel. As a reference, the contours corresponding to a DPOAE level of -6 dB SPL (a level that exists in all but three panels) are indicated with a thicker line than the other contours. There is no reference line for the conditions where  $f_2 = 8$  kHz and  $f_2/f_1 = 1.40, 1.35,$  or  $1.05$ . Here, the maximum DPOAE level was -8 dB SPL. Also shown as solid sloping lines in each panel are the average optimal linear  $L_1, L_2$  stimulus paths obtained by averaging the coefficients for each subject's optimal path for each  $f_2$  and  $f_2/f_1$  combination. The length of the average optimal-path line in each panel indicates the  $L_2$  range over which the SNR was  $\geq 12$  dB, the minimum SNR requirement for points included in our optimal-line fit. For certain conditions, typically the largest and smallest frequency ratios, the average optimal-path line includes data from less than 20 subjects because not every subject produced DPOAEs with SNRs exceeding 12 dB.

In general, the slope of the optimal path becomes steeper as the primaries are more closely spaced at each  $f_2$ . When the primaries are broadly spaced ( $f_2/f_1 = 1.35$  or  $1.40$ ), the largest DPOAE levels were obtained when  $L_1$  was much bigger than  $L_2$  at low levels of  $L_2$  and increased slowly as  $L_2$  increased. For more closely spaced primaries, the largest DPOAE levels were obtained when  $L_1$  was more similar in level to  $L_2$  and increased more rapidly with  $L_2$ .

The slope of the optimal path and its relation to  $f_2/f_1$  and  $f_2$  is summarized in Fig. 2. Here, the slope of the average optimal path is plotted as a function of  $f_2/f_1$  with  $f_2$  as the parameter. As shown in Fig. 1, the slope of the average optimal path decreases as  $f_2/f_1$  increases at each  $f_2$ . This change in slope is consistent with expected changes in relative response growth at the  $f_2$  place as the spacing between the two primaries increases. Additionally, for frequency ratios greater than 1.15, the slope of the optimal path tends to decrease as  $f_2$  increases from 1 to 8 kHz, suggesting that, for a given frequency ratio, the overlap between the primaries at the  $f_2$  place decreases as  $f_2$  increases.

## B. Responses to linear-path stimuli

DPOAE I/O functions, averaged across subjects, are shown in Fig. 3. Each panel represents data for a different  $f_2$  with  $f_2/f_1$  as the parameter. These data were obtained with  $L_1$  set according to each subject's optimal path for each  $f_2/f_1$  at each  $f_2$ . Data were included in Fig. 3 only for those conditions on the averaged I/O function where the SNR was  $\geq 6$  dB. This SNR criterion was invoked in this and subsequent figures (Figs 4-6), in order to plot only those points that were reliably measured with minimal influence from noise. The solid, thick line represents the I/O function for  $f_2/f_1 = 1.20$ . The longer dashed lines are for  $f_2/f_1 < 1.20$  and the shorter dashes are for  $f_2/f_1 > 1.20$ . The thickness of the dashed lines indicates the distance the frequency ratio is from 1.20, with the dashed lines becoming progressively thinner as  $f_2/f_1$  approaches either 1.05 or 1.40. The thinnest lines are for frequency ratios of 1.05 and 1.40. For  $f_2 = 4$  and 8 kHz, the maximum DPOAE level for essentially all  $L_2$  was achieved when  $f_2/f_1 = 1.20$ . Both increases and decreases in  $f_2/f_1$  resulted in reductions in DPOAE level relative to the levels observed when  $f_2/f_1 = 1.20$ . However, for  $f_2 = 1$  and 2 kHz, there was an interaction between optimal  $f_2/f_1$  and  $L_2$ . For  $L_2 < 40$  dB SPL, maximum DPOAE level occurred when  $f_2/f_1 = 1.20$ ; for  $L_2 > 40$  dB SPL, frequency ratios greater than 1.20 resulted in an increase in DPOAE level, achieving a maximum increase of approximately 5 dB.

An alternative view of the effect of frequency ratio as stimulus level is varied is shown in Fig. 4. Here, the DPOAE I/O functions shown in Fig. 3 are replotted as DPOAE-level versus  $f_2/f_1$  functions with  $L_2$  as the parameter. Plots like these have sometimes been referred to as DPOAE frequency or filter functions (e.g., Stover et al., 1999). Each panel represents data for a different  $f_2$ , with line thickness decreasing as  $L_2$  increases. As in Fig. 3, only points where the SNR was 6 dB or greater are plotted. The lines are shown for 10-dB increments of  $L_2$ . For  $f_2 = 1, 2,$  and 4 kHz,  $L_2$  ranges from 20 to 80 dB SPL.  $L_2$  ranges from 30 to 80 dB SPL for  $f_2 = 8$  kHz, a consequence of the reduced range over which reliable measurements were possible at this  $f_2$ . For  $f_2 = 8$  kHz,  $f_2/f_1 = 1.20$  resulted in the maximum DPOAE levels for all  $L_2$ 's except 40 dB SPL. For all other  $f_2$  frequencies, the  $f_2/f_1$  producing the largest DPOAE increased with  $L_2$ . These data suggest that it is possible to obtain larger DPOAE levels if  $f_2/f_1$  is varied with  $L_2$ , in addition to varying  $L_1$  (e.g., Kummer et al., 1998; Neely et al., 2005), although the size of the effect is small, compared to the influence of  $L_1$  variation.

Data describing the inter-subject variability in DPOAE level are plotted in Fig. 5. Here, a portion of the data shown in Fig. 4 ( $f_2 = 4$  kHz,  $L_2 = 20, 50,$  and 80 dB SPL) have been replotted with the addition of error bars representing  $\pm 1$  standard deviation. In general, the variability across subjects is less for the high-level stimuli ( $L_2 = 50$  and 80 dB SPL) and for frequency ratios between 1.15 and 1.30. Standard deviations for other stimulus conditions (i.e., the



complete set of  $f_2$  and  $L_2$  shown in Fig. 4) are comparable to those shown in Fig. 5, suggesting similar inter-subject variability across stimulus condition.

### C. Optimal stimulus parameters

Figure 6 summarizes our approach for specifying stimulus conditions that (on average) elicit larger DPOAE levels than those obtained when only  $L_1$ - $L_2$  is varied. The upper panel plots  $L_1$  as a function of  $L_2$ , while the lower panel plots  $f_2/f_1$  as a function of  $L_2$ . The parameter in each panel is  $f_2$ , shown with different symbols as indicated in the upper panel. Data points are plotted at values that represent the maximum responses to the Lissajous-path stimuli shown in Fig. 1. As in previous figures, data are included only if the SNR  $\geq 6$  dB. The values of  $L_1$  and  $f_2/f_1$  at which each symbol in Fig. 6 is plotted can be viewed as the stimulus conditions resulting in the maximum average DPOAE level for each  $L_2$  and  $f_2$ . However, using the stimulus conditions described by the individual data points limits the degree to which these data can be used to generalize to stimulus conditions for  $f_2$  frequencies other than those tested in this study. Therefore, equations describing the relations among stimulus parameters were developed.

In specifying the form of these equations, emphasis was placed on developing as simple a model as possible that also provided a reasonable fit to the data. Changes in  $f_2/f_1$  with  $L_2$  and  $f_2$  were motivated by data shown in Fig. 4, where larger frequency ratios produced bigger DPOAE levels as either  $f_2$  decreased or  $L_2$  increased. An additional constraint on the model was that the relationship between  $L_1$  and  $L_2$  be described by a straight line in the same manner as previous descriptions of the relationship between  $L_1$  and  $L_2$  (e.g., Kummer et al., 1998, 2000; Neely et al., 2005). For a particular  $f_2$  and  $L_2$  combination,  $L_1$  is set according to:

$$L_1 = 80 + a \cdot \log_2(b/f_2) \cdot (L_2 - 80).$$

Likewise,  $f_2/f_1$  is set according to:

$$f_2/f_1 = c + \log_2(d/f_2) \cdot (L_2/e)^2.$$

The equation parameters were determined first by constraining  $L_1 = 80$  dB SPL when  $L_2 = 80$  dB SPL. The 5 additional parameters (a-e) were determined by minimizing the sum of the squared deviations between the DPOAE levels obtained with freely varying stimulus parameters (which we refer to as  $L_{dmax}$ ) and the DPOAE levels obtained for stimulus parameters specified by the equations shown in each panel (which we refer to as  $L_{dpar}$ ). The final parameter values are shown in the equations plotted on Fig. 6. These parameters represent the values resulting in the smallest squared deviation between  $L_{dmax}$  and  $L_{dpar}$ . Functions derived from these equations are shown as solid (1 kHz) and dashed (2, 4, 8 kHz) lines in the figure, the shorter the dash, the higher the  $f_2$ .

In Fig. 6, the fit between the solid/dashed lines and the individual data points suggests that the stimulus parameters recommended by these two equations deviate from the stimulus parameters associated with  $L_{dmax}$ , and that perhaps these equations do not provide a good representation of the stimulus conditions producing the largest DPOAEs. However, the method by which we determined the equation parameters placed an emphasis on equating DPOAE levels for  $L_{dmax}$  and  $L_{dpar}$  rather than fitting the freely varying stimulus parameters. The extent to which  $L_{dmax}$  and  $L_{dpar}$  differ is shown in Fig. 7, which, in the final analysis, probably represents a better test of the appropriateness of using these equations to select stimulus conditions that optimize response level.

DPOAE I/O functions for  $L_{dmax}$  and  $L_{dpar}$  are plotted in Fig. 7, along with I/O functions using the  $L_1$ ,  $L_2$  relations described by Kummer et al. (1998) and Neely et al. (2005). For these latter two functions, the frequency ratio is fixed at 1.20, which is the frequency ratio used in the two previous studies. The horizontal lines between -10 and -20 dB SPL represent the noise level.

Again, only points with  $\text{SNR} \geq 6$  dB are shown. Data obtained with the Kummer et al. stimulus conditions are shown as solid lines. The corresponding response levels for the Neely et al. stimulus conditions are shown as the longest dashed lines. The DPOAE levels for the  $L_{\text{dmax}}$  condition are represented by the shortest dash and the DPOAE levels for the  $L_{\text{dpar}}$  condition are shown as dashed lines intermediate in length to those used for  $L_{\text{dmax}}$  and those used to depict the DPOAE levels for the Neely et al. stimulus conditions. For all conditions, the DPOAE and noise levels were taken from the response to the Lissajous-path stimuli. Recall that because these data were collected rapidly with associated smoothing of the response, the DPOAE levels are not directly comparable to levels obtained with more traditional stimulus and response conditions. Therefore, the I/O functions shown in Fig. 7 should be evaluated in relative terms and not in relation to those shown in Fig. 3 or elsewhere in the DPOAE literature.

If we use the Kummer et al. levels as the reference point (measured under conditions in which both  $f_2/f_1$  and  $L_1-L_2$  were independent of  $f_2$ ), the other I/O functions describe the extent to which it is possible to increase the DPOAE level by adjusting only the  $L_1-L_2$  (Neely et al.) or by varying both  $L_1-L_2$  and  $f_2/f_1$  ( $L_{\text{dmax}}$ ,  $L_{\text{dpar}}$ ) as a function of  $f_2$ . In general, the DPOAE levels for the Kummer et al. condition are equivalent to or less than those recorded for any of the other three conditions. For  $f_2 = 8$  kHz, Neely et al.,  $L_{\text{dpar}}$ , and  $L_{\text{dmax}}$  all produce equivalent DPOAE levels, which might be expected given the similarity in stimulus conditions for Neely et al.,  $L_{\text{dpar}}$ , and  $L_{\text{dmax}}$ . This observation also provides further validation of the results observed in Neely et al. (2005) regarding the optimal relationship between  $L_1$  and  $L_2$  when  $f_2 = 8$  kHz. As  $f_2$  decreases from 4 to 1 kHz,  $L_{\text{dpar}}$  and  $L_{\text{dmax}}$  produce increasingly larger DPOAE levels relative to Neely et al. While the stimulus conditions for  $L_{\text{dmax}}$  (as expected) always produce responses that are equal to or greater than those produced by the stimulus conditions for  $L_{\text{dpar}}$ , the differences seldom exceed a few dB. When  $f_2 = 4$  kHz and  $L_2 < 40$  dB HL, DPOAE levels associated with  $L_{\text{dpar}}$  are less than those associated with the other three sets of stimulus conditions, suggesting that  $L_{\text{dpar}}$  may not be a good choice for specifying stimulus conditions for this  $f_2$  and  $L_2$ . This observation also suggests that it might be possible to improve our approach to specifying stimulus parameters for  $L_{\text{dpar}}$ . However, even with the  $L_{\text{dpar}}$  stimulus conditions at  $f_2 = 4$  kHz, DPOAEs were recorded with a positive SNR for  $L_2 = 17$  dB SPL. Furthermore, for all other combinations of  $f_2$  and  $L_2$ , the response levels for  $L_{\text{dpar}}$  exceeded the levels achieved with the approach recommended by Kummer et al. (1998), were equal to or greater than the levels achieved by Neely et al. (2005), and were only slightly less than the maximum levels achieved by freely varying stimulus conditions ( $L_{\text{dmax}}$ ). We, therefore, view the stimulus conditions associated with  $L_{\text{dpar}}$  as representing an acceptable compromise between achieving the maximum possible DPOAE levels ( $L_{\text{dmax}}$ ) and specifying a simple stimulus model that can be generalized to other  $f_2$  frequencies.

When  $f_2 = 2$  kHz, the noise levels associated with  $L_{\text{dmax}}$  and  $L_{\text{dpar}}$  increase as stimulus levels increase, which can be attributed to changes in DPOAE frequency with changes in  $f_2/f_1$ . As  $f_2/f_1$  increases, the frequency at which the DPOAE is measured decreases. When  $f_2 = 1$  and 2 kHz, frequency ratios exceeding 1.25 are recommended for the highest stimulus levels. For these conditions, the DPOAE was recorded at lower frequencies (because  $2f_1-f_2$  decreases as  $f_2/f_1$  increases). Noise levels increase as  $2f_1-f_2$  decreases (Gorga et al., 1993), which occurs when either  $f_2$  decreases or  $f_2/f_1$  increases. At 2 kHz, the shift in the DPOAE frequency appears to be associated with larger increases in noise level than for other  $f_2$  frequencies.

Data in support of this interpretation are shown in Fig.8, where the noise level averaged across the entire DPOAE I/O function is plotted as a function of frequency ratio. Each panel represents data for a different  $f_2$  with the noise levels for each primary-level path as the parameter. The triangles represent the noise levels when the Kummer et al. (1998) primary-level relation is used at each frequency ratio (recall that this level ratio is the same for all  $f_2$  frequencies). The circles represent the corresponding noise levels when the Neely et al. (2005) primary-level

relations are used; in this case, a different primary-level relation is specified at each  $f_2$ , but the same level relation is used for each frequency ratio within an  $f_2$ . Finally, the squares represent the case when the average optimal paths are used to specify the  $L_1, L_2$  relationship. These paths correspond to the average optimal paths plotted on the contour plots in Fig. 1; in this case, a different primary-level relation is used at each  $f_2$  and  $f_2/f_1$ .

As expected, there is a tendency for overall noise levels to increase as  $f_2$  decreases (going from bottom to top in Fig. 8). Within each panel, the primary determining factor for noise level is the frequency ratio; within a given frequency ratio, there is no difference in noise level across the three primary-level paths. For  $f_2 = 1$  and 2 kHz, the noise level increases as frequency ratio increases. When  $f_2 = 4$  kHz, the noise level remains relatively constant across frequency ratio. For  $f_2 = 8$  kHz, the noise level decreases by 2 - 3 dB between  $f_2/f_1 = 1.20$  and  $f_2/f_1 = 1.35$ . The decrease in noise level with increases in  $f_2/f_1$  for  $f_2 = 8$  kHz was unexpected given previous observations (e.g., Gorga et al., 1993), and the mechanism responsible for this change at 8 kHz is unclear. For  $f_2 = 2$  kHz, the increase is approximately 5 dB, which is a larger effect than was observed for the other frequencies.

## IV. DISCUSSION

The results described above summarize a broad exploration of the DPOAE parametric space in humans. These results suggest that it is possible to record larger DPOAE levels in normal-hearing human ears if the  $L_1, L_2$  and  $f_2/f_1$  relations are allowed to vary with both  $L_2$  and  $f_2$ . Extensive parametric investigations for individual subjects are impractical due to the significant time involved in collecting these data. However, we have described an approach to specifying optimal stimulus conditions that are expected, on average, to result in larger DPOAE levels in normal-hearing human subjects.

### A. Frequency dependence of average, optimal $L_1, L_2$ difference

The data displayed in Figs. 1 and 2 demonstrate systematic variations in the average optimal  $L_1, L_2$  stimulus path as both  $f_2$  and  $f_2/f_1$  are varied. Two trends are apparent in these data. First, across  $f_2$ , the slope of the optimal path decreases with increasing frequency ratio (which corresponds to broader frequency spacing of the primaries). Second, within a given frequency ratio, there is a trend for the optimal-path slope to increase with decreasing  $f_2$ . These results suggest that if we increase the separation of the two primaries in the cochlea either by presenting high-frequency stimuli, for which we presume there is sharper frequency resolution, or by increasing the frequency ratio, an increase in  $L_1$  is necessary to produce “optimal” overlap of the primaries at the  $f_2$  place. The shallower optimal-path slope and higher intercept represent this compensation. The higher intercept is a result of the increase in  $L_1$  for low-level stimuli, which is necessary because of the increased separation in the cochlear representation of the primaries for large frequency ratios or high  $f_2$  frequencies. The shallow slope reflects a subsequent slow change in  $L_1$  as  $L_2$  increases.

The shallower optimal-path slope for broadly spaced primaries is also consistent with expected changes in growth of response to  $f_1$  at the  $f_2$  place. In the generation of DPOAEs, the primary nonlinear interaction is believed to occur near the  $f_2$  place (e.g., Brown and Kemp, 1984; Harris et al., 1992). Response growth for the  $f_2$  primary is, therefore, expected to be nonlinear. As the frequency ratio is increased, a larger  $L_1$  would be needed for low levels of  $L_2$  and response growth for the  $f_1$  primary at the  $f_2$  place would be expected to become increasingly more linear. This linearizing of the  $f_1$  response at the  $f_2$  place results in relatively little change in  $L_1$  for relatively large changes in  $L_2$ . Stated another way, as frequency ratio increases, the response to the  $f_1$  primary grows increasingly more rapidly than the response to the  $f_2$  primary at the  $f_2$  place. This results in a smaller increase in  $f_1$  relative to  $f_2$  for the same relative representation at the  $f_2$  place. This interpretation is consistent with arguments made in the psychoacoustics



literature to explain differences in growth of masking for on- versus off-frequency maskers (e.g., Stelmachowicz et al., 1987; Oxenham and Plack, 1997) and in the DPOAE suppression literature to explain differences in growth of suppression for on- versus off-frequency suppressors (e.g., Gorga et al., 2002).

Changes in the optimal-path slope across  $f_2$  also are consistent with expected variations in frequency resolution and cochlear nonlinearity as a function of frequency. Direct observation of basilar-membrane motion in lower animals suggests broader tuning at the cochlear apex as compared to its base (e.g., Cooper and Rhode, 1997; reviewed in Robles and Ruggero, 2001). While the extent to which cochlear nonlinearity differs between the base and the apex remains controversial (contrast, for example, the behavioral data of Oxenham and Plack, 2000 with behavioral data of Plack and Drga, 2003), more recent evidence points to similar cochlear nonlinearity at both the base and apex (e.g., Nelson and Schroder, 2004; Oxenham & Dau, 2004). Additionally, data from the chinchilla suggest nonlinear responses at the apex, but also suggest that they are more distributed and less sharply tuned than those observed at the base (Cooper and Rhode, 1997). In the present data, the lowest  $f_2$  frequency for which measurements were made was 1 kHz, so these data do not represent responses from extreme apical regions of the cochlea. However, the observation of consistently steeper optimal  $L_1$ ,  $L_2$  relationships for  $f_2 = 1$  kHz as compared to  $f_2 = 8$  kHz, suggest more similar growth of response for the  $f_1$  primary at the  $f_2$  place when  $f_2 = 1$  kHz than when  $f_2 = 8$  kHz. This would be expected if there were more broadly tuned responses with more distributed nonlinearity in the more apical regions of the cochlea.

## B. Interactions between primary-level ratios and primary-frequency ratios

As discussed above, one hypothesis at the outset of this investigation was that differences in frequency resolution along the length of the cochlea might underlie the frequency dependence of the optimal  $L_1$ - $L_2$  observed in Neely et al. (2005). If this hypothesis was true, the optimal  $L_1$ - $L_2$  for each  $f_2$  might be more similar if the frequency ratio were adjusted to maintain more consistent overlap at the  $f_2$  place. The present results suggest that our hypothesis was too simplistic. If it were possible to compensate for differences in frequency resolution between the base and apex by varying either the primary-frequency or primary-level ratio, the optimal-path I/O functions in Fig. 3 would be superimposed. The horizontal and vertical offsets to these I/O functions suggest that it is not entirely possible to compensate for differences in basilar-membrane frequency selectivity by either decreasing  $f_2/f_1$  or increasing  $L_1$ .

We had anticipated that frequency ratios  $< 1.20$  would be optimal for the higher frequency stimuli, particularly  $f_2 = 8$  kHz. However, frequency ratios less than 1.20 were rarely associated with maximum DPOAE level (see Figs. 3 and 4). Additionally, for frequency ratios  $< 1.20$  there was a decrease in DPOAE level for all  $f_2$  frequencies except 1 kHz (see Fig. 4). This decrease in level for  $f_2/f_1 < 1.20$  occurs despite optimizing the  $L_1$ - $L_2$  to produce the maximum DPOAE level. One possible mechanism for this observation is that the primaries may be suppressing each other and possibly the DPOAE component for frequency ratios less than 1.20, thus counterbalancing the increase in DPOAE level associated with more “optimal” overlap of the cochlear representation of the primaries. This explanation has been proposed in the modeling work of Kanis and de Boer (1997) and Lukashkin and Russell (2001). Experimental observations in support of this view also have been reported by Cooper and Rhode (1997), based on direct observations of basilar-membrane motion under conditions of single- and two-tone stimulation.

The observation of a less steep decline in DPOAE level for  $f_2/f_1 < 1.20$  when  $f_2 = 1$  kHz (see Fig. 4), also may be consistent with the two-tone suppression interpretation. Cooper and Rhode (1997) observed an essentially flat frequency-ratio function for  $f_2/f_1 < 1.40$  in mechanical responses in the apical region of chinchilla cochlea. This observation was in contrast to the

more sharply tuned frequency-ratio function in the basal region of guinea pig cochlea. They attributed this difference in frequency-ratio tuning between the base and apex to the observation in their own work (Cooper and Rhode, 1996) and the work of Delgutte (1990), that two-tone suppression is stronger in the base than in the apex. The flatter frequency-ratio function when  $f_2 = 1$  kHz as compared to higher  $f_2$  frequencies in the present data suggest less suppression among the primaries and the DPOAE component when  $f_2 = 1$  kHz.

### C. Optimal stimulus parameters

The stimulus conditions associated with the maximum DPOAE levels (see Fig. 6), as well as our model for describing them, are consistent with hypothesized interactions among  $f_2/f_1$ ,  $L_1-L_2$ , and  $L_2$ . As described above, frequency resolution is sharper for high frequencies than for low frequencies. However, for a given frequency, a broader cochlear representation is expected as level is increased. Therefore, larger frequency ratios were required for maximum DPOAE levels as either  $f_2$  decreased or  $L_2$  increased. Although the largest DPOAE levels were obtained using freely varying stimulus combinations ( $L_{dmax}$ ), the time required to determine the stimulus conditions resulting in  $L_{dmax}$  for individual subjects may argue against its use. The DPOAE levels obtained from stimulus conditions described by the equations shown in Fig. 6 were less than  $L_{dmax}$  for some conditions, but were greater than those obtained by allowing only  $L_1-L_2$  to vary (e.g., Kummer et al., 1998; Neely et al., 2005). These equations may have an added benefit, in that they could be used to specify stimulus conditions for  $f_2$  frequencies other than the ones used in this study.

The manner in which stimulus level is calibrated is expected to have an influence on the optimal stimulus parameters for recording DPOAEs. It has been shown that differences in sound pressure level exist at the tympanic membrane (TM) when stimuli are calibrated at the plane of the probe as compared to the plane of the TM, or when using an isovoltage strategy (e.g., Siegel, 1994; Siegel and Hirohata, 1994; Whitehead et al., 1995b). These differences are most pronounced for frequencies exceeding 2-3 kHz and are variable across individuals. They are a consequence of the presence of standing waves in the ear canal, which vary with probe-insertion depth and ear-canal geometry for an individual ear. There is no simple method for accounting for these calibration errors, although Neely and Gorga (1998) suggest calibrating in acoustic intensity rather than acoustic pressure as a way to avoid standing-wave influences on stimulus level. Unfortunately, acoustic intensity calibrations have not been widely utilized. While the optimal stimulus parameters described here may not generalize to alternate calibrations strategies, they are expected to result, on average, in the largest DPOAE levels in subjects with normal hearing for applications where stimulus levels are calibrated at the plane of the measurement probe. Furthermore, it may be of value to note the calibration was the same, regardless of which stimulus paradigm (Kummer et al., 1998; Neely et al., 2005; the present approach) was used to set stimulus conditions.

Investigations of the complete DPOAE parametric space are rarely attempted in humans because of the time involved in recording DPOAE responses for the large number of stimulus conditions that are necessary to explore the stimulus space. Mills (2002) described results from a comprehensive investigation of the DPOAE parametric space in Mongolian gerbil. Similarly comprehensive investigations in humans are impractical. Parametric investigations in humans typically focus on a restricted region of the primary level or frequency space (e.g., Harris et al., 1989; Gaskill & Brown, 1990; Kummer et al., 1998; Neely et al., 2005). The equations shown in Fig. 6, however, may obviate the need for comprehensive evaluations of stimulus conditions in individual subjects. Although the fits of these equations to the data shown in Fig. 6 may not appear compelling, the more important observation is how close the DPOAE levels were for the  $L_{dmax}$  and  $L_{dpar}$  stimulus conditions. Thus, the stimulus conditions defined by  $L_{dpar}$  may be a good compromise, in that they do not require a complete exploration of the

primary-level and primary-frequency-ratio space with every subject and they can be used with  $f_2$  frequencies other than the ones used in the present study.

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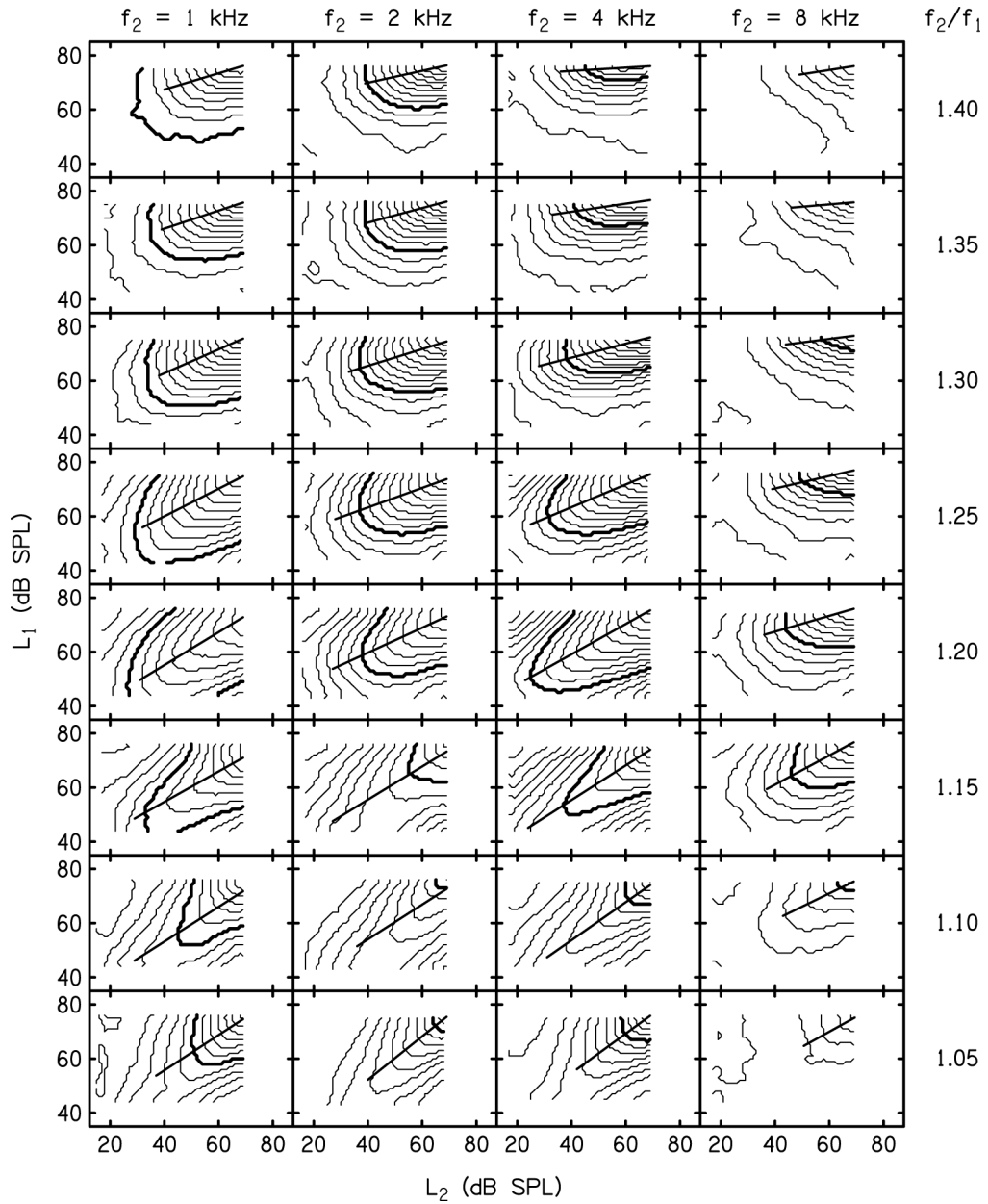
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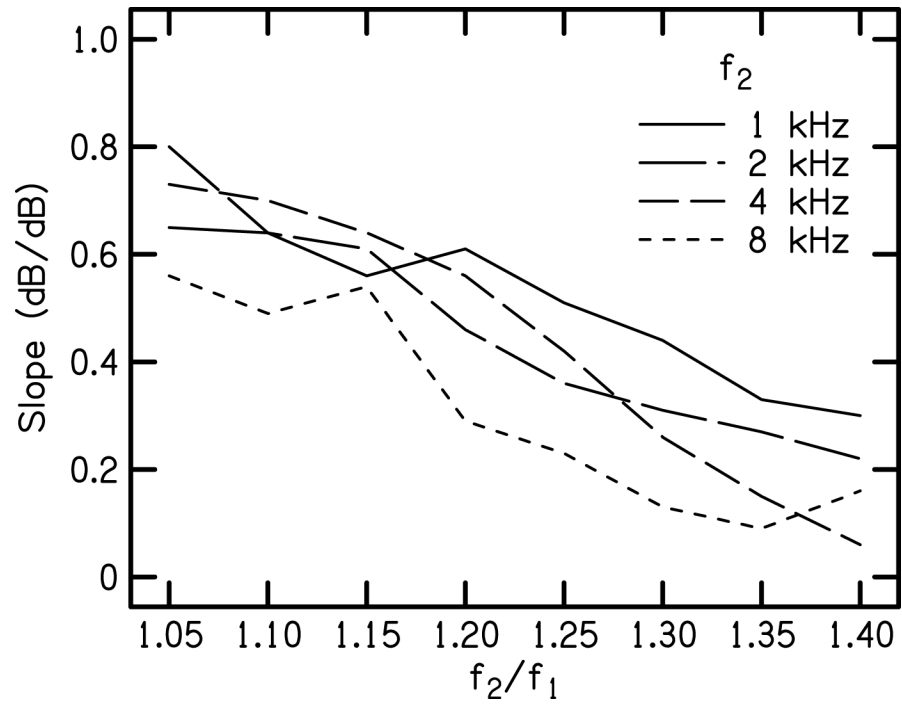
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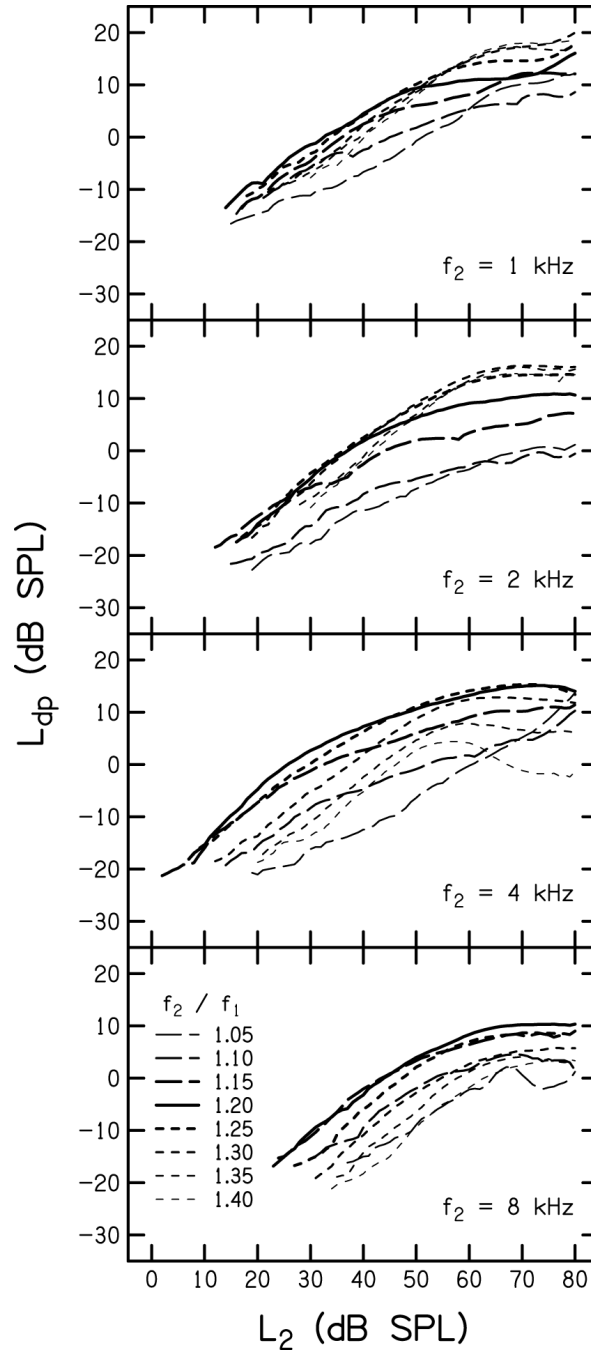


**Figure 1.**

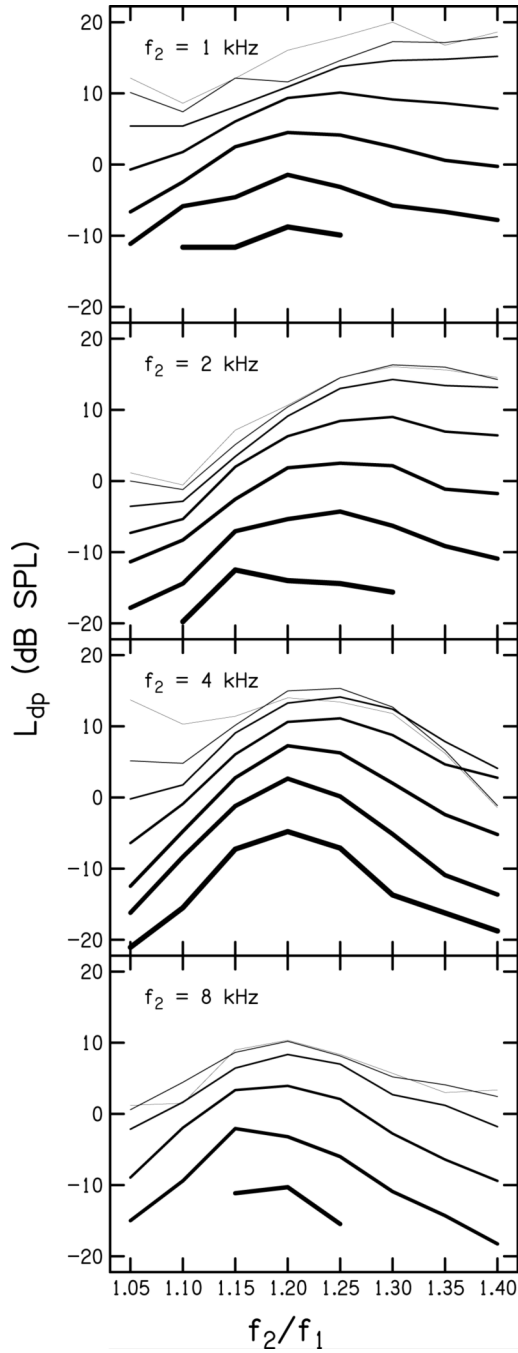
Contour plots representing DPOAE level in  $L_1, L_2$  stimulus space. Each column represents data for a different  $f_2$  and each row represents a different  $f_2/f_1$ , as indicated on the figure. The contours are spaced in 2-dB increments of DPOAE level. As a reference, the contour corresponding to -6 dB SPL is indicated with a thicker line. The maximum DPOAE level in panels without a reference ( $f_2 = 8 \text{ kHz}$ ,  $f_2/f_1 = 1.40, 1.35, 1.05$ ) is -8 dB SPL. The slanting, straight lines in each panel describe the  $L_1, L_2$  relationship producing the largest DPOAE level at each  $L_2$ . Our approach for fitting this line is described in the text.



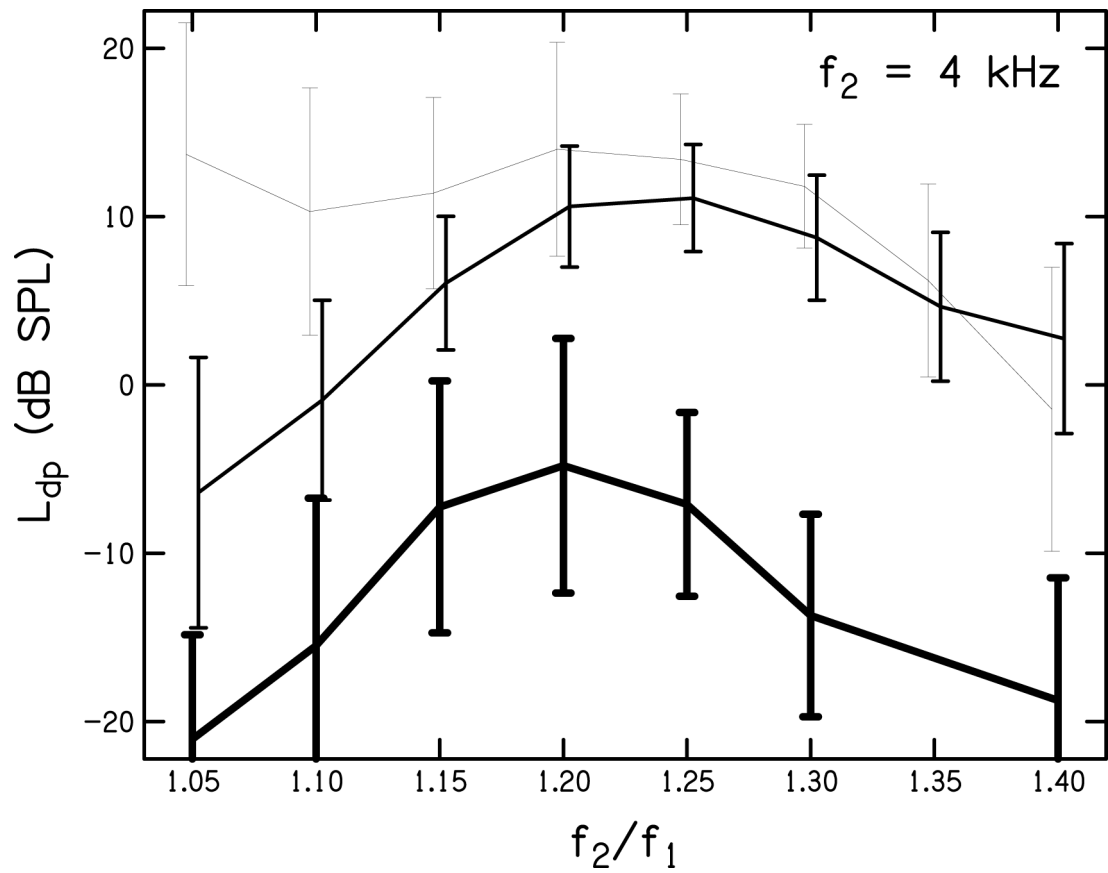
**Figure 2.** The slope of the average, optimal path as a function of  $f_2/f_1$ . The parameter is  $f_2$ .



**Figure 3.** DPOAE level ( $L_{dp}$ ) is plotted as a function of  $L_2$  with primary-frequency ratio as a parameter. Each panel represents a different  $f_2$ , as indicated. The solid line in each panel represents DPOAE level for  $f_2/f_1 = 1.20$ . Shorter dashes correspond to  $f_2/f_1 > 1.20$  and longer dashes correspond to  $f_2/f_1 < 1.20$ . The line thickness represents the distance the frequency ratio is from 1.20, with  $f_2/f_1 = 1.05$  and 1.40 indicated by the thinnest dashed lines.

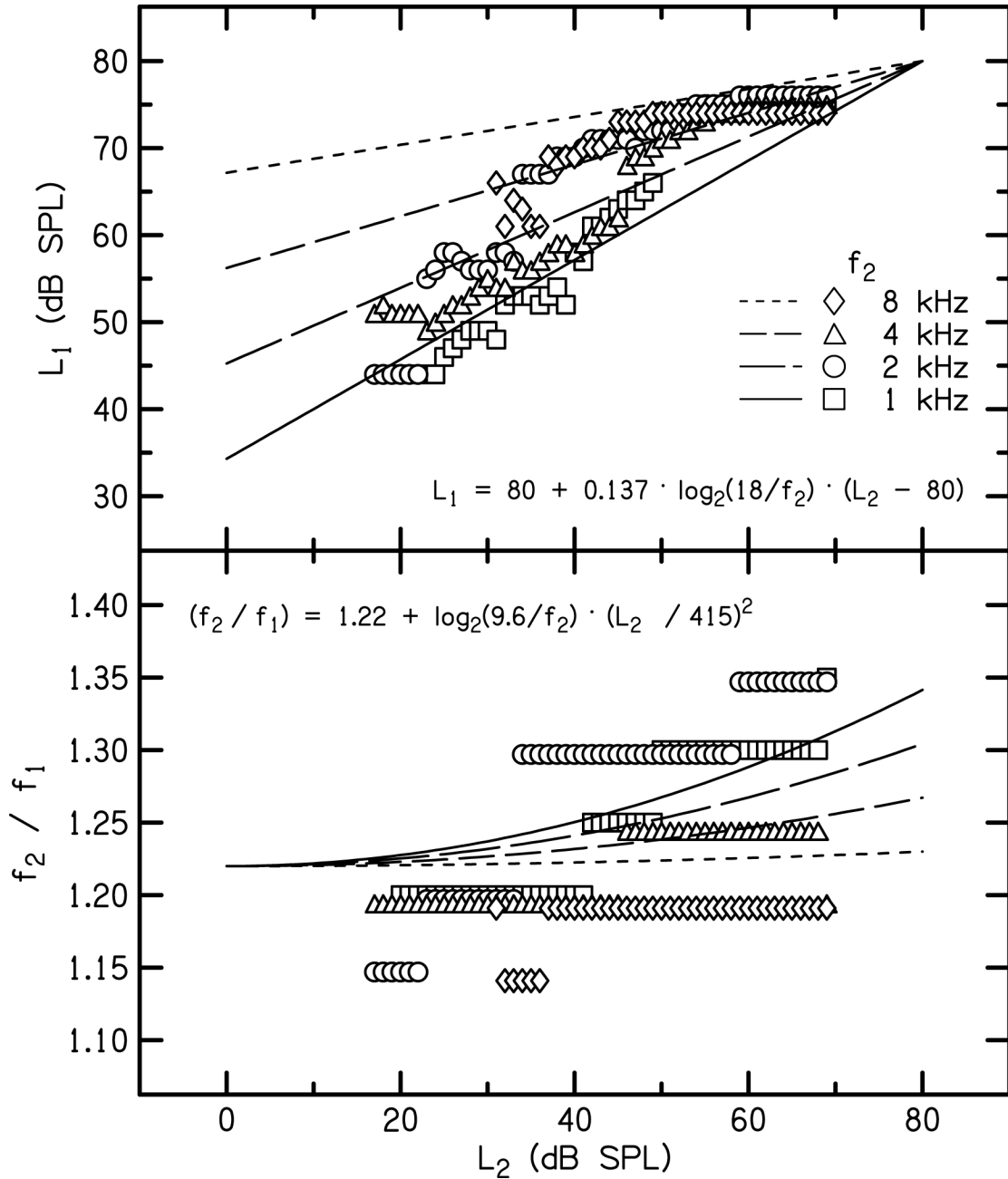


**Figure 4.** Mean DPOAE level ( $L_{dp}$ ) as a function of frequency ratio. Each panel represents data for a different  $f_2$ . Here, the parameter is  $L_2$ , with decreasing line thickness indicating increasing  $L_2$  in 10-dB increments of  $L_2$ . When  $f_2 = 8$  kHz, data for  $L_2 = 30$  to 80 dB SPL are plotted, for all other  $f_2$  frequencies data are plotted for  $L_2$  ranging from 20 to 80 dB SPL.

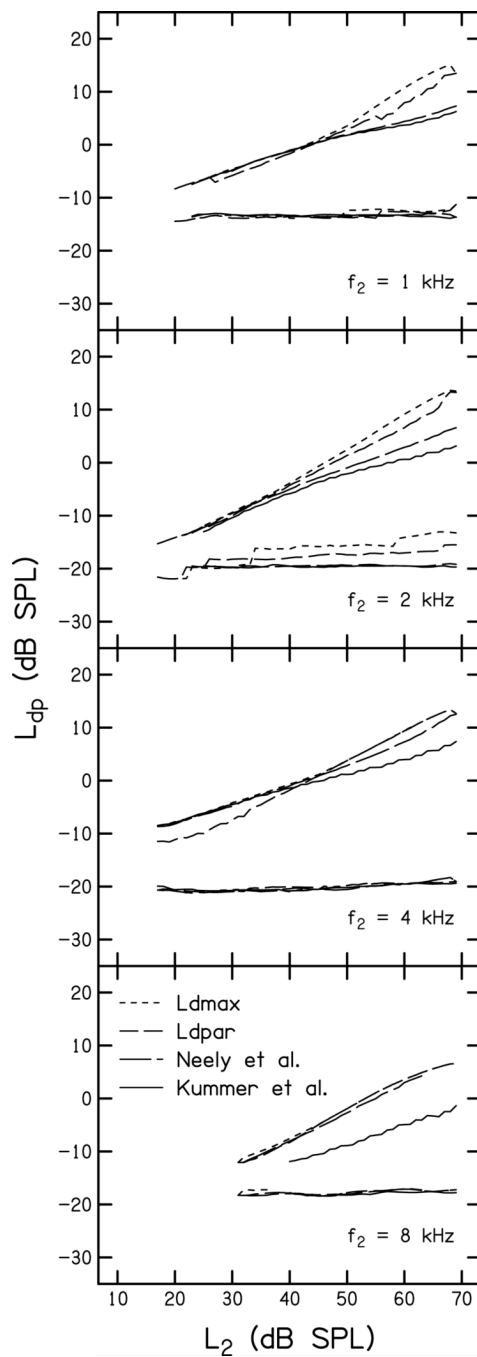


**Figure 5.** Mean DPOAE level ( $L_{dp}$ ) as a function of frequency ratio when  $f_2 = 4$  kHz and  $L_2 = 20, 50,$  and  $80$  dB SPL (indicated with decreasing line thickness). Errors bars represent  $\pm 1$  standard deviation.

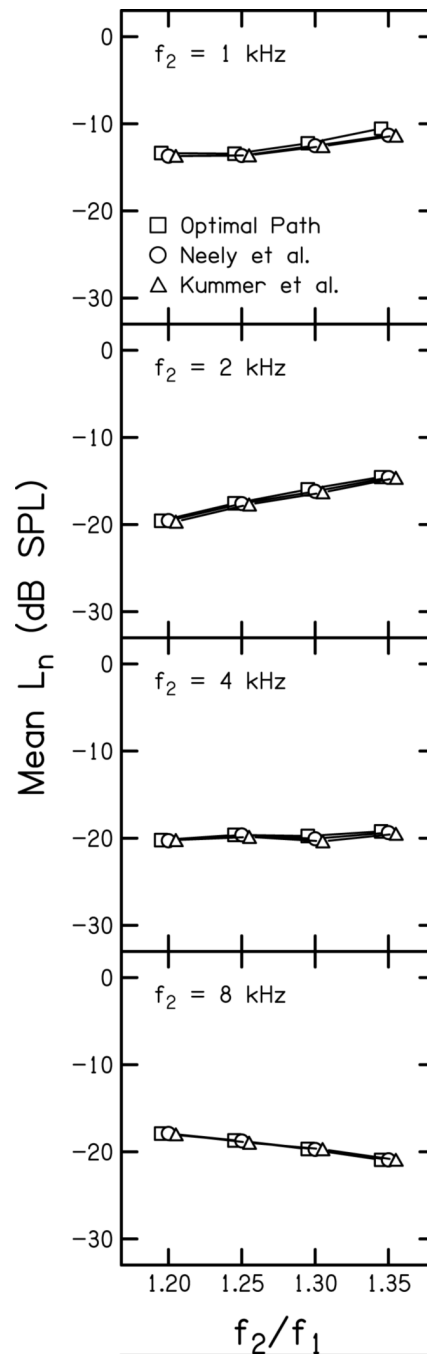




**Figure 6.** Our approach to specifying optimal stimulus parameters. The upper panel plots  $L_1$  as a function of  $L_2$  while the lower panel plots  $f_2/f_1$  as a function of  $L_2$ . The parameter is  $f_2$ , as indicated within the upper panel. The symbols shown in each panel correspond to the  $L_1$  (upper panel) or  $f_2/f_1$  (lower panel) producing the largest DPOAE at each  $L_2$ . The lines in each panel represent the best fit to the stimulus conditions producing the maximum DPOAE according to the approach described in the text. The equations describing these lines are shown as an inset in each panel.



**Figure 7.** DPOAE level ( $L_{dp}$ ) as a function of  $L_2$ . Each panel represents a different  $f_2$ . The parameter is the stimulus condition used to record the DPOAE, as indicated in the legend. The nearly horizontal lines near the bottom of each panel represent the corresponding noise levels.



**Figure 8.** DPOAE noise levels ( $L_n$ ) as a function of frequency ratio with each panel corresponding to a different  $f_2$ . Each symbol corresponds to a different  $L_1, L_2$  path as indicated in the legend.