Growth of suppression in humans based on distortion-product otoacoustic emission measurements

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Distortion-product otoacoustic emissions (DPOAEs) were used to describe suppression growth in normal-hearing humans. Data were collected at eight f_2 frequencies ranging from 0.5 to 8 kHz for L_2 levels ranging from 10 to 60 dB sensation level. For each f_2 and L_2 combination, suppression was measured for nine or eleven suppressor frequencies (f_3) whose levels varied from −20 to 85 dB sound pressure level (SPL). Suppression grew nearly linearly when $f_3 \approx f_2$, grew more rapidly for $f_3 < f_2$, and grew more slowly for $f_3 > f_2$. These results are consistent with physiological and mechanical data from lower animals, as well as previous DPOAE data from humans, although no previous DPOAE study has described suppression growth for as wide a range of frequencies and levels. These trends were evident for all f_2 and L_2 combinations; however, some exceptions were noted. Specifically, suppression growth rate was less steep as a function of f_3 for f_2 frequencies ≤ 1 kHz. Thus, despite the qualitative similarities across frequency, there were quantitative differences related to f_2, suggesting that there may be subtle differences in suppression for frequencies above 1 kHz compared to frequencies below 1 kHz. © *2011 Acoustical Society of America*.

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I. INTRODUCTION

The purpose of this study was to provide a description of the growth of suppression in humans with normal hearing, based on measurements of distortion-product otoacoustic emissions (DPOAEs). Suppression growth is described for probe frequencies (f_2) ranging from 0.5 to 8 kHz (in roughly 1/2 octave steps) and for levels (L_2) ranging from 10 or 20 to 50 or 60 dB sensation level (SL) relative to behavioral threshold for each subject at f_2. The data presented in this paper provide a relatively complete description of the growth of DPOAE suppression in humans with normal hearing.

Suppression effects have been documented in both the mechanical responses of the basilar membrane (e.g., Rhode, 1977; Ruggero *et al.*, 1992; Cooper and Rhode, 1996; Rhode and Cooper, 1993) and in the responses of auditory-nerve fibers (e.g., Sachs and Kiang, 1968; Abbas and Sachs, 1976; Ruggero *et al.*, 1992; Delgutte, 1990; Pang and Guinan, 1997). These studies have increased our understanding of the nonlinear response properties of the auditory periphery in mammals. There are some general observations that can be made, based on these mechanical and electrophysiological data. One consistent observation is that suppression-growth rate depends on the relationship between suppressor frequency and characteristic frequency (CF), where CF refers either to the frequency to which a single auditory-nerve fiber has its lowest threshold or the frequency for which a specific place along the basilar membrane is most sensitive. Suppressor tones below CF by an octave or more have higher suppression thresholds, compared to suppressor tones close to CF. However, once suppression threshold is exceeded, suppressive effects grow more rapidly for suppressors lower in frequency than CF. In contrast, suppressor tones higher in frequency relative to CF also have higher suppression thresholds (depending on how much their frequency exceeds CF), but the suppressive effect grows slowly as suppressor level is increased. To a large extent, this is true regardless of whether suppression estimates are based on measurements of the basilar-membrane response or based on measurements of rate suppression in auditory-nerve fibers. These and other data have led to the view that suppression effects in peripheral-response properties reflect mechanical suppression (Ruggero *et al.*, 1992). The combination of mechanical and single-unit measurements provides an extensive description of suppression in lower animals.

While it is reasonable to assume that similar patterns will be observed among mammals, including humans, direct description of suppressive effects in humans has potential value beyond what has been learned from studies in lower animals. At the least, a demonstration of similar effects would provide support for the use of lower animals as models of auditory nonlinear function in humans with both normal and impaired hearing. Furthermore, a comprehensive description of suppression growth in humans would extend our knowledge of suppressive effects in relation to both the frequency and level of the stimulus whose response is being suppressed. Finally, measurements of suppression growth could be used to provide an indirect estimate related to auditory response growth in humans. This description may be useful when these measurements are applied to humans, for whom abnormal response growth is a common sequela to cochlear damage underlying hearing loss. Estimates of response growth would be important in the treatment of hearing loss if it can be shown that these measurements can be made objectively, without a voluntary response from the subject, and predict

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changes in behavioral response growth due to cochlear damage. DPOAE measurements meet the first of these two requirements and work is currently under way to determine the extent to which they can be used to predict behavioral response growth. Objective measures of response growth are important because current signal-processing strategies to ameliorate the effects of hearing loss are limited to options that compensate for threshold elevation and for the reduced dynamic range that typically accompanies cochlear damage affecting outer hair cells, which are thought to be the generators of DPOAEs. Other than frequency compression or frequency transposition, there are no signal-processing options that attempt to address changes to frequency or temporal resolution. It should be noted, however, that even if DPOAE suppression measurements can be used to predict response growth in cases of hearing loss, it will be limited to patients with mild-to-moderate hearing loss, given the dynamic range of DPOAE measurements.

Suppression based on DPOAE measurements has been described in several studies involving both humans and lower animals (e.g., Abdala, 1998, 2001, 2004, 2005; Brown and Kemp, 1984; Gorga *et al.*, 2002, 2008; Martin *et al.*, 1987, 1998a, 1998b; Mills, 1998; Pienkowski and Kunov, 2001). In these and other DPOAE suppression experiments, DPOAEs are elicited by a pair of primary tones (f_2, f_1; $f_2/f_1 \approx 1.2$), whose levels are held constant while a third, suppressor tone (f_3) is presented. The suppressive effect of f_3 is defined as the amount by which its presence reduces the DPOAE level in response to the primary-tone pair. By varying both the frequency and the level of f_3, information about the influence of the frequency relation between suppressor tone and primary tone (primarily f_2) on the amount of suppression has been obtained. As a general rule, DPOAE suppression grows more rapidly for suppressor frequencies lower than f_2, compared to the suppressors close to or slightly above f_2. This pattern is reminiscent of the pattern that has been observed in mechanical and neural responses from lower animals.

Beyond being applicable with humans, DPOAE measurements have the added advantage that they do not require a voluntary response from subjects. This feature has been exploited in a series of studies in which DPOAE suppression measurements were made in infants and young children in efforts to describe developmental changes in peripheral auditory function (e.g., Abdala, 1998, 2001, 2003, 2004; Abdala and Chatterjee, 2003; Abdala *et al.*, 1996).

Within individual studies of DPOAE suppression, measurements are typically restricted to a relatively small number of f_2 frequencies and to a limited range of L_2 levels. Rarely are data provided for more than two or three f_2 frequencies and two to three L_2 levels. In most cases, stimulus levels below 40 dB sound pressure level (SPL) have not been explored. However, DPOAE suppression data at low stimulus levels are of interest, since evidence suggests that DPOAE estimates of cochlear gain are greatest for low-level stimuli (Gorga *et al.*, 2003, 2008).

Several factors may have contributed to the choice of stimulus conditions that have been explored previously, especially in humans. First, it is unreasonable to expect humans to participate in individual data-collection sessions lasting more than about 2 h. As a consequence, multiple sessions may be needed to collect data for a wide range of L_2 levels, even when only one f_2 is being tested. The number of sessions would increase further if data were to be collected for several f_2 frequencies and for a wide range of L_2 levels. It is often not possible for subjects to commit to many data-collection sessions, making it difficult to acquire data for a large combination of frequencies and levels.

A second factor relates to the influence of f_2 and L_2 on the reliability of the measurements [defined by the signal-to-noise ratio (SNR) in the absence of a suppressor tone]. As a general rule, noise level increases as f_2 decreases because the primary sources of noise in DPOAE measurements are subject breathing and movement, which produce noise primarily at lower frequencies. This problem is compounded during DPOAE measurements because the largest distortion product in mammals is observed at a frequency equivalent to $2f_1$–f_2, the frequency on which most DPOAE measurements are focused. However, $2f_1$–f_2 occurs at a frequency that is about 1/2 octave below f_2 (the frequency about which predictions of cochlear function are being made), which results in a decrease in SNR for mid and low f_2 frequencies due to the dependence of noise level on frequency. Noise characteristics, no doubt, have limited the extent to which low f_2 frequencies have been used as stimuli during DPOAE suppression studies.

In addition, low-level stimuli produce smaller responses compared to high-level stimuli, even for high f_2 frequencies, for which noise levels typically are low. Assuming the noise level remains constant regardless of stimulus level, the use of low-level stimuli results in a smaller SNR (regardless of f_2), thus reducing the reliability of the measurements. The effect of suppressor tones is to further reduce the level of the response, thus reducing the SNR by decreasing the difference between DPOAE and noise levels, and making it even more difficult to reliably measure changes in response level. Indeed, it is noteworthy that Abdala and colleagues have been able to describe DPOAE suppression in neonates and young infants because these subjects have noise levels that are typically higher than those encountered when testing cooperative adults. In any case, it is for all of the above reasons that the stimulus conditions for which DPOAE suppression has been explored in humans include mostly higher f_2 frequencies and no lower than moderate-level primaries.

The purpose of the present study is to describe the growth of DPOAE suppression in humans for a wide range of suppressor frequencies (f_3) at each of eight f_2 frequencies (0.5–8 kHz) whose levels ranged from just above behavioral threshold (10 or 20 dB SL relative to behavioral threshold at f_2) to moderate stimulus levels (50 or 60 dB SL). Techniques are used that enable reliable DPOAE measurements for conditions that have not been studied previously, for the reasons described above. These data not only provide a description of suppression growth for a wide range of frequencies and levels in humans with normal hearing, but they may also provide a data set to which results from patients with mild-to-moderate hearing loss can be compared.

II. METHODS

A. Subjects

A total of 63 subjects (23 males, 40 females) participated in this study, although no subject participated in data collection at all f_2 frequencies. Subjects ranged in age from 15 to 55 yr, with a mean age of 26.5 yr. Each subject had normal hearing, defined as pure-tone thresholds of 10 dB HL or better (ANSI, 2004), for standard octave and inter-octave frequencies from 0.25 to 8 kHz. This audiometric-inclusion criterion was selected in efforts to maximize the range of L_2 levels over which reliable DPOAE responses could be measured in unsuppressed conditions, particularly low-level conditions. In addition, all subjects had normal 226-Hz tympanograms on each day on which DPOAE data were collected. This criterion was included as a gross measure aimed at assuring that middle-ear function was normal.

In the present experiment, data were collected at the six f_2 frequencies of 1, 1.4, 2, 2.8, 5.6, and 8 kHz. Ideally, it would have been preferable to collect data at all f_2 frequencies in each subject. Unfortunately, it was not possible for any subject to participate long enough for data collection at all combinations of probe frequency (f_2) and level (L_2). As a result, subjects were enrolled in data collection for a subset of f_2 frequencies, although, once enrolled, data were collected at all L_2 levels for the f_2 frequency being tested with one exception. As will be described subsequently, data for f_2 frequencies of 0.5 and 4 kHz were taken from a previous study (Gorga *et al.*, 2008).[1] Because no data were collected for L_2 levels of 60 dB SL as part of that study, data for $f_2 = 4$ kHz and $L_2 = 60$ dB SL were collected on a group of subjects, which was not the same group that contributed data at lower L_2 levels at this frequency. No data were collected when $f_2 = 0.5$ kHz and $L_2 = 60$ dB SL in the present study, due to the time commitment required to obtain data at this frequency.[2]

Some subjects participated in data collection for as few as one f_2 frequency (at all six L_2 levels), while other subjects participated in data collection for as many as five f_2 frequencies for the entire range of L_2 levels. For L_2 levels from 20 to 60 dB SL, data were obtained from 19 to 20 subjects at every f_2 frequency. At the lowest test level ($L_2 = 10$ dB SL), it was more difficult to obtain large enough DPOAE levels (L_d) so that suppression could be reliably measured. However, reliable suppression measurements were possible in at least ten subjects when $L_2 = 10$ dB SL.

In the present study as well as in previous work from which data for $f_2 = 0.5$ and 4 kHz were drawn (Gorga *et al.*, 2008), a two-alternative forced-choice, transformed up-down procedure (Levitt, 1971) was used to estimate threshold at each f_2 frequency in which a subject participated during DPOAE measurements. Figure 1 provides the mean threshold (dB SPL) ±1 standard deviation (SD) at each f_2 for the 19–20 subjects who participated at that frequency. During suppression measurements, L_2 was specified relative to each subject's behavioral threshold at each f_2 frequency for which the subject contributed data. This decision was made in an effort to assure that the input to the cochlea was nearly the same for each subject and each f_2. This decision was based, in part, on the view that (to a first approximation) threshold of audibility as a function of frequency is determined by the forward transfer function of the middle ear, at least in subjects with normal hearing. By specifying L_2 in dB SL, it was hoped that small differences in middle-ear transmission as a function of f_2 were at least partially controlled. Thus, throughout this paper, L_2 will be specified in dB SL. Of course, any small differences in absolute threshold could be a consequence of subtle differences in cochlear status; thus, our assumptions regarding equating stimulus level in each cochlea would be violated. However, subjects had no history to suggest cochlear problems and all subjects had thresholds well within the range of normal hearing. Even though data will be reported in dB SL in subsequent figures, Fig. 1 provides mean thresholds in dB SPL at each f_2, providing information that can be used to convert from mean dB SL to mean dB SPL in any of the figures to follow. Note that mean behavioral thresholds range from about 4 dB SPL (4 kHz) to 17 dB SPL (8 kHz). This means that the suppression growth was measured for L_2 levels that, on average, ranged from 14 to 64 dB SPL (4 kHz) and 27 to 77 dB SPL (8 kHz) for the range of SLs studied (10–60 dB).

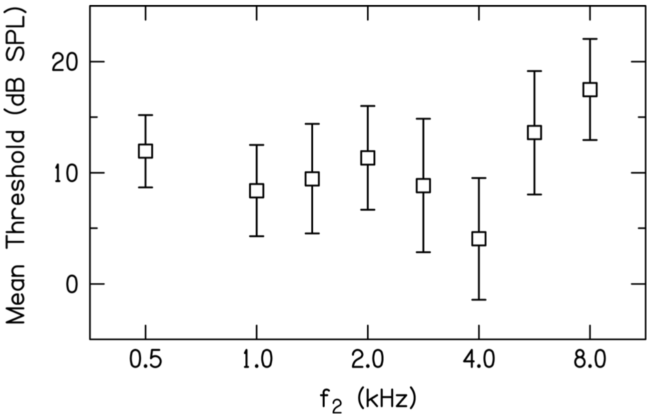

FIG. 1. Mean behavioral threshold (dB SPL) as a function of f_2 frequency (kHz). Error bars represent ±1 SD. Data from 19 to 20 normal-hearing subjects were used to derive these values, although the same subjects are not represented at each frequency.

B. Stimuli

DPOAEs were elicited in response to primary pairs (f_1 and f_2, $f_2/f_1 \approx 1.2$), with $f_2 = 1$, 1.4, 2, 2.8, 5.6, and 8 kHz. The level of f_2 (L_2) was varied from 10 to 60 dB SL in 10-dB steps. The level of f_1 (the lower frequency primary in each primary-frequency pair) was determined empirically and individually, using a paradigm in which both L_1 and L_2 were continuously varied, resulting in a Lissajous pattern of L_d. The L_1 resulting in the largest L_d for each L_2 was fit with a linear equation, which was subsequently solved to determine the L_1 level for each of the six L_2 levels used during DPOAE input/output (I/O) and suppression measurements. This paradigm was chosen because previous work suggests that individually "optimized" stimulus conditions result in the largest L_d for normal-hearing subjects (Neely *et al.*, 2005; Johnson *et al.*, 2006). Choosing stimulus conditions that produced the largest L_d was motivated by our desire to obtain reliable measurements of suppression for all stimulus conditions, including the low-level primary conditions (L_1, L_2) where L_d typically is small. In general, this approach resulted in the selection of L_1 levels that were higher than those previously recommended (Kummer *et al.*, 1998) and, unlike previous work (Kummer *et al.*, 2000), were frequency dependent. The Lissajous procedure has been described elsewhere (Neely *et al.*, 2005; Johnson *et al.*, 2006), and it is identical to the one used to select primary levels in previous measurements of DPOAE I/O functions and DPOAE suppression from our laboratory (Gorga *et al.*, 2007, 2008). As a consequence, it will not be described here. However, using identical experimental methods in the present study and in a previous experiment (Gorga *et al.*, 2008) allowed us to combine previously collected data at $f_2 = 0.5$ and 4 kHz with the data collected as part of this study.

The Lissajous approach was followed for f_2 frequencies ranging from 2 to 8 kHz because these frequencies are characterized by relatively low noise levels. It was not possible to use this approach when $f_2 = 1$ or 1.4 kHz because of the higher noise levels that are associated with measurements at those frequencies. The Lissajous paradigm that was used to determine optimal levels at higher f_2 frequencies (where noise levels are lower) does not include sufficient averaging time to reduce the noise to low enough levels for reliable measurements in conditions in which the noise level is high. As a result, it was inadequate for low f_2 frequencies (≤ 1.4 kHz). However, our interest was in optimizing stimulus levels for all frequencies. To meet this need, an alternative approach was taken to determine optimal primary-level conditions. In this alternative approach, L_2 was fixed at one of four levels (40, 50, 60, or 70 dB SPL), and L_1 was varied (5-dB steps) over a range that allowed us to determine the L_1 for each L_2 that produced the largest L_d. These measurements were made with locally developed data-acquisition software (EMAV; Neely and Liu, 1994) that allowed for long averaging times that enabled sufficient noise reduction for reliable measurements. Like the results derived from the Lissajous-pattern paradigm, the L_1, L_2 combinations resulting in the largest L_d were fit with a linear equation, which was then solved to provide the L_1 levels used at each of the six L_2 levels in subsequent measurements. In this way, we were able to determine "optimal" primary-level conditions for each subject and frequency, including f_2 frequencies for which the noise levels are high. Like the Lissajous-pattern approach, details of this procedure are provided elsewhere (Gorga *et al.*, 2007, 2008). Notably, this is the same procedure that was used previously to select L_1 levels when $f_2 = 0.5$ kHz (Gorga *et al.*, 2008).

For each combination of f_2 and L_2, 11 suppressor frequencies (f_3) were used. These suppressor frequencies were chosen to extend from about 1 or 2 octaves below f_2 to about 1/4–1/2 octave above f_2 on a roughly equivalent octave scale relative to f_2. Suppressor levels (L_3) ranged from -20 to 85 dB SPL in 5-dB steps.

C. Procedures

Once the optimal primary-level conditions were determined individually for a given f_2, all subsequent DPOAE measurements were made using EMAV (Neely and Liu, 1994) and a 24-bit soundcard (CardDeluxe, Digital Audio Labs, Chanhassen, MN). This system generated all stimuli and recorded all responses. A probe-microphone system (ER-10C, Etymōtic Research, Elk Grove Village, IL) was used to present stimuli and to record levels in the ear canal. The "receiver equalization" of the ER-10C was removed in order to increase output by as much as 20 dB. One channel of the probe system was used to present f_1 while f_2 and f_3 (for conditions in which the suppressor was included) were presented on the second channel. A microphone housed in the probe unit was used to measure stimulus and response levels in the ear canal. Prior to data collection in each subject for each condition, a chirp was presented sequentially on each channel and the ear-canal level (in dB SPL) was measured. This reference was then used to set the level of stimuli during all DPOAE measurements. We recognize that SPL calibrations in closed ear canals are sometimes characterized by errors introduced as a result of standing waves (e.g., Siegel, 1994, 2002; Siegel and Hirohata, 1994; Scheperle *et al.*, 2008). In this study, however, SPL calibrations were chosen in order to use conditions identical to those used in our previous study, the data from which are being combined with the present data.[1] During data collection, waveforms were alternately stored in one of two buffers. The contents of the buffers were added and the level in the $2f_1$–f_2 frequency bin was defined as DPOAE level (L_d). Subsequently, the two buffers were subtracted and the contents in the $2f_1$–f_2 frequency bin and in the five frequency bins above and below this bin were used to provide an estimate of noise level.

Prior to data collection, cavity measurements were used to determine the level at which system distortion occurred. System distortion was level dependent and below –25 dB SPL for the low-level stimulus conditions, but was –15 dB SPL for high-level conditions. This level-dependent distortion was taken into account during data collection and analyses, but to simplify matters, the noise-level stopping rule was set to ≤ -25 dB SPL during DPOAE data collection.

Following audiometric and tympanometric testing and the determination of optimal stimulus levels, a DPOAE I/O function was measured prior to suppression measurements at each f_2 frequency for which the subject participated. These data represent the equivalent of control conditions, in which no suppressor was present and were useful in determining that there was a sufficient SNR in control conditions so that suppressive effects could be measured over a wide range for a given subject.

For each subject, an f_2 was selected and its level was fixed at one of six levels (10–60 dB SL, 10-dB steps). The only exception to this rule occurred at 0.5 kHz, a frequency for which no attempt was made to collect data at 10 dB SL due to the noise levels (Gorga *et al.*, 2008) and for which no data were collected at 60 dB SL. Next, a suppressor frequency was selected and presented in increasing level from -20 to 85 dB SPL (5-dB steps). Prior to and just following the presentation of a suppressor-level series for each f_3, a control condition was included in which no suppressor was presented. If L_d for the two controls differed by more than 6 dB when $L_2 = 10$ or 20 dB SL or by 4 dB for higher L_2 levels, the condition was repeated. The L_d for these two control conditions was averaged and the L_d in the presence of the suppressor was subtracted from this average to provide an estimate of the amount of suppression produced by the suppressor (referred to as *decrement*). Once data collection was complete for one f_3, another f_3 was selected and this process was repeated until decrement vs suppressor-level functions were measured at each of 11 f_3 frequencies. Following the collection of suppression data for all f_3 frequencies at a given L_2, another L_2 (for the same f_2) was selected and the entire process was repeated until suppression data were collected at all six L_2 levels. The order of suppressor frequency varied across L_2 (and across subjects). This process was completed for each f_2 frequency. In this way, suppression growth was estimated at each of 11 suppressor frequencies, eight f_2 frequencies, and as many as six L_2 levels.

In the present study, data-collection time ranged from about 3 h per subject for conditions in which the SNR was favorable (e.g., $f_2 = 5.6$ kHz) to as much as 20 h per subject for conditions in which the SNR was low ($f_2 = 1$ kHz). In total, it took 950 h to complete data collection on six f_2 frequencies (see Footnote 1 for information regarding data collection when $f_2 = 0.5$ and 4 kHz). The overall long data-collection time was a consequence of our use of measurement-based stopping rules, which were chosen in the hope that this would increase our chances of obtaining reliable data for a wide range of stimulus conditions. Data collection for each stimulus condition (i.e., the measurement of DPOAE I/O functions and DPOAE suppression measurements) continued until one of the following conditions was met: (1) the noise level ≤ -25 dB SPL, (2) the SNR ≥ 20 dB, or (3) 210 s of artifact-free averaging time had expired. These rules were used for data collection for f_2 frequencies ≥ 1.0 kHz, including the previously collected data at 4 kHz (Gorga *et al.*, 2008) which are included in this paper. Because of the higher noise levels when $f_2 = 0.5$ kHz, the SNR stopping rule was reduced to 12 dB. This compromise was necessary in the interest of data-collection time. The data when $f_2 = 0.5$ kHz, like the previously collected data at 4 kHz, are combined with the present data to provide a description of suppression growth from 0.5 to 8 kHz. For most f_2 frequencies, averaging stopped either on the noise-floor or SNR criterion. At 0.5 kHz in the previous study, testing seldom stopped on the noise-floor criterion, even after 210 s of averaging time. At this frequency, averaging stopped on SNR criterion in some cases (i.e., for high L_2 levels), but mostly on the averaging-time criterion. At 1 and 1.4 kHz in the present study, averaging time required to reach the SNR or noise-floor stopping criteria was greater than for higher f_2 frequencies. Thus, disproportionate amounts of data-collection time were devoted to $f_2 = 0.5$ kHz in our earlier study and to $f_2 = 1$ and 1.4 kHz in the present study. Even so, these stopping rules resulted in reliable data for a wide range of f_2, L_2 combinations for every suppressor frequency.

III. RESULTS AND DISCUSSION

A. Control conditions

Figure 2 plots mean (± 1 SD) DPOAE (L_d) and noise levels as a function of L_2 (dB SL) for the subjects who participated in data collection at each of the f_2 frequencies for which data are available. In this and all subsequent figures, data from the present study ($f_2 = 1$, 1.4, 2, 2.8, 5.6, and 8 kHz) are combined with data from a previous study ($f_2 = 0.5$ and 4 kHz).[1] With 11 f_3 frequencies per L_2, f_2 combination (there were nine f_3 frequencies when $f_2 = 0.5$ kHz) and with a control condition preceding and following each L_3 series, the mean L_d and noise levels for each subject were derived from 18 to 22 measurements. These individual means were then used to calculate the grand means and SDs plotted in Fig. 2. The mean SNR for control conditions (those in which no suppressor was presented) can be ascertained at each f_2 from the dB difference between L_d and noise levels at each L_2. As can be seen from the data summarized in this figure, the smallest SNR was observed when $f_2 = 0.5$ kHz, which is to be expected because noise levels

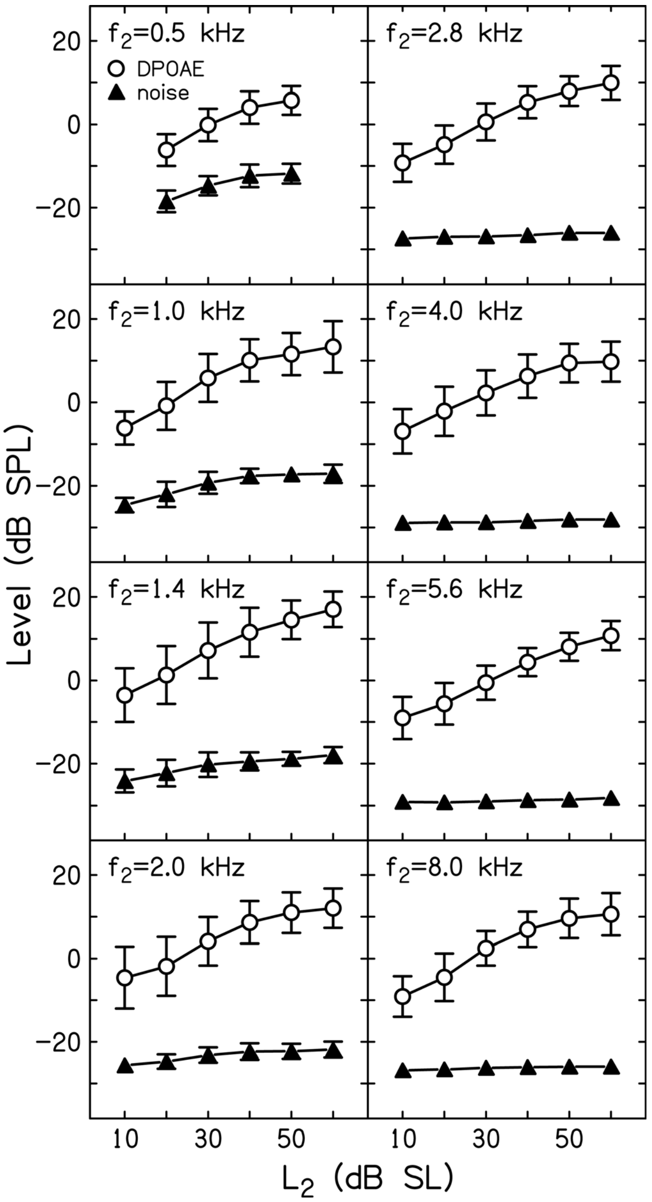

FIG. 2. Mean level (dB SPL) ± 1 SD as a function of L_2 (dB SL). Open circles represent mean DPOAE level (L_d), while filled triangles represent mean noise levels. These data represent the mean levels measured during control conditions when no suppressor was present.

are high at this frequency, despite averaging for as long as 210 s. Even so, L_d levels were, on average, at least 12 dB above the noise floor, including low-level stimulus conditions at this frequency. At higher f_2 frequencies and/or at higher L_2 levels, the SNR was larger, and, in some cases, exceeded 30 dB. With such large SNRs for control conditions, it was possible to reliably measure DPOAE suppression over a wide range of suppressor levels.

Even among subjects with the same auditory thresholds, DPOAE levels are variable and the factors contributing to that variability are not well understood (e.g., Garner *et al.*, 2008). The SDs for L_d in Fig. 2 reflect this intersubject variability. On the other hand, the SDs for noise levels were smaller and error bars are often obscured by the symbol representing the mean. This occurred when $f_2 > 2$ kHz, and is a consequence of our stopping rule, which allowed averaging to continue until the noise level was ≤ -25 dB SPL. For f_2 frequencies above 2 kHz, averaging almost always stopped on the noise-floor rule, resulting in little variability in noise levels.

In contrast, there was greater variability in mean absolute L_d across subjects, as reflected in the larger error bars for L_d in Fig. 2, regardless of f_2. This intersubject variability is perhaps less important than intrasubject variability for control conditions because we were interested in measuring the extent to which the presence of a suppressor reduced the DPOAE response relative to the response that was measured during control conditions for each subject. This makes within-subject variability in the control condition a more important estimate of the reliability of suppression measurements. Table I provides a summary relevant to this issue. This table includes the mean standard deviations (Mean_{SD}) for the control conditions for each f_2, L_2 combination across subjects, along with the SD of these standard deviations (SD_{SD}). Assuming that the SDs from individual control conditions provide an estimate of intrasubject variability, the Mean_{SD} describes the average variability of the control condition across subjects. In every case, the Mean_{SD} was less than 3 dB and, in fact, was less than 2 dB in 40 of 46 conditions.[2] The SD_{SD} provides information on the consistency with which these SDs were obtained. In 42 of 46 conditions, the SD_{SD} was less than 1 dB, and, in the other four cases, it was less than 1.25 dB. The summary provided in Table I indicates that across the subjects who contributed data at each f_2, L_2 combination, the control conditions were consistent. In total, the data shown in Fig. 2 and Table I suggest that the use of measurement-based stopping rules (as opposed to terminating measurements after a fixed number of averages or after a fixed amount of time regardless of response conditions) resulted in reliable measurements for all conditions of interest. No doubt, terminating averages when the noise floor was ≤ -25 dB SPL and/or allowing averages to continue for 210 s when this noise floor was not achieved added to data-collection time, but also contributed to the reliability of the measurements.

TABLE I. Mean_{SD} and SD_{SD} for the control conditions for all eight f_2 frequencies (kHz) and six L_2 levels (dB SL).

f_2 (kHz)		10 dB	20 dB	30 dB	40 dB	50 dB	60 dB
0.5	Mean_{SD}	—	2.75	2.13	2.01	2.10	—
	SD_{SD}	—	0.81	0.47	0.52	0.93	—
1.0	Mean_{SD}	2.25	1.44	1.25	1.21	1.20	1.14
	SD_{SD}	1.23	0.53	0.40	0.56	0.42	0.34
1.4	Mean_{SD}	1.74	1.41	1.21	1.06	0.93	0.90
	SD_{SD}	0.80	0.23	0.26	0.26	0.32	0.37
2.0	Mean_{SD}	1.46	1.38	1.11	1.11	0.97	0.91
	SD_{SD}	0.37	0.35	0.25	0.37	0.41	0.36
2.8	Mean_{SD}	1.51	1.28	1.05	1.11	1.07	1.05
	SD_{SD}	0.40	0.36	0.43	0.42	0.46	0.43
4.0	Mean_{SD}	2.18	1.89	1.90	1.74	1.76	0.44
	SD_{SD}	0.84	0.76	1.13	1.08	1.16	0.24
5.6	Mean_{SD}	1.57	1.44	1.23	1.24	1.21	1.24
	SD_{SD}	0.46	0.46	0.47	0.52	0.59	0.46
8.0	Mean_{SD}	1.50	1.23	1.06	0.91	0.97	1.11
	SD_{SD}	0.42	0.42	0.47	0.46	0.42	0.47

B. Conversions to decrements, data transformation, and suppression-threshold estimates

Figure 3 shows examples of DPOAE suppression measurements, the conversion of these data into decrements, transformation of these data, simple linear fits to the transformed data, and finally the determination of suppression thresholds that were used to construct suppression tuning curves (STCs) that are the focus of a companion paper (Gorga *et al.*, 2011). Each row shows data for a different f_2, all of which were presented at an L_2 of 40 dB SL. In each case, the suppressor frequency (f_3) was slightly higher than f_2, and was defined as the "on-frequency" condition. It is not possible to present a suppressor at exactly the same frequency as f_2 because it needs to be separable from f_2 in order to have a level (L_3) that is distinct from L_2. The left column plots mean L_d (squares) and noise levels (triangles), along with SDs, all of which are based on data from 19 or 20 subjects. The SDs associated with L_d in the left column of this figure reflect the variability in absolute L_d even among subjects with normal hearing. The smaller SDs for noise levels are a consequence of the measurement-based stopping rules, the most important of which caused data collection to terminate when noise achieved a level of ≤ -25 dB SPL. Note that for L_3 levels up to about 40–50 dB SPL (levels roughly equivalent to L_2), there was no suppression. As L_3 increased above 40–50 dB SPL, L_d decreased, and by the time L_3 was 70–80 dB SPL, the response was completely suppressed into the noise floor. The variability in L_d was slightly dependent on L_3, in that it increased as the response was suppressed. Under these circumstances, the contribution of noise variance to L_d increased because the SNR decreased, resulting in greater variability in L_d.

The right column of Fig. 3 represents the same conditions as shown in the left column, only here the data were converted into decrements (open circles), which is the amount by which L_d was reduced as a consequence of the presence of the suppressor. This conversion was accomplished by averaging the L_d for control conditions (conditions in which no suppressor was present) just prior to and just following an L_3 series for a given f_3, and then subtracting the L_d during the presentation of the suppressor from the average L_d for the control conditions. There are several advantages of

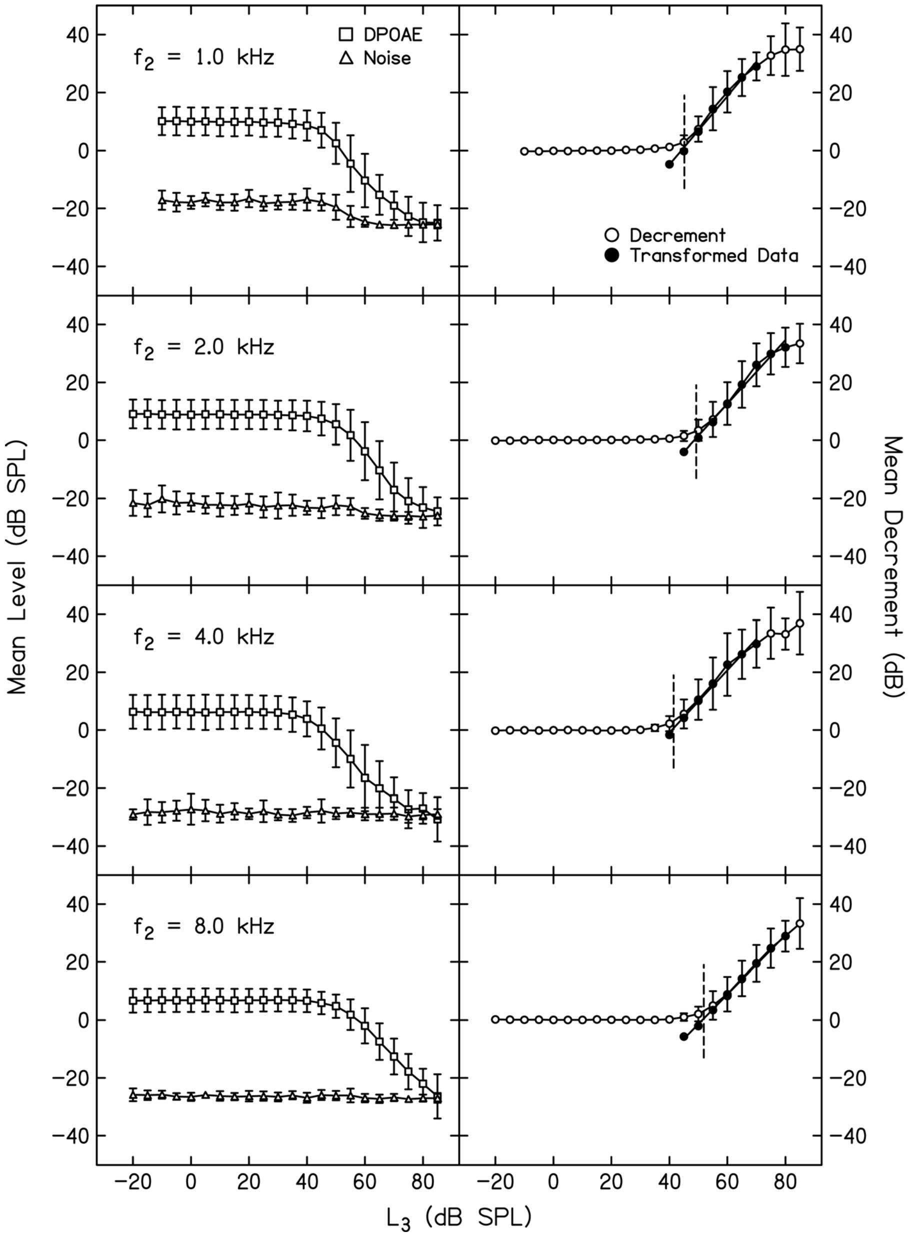

FIG. 3. Left column: Mean L_d (squares) and noise levels (triangles) as a function of L_3 (dB SPL). Error bars represent ±1 SD. Data for a different f_2 are shown in each row. In all four rows, $L_2 = 40$ dB SL (relative to each subject's behavioral threshold at f_2). Right column: Decrement in dB (open circles) obtained by subtracting the L_d in the presence of a suppressor from the average of two control conditions, in which no suppressor was present (see text for additional details). Only those points that showed at least 1 dB decrements and SNR ≥ 3 dB were included in a transformation (see text) and were subsequently fit with a straight line. The transformed data points are shown as filled circles. The fits to the transformed data provided the estimate of slope and were solved for the L_3 resulting in 3 dB of suppression, which was then used to construct the STCs in a companion paper (Gorga *et al.*, 2011).

converting the data into decrements. Decrements represent the measurement of interest (amount of suppression) and they reduce the influence of variability in L_d. This is evident in the small SDs (completely obscured by the symbols when the suppressor has no effect on the response) for low L_3 levels, and is still evident when L_3 begins to cause suppression.

To estimate the slope of these functions and to determine suppression thresholds for the purposes of constructing STCs, which is the focus of the companion paper (Gorga *et al.*, 2011) any data point for which the decrement was zero (or negative) was eliminated from further analyses. In addition, only data points for which the SNR was ≥ 3 dB were included, which eliminated those points for which the response was completely suppressed. In the right column, these data are represented by the open circles at high L_3 levels. At the outset, we established an inclusion rule, such that only data points for which the decrement increased monotonically were included in the analyses. However, non-monotonicities were never observed in any of the examples shown in Fig. 3 or any of the other mean decrement-vs-L_3 functions. Apparently, averaging across subjects eliminated the rare non-monotonicities in the data from individual subjects. Once the set of data points was reduced by the application of these three inclusion criteria, remaining data points were transformed by the following equation:

$$D = 10\log_{10}\left(10^{\mathrm{decr}/10} - 1\right). \qquad (1)$$

The transformed data points (means and SDs) are represented as filled symbols in the right column of panels. The transformed data were fit with a simple linear regression (SLR), providing slopes of the suppression-growth functions. The regressions also were solved for the L_3 resulting in a decrement of 3 dB ($D = 0$), which was defined as suppression threshold when constructing STCs in the companion paper (Gorga *et al.*, 2011). The short vertical dashed lines in the right column represent the suppression threshold so derived.

A comparison of the SDs around the decrement at this suppression threshold, compared to the equivalent SDs around the absolute L_d at the same L_3 in the left column demonstrates one advantage of converting to decrements, which is to reduce the influence of variability in L_d by having each subject serve as his or her own control. This is important for the conditions that will be used to define the suppression thresholds and plotted as STCs in the companion paper. The entire process described above was completed for all f_3 frequencies, of which there were 11, and at all combinations of f_2 and L_2.[1]

C. Examples of decrement vs L_3 functions for all f_3 frequencies

Figure 4 shows mean decrement (±1 SD) vs L_3 functions for all 11 f_3 frequencies when L_2 was set to 30 dB SL and $f_2 = 1$ kHz. Figure 5 provides similar data when $f_2 = 5.6$ kHz and $L_2 = 30$ dB SL. In both figures, data from 20 normal-hearing subjects are included, although not necessarily the same 20 subjects at both frequencies. These two f_2 frequencies were selected to provide examples of decrement functions for a relatively low f_2 and a relatively high f_2 from the set of f_2 frequencies for which suppression was measured in the present study (similar examples of decrement functions for $f_2 = 0.5$ and 4 kHz were provided in Gorga *et al.*, 2008). Although not shown in this figure, on average, the noise level was about 8–10 dB higher for $f_2 = 1$ kHz, compared to when $f_2 = 5.6$ kHz (see Fig. 2). Still, a sufficient SNR was achieved in both cases for reliable measurements of suppression for a wide range of f_3 frequencies and L_3 levels. In fact, the patterns across f_3 for these two f_2 frequencies are sufficiently similar that we will describe the data in these two figures at the same time.

Open circles represent the mean decrements (±1 SD) as a function of L_3. As stated above, the conversion to decrements reduces the influence of differences in absolute L_d across subjects. With the exception of cases in which $f_3 > f_2$, the variability (as estimated by the SD) increased as L_3 increased. Even for $f_3 > f_2$, the SD increased at high L_3 levels. This is to be expected because the SNR decreased as L_3 increased because L_d decreased (due to suppression) while noise level remained the same (i.e., it was unaffected by the

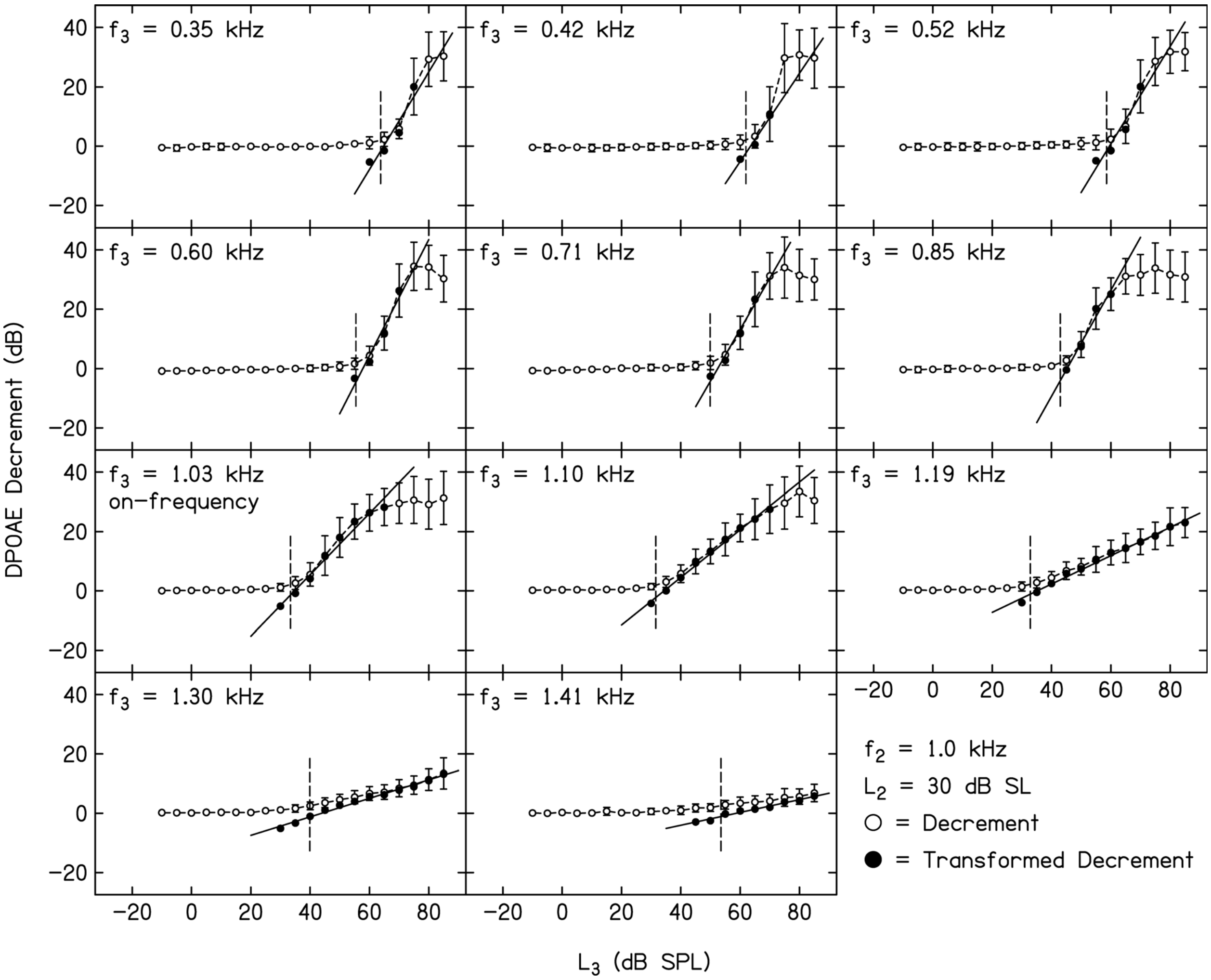

FIG. 4. Mean decrement (dB) as a function of suppressor level, L_3 (dB SPL). $f_2 = 1$ kHz and $L_2 = 30$ dB SL. Each panel represents data for a different f_3. Open circles represent the mean difference in L_d between control conditions and the conditions in which a suppressor was present. Error bars represent ±1 SD. Filled circles represent the decrements after they were transformed using Eq. (1) (see text). Lines represent best fits to the transformed decrements. The fits to the transformed data provided the estimate of slope and were solved for the L_3 resulting in 3 dB of suppression, which was then used to construct the STCs in a companion paper (Gorga *et al.*, 2011).

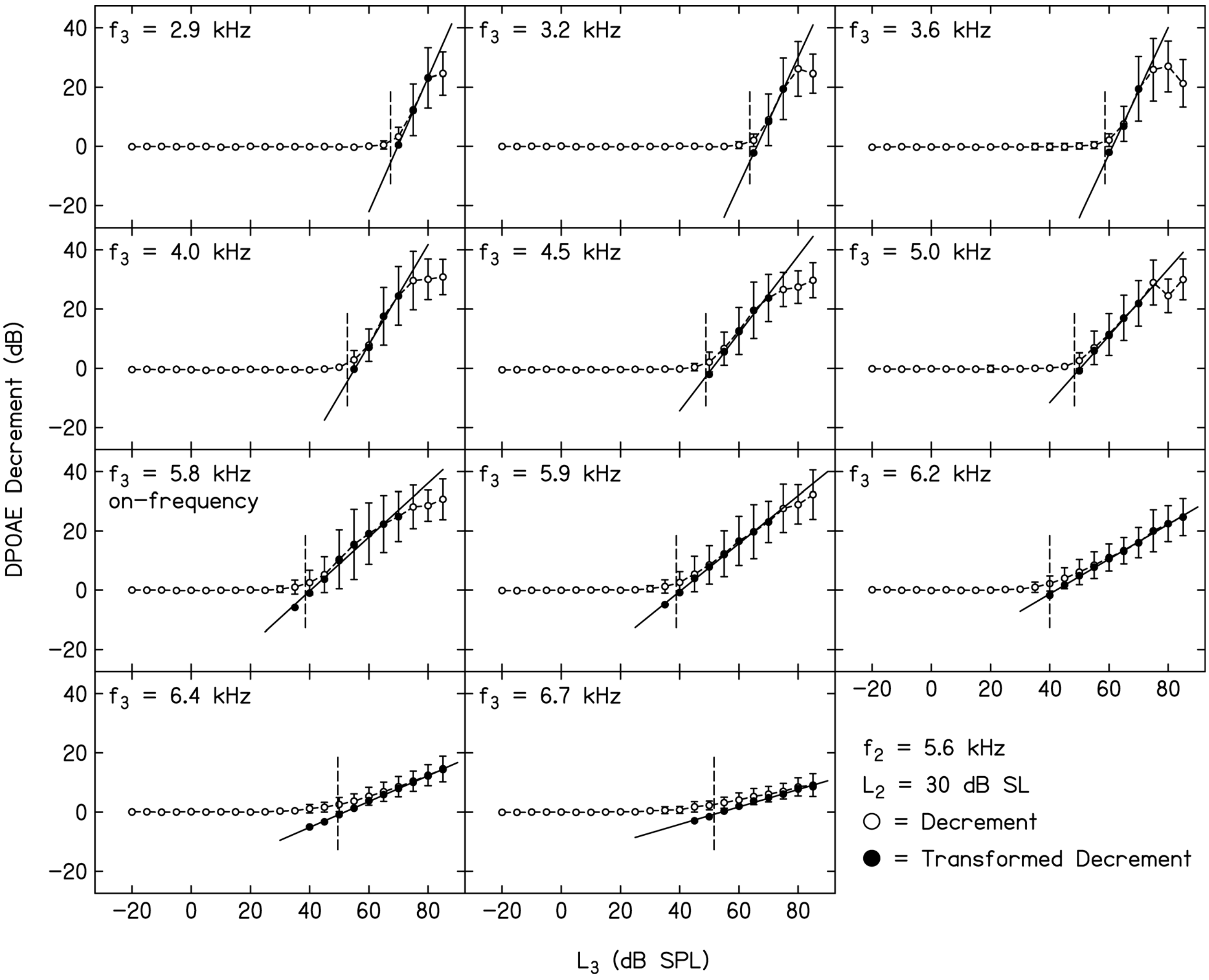

FIG. 5. Same as Fig. 4, only here $f_2 = 5.6$ kHz and $L_2 = 30$ dB SL.

suppressor), resulting in greater variability due to the increased influence of noise variance on estimates of L_d. There was a smaller effect of L_3 on variability when $f_3 > f_2$ because the reduction in L_d was small, meaning that the contribution of noise variance to variability in L_d was also small.

Of interest in both Figs. 4 and 5 is the relative frequency dependence (f_3 relative to f_2) of the slope of the decrement function (growth rate of suppression) as a function of L_3. This can be seen in the raw decrement data (open circles), as well as in the transformed data to which a line was fit. An examination of the data shown in these two figures indicates that the trends at 1 and 5.6 kHz are similar. Specifically, low-frequency suppressors relative to f_2 require a high L_3 in order for suppression to occur (see upper left panel in both figures), but once suppression starts to occur, it grows rapidly with further increases in L_3. Both suppression threshold and the rate at which it grows decreased as f_3 increased. In general, the lowest suppression threshold occurred for the f_3 that was closest to but slightly higher than f_2. For convenience, this f_3 is referred to as the "on-frequency" suppressor. As f_3 increased above this frequency, the rate at which suppression grew decreased systematically with f_3. "Suppression threshold" increased slowly as f_3 increased above f_2, compared to what might be expected for single-unit rate-vs-level functions sharing similar frequency relationships (e.g., Sachs and Abbas, 1974). This effect, however, is consistent with the observation of wider STCs, compared either to excitation tuning curves at the single-unit level or differences between simultaneous and forward-masking psychophysical tuning curves in humans (e.g., Sachs and Kiang, 1968; Ruggero and Temchin, 2005; Jesteadt and Norton, 1985; Moore *et al.*, 1984; Shannon, 1976). For the L_2 condition shown in these two figures ($L_2 = 30$ dB SL), it was possible to completely suppress the response (as evident both in the asymptotic portions of some of the decrement functions and in the open symbols at high L_3 levels, indicating that the SNR <3 dB). Complete suppression occurred for some, but not all, f_3 frequencies. This was especially true on the high-frequency side of f_2 because there were insufficient suppressor levels to result in complete suppression (see the panels describing suppression for the three highest f_3 frequencies at both f_2 frequencies). These general patterns were observed at other f_2 frequencies and L_2 levels, including the data for $f_2 = 0.5$ and 4 kHz, which were taken from a previous paper (Gorga *et al.*, 2008).[1]

D. Examples of decrement vs L_3 functions for all f_2 frequencies

Whereas, Figs. 4 and 5 provide mean decrement vs L_3 functions for all 11 f_3 frequencies, but for only two f_2

frequencies and one L_2 level, Figs. 6–8 provide mean decrement vs L_3 functions for all f_2 frequencies, but only for subsets of f_3 frequencies and L_2 levels. The f_3 frequencies were chosen, in part, because they represent frequencies that have been of interest in other measures of cochlear nonlinearity, including suppression. Each figure provides data for a single f_3 relative to f_2 while separate panels within each figure provide data for one of eight f_2 frequencies. Data are shown for $f_3 \approx f_2 - 1$ octave (Fig. 6), the on-frequency case when $f_3 \approx f_2$ (Fig. 7), and when $f_3 \approx f_2 + \frac{1}{4}$ octave (Fig. 8).

In all three figures, the results for different L_2 levels are represented by different line weights, with the results for the lowest L_2 (10 dB SL) shown with the thinnest line, and progressively thicker lines for the higher two L_2 levels (30 and 50 dB SL). There are no data for the case when $f_2 = 0.5$ kHz and $L_2 = 10$ dB SL because the high noise levels for this f_2 combined with the low L_d at this L_2 prevented reliable DPOAE measurements and, therefore, prevented reliable measurements of suppression. As a result, there are only two functions in the panels depicting results when $f_2 = 0.5$ kHz.

First, consider the low-frequency suppressor results in Fig. 6. Note that for all f_2 frequencies and the three L_2 levels for which data are shown, suppression threshold was relatively high, but only slightly dependent on L_2. For a 40-dB range in L_2 (10–50 dB SL), suppression threshold changed by 20 dB or less. However, once suppression threshold was reached, the decrement increased rapidly with further increases in L_3. In many (but not all) cases, these low-frequency suppressors resulted in complete suppression of the response, as indicated by the asymptotic decrements at high L_3 levels. Not surprisingly, this was more likely to occur when $L_2 = 10$ or 30 dB SL, but did not occur when $L_2 = 50$ dB SL because the response at this level was too large to be completely suppressed, even for the highest L_3 levels.

Figure 7 provides examples of mean decrement vs L_3 functions when $f_3 \approx f_2$. Note that the L_3 at which decrements first occurred was lower in this case, compared to the results shown in Fig. 6, meaning that suppression thresholds were lower when f_3 was close to f_2. Unlike the results shown in Fig. 6, suppression threshold appeared to be more dependent on L_2, such that there was about a 20-dB increase in suppression threshold for each 20-dB increase in L_2. As expected, complete suppression was a more common occurrence when $f_3 \approx f_2$, which is evident in the larger number of conditions for which asymptotic decrements occurred at high L_3 levels.

Figure 8 provides examples of decrement vs L_3 functions when $f_3 \approx f_2 + \frac{1}{4}$ octave. Suppression thresholds were higher in this case, compared to when $f_2 \approx f_3$ (Fig. 7), and once suppression threshold was reached, the amount of suppression grew slowly with increases in L_3. With the exception of the condition in which $f_2 = 1$ kHz and $L_2 = 10$ dB SL, there was no indication of complete suppression, even for the highest L_3.

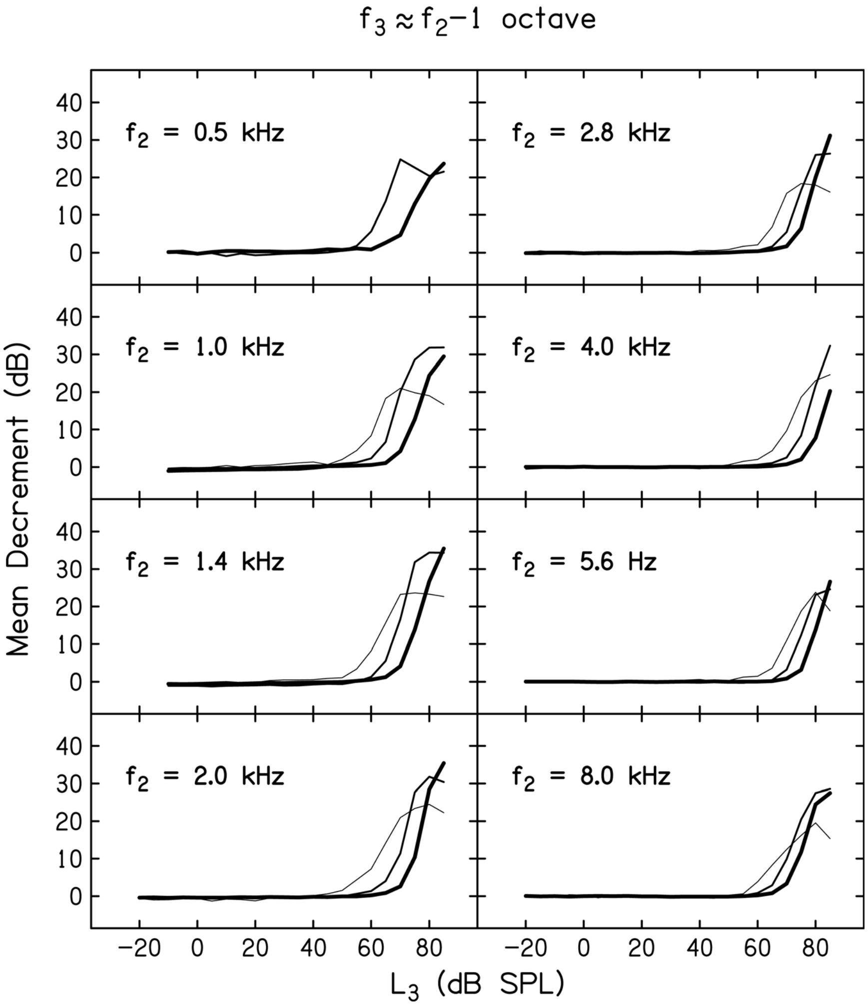

FIG. 6. Mean decrement (dB) as a function of suppressor level, L_3 (dB SPL). Data for a different f_2 are represented in each panel. Within each panel, data are shown for L_2 levels of 10, 30, and 50 dB SL, with the thinnest line representing data for the 10-dB SL condition and progressively heavier lines representing data for $L_2 = 30$ and 50 dB SL. In all panels, $f_3 \approx f_2 - 1$ octave.

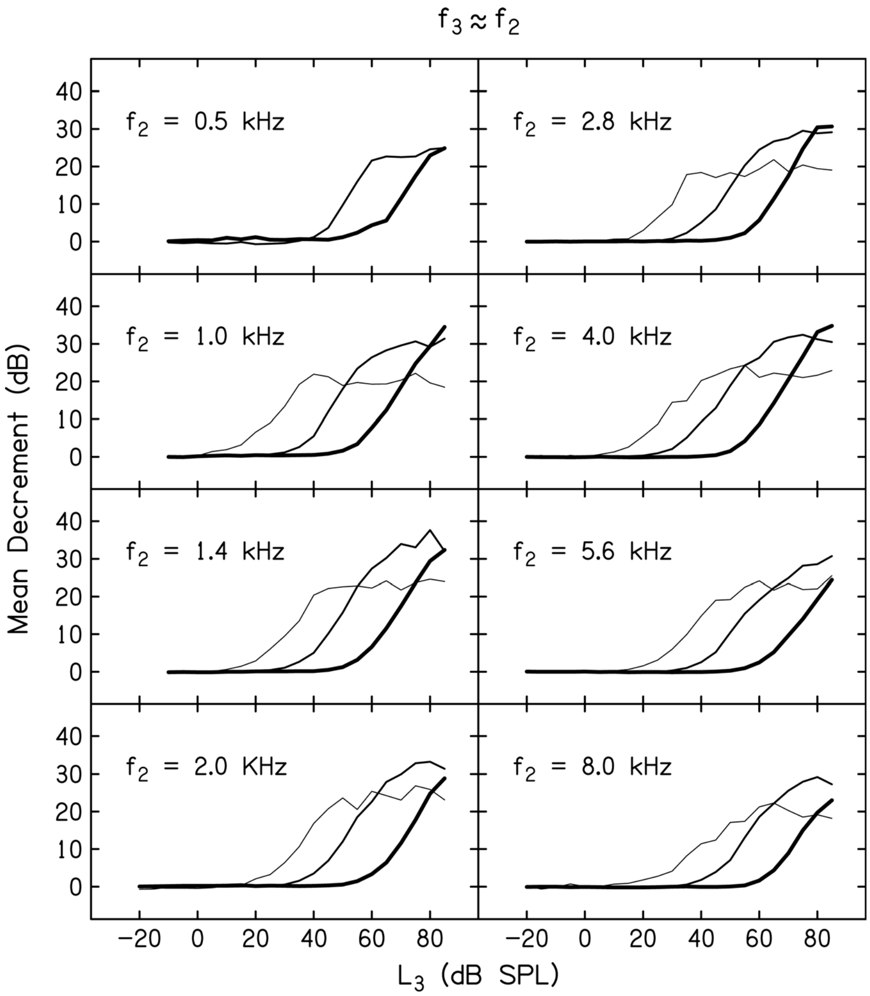

FIG. 7. Same as Fig. 6, only here $f_3 \approx f_2$.

Like the more detailed comparisons in Figs. 4 and 5, the summaries provided in Figs. 6–8 indicate that, while there are differences across f_2 frequencies, these differences are relatively small and the general trends are the same regardless of frequency and level. These data are consistent with previous growth of suppression data based on auditory-nerve fiber responses in lower animals (e.g., Abbas and Sachs, 1976; Delgutte, 1990; Pang and Guinan, 1997) and are also consistent with measurements of suppression in basilar-membrane responses (e.g., Ruggero *et al.*, 1992; Cooper and Rhode, 1996; Rhode and Cooper, 1993). Similar patterns have been observed in previous DPOAE suppression data as well (e.g., Abdala, 1998, 2001; Abdala and Fitzgerald, 2003; Abdala and Charterjee, 2003; Gorga *et al.*, 2002, 2003; Kummer *et al.*, 1995). Specifically, these previous studies showed that suppression grows most rapidly for suppressors lower in frequency than the signal frequency and that the growth of suppression decreases as suppressor frequency increases. In many respects, it is easier to interpret the single-unit and mechanical data from lower animals because fewer assumptions are needed regarding the stimuli and the location at which the response is generated in the cochlea. With DPOAE measurements in humans, two tones are used to represent the "signal," so presumably the suppression of the representation of one or the other tone might result in a reduction in L_d. The distortion measured in the ear canal is complex (in that it may include contributions from both a distortion and a reflection source (e.g., Shera and Guinan, 1999); theoretically, suppression of either source might result in a phase-dependent reduction or enhancement of L_d. Finally, it is not possible in humans to know the exact location of the generator site within the cochlea, and, in fact, the generator sites might be dispersed along regions basal to the characteristic place of f_2 (e.g., Martin *et al.*, 2010), although others have questioned this view (Withnell and Lodde, 2006). Despite these limitations, the human data in Figs. 4–8, as well as previous DPOAE suppression data, are consistent with results obtained in lower animals using more invasive procedures. Thus, we take these data to suggest that DPOAE suppression measurements in humans are, at least to a first approximation, describing the same underlying processes that have been described more directly in lower animals.

E. Slopes of decrement vs L_3 functions

Figure 9 plots the slope of mean decrement vs L_3 functions for all eight f_2 frequencies, as many as six L_2 levels, and as many as 11 f_3 frequencies. In all cases, data from at least 10 but no more than 20 subjects are included in each panel (as few as ten subjects provided reliable data when $L_2 = 10$ dB SL for some f_2 frequencies), but data are not from the same subjects in all 46 panels. As in other figures,

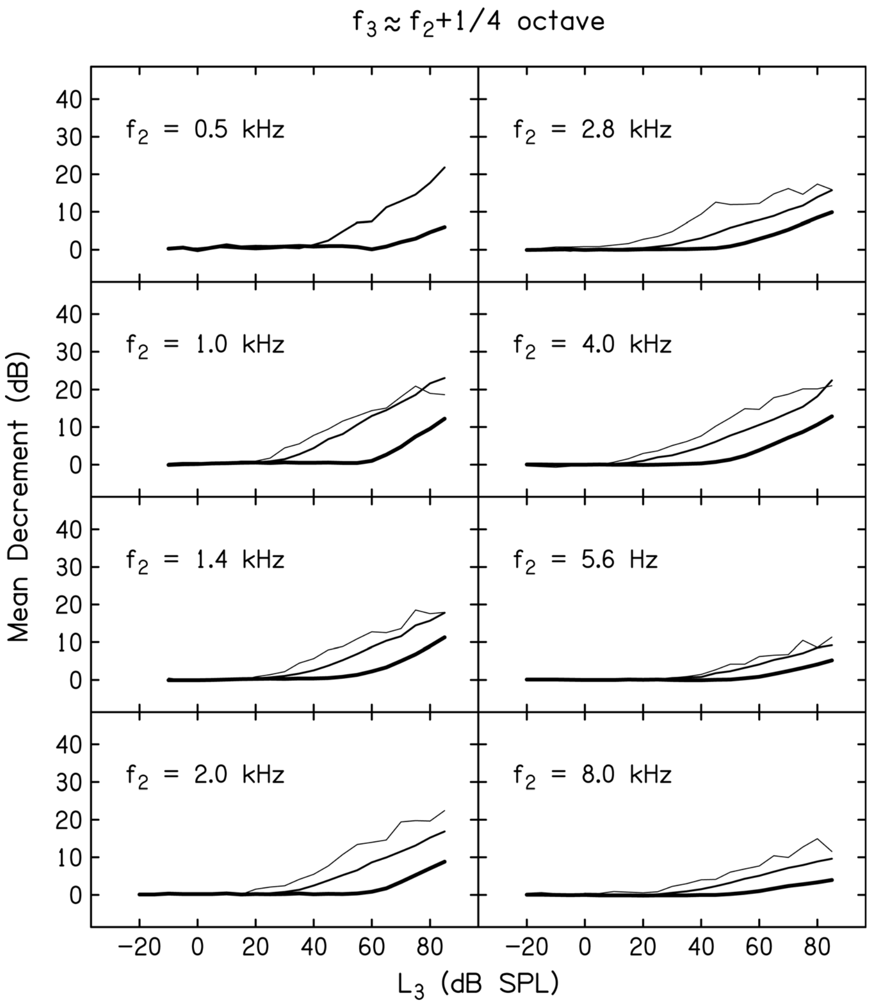

FIG. 8. Same as Fig. 6, only here $f_3 \approx f_2 + \frac{1}{4}$ octave.

there are no data for $f_2 = 0.5$ kHz and $L_2 = 10$ or 60 dB SL because these conditions were not measured.[2] These slopes were calculated based on SLR, in which decrement functions were fit independently for each f_3, L_2 combination. Data for a different f_2 are shown in each row while the results for each L_2 are shown in separate columns. In this figure, f_3 is plotted on an octave scale relative to f_2, which is a form of normalization that may be preferred for comparison across f_2.

Clearly, there were differences across frequency and level. For example, there appeared to be a range of f_3 frequencies for which the slope is relatively constant when $f_2 = 0.5$ and 1 kHz. This trend was either less evident or absent for higher f_2 frequencies. Part of this observation relates to the fact that it was possible to suppress the response to lower f_2 frequencies with f_3 frequencies in some cases as much as 1.5–2 octaves below f_2 (0.5 and 1 kHz). While this was true for several low-frequency f_2 frequencies, it was seldom possible to produce suppression with f_3 frequencies $< f_2 - 1$ octave at higher f_2 frequencies. One factor contributing to this effect may be the output limitations in our hardware, but it is unlikely that this alone accounted for the more limited range of low f_3 frequencies for which suppression was produced for higher f_2 frequencies. Thus, this may represent a difference in DPOAE suppression effects between low and high f_2 frequencies. Qualitatively, this frequency difference is not unlike similar effects observed in single-unit measurements (Delgutte, 1990) and in derived measurements from otoacoustic emission (OAE) latencies (Shera *et al.*, 2010). There also was evidence that the slope of the decrement functions sometimes decreased non-monotonically with f_3, but this effect was not a systematic function of frequency, as it was evident for both high and low f_2 frequencies for some L_2 levels and it did not occur at the same f_3 relative to f_2 as might be expected if the non-monotonicities were caused by the complex interaction of distortion and reflection sources.

These differences across f_2 notwithstanding, the general trends were similar across f_2 frequency and L_2 level. That is, the steepest slopes were observed for conditions in which $f_3 < f_2$, slope decreased as f_3 increased, and the shallowest slopes were observed for conditions in which $f_3 > f_2$. When $f_3 \approx f_2$, the slope of the decrement function (i.e., the suppression-growth rate) was close to 1.

The data summarized in Figs. 4–8 are consistent with previous descriptions of DPOAE suppression in humans (Abdala, 1998, 2001; Abdala *et al.*, 1996; Abdala and Chatterjee, 2003; Abdala and Fitzgerald, 2003; Gorga *et al.*, 2002a,b, 2003; Brown and Kemp, 1983; Kummer *et al.*, 1995). Data from these studies showed the same dependence of growth of suppression on the relation between f_3 and f_2. The present paper differs from these previous efforts in terms of the range of f_2 frequencies and L_2 levels that are described

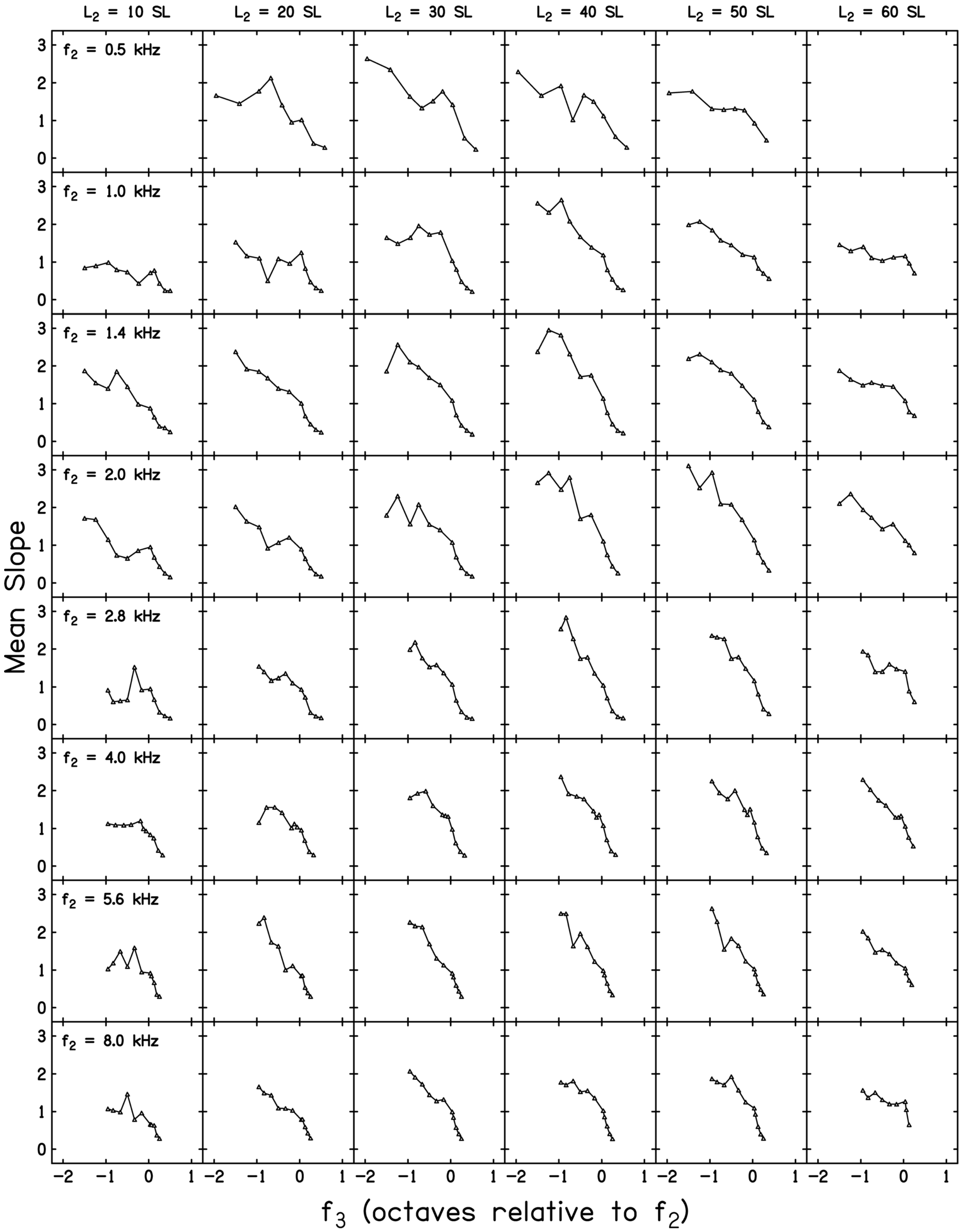

FIG. 9. Slope of the decrement function as a function of f_3 in octaves relative to f_2. Data for a different f_2 are shown in each row and data for a different L_2 are shown in each column. Slopes are estimated from a SLR in which only L_3 was a variable.

herein. For example, L_2 levels ranged from as low as 10 to as high as 60 dB SL in the present study. On the low end (10 dB SL), this translates into L_2 levels in dB SPL that ranged from about 14 dB SPL at 4 kHz to about 28 dB SPL at 8 kHz (see Fig. 1). Few studies of DPOAE suppression report data for L_2 levels as low as these levels and it is not common to find suppression data for 5–6 L_2 levels. Finally, there are few papers that include data from 0.5 to 8 kHz. Thus, the present work provides a description of suppression growth for an unusually wide range of frequencies and levels.

Other differences exist between previous data and the results reported here. In addition to the use of the present measurement-based stopping rules, data were converted into decrements, specific inclusion criteria were applied to determine the data points for further analysis, these data points were transformed, and then fit with a linear equation. As a consequence, only qualitative comparisons seem appropriate. Even so, it is noteworthy that the many previous studies in humans have described similar frequency dependence of the slope of the suppression functions.

F. Multivariate linear regressions

Whereas, Fig. 9 provides estimates of slope based on SLRs in which only L_3 was an input variable, Fig. 10 provides estimates of slope based on multiple linear regressions (MLRs), in which both L_2 and L_3 served as input variables. Although it covered a smaller range and was varied with less precision during data collection, compared to L_3, L_2 still varied from 10 or 20 to 50 or 60 dB SL in 10-dB steps. The left panel of Fig. 10 plots slope on a log-frequency scale, while the right panel plots slope on an octave scale relative to f_2. The open symbols in each panel provide slope estimates when L_3 is the variable and filled symbols in each panel describe slopes when L_2 is the variable. In the left panel, it can be seen that slope functions for both L_3 and L_2 moved toward higher frequencies as f_2 increased. This panel allows one to discern the slope of these decrement functions for each f_2, which appear to be similar (although not identical) across f_2. Given the summaries in earlier figures, this is the expected outcome. There is less variation in slope when L_2 is the variable of interest, as evident in the functions at the bottom of the left panel. However, there is a local minimum on each of these functions, which occurs when $f_3 \approx f_2$, and the slope is close to -1. This means that when $f_3 \approx f_2$, every 10-dB increase in L_2 was accompanied by about a 10-dB increase in L_3.

The right panel of Fig. 10 plots these same slope values, only here an octave-frequency scale relative to f_2 is used. On this x-axis scale, both similarities and differences as a function of f_3 are emphasized. For example, the growth of suppression was greatest when f_3 was an octave or more below f_2, decreased as f_3 increased, and had a minimum for f_3 frequencies higher than f_2. With the exceptions of $f_2 = 0.5$ and 1 kHz, these slopes overlapped for all f_2 frequencies. When L_2 is the variable, there was more uniformity of slope across f_2. The minimum L_2 slope occurred when $f_3 \approx f_2$ regardless of f_2. The slopes based on MLR and plotted on an octave scale suggest that growth of suppression is similar across a wide range of frequencies in humans. The exceptions to this observation occurred when $f_2 = 0.5$ and 1 kHz, but even in these cases, the overall pattern was at least qualitatively similar to what was observed at other f_2 frequencies.

The results for f_2 frequencies of 0.5 and 1 kHz are reminiscent of stimulus frequency otoacoustic emission (SFOAE) data reported by Shera *et al.* (2010). They measured SFOAE latencies in humans, and noted that the function relating latency to frequency appeared to have different slopes for frequencies >1 kHz, compared to frequencies ≤ 1 kHz. The underlying mechanism responsible for this change in slope is not obvious, but the results shown in the right panel of Fig. 10 may be consistent with the findings of Shera *et al.* in suggesting different behavior below 1 kHz. The slope of the DPOAE decrement functions when $f_2 = 0.5$ and 1 kHz change more gradually as f_3 frequency increases, compared to the results for higher f_2 frequencies. These results also share similarities with auditory-nerve data reported by Delgutte (1990). For example, Delgutte reported a more gradual change in suppression-growth rate as suppressor frequency increased for fibers having CFs <2 kHz, and a more abrupt change in slope with frequency for fibers with CFs >2 kHz. In addition, he observed more rapid growth in suppression for low-frequency suppressors relative to CF, even when suppressor frequency was normalized (see Fig. 9; Delgutte, 1990). Comparisons of auditory-nerve data to DPOAE data are complicated by many factors, not the least of which is the differences in the stimuli that are used to elicit these different responses. For example, single-fiber response properties can be probed by presenting a single signal frequency, whereas DPOAE measurements must use a "signal" that consists of two pure tones whose relative levels add complexity to the stimulus paradigm. We do not intend to minimize these differences, but it is unlikely that the similarities and consistencies in the present data, relative to data from lower animals, are coincidental. To the extent that f_2 frequency can be

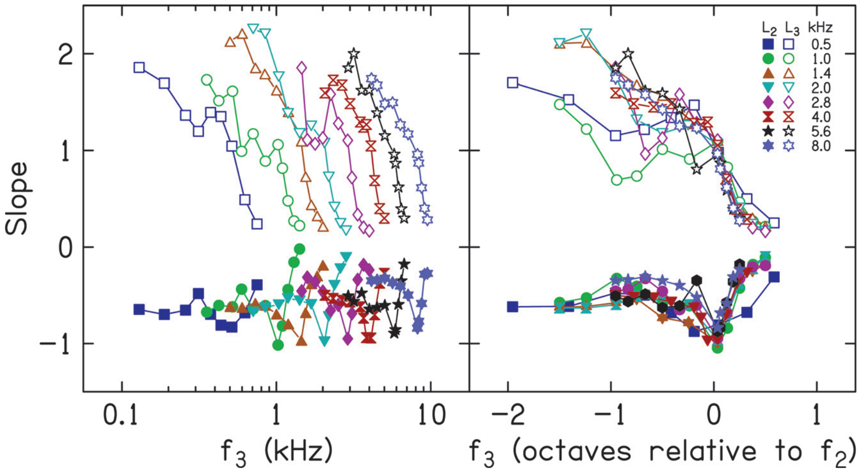

FIG. 10. (Color online) Slopes from multivariate linear regressions in which L_3 and L_2 were included. Left panel: f_3 is plotted on a log-frequency scale. Right panel: f_3 plotted on an octave frequency scale relative to f_2. Within each panel, the parameter is f_2. Open symbols represent slopes as a function of L_3, while filled symbols represent slopes as a function of L_2.

considered as an approximation of CF, the results shown in Fig. 10 of the present study share similarities with the auditory-nerve data reported by Delgutte. Delgutte provided a detailed description of growth of suppression based on changes in auditory-nerve fiber responses and there were differences in how suppression was quantified in the present study, compared to the approach taken by Delgutte. However, the present results are consistent with the results based on auditory-nerve data and cover a wide range of frequencies (although not as wide as the animal work). Thus, the present study provides a description of DPOAE suppression in humans, which shares at least qualitative similarities with data from lower animals.

In this study (as in virtually all other studies of DPOAE suppression), we did not use methods in which the influence of complex source contributions on suppressive effects was evaluated. There are several reasons for this, including potentially complex stimulus conditions when attempting to control the reflection source and the observation in many studies of DPOAE suppression (including this study) that evidence of the influence of source contribution is not obvious. Still, DPOAEs include both a distortion source (presumably located near the f_2 place) and a reflection source (at the $2f_1$–f_2 place), both of which contribute to the L_d measured in the ear canal (e.g., Shera and Guinan, 1999). Depending on the relative level and phase of the components from these two sources, either constructive or destructive interference will occur. In the context of the present study, one might predict that the decrement functions would be altered when f_3 was close to $2f_1$–f_2. However, we observed no evidence to suggest that this was occurring, at least not in the mean data. This observation alone does not necessarily indicate that there were no contributions from the reflection source because any effects might average out, due to variations in phase for the component coming from that source.

IV. SUMMARY AND CONCLUSIONS

DPOAE suppression is reported for f_2 frequencies ranging from 0.5 to 8 kHz and for L_2 levels ranging from 10 or 20 to 50 or 60 dB SL. For each f_2, L_2 combination, suppression was measured for up to 11 suppressor frequencies ranging in level from −20 to 85 dB SPL. With the exception of 0.5 kHz where no data were collected when $L_2 = 10$ or 60 dB SL, data were collected from between 10 and 20 subjects with normal hearing. Measurement techniques were used that reduced noise levels to as low as −25 dB SPL, thus permitting reliable estimates for a wide range of conditions. The growth of suppression was greatest for f_3 frequencies below f_2, decreased as f_3 increased, and was slowest for f_3 frequencies above f_2. This dependence of suppression growth on the relation between f_3 and f_2 was observed for all f_2 frequencies and all L_2 levels, although the behavior at 0.5 and 1 kHz differed from what was observed at higher frequencies. These results are consistent with similar data obtained from invasive techniques in lower animals and are similar to previous DPOAE suppression data from both lower animals and humans. The results are unique in that they cover a wider range of frequencies and levels than previously reported.

Controversy remains as to what OAE measurements like the present measurements tell us about cochlear function. Of necessity, these measurements rely on indirect techniques, complex stimulus paradigms, and interpretations that are based on the assumption that these data are describing underlying processes based on the similarity in patterns, compared to more direct measurements in lower animals. It is impossible to perform direct measurements in humans, but the measurements described here could be used to obtain data in lower animals that could then be compared to data obtained from more invasive measurements in the same animal. Such a comparison would provide a more direct test of the extent to which OAE measurements describe underlying cochlear processes.

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[1] Data when $f_2 = 0.5$ and 4 kHz from a previous study (Gorga *et al.*, 2008) were combined with the data collected as part of this study. Because the conditions from the present study are identical in all respects with those used previously, it was decided to combine the previously collected data for $f_2 = 0.5$ and 4 kHz with the presently collected data at an additional six f_2 frequencies, thus providing a description of DPOAE suppression from 0.5 to 8 kHz. This seemed reasonable because identical subject-selection criteria and experimental procedures were used in the previous and present data-collection efforts. Furthermore, the collection of data for $f_2 = 0.5$ and 4 kHz consumed approximately 800 h of data-collection time (the majority of which was devoted to data collection when $f_2 = 0.5$ kHz). Repeating that effort, in addition to the 950 h of data-collection time that was needed for the six new f_2 frequencies with which those data are now being combined, would have been prohibitive and perhaps an inappropriate use of resources. Even in the present study, no subject participated in data collection at all six f_2 frequencies because to do so would have required an unacceptable and unachievable time commitment from most subjects. In our previous efforts, it was not possible to collect data when $f_2 = 0.5$ kHz and $L_2 = 10$ dB SL because the SNR was not sufficient for reliable suppression measurements for that condition even after as much as 210 s of artifact-free averaging time. We did not collect suppression data at 0.5 kHz when $L_2 = 60$ dB SL, due to limitations in the amount of time subjects were willing to dedicate to data collection. These are the only frequency and level combinations for which no data were collected in either study. Instead, we focused our data-collection efforts on L_2 levels from 20 to 50 dB SL when $f_2 = 0.5$ kHz.

[2] Even though there were eight f_2 frequencies and six L_2 levels, there are only 46 conditions because we did not measure suppression when $f_2 = 0.5$ kHz for $L_2 = 10$ and 60 dB SL. Recall that the data for $f_2 = 0.5$ and 4 kHz came from a previous paper (Gorga *et al.*, 2008). At that time, data were not collected for either of these two f_2 frequencies at $L_2 = 60$ dB SL. In the previous study, we attempted to collect suppression data when $f_2 = 0.5$ kHz and $L_2 = 10$ dB SL, but the measurements were unreliable for the reasons stated in Footnote 1. However, we were able to obtain data when $f_2 = 4$ kHz and $L_2 = 10$ dB SL previously, and those data are included here. In the course of the present study, additional data were collected for $f_2 = 4$ kHz and $L_2 = 60$ dB SL because those data could be collected quickly. It was decided not to collect additional data when $f_2 = 0.5$ kHz and $L_2 = 60$ dB SL because this would have increased data-collection time, which already was extensive in this study.

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