Multi-tone suppression of distortion-product otoacoustic emissions in humans

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The purpose of this study was to investigate the combined effect of multiple suppressors. Distortion-product otoacoustic emission (DPOAE) measurements were made in normal-hearing participants. Primary tones had fixed frequencies ($f_2 = 4000$ Hz; $f_1 / f_2 = 1.22$) and a range of levels. Suppressor tones were at three frequencies ($f_s = 2828, 4100, 4300$ Hz) and range of levels. *Decrement* was defined as the attenuation in DPOAE level due to the presence of a suppressor. A measure of suppression called *suppressive intensity* was calculated by an equation previously shown to fit DPOAE suppression data. Suppressor pairs, which were the combination of two different frequencies, were presented at levels selected to have equal single-suppressor decrements. A hybrid model that represents a continuum between additive intensity and additive attenuation best described the results. The suppressor pair with the smallest frequency ratio produced decrements that were more consistent with additive intensity. The suppressor pair with the largest frequency ratio produced decrements at the highest level that were consistent with additive attenuation. Other suppressor-pair conditions produced decrements that were intermediate between these two alternative models. The hybrid model provides a useful framework for representing the observed range of interaction when two suppressors are combined. © 2016 Acoustical Society of America.

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I. INTRODUCTION

Suppression occurs when the response to one stimulus is reduced by the presence of another stimulus. Suppression in level of distortion-product otoacoustic emissions (DPOAEs) due to the presence of a suppressor tone can be measured noninvasively, so it is accessible for study in humans. The purpose of this study was to investigate how the combined effect of two tonal suppressors on DPOAEs is related to the effects of the individual suppressors when presented separately. The interaction of multiple tonal suppressors has relevance to the role that suppression plays in the processing of complex stimuli, such as speech.

Physiological studies in animals have observed tone-on-tone suppression, called two-tone suppression, in recordings from single auditory-nerve fibers and in direct measures of basilar-membrane (BM) vibration (e.g., Delgutte, 1990b; Pang and Guinan, 1997; Cooper, 1996). Horst *et al.* (1986, 1990) used multicomponent stimuli to analyze the representation of complex stimuli in responses of the auditory nerve in cat. In their study, the response to the center component became increasingly suppressed as the number of stimulus components increased (from 4 to 64). Rhode and Recio (2001a) used amplitude-modulated signals with varying modulation depths to measure the response of the BM to complex stimuli near the 7-kHz place in chinchilla.

Suppression was as much as 35 dB and decreased when the frequency-component separation was greater than 600 Hz. Subsequently, Rhode and Recio (2001b) found that suppressors that were lower in frequency than the best frequency resulted in the greatest amount of suppression at high levels, while suppressors that were similar in frequency to the best frequency resulted in the largest amount of suppression at low levels. Although additional suppressors generally produced greater amounts of suppression, they were sometimes observed to produce less suppression.

Cooper (1996) showed that root-mean-squared displacement due to a suppressor predicts two-tone suppression in guinea-pig BM measurements. This finding was extended by Versteegh and van der Heijden (2012) in gerbils to a wide range of experimental conditions that included wideband stimuli. Both single-tone and wideband stimuli were observed to reduce cochlear sensitivity in a similar manner. The sensitivity loss due to wideband stimuli could be predicted from single-tone responses by summing the mean-squared displacement of frequency components.

It is not possible to observe suppression of BM or auditory-nerve responses in humans, due to the invasive nature of these measurements, so comparisons must rely on indirect measures. DPOAEs have been used to study suppression in humans for a wide range of frequencies. The growth of suppression in normal-hearing listeners follows predictable patterns that are dependent upon the frequency relationship of the probe frequency (f_2) used to elicit the DPOAE and the frequency of the suppressor (f_s) (e.g., Brown and Kemp, 1984; Kummer *et al.*, 1995; Abdala and

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Chatterjee, 2003; Gorga *et al.*, 2008; Gorga *et al.*, 2011b). Specifically, suppression is observable at the lowest suppressor level (L_s) when $f_s \approx f_2$, a condition for which the slope of the function (i.e., amount of suppression of the DPOAE as function of suppressor level) is ≈ 1 . When $f_s < f_2$, suppression begins to occur at a higher L_s , but the slope of the function is > 1 ; when $f_s > f_2$, the L_s at which suppression begins to occur is higher than it is for the case when $f_s \approx f_2$; however, the slope of the function is < 1 . These findings are consistent with direct measurements of BM motion (e.g., Cooper, 1996; Rhode and Cooper, 1993; Ruggero *et al.*, 1992) and auditory-nerve fiber responses from laboratory animals (e.g., Abbas and Sachs, 1976; Delgutte, 1990b; Pang and Guinan, 1997). The observed consistency of DPOAE suppression with BM and auditory-nerve measurements supports the view that indirect noninvasive DPOAE measurements in humans may provide insights into underlying cochlear processes.

Gorga *et al.* (2008) and Gorga *et al.* (2011b) obtained suppression functions by making DPOAE suppression measurements over a range of frequencies and levels. To represent the amount of suppression, decrement functions were calculated as the difference between DPOAE levels measured with and without suppressors. Stated another way, *decrement* represents the attenuation of DPOAE level due to the presence of a suppressor. Measured decrement functions (*decr*) were transformed using the following equation:

$$D = 10 \log_{10}(10^{decr/10} - 1). \quad (1)$$

Following this transformation, the *transformed decrements* (D) were fitted by a simple linear regression (of D onto L_s) to obtain the slopes and intercepts that were used to estimate the growth and threshold of suppression, respectively.

Rasetshwane *et al.* (2014) used data from Gorga *et al.* (2008) and Gorga *et al.* (2011b) to develop a signal-processing algorithm for hearing aids that aims to restore, among other things, normal suppression, which presumably would be beneficial to individuals with hearing loss because they lack normal cochlear suppression (Abdala and Fitzgerald, 2003; Gorga *et al.*, 2003; Birkholz *et al.*, 2012; Gruhlke *et al.*, 2012). In order to generalize the suppressive effect of a single suppressor tone to the case when there are multiple frequency components, Rasetshwane *et al.* (2014) assumed that suppressive effects were additive in terms of variables that represented the relative intensities of different frequency components. We adopted a similar approach in this study by defining a quantity based on Eq. (1) that we call *suppressive intensity*:

$$I_s = 10^{D/10}. \quad (2)$$

Note that when D is a linear function of L_s , which we typically observe to be a good approximation in our DPOAE suppression data, then I_s is proportional to the physical intensity of f_2 raised to some power. Combining Eqs. (1) and (2) yields an equation for *decr* as a function of I_s :

$$decr = 10 \log_{10}(1 + I_s). \quad (3)$$

In effect, this equation represents the attenuation due to the suppressor as the sum of the unsuppressed response, which is represented by 1, and the suppressive intensity, I_s . In other words, Eq. (3) represents an *additive-intensity* model of suppression for the case of one suppressor. This model provides a good description of DPOAE suppression data (e.g., Gorga *et al.*, 2008; Gorga *et al.*, 2011a,b). Here we consider a straightforward, but untested, extension of the additive-intensity model for the case of two suppressors as follows:

$$decr_{1+2} = 10 \log_{10}(1 + I_{s1} + I_{s2}), \quad (4)$$

where $I_{s1} = 10^{D_1/10}$ and $I_{s2} = 10^{D_2/10}$ are the individual suppressive intensities.

A potentially attractive feature of the additive-intensity model is that it is reminiscent of the models of additivity of psychophysical masking that invoke *energy summation* to predict the amount of masking due to combined maskers (e.g., Oxenham and Moore, 1995). Additivity of masking and its relation to suppression will be further discussed in Sec. IV.

An alternative model of combined suppression was suggested by Versteegh and van der Heijden (2013) based on BM measurements. Because suppression was observed to build-up spatially, just as cochlear-amplifier gain builds up spatially, they suggested that two suppressors, when sufficiently separated in frequency, act in series with each other such that their combined attenuation approximates the sum of the two attenuations that the individual suppressors would have produced separately. In the context of the decrement functions described above, this *additive-attenuation* model of suppression becomes

$$decr_{1+2} = decr_1 + decr_2. \quad (5)$$

The additive-attenuation model may be expressed in terms of suppressive intensities by combining Eqs. (3)–(5) as follows:

$$decr_{1+2} = 10 \log_{10}(1 + I_{s1} + I_{s2} + I_{s1}I_{s2}). \quad (6)$$

Considering the similarity between Eqs. (4) and (6), we propose a hybrid model of suppression,

$$decr_{1+2} = 10 \log_{10}(1 + I_{s1} + I_{s2} + \alpha I_{s1}I_{s2}), \quad (7)$$

which becomes equivalent to the additive-intensity model [Eq. (4)] when $\alpha = 0$ and becomes equivalent to the additive-attenuation model [Eq. (6)] when $\alpha = 1$. The hybrid model allows for decrements that are intermediate between these two extremes when α is between 0 and 1. To our knowledge, data do not exist in humans describing multi-tone suppression or that test how well suppressive effects in humans are described by either the additive-intensity or additive-attenuation models. The generalizability of the hybrid model (which is compatible with both the additive-intensity or additive attenuation models) may provide a useful initial description of multi-tone suppression.

The aims of the present study were to provide multi-tone DPOAE suppression data and to assess the validity of

the hybrid model [Eq. (7)] by comparing predicted decrements (that are based on measured decrements for single-tone suppressors) with measured decrements when two tonal suppressors are presented simultaneously.

II. METHODS

A. Participants

Twenty-two normal-hearing participants, ages 19–51 year [median = 24 year, standard deviation (SD) = 6.54 year], served as subjects in this study. Normal hearing was defined as thresholds ≤ 15 dB hearing level (HL) (see American National Standards Institute, 2004) at octave frequencies from 250 to 8000 Hz, as well as at 3000 and 6000 Hz. Behavioral thresholds were measured using standard clinical procedures (American Speech and Hearing Association, 2005). Normal middle-ear function was determined with a 226-Hz tympanogram, and defined as static acoustic admittance of 0.3 to 2.5 mmhos and tympanometric peak pressure of -100 to 50 daPa. One ear was chosen at random when both ears met the threshold and middle-ear criteria, otherwise the better ear was used for testing. An otoscopic inspection performed on the day of testing ensured that the external ear canal was free of debris. Participants were paid for their participation in this study. The experimental protocol was approved by the Institutional Review Board of the Boys Town National Research Hospital.

B. Stimuli

DPOAEs were elicited using a pair of primary frequencies, f_1 and f_2 . In this experiment, f_2 was held constant at 4000 Hz. This frequency was chosen because noise levels are relatively low around this frequency, thus facilitating data collection. The f_2/f_1 ratio was 1.22, so $f_1 = 3279$ Hz. The level of f_2 (L_2) was set to 30, 40, 50, or 60 dB sound pressure level (SPL), while the level of f_1 (L_1) was calculated using the *scissor paradigm* (Kummer *et al.*, 1998),

$$L_1 = 0.4L_2 + 39. \quad (8)$$

Prior to making DPOAE measurements, stimulus levels were calibrated in the ear canal. Although it is known that standing waves may influence estimates of SPL under these conditions (e.g., Richmond *et al.*, 2011; Scheperle *et al.*, 2008; Siegel and Hirohata, 1994), the decision was made to use SPL calibrations because of the relative ease of performing SPL calibrations and because the present study was designed to extend results obtained by using this method in previous DPOAE studies.

The experiment consisted of two parts, with SPL calibration performed (in the ear) prior to each suppressor-frequency condition in both parts of the experiment. In the first part, DPOAE levels were measured individually for three suppressor frequencies ($f_s = 2828, 4100, 4300$ Hz) with L_2 fixed at one of four levels ($L_2 = 30, 40, 50, 60$ dB SPL), resulting in a set of 12 functions per participant that were subsequently converted into decrements. Suppressor frequencies were chosen to be both above and below f_2 in order

to include frequency-dependent differences in suppressor effects (e.g., Gorga *et al.*, 2011b). The middle frequency (4100 Hz) was chosen to be near f_2 , but also sufficiently separated from f_2 to permit independent analysis. Suppression functions were measured for L_s levels ranging from -20 to 80 dB SPL in 5-dB steps. Each suppressor-level series was bracketed (i.e., preceded and followed) by control conditions in which no suppressor was present. DPOAE levels in the two control conditions were averaged and then the DPOAE level in the presence of each suppressor level was subtracted from this average in order to convert the measured levels into decrements (i.e., amount of suppression).

In Fig. 1, the conversion from DPOAE levels (left column) to decrements (right column) is illustrated for a representative participant. Each row shows data for a different suppressor frequency. The parameter in each panel is L_2 level. Note that the shape of the DPOAE-level curves is unchanged as they are inverted and shifted vertically by the conversion to decrement functions. Also note that the single-suppressor additive-intensity model [right column, dash-dot lines, see Eq. (3)] provides a good, although imperfect, fit to the measured decrement functions.

The second part of the experiment consisted of the simultaneous presentation of two suppressor tones. Suppressor-pair frequencies will be denoted as $f_{sp} = (f_{s1}, f_{s2})$, where f_{s1} and f_{s2} are the two suppressor frequencies (in Hz). DPOAE levels were measured for three frequency pairs at each L_2 , $f_{sp} = (2828, 4100)$, $(2828, 4300)$, and $(4100, 4300)$. The two suppressor levels in each pair of levels (L_{s1}, L_{s2}) were selected to produce equal amounts of suppression when presented alone. The lowest suppressor-level pair was selected to produce 3 dB of suppression for each single suppressor. Because DPOAE levels cannot be measured below the noise floor, the maximum decrement that could be measured reliably is approximately equal to the signal-to-noise ratio (SNR) in the control conditions. Suppressor levels were chosen for the highest suppressor-level pair that resulted in decrements that were 6 dB less than the maximum decrement (which is equivalent to complete suppression). For single-suppressor conditions in which the DPOAE was not fully suppressed, the maximum suppressor level was set to 80 dB SPL, which was also the highest suppressor level tested in any single-suppressor condition. Three other level combinations were selected such that the decrements they produced were equally spaced between these two limiting conditions. The sequence of suppressor-pair measurements consisted of five suppressor-level pairs (L_{s1}, L_{s2}) bracketed by two control conditions (i.e., with no suppressor). As in the single-suppressor conditions, decrements were calculated by subtracting the DPOAE levels with suppressors from the average DPOAE level in the two control conditions.

In Fig. 2, the procedure for selecting the five suppressor levels for each suppressor-frequency pair is illustrated (for the same representative participant whose data appeared in Fig. 1). At fixed decrement values for each single suppressor, horizontal lines were drawn to intersect the decrement functions. Intersection points were calculated by linear interpolation between nearby data points. Vertical lines were dropped from the intersection points to determine the suppressor

FIG. 1. (Color online) Suppression functions (left column) and decrements (right column), both as functions of suppressor level, for a representative participant. Data for the three suppressor frequencies, which are indicated in the top left corner of each panel, are shown in separate rows. For comparison, recall that f_2 and f_1 were at 4000 and 3279 Hz, respectively. Data are shown for $L_2 = 30$ –60 dB SPL, in 10-dB steps (as indicated in the legend in the top-left panel). In the left column, the solid lines represent the level of the DPOAE and the dashed lines represent the level of the noise floor. In the right column, the solid lines are the measured decrements and the dash-dot lines are the fitted decrement functions.

levels for different suppressor frequencies that result in the same amount of suppression.

C. Equipment

Stimuli were produced at a sampling rate of 32 kHz by a Layla 3G 24-bit sound card (Echo, Santa Barbara, CA) that controlled an ER-10 C probe-microphone system (Etymotic Research, Elk Grove Village, IL). DPOAE data were collected using custom software (EMAV version 3.32; Neely and Liu, 1994). During the stimulus presentation, f_1 and f_2 were presented on separate channels. When suppressors were presented, they were added to the same channel as f_2 . Each stimulus/response buffer contained 8192 samples. Specified frequencies were always adjusted slightly by EMAV to ensure an integer number of cycles in each buffer. Thus, the specified sampling rate and buffer length provided a frequency resolution of 3.9 Hz.

D. Procedures

After obtaining informed consent, an otoscopic examination was completed and behavioral thresholds and middle-ear function were measured using the procedures described above. Participants were then seated in a reclining chair in a sound-attenuated room and were instructed to be as still as possible. DPOAE-suppression functions were obtained using two measurement-based stopping rules. Measurements continued until (1) the noise floor was ≤ -25 dB SPL or (2) 32 s of artifact-free averaging had taken place. In most

conditions, averaging stopped when the noise floor reached ≤ -25 dB SPL. This level was chosen because it was above the maximum level of system distortion; thus, any measured signal above the noise floor was assumed to be biological in origin. Given the favorable noise levels around the distortion product frequency ($2f_1 - f_2 = 2558$ Hz), averaging times usually were less than the 32 s limit.

E. Data Analysis

To validate the additive-intensity model for single suppressors, a multiple linear regression (MLR) was performed of the transformed decrements onto the primary level L_2 and suppressor level L_s ,

$$D = a_1 + a_2 L_2 + a_3 L_s. \quad (9)$$

A separate set of MLR coefficients (a_1 , a_2 , and a_3) was obtained for each suppressor frequency and for each participant. In previous studies (Gorga *et al.*, 2011b), the MLR described by Eq. (9) has been shown to provide a relatively comprehensive description of DPOAE suppression data. In the present study, the MLR provides a convenient way to quantify how well Eq. (9) describes the data. However, the MLR coefficients were not used in any subsequent prediction of decrements or analysis of results for conditions in which multi-tone suppressors were used.

The hybrid model described by Eq. (7) was fit to the measured decrements by calculating predicted decrements

FIG. 2. (Color online) Illustration of the selection of suppressor levels used for the multi-tone suppressor condition. Decrements as a function of suppressor level are shown for the same participant as in Fig. 1. In the first row, $f_{sp} = (2828, 4100)$; in the second row, $f_{sp} = (2828, 4300)$; and in the third row, $f_{sp} = (4100, 4300)$. In all cases, $f_2 = 4000$ Hz and $L_2 = 40$ dB SPL. The dashed lines are simple linear regression fits to the transformed decrements [see Eq. (7)]. The horizontal dotted lines represent the decrement and are drawn so that the amount of decrement can be equated for the two suppressors. Where these horizontal lines intersect with the decrement functions, is where the vertical dotted lines are drawn down to the x axis. This allows for the presentation of suppressors that are equated in terms of the amount of suppression each one provided individually.

for α between 0 and 1 in increments of 0.01, then selecting the α with the smallest mean-squared deviation. A separate value of α was calculated for each subject, suppressor pair, and L_2 . Recall that model fits with $\alpha = 0$ would be consistent with an additive-intensity model, while $\alpha = 1$ would be consistent with an additive-attenuation model. Thus, α will be used to indicate which of these two models best describes our multi-tone suppression data, or the extent to which the more general hybrid model is needed. Data with poor SNR (i.e., less than 3 dB) were excluded from this analysis.

III. RESULTS

A. Single-suppressor decrement functions

In the representative example shown in Fig. 1, the horizontal portions of the DPOAE-level curves (near the top of each panel in the left column) represent conditions for which the suppressor level was too low to produce suppression. Hence, the DPOAE level is approximately the same as during the control conditions. The fact that DPOAE-level curves appear to shift to the right (without much change in shape) as L_2 increases, which causes the onset of suppression to shift to a higher suppressor level, suggests nearly linear dependence of suppression on L_2 . For example, when $f_s = 4100$ Hz (left column, middle panel), an increase of L_2 by 10 dB is accompanied by a shift to the right of the entire DPOAE-level function by about 10 dB. However, when $f_s = 2828$ Hz (left column, top panel), the DPOAE-level function shifts to the right by less than 10 dB. Finally, when $f_s = 4300$ Hz (left column, bottom panel), the DPOAE-level function shifts to the right by more than 10 dB. Note that suppression onset occurs at the lowest suppressor level when $f_s = 4100$ Hz, at a slightly higher suppressor level when $f_s = 4300$ Hz, and at a still higher suppressor level when $f_s = 2828$ Hz.

To assess the stability of the control conditions, a standard deviation was calculated for each participant across all six unsuppressed DPOAE-level measurements at each L_2 level. Ideally, DPOAE levels would be invariant across constant L_2 , in which case, their standard deviations would be 0. In our measurements, the average control-condition standard deviation across all participants ranged from 1.0 to 1.9 dB, depending on L_2 . However, the effect of this variability on our data analysis was reduced by using the average of two control conditions in the calculation of decrement functions.

The right column of Fig. 1 shows the same data as in the left column after conversion to decrements. (The procedure for calculating decrements was described in Sec. II.) The solid lines within each panel represent the measured decrement functions while the dash-dot lines represent the MLR-predicted decrements (in which both L_2 and L_s are variables). The slopes of the decrement functions are approximately equal to 1 when $f_s = 4100$ Hz, less than 1 when $f_s = 4300$ Hz and greater than 1 when $f_s = 2828$ Hz. These findings are in agreement with previous observations of suppression growth (e.g., Kummer *et al.*, 1995; Abdala, 2001; Gorga *et al.*, 2002; Gorga *et al.*, 2008; Gorga *et al.*, 2011b). The nonmonotonic portions of some functions (e.g., $f_s = 4100$ Hz, $L_2 = 30$ and 40 dB SPL, right column, middle panel) are due to the response being fully suppressed into the noise floor at high suppressor levels. Regardless of f_s , these functions show how the decrement functions vary with changes in L_2 ; decrements > 0 are observed at a lower L_s when L_2 is lower.

Across all subjects, all suppressor frequencies, and all L_2 levels, the MLR accounted for 94% of the variance¹ in the measured decrement functions. When each suppressor frequency ($f_s = 2828, 4100, 4300$ Hz) was considered separately, the variance accounted for was 92%, 94% and 95%. The MLR accounted for 89%, 95%, 95%, and 95% of the variance for $L_2 = 30, 40, 50$ and 60 dB SPL, respectively.

The reason that the variance accounted for is greater for $L_2 > 30$ dB SPL is likely due to the SNR being larger for these conditions, compared to when $L_2 = 30$ dB SPL. In any event, these findings, suggest that the MLR provided a good description of the data for all conditions.

B. Two-suppressor decrement functions

Figure 3 shows results for two-suppressor conditions for the same subject whose data for the single-suppressor frequency conditions were shown in Figs. 1 and 2. Each row shows data for a different suppressor-frequency pair. The parameter in each panel is L_2 , as defined by the inset in the upper-left panel. The left column of Fig. 3 shows predicted (dashed lines) and measured (solid lines) decrement functions for two simultaneous suppressors. The x axis represents the decrements for one suppressor (i.e., the matched decrements at which the horizontal dotted lines were drawn in Fig. 2). The predicted decrements are calculated using Eq. (7), which represents the hybrid model. The parameter α was determined separately in each case, and was selected to minimize the difference between the measured and predicted decrements in the two-suppressor conditions. The distribution of α and its dependence on L_2 will be described later. The measured decrements are plotted only when the suppressed DPOAE level was above the noise floor. The predicted decrements are not plotted beyond the upper limit of the corresponding measured decrement.

The right column of Fig. 3 converts the results shown in the left column into *excess suppression*, which is defined as

the difference between the predicted and measured decrements. The horizontal dashed line at zero is provided as a reference, and represents the case when there is no difference between predicted and measured decrements. Points that fall above the horizontal line represent conditions in which there was more suppression than predicted, and points below this line represent conditions in which less suppression was observed than predicted. In this example, the magnitude of the excess suppression was usually less than 5 dB.

Figure 4 shows excess suppression for all 22 participants superimposed. Data for each of the three suppressor-frequency pairs are shown in separate panels. A different symbol is used for each of four L_2 levels. Although difficult to see because of overlap, there are 440 observations in each panel (5 decrements $\times$ 4 L_2 levels $\times$ 22 participants). The solid lines represent LOESS (LOcal regrESSion) trend lines (Cleveland, 1979) that were fit to the data with smoothing set to 0.25. For $f_{sp} = (4100, 4300)$ (bottom panel), the trend line is below 0 by about 2 dB, over the range of single-tone decrements from 3 to 20 dB. In contrast, the trend lines for the other two suppressor pairs are above 0 by about 2 dB, over a range of single-tone decrements from 3 to 12 dB. This means that, even with α allowed to vary from 0 to 1 in order to minimize the differences between predicted and measured decrements, the hybrid model tended to overestimate the measured decrement for $f_{sp} = (4100, 4300)$ and underestimated the measured decrement for the other two suppressor pairs. The trend lines are probably less reliable for single-tone decrements greater than 20 dB due to the sparsity of data in

FIG. 3. (Color online) The left column shows the combined decrement measured in the second phase of the experiment as a function of decrement for a single suppressor, in dB, for the same, individual participant whose data were shown in Figs. 1 and 2. Data are shown for $L_2 = 30$ –60 dB SPL, in 10-dB steps (as indicated in the legend in the top panel). The solid lines represent the measured decrement and the dashed lines represent the predicted decrement [see Eq. (2)]. The right column shows excess suppression (in dB) as a function of the decrement for a single suppressor (see text). The dashed line at 0 represents the case when there was no difference between measured and predicted values.

FIG. 4. (Color online) Excess suppression (prediction error) for three suppressor pairs as function of decrement for a single suppressor. Each symbol represents data from an individual participant. In the first row, $f_{sp} = (2828, 4100)$; in the second row, $f_{sp} = (2828, 4300)$; and in the third row, $f_{sp} = (4100, 4300)$. Excess suppression is shown for $L_2 = 30, 40, 50$, and 60 dB SPL, as indicated in the legend. The dashed line represents a prediction error of zero. The solid line in each panel represents the LOESS trend line.

combination with the fact that, for these conditions, the SNR is low. The dependence of excess suppression on L_2 is difficult to visualize in this plot and will be considered next.

Figure 5 shows the distribution of excess suppression (in the form of box and whisker plots) at each of four L_2 levels for each of the three suppressor-frequency pairs. Each box and whisker describes the distribution of 110 data points. The top and bottom of each box represents the 75th and 25th percentile (i.e., interquartile ranges) of the distributions and the midline represents the medians (i.e., 50th percentile). The whiskers extend above and below the box by a distance that is 1.5 times the interquartile range. The circles show the mean values and the pluses represent outliers. Although there appears to be a trend for slightly more positive excess suppression with increasing L_2 for $f_{sp} = (2828, 4100)$ (middle panel), this effect is small compared to the interquartile range.

FIG. 5. (Color online) Distributions of excess suppression for each probe level. Each distribution has a *box* and *whisker* representation. Data for different suppressor-frequency pairs are shown within each panel. The horizontal lines of each box indicate the 25th, 50th, and 75th percentiles of the corresponding distribution. The vertical lines above and below the box (called *whiskers*) extend to the furthest data points that are no further than 1.5 times the interquartile range above and below the median. Data points that are further from the median are deemed *outliers* and are plotted as plus symbols. The circle indicates the mean. Visual inspection of these excess-suppression distributions reveals no apparent dependence on L_2 that could generalize to all three suppressor-frequency pairs.

Figure 6 shows the distributions of α values (again, in the form of box and whisker plots) at each of four L_2 levels and each of the three suppressor-frequency pairs. The interquartile ranges, medians, means and outliers are shown for each distribution, following the convention that was used in Fig. 5. The most obvious feature of these distributions is that α is near 0 for $f_{sp} = (4100, 4300)$ (lower panel) and greater than 0 for the other two suppressor pairs. For both of the suppressor pairs where $\alpha > 0$, there is a trend for the mean α to increase with L_2 level. For the suppressor pair with the widest frequency separation [$f_{sp} = (2828, 4300)$ (middle panel)] and highest L_2 level (60 dB SPL) the median α is 1. These results suggest that the measured decrements are more consistent with the additive-intensity model when $f_{sp} = (4100,$

FIG. 6. (Color online) Distributions of α for each L_2 level. Each distribution has a *box* and *whisker* representation. (See Fig. 5 caption for details regarding the box and whiskers.) Data for different suppressor-frequency pairs are shown within each panel. In the lower panel, where $f_{sp} = (4100, 4300)$, the distributions collapse to $\alpha = 0$, which favors the additive-intensity model. In the middle panel, where $f_{sp} = (2828, 4300)$, the distributions collapse to $\alpha = 1$ at the highest L_2 level, which favors the additive-attenuation model. The other suppressor conditions in the upper two panels show widely distributed intermediate values of α , which suggests the need for a hybrid model.

4300) and more consistent with the additive-attenuation model when $f_{sp} = (4100, 4300)$ and $L_2 = 60$ dB SPL. The decrements observed for the other suppressor conditions are intermediate between these two extremes.

IV. DISCUSSION

Little is known about the suppressive effects resulting from the simultaneous presentation of multiple suppressor tones in humans. The purposes of this study were to provide DPOAE data for conditions in which multi-tone suppressors were used and to investigate whether the combined effect of multiple suppressors on DPOAE levels could be predicted from the effects of individual suppressors.

Although DPOAE generation mechanisms may be more complex theoretically compared to SFOAEs, DPOAEs were favored for this study because (1) we have experience measuring DPOAE suppression in previous studies (e.g., Gorga *et al.*, 2008; Gorga *et al.*, 2011a,b; Gruhlke *et al.*, 2012; Birkholz *et al.*, 2012) and (2) the study was motivated by a recent paper by Rasetshwane *et al.* (2014) describing a signal-processing algorithm inspired by DPOAE suppression data that assumes an additive-intensity model.

The single-suppressor results shown in Fig. 1 are similar to previously reported DPOAE suppression data (e.g., Kummer *et al.*, 1995; Abdala, 2001; Gorga *et al.*, 2002; Gorga *et al.*, 2008; Gorga *et al.*, 2011b). Specifically, suppression threshold and growth depend on the relation between probe frequency and level (f_2 and L_2) and suppressor frequency (f_s). Previous studies have described details of DPOAE suppression characteristics for single suppressors for both normal-hearing (Abdala, 2001; Abdala and Chatterjee, 2003; Gorga *et al.*, 2011a,b) and hearing-impaired subjects (Abdala and Fitzgerald, 2003; Gorga *et al.*, 2003; Birkholz *et al.*, 2012; Gruhlke *et al.*, 2012). In the present study, the fact that the MLR accounted for 94% of the variance across all participants in the single-suppressor decrement functions validates the transformation described by Eq. (1), as well as the additive-intensity model for single suppressors described by Eq. (3). Furthermore, these observations provide confidence in the validity of the procedures that were used to collect data, including measurements of multi-tone suppression, which were the main focus of the present study.

It should be noted that the linear-regression method that was used to fit the single-suppressor data effectively excluded from our fits the low-level portion of the decrement function where decrements were less than or equal to 0. Although this was intentional, in order to focus our attention on the portion of the decrement function where the suppressor was influential, it may not provide the best description of the entire decrement function. An alternative approach would be to fit Eq. (3) to the decrement function using a nonlinear regression method such as the `lsqcurvefit` function available in MATLAB. Because it avoids some of the limitations of our linear-regression method, a non-linear-regression method may yield more accurate estimates of suppression threshold and suppression growth rate. However, these two metrics were not the focus of the present study. Thus, we opted to use the linear-regression model, which we have used successfully to describe decrement functions in previous data from our laboratory.

Five different decrements were selected to span the observed range of decrements with a manageable number of conditions. A different set of five decrement values was selected for each L_2 , suppressor-frequency pair, and for each participant. While it would have been preferable to choose suppressor levels that produced the same decrements for all conditions, the variance across conditions and participants precluded this possibility. On the other hand, this variability in matched decrements for the two-suppressor conditions resulted in data for all decrements between 3 and 30 dB, and, thus, provided a relatively complete description of additive effects (see Fig. 4). Selecting suppressors in this manner

resulted in the largest amount of suppression for two-suppressor conditions and maximized the sensitivity to deviations from predictions. Had suppressors been used that were not equated in terms of their suppressive effects, the suppressor that resulted in the greater amount of suppression would have dominated the decrement when the two suppressors were presented simultaneously. As a consequence, additional data collection would have been necessary in order to assure that the range of conditions in which additivity was observed were included. The approach we followed is also qualitatively similar to the approach that has been used in psychophysical studies of additivity of masking, in which maskers were equated in terms of the amount of masking that each masker produced independently (e.g., Green, 1967; Humes *et al.*, 1992; Laback *et al.*, 2013; Oxenham and Moore, 1995). Models of the additivity of masking predict the largest effect for combinations of two maskers when their individual effects are equated (Humes and Jesteadt, 1989).

The excess suppression for the representative participant whose data were shown in Fig. 3 is between -5 and 5 dB; however, deviations do not appear to be random. Some trends in the excess suppression suggest that the hybrid model might not be accurately representing important details. For example, excess suppression for $f_{sp} = (4100, 4300)$ is less than 0 for all values of L_2 , except $L_2 = 50$ dB SPL. This suggests (1) that the additive-intensity model usually overestimates combined decrements and (2) decrements have dependence on L_2 that is not entirely captured by the hybrid model. At the other extreme, the additive-attenuation model often underestimates decrements for $f_{sp} = (2828, 4300)$. In one case, when $L_2 = 50$ dB SPL, suppressors that each produced 7 dB of attenuation of DPOAE level individually produced 27 dB of attenuation when presented simultaneously. The extent to which certain cases exceed the range of predictions of the hybrid model suggest that, even with its flexibility to vary between additive intensity and additive attenuation, it may still be an oversimplification of additivity of suppression.

Data from all L_2 levels, the three multi-tone suppressor pairs, and all participants were included in Fig. 4. Some of the trends observed for the representative participant in Fig. 3 were observed in the data from other participants, as shown in Fig. 4. For example, excess suppression as represented by the LOESS trend is below 0 (by about 2 dB) for the suppressor pair with the smallest frequency ratio ($4300/4100 = 1.05$). On the other hand, the LOESS trend is positive (about 6 dB) for the suppressor pair with the largest frequency ratio ($4300/2828 = 1.52$). The dependence of excess suppression on individual decrement, which is the quantity represented on the x axis in Fig. 4, was not consistent across different suppressor-frequency pairs. Likewise, the dependence of excess suppression on L_2 , which is shown in Fig. 5, also was not consistent across suppressor-frequency pairs. Figure 4 shows further that distributions of excess suppression are centered near 0 , which suggests that the hybrid model is not biased, except perhaps for $f_{sp} = (4100, 4300)$ where the additive-intensity model overestimates the amount of suppression by a few dB.

The distributions of α , shown in Fig. 6, are perhaps the most interesting result of this study because they describe (to a first approximation) the interaction of frequency components in multi-tone suppressors. The boxes in this figure represent 50% confidence intervals between their top and bottom. When the bottom of the box touches $\alpha = 0$ or the top of the box touches $\alpha = 1$, then those values lie within the interquartile range, which is equivalent to a 50% confidence interval. In most cases, the interquartile range includes exactly one of these two extreme values, so the choice between additive-intensity or additive-attenuation models has reasonable confidence.

It was expected that the additive-intensity model (the model that has been used to account for psychophysical additivity of masking) would provide a reasonable prediction of decrement for two suppressors under most conditions. The hybrid model is equivalent to the additive-intensity model when $\alpha = 0$. The distributions in Fig. 6 suggest that this is a good description of the data only for the smallest suppressor-frequency ratio (lower panel). Note that both suppressor frequencies in this pair are above f_2 . At the other extreme, the additive-attenuation model, which has been used to explain BM suppression data (Versteegh and van der Heijden, 2013) and is equivalent to the hybrid model when $\alpha = 1$, provides a better description of the present suppression data for the largest suppressor-frequency ratio (middle panel) compared to the additive-intensity model, especially at the highest L_2 level. The top panel shows mixed results because the two highest L_2 levels include $\alpha = 1$ within the interquartile range and the two lower levels include neither of the extreme values of α . Note that the two suppressor-frequency pairs that are least compatible with the additive-intensity model are distinguished by both having a low-frequency suppressor.

Although we have only three suppressor-frequency ratios from which to generalize, it appears from the trends observed in Fig. 6 that combined suppressors are less effective for small suppressor-frequency ratios and more effective for large suppressor-frequency ratios. The reason for the reduced effectiveness at small frequency ratios may be that the suppressors are suppressing each other due to overlapping excitation patterns within the cochlea. Data from a larger number of suppressor-frequency pairs would be required to evaluate this hypothesis.

An alternative explanation for the present results might relate to differences in suppressive effects not at the distortion source, but at the reflection source. The $2f_1f_2$ frequency for the present stimulus conditions was 2558 Hz, which is close in frequency to the low-frequency suppressor used in the present study (2828 Hz). In addition to suppressing the response from the distortion source (thought to be basal to the place(s) where f_2 is represented), the low-frequency suppressor could have also suppressed the response coming from the reflection source associated with the distortion frequency. If the contributions from the distortion and reflection sources added positively, then suppressing both sources might result in greater excess suppression, compared to cases in which the reflection source was not suppressed. We can only speculate about this hypothesis because no effort was

made in the present measurements to separate the two sources and parse relative contributions to the amount of suppression in the two-suppressor conditions.

The wide variability in the value of α across subjects under most stimulus conditions is also worth noting. The least variability was observed for the (4100, 4300) suppressor-frequency pair, as shown in the lower panel of Fig. 6 by boxes that have practically no height. In contrast, the interquartile ranges (represented by each box) span more than half the [0,1] range of α for several of the stimulus conditions shown in the other two panels. One possible interpretation is that additive-intensity is advantageous and attainable only for narrowband stimuli, while more widely separated tones interact in a manner that is better described as additive attenuation. The suppression exhibited by tone pairs that have an intermediate frequency separation could be a variable blend of the two extremes representing a transition region in which the goal of attaining additive intensity is attained with varying degrees of success. Further research will be needed to advance our understanding of the interaction of suppressors beyond this admittedly speculative interpretation.

There have been studies that demonstrate that there may be contributions to the DPOAE level measured in the ear canal from regions basal to the region at which f_2 is located (Martin *et al.*, 2010; Martin *et al.*, 2011). This possibility was not considered in the design of the present experiment. However, it would have been impractical to present an “interference tone” in combination with the two suppressors and the two tones that elicited the DPOAE. Thus, the present study does not include data that would allow us to address this possibility. Having said that, excess suppression was observed for conditions that included the low-frequency suppressor, suggesting that this frequency (with its characteristic place located apically relative to the characteristic place for f_2) controlled the effect. Thus, it is not clear how contributions from more basal locations would result in the effects observed in the present study.

Psychophysical masking is a reduction in the perceived intensity of a sound due to the presence of another sound. Suppression is thought to be a major contributor to simultaneous masking based, in part, on modeling of measurements from single auditory-nerve fibers (e.g., Delgutte, 1990a,b). In human subjects, differences in the amount of simultaneous and forward masking have been shown to approximate DPOAE measurements of suppression (Rodríguez *et al.*, 2010). These observations motivated comparisons of the present data to psychophysical data in which two maskers were presented.

The amount of *excess suppression* observed in the present study, beyond predictions of an additive-intensity model, was within the range of *excess masking* reported in studies using simultaneous maskers (e.g., Green, 1967; Humes and Jesteadt, 1989; Laback *et al.*, 2013; Lutfi, 1983). Additionally, excess suppression varies as a function of the combination of suppressor frequencies, as masking does in the additivity of masking literature (e.g., Laback *et al.*, 2013). Unlike excess masking, however, excess suppression may be limited to stimulus configurations where one

suppressor is lower in frequency than the probe frequency and cannot be attributed to strategies such as off-frequency listening.

V. CONCLUSIONS

The present results suggest that the combined effect of multi-tone suppressors is not well described by simple additive-intensity or additive-attenuation models. This finding may have implications for the remediation of hearing loss when attempting to restore normal hearing because suppression is a feature of normal hearing. Although, the proposed hybrid model fails to fully describe the observed range of interaction when two suppressors are combined, it provides a better description of this interaction than either of the two simpler models. Furthermore, the hybrid model offers a framework for further modeling efforts that, in combination with additional multi-suppressor data, could potentially generalize the parameter α to become a continuous function of multi-suppressor frequencies and multi-suppressor levels.

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¹The variance accounted for was calculated as $1 - SS_{res}/SS_{tot}$, where SS_{tot} is the total sum of squares (which is proportional to the variance of the data) and SS_{res} is the sum of squares of the residuals. This calculation is a generalization to nonlinear data of the coefficient of determination, R^2 .

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