The role of suppression in psychophysical tone-on-tone masking[a)]

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This study tested the hypothesis that suppression contributes to the difference between simultaneous masking (SM) and forward masking (FM). To obtain an alternative estimate of suppression, distortion-product otoacoustic emissions (DPOAEs) were measured in the presence of a suppressor tone. Psychophysical-masking and DPOAE-suppression measurements were made in 22 normal-hearing subjects for a 4000-Hz signal/f_2 and two masker/suppressor frequencies: 2141 and 4281 Hz. Differences between SM and FM at the same masker level were used to provide a psychophysical estimate of suppression. The increase in L_2 to maintain a constant output (L_d) provided a DPOAE estimate of suppression for a range of suppressor levels. The similarity of the psychophysical and DPOAE estimates for the two masker/suppressor frequencies suggests that the difference in amount of masking between SM and FM is at least partially due to suppression.
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I. INTRODUCTION

Suppression, defined as the reduction in the response to one stimulus by the simultaneous presentation of another stimulus, has been demonstrated at several different levels in the auditory system. Psychophysical masking occurs when the presence of one sound causes an elevation in the threshold of another sound. Although controversial, it has been hypothesized that suppression contributes to differences between simultaneous masking (SM) and forward masking (FM). The purpose of this study was to investigate the role of suppression in psychophysical tone-on-tone masking.

Suppression was first described by Wever *et al.* (1940) based on measurements of the cochlear microphonic, and later demonstrated in physiological studies of auditory-nerve fibers (ANFs) (e.g., Galambos and Davis, 1944; Sachs and Kiang, 1968; Arthur *et al.*, 1971; Abbas and Sachs, 1976; Javel *et al.*, 1983). Sachs and Kiang (1968) recorded a reduction in firing rate to one tone, usually at a fiber's characteristic frequency (CF), by the addition of a second tone of appropriate frequency and intensity. Suppression has been observed in the responses of outer hair cells (Sellick and Russell, 1979) and in compound action potentials (Dallos *et al.*, 1974; Harris, 1979). Evidence of suppression has also been observed in the vibration patterns of the basilar membrane (BM) (e.g., Rhode, 1977; Ruggero *et al.*, 1992). Both mechanical and neural studies have observed that suppression grows more rapidly for suppressors lower in frequency than CF, compared to suppressors close to CF (e.g., Delgutte, 1990b; Pang and Guinan, 1997; Ruggero *et al.*, 1992).

Evidence of suppression also has been observed in otoacoustic emission (OAE) data (e.g., Brown and Kemp, 1984; Harris *et al.*, 1992; Kummer *et al.*, 1998; Abdala, 1998; Gorga *et al.*, 2003, 2008). Interestingly, psychophysical and OAE data appear to share the same dependence on the relation between signal and suppressor frequency that is evident in both mechanical and neural responses from lower animals.

Excitation, suppression, and adaptation are physiological mechanisms thought to contribute to psychophysical masking (Delgutte, 1990a, 1990b). Studies of single ANFs reveal that excitatory or line-busy masking occurs when the overall discharge rate in the presence of a signal and a masker is not higher than the discharge rate observed when only the masker is present. In contrast, suppression does not produce an increase in discharge rate, but shifts the rate-level function for the signal toward higher intensities, resulting in threshold elevation. This effect is especially evident for off-frequency suppressors where the suppressor is about an octave below the signal. Both line-busy masking and suppression require that the signal and masker be presented simultaneously. Masking due to adaptation occurs when the masker is presented prior to the presentation of the signal. Under these conditions, the response of an ANF to a subsequently presented signal will be reduced compared to the discharge rate the signal would typically elicit when presented alone (e.g., Smith, 1977, 1979; Harris and Dallos, 1979). Adaptation has been suggested as the primary mechanism underlying FM, although temporal integration of masker and signal has been suggested as an alternative (e.g., Delgutte, 1990a, 1990b; Pang and Guinan, 1997; Oxenham, 2001). Delgutte (1990a) suggested that the main difference between SM and FM was the absence of suppression in the FM condition. Depending on stimulus conditions, all of these mechanisms may contribute to the masking of a signal.

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The contribution of suppression to masking has been described in psychophysical studies (e.g., Shannon, 1976; Weber and Green, 1978; Duifhuis, 1980; Moore *et al.*, 1984; Bacon *et al.*, 1999), but it is difficult to separate suppression effects from other effects based on psychophysical data alone. In the psychophysical-masking task, an increase in masker level (ML) requires a similar increase in signal level when masker and probe are close in frequency because response growths of the masker and signal are similar. Masking is strongest as the masker frequency (f_m) approximates the signal frequency (f_p). When f_p and f_m are close to one another, it is assumed that their excitation patterns overlap and are being processed by the same compressive nonlinearity; thus, the response to probe and masker grows at about the same rate. For maskers lower in frequency than the signal, masker level must be increased in order for masking to be observed, but once masking threshold is exceeded, masking grows by as much as 2–2.5 dB/dB for low-frequency maskers (e.g., Wegel and Lane, 1924; Egan and Hake, 1950; Stelmachowicz *et al.*, 1987; Plack and Oxenham, 1998). This result is often referred to as upward spread of masking. The contribution of suppression to upward spread of masking is unclear (Oxenham and Plack, 1998; Yasin and Plack, 2005).

Moore *et al.* (1984) suggested that when psychophysical tuning curves (PTCs) are measured using procedures to minimize off-frequency listening, the main factor contributing to the SM-FM difference was suppression. Several earlier psychophysical studies accounted for these differences in terms of suppression as well (e.g., Houtgast, 1972; Shannon, 1976; Vogten, 1978; Wightman *et al.*, 1977), but later studies suggested that suppression was not the only factor involved (e.g., Weber, 1983; Jesteadt and Norton, 1985; Neff, 1986). The extent to which suppression contributes to SM-FM differences remains unresolved.

Distortion-product otoacoustic emissions (DPOAEs) may be observed when two tones (f_2 and f_1, $f_2 > f_1$) are presented at the same time. The response (at frequency $f_d = 2f_1 - f_2$) is not present in the original two-tone stimulus. The response is typically measured at the $2f_1 - f_2$ frequency because it is the largest distortion product in humans. It is generally assumed that DPOAEs arise from two places along the BM, a distortion source near the f_2 place and a coherent-reflection source at the DPOAE-frequency place (e.g., Zweig and Shera, 1995; Talmadge *et al.*, 1998; Shera and Guinan, 1999). The distortion component results from the nonlinear interaction between f_1 and f_2; this interaction creates energy at the DPOAE frequency that then travels both apically and basally within the cochlea. The apically traveling energy reaches the $2f_1 - f_2$ place on the BM and is then reflected back basally. Brown and Kemp (1984) demonstrated that the introduction of a third, suppressor tone (f_3), in addition to the two-tone probe, could result in the suppression of the DPOAE. By keeping the level of the two-tone probe constant and varying f_3 in frequency and level, growth of DPOAE suppression can be measured. Suppression-growth functions share many similarities with psychoacoustical and physiological measures of cochlear response, and have been studied in normal and hearing-impaired ears (e.g., Abdala, 1998; Martin *et al.*, 1998; Abdala and Fitzgerald, 2003; Gorga *et al.*, 2003). In studies of DPOAE suppression, the f_2, f_1 primary pair is regarded as the "probe," because it is assumed that their interaction near the f_2 place results in the initial generation of the DPOAE, and f_3 is viewed as the equivalent of the "masker" typically used in psychoacoustical studies (e.g., Abdala and Chaterjee, 2003; Gorga *et al.*, 2002, 2008).

Growth of DPOAE suppression follows the same pattern as the growth of masked threshold as a function of masker level, in that the slope is steepest for low-frequency suppressors and shallow for high-frequency suppressors relative to f_2. A slope of nearly 1 is observed for suppressor frequencies near f_2 (e.g., Brown and Kemp, 1984; Harris *et al.*, 1992; Abdala, 1998; Abdala and Chaterjee, 2003; Gorga *et al.*, 2003, 2008). As stated earlier, these general trends are at least qualitatively similar to trends observed in both ANF and BM responses.

It is generally thought that suppression is the mechanism that accounts for changes in DPOAE level as a consequence of the presentation of a third tone. In contrast, SM combines both suppression and excitatory effects (such as line-busy masking). It may be possible, therefore, to use DPOAE-suppression measurements to gain insights into the causes of differences between SM and FM. This study investigated the role of suppression in psychophysical masking by comparing behavioral estimates of suppression (defined as the difference between SM and FM) and DPOAE estimates of suppression in the same group of subjects.

II. METHODS

A. Subjects

Twenty-two subjects participated in this study. They were selected on the basis of hearing sensitivity and production of DPOAEs for a wide range of levels, including low-level stimuli. Subjects ranged in age from 16 to 47 years, with a mean age of 20 years. Each subject had thresholds $\leq$25 dB hearing loss (HL) (re ANSI, 1996) for standard octave and inter-octave audiometric frequencies from 250 to 8000 Hz. Behavioral thresholds for the purposes of meeting inclusion criteria were measured using routine clinical procedures. Subjects were also required to have thresholds of 20 dB sound pressure level (SPL) or better at the stimulus frequencies of 2141, 4000, and 4281 Hz. A normal 226-Hz tympanogram was also required on each day on which DPOAE measurements were made. Only one ear of each subject was selected for study, and was chosen as the ear with the lowest thresholds at 2141, 4000, and 4281 Hz, and most favorable tympanometric results. If there were no differences between ears of a given subject, the test ear was chosen randomly.

B. Stimuli and apparatus

For the psychophysical experiments, the probe signal (f_p) was set to 4000 Hz. The masker frequencies (f_m) were 2141 and 4281 Hz. The term "off-frequency" will be used to describe conditions in which the masker/suppressor frequency=2141 Hz and "on-frequency" to refer to conditions in which the masker/suppressor frequency=4281 Hz.

During the psychophysical measurements, probe level was held constant at levels ranging from 20 to 45 dB SPL (5-dB steps) for FM and from 20 to 70 dB SPL (10-dB steps) for SM; masker level (L_m) was adaptively varied, with a maximum level of 95 dB SPL. The signal was gated with 5-ms rise and fall Blackman windows, and no steady-state portion. The maskers were 200 ms in duration including rise and fall times of 5 ms (Blackman windows). For the FM condition, the masker-signal delay was 0 ms (measured from the final point of the masker to the initial point of the probe) to minimize recovery from adaptation or maximize masker persistence. For the SM condition, the signal was presented 15 ms before the end of the masker. All stimuli for the psychophysical portion of the study were generated digitally via MATLAB at a sampling rate of 44 100 Hz with 24-bit resolution and output by a soundcard (CardDeluxe, Digital Audio Labs, Minneapolis, MN). The headphone output of the soundcard was fed to a remote passive attenuator in a sound-treated room, and then to a Sennheiser HD 250 Linear II headphone.

DPOAEs were elicited with f_2=4000 Hz (i.e., the same as the signal frequency in the masking measurements) and f_1=3279 Hz. The f_2, f_1 primary pair is viewed as a probe for the DPOAE measurement in much the same way that the signal toneburst is viewed as a probe for the masking measurements. The suppressor frequencies (f_3) were the same as the masker frequencies (2141 and 4281 Hz) in the psychophysical measurements. The higher frequency (4281 Hz) was selected to serve as the on-frequency masker/suppressor for SM, FM, and DPOAE studies because it produced the greatest amount of suppression in a previous study of DPOAE suppression when f_2=4000 Hz (Gorga *et al.*, 2008). Additionally, the growth of suppression is nearly linear when f_2=4000 Hz and f_3=4281 Hz (Gorga *et al.*, 2008), indicating that both frequencies are being processed similarly. Although this observation provides additional support for the use of 4281 Hz as the on-frequency suppressor, it should be noted that it is not on-frequency as defined in the psychophysics literature; as a consequence, the on-frequency slopes obtained for the psychophysical portion of the experiment might differ from previously reported findings. The lower masker/suppressor frequency is an octave below the higher masker/suppressor frequency and was selected to be low enough to be outside the frequency range where compressive response growth is observed, while still being near enough to the signal/f_2 frequency to influence its response. It should be noted that there is ongoing debate regarding compression estimates obtained with a low-frequency masker an octave below f_2 as a linear reference (Lopez-Poveda and Alves-Pinto, 2008; Wojtczak and Oxenham, 2009), but that issue is beyond the scope of this study. Although the low-frequency masker/suppressor may not result in a completely linear response at the signal/f_2 frequency, the influence of this problem is mitigated by using the same low-frequency masker/suppressor for SM, FM, and DPOAE conditions.

For all DPOAE measurements, response waveforms with duration of approximately 250 ms were averaged in two alternating buffers. These buffers were summed and, after a Fourier transformation, the frequency component in the $2f_1-f_2$ bin was used to estimate DPOAE level. These two buffers were subtracted and the squared-magnitudes in the $2f_1-f_2$ bin and the five bins above and below $2f_1-f_2$ were averaged to provide an estimate of noise level.

DPOAE stimuli were produced at a sampling rate of 32 000 Hz by a 24-bit soundcard (CardDeluxe, Digital Audio Labs) that drove a probe-microphone system (Etymotic Research, ER-10C). The "receiver equalization" of the ER-10C was bypassed to allow for the production of high stimulus levels. DPOAE data were collected with custom-designed software (EMAV, Neely and Liu, 1994). Both channels of the soundcard and probe-microphone system were used during DPOAE measurements, with f_2 presented on one channel and f_1 presented on the other. When a suppressor was included, it was presented on the same channel as f_2. For DPOAE measurements, in-the-ear forward-pressure level (FPL) calibration (Scheperle *et al.*, 2008) was used to determine stimulus levels. FPL calibration avoids the influence of standing waves and has been shown to result in less variability in DPOAE measurements (Scheperle *et al.*, 2008).

C. Procedure

For the psychophysical measurements, trials were presented in blocks of 50. Each trial consisted of a 500-ms warning interval, two 300-ms observation intervals separated by 300 ms, and a 300-ms feedback interval following the response of the subject. There was an interval of 500 ms before the beginning of the next trial. Subjects were given visual markers for the warning and observation intervals and correct-interval feedback in a message window on a keypad that they used to indicate their responses. In one interval, the masker and signal were presented together, while in the other interval, the masker was presented alone. A two-down, one-up adaptive tracking procedure was used to estimate the 71%-correct point on the psychometric function (Levitt, 1971). The masker level (L_m) was initially varied with a step size of 4 dB, which was reduced to 2 dB after the first four reversals. The threshold estimate was taken as the mean L_m at the turn points after the first four reversals of each 50-trial block. Trial blocks with standard deviations exceeding 5 dB were not accepted.

For DPOAE measurements, the level of the higher-frequency primary (L_2) was set to one of eight levels (25–60 dB FPL in 5-dB steps). The level of f_1 (L_1) was set to $0.4L_2+39$ dB (Kummer *et al.*, 1998). DPOAE-suppression measurements were obtained by presenting a third (suppressor) tone (f_3) at one of two frequencies (f_3=2141 and 4281 Hz), whose level (L_3) was set to each of 22 levels (−20 to 85 dB FPL, 5-dB steps). A control condition with no suppressor was included before and after all suppressor levels at each f_3. This sequence of suppressor conditions was presented at both suppressor frequencies and all L_2 levels for each subject. Measurements continued until the noise floor averaged down to −25 dB SPL, or until 64 s of artifact-free averaging had taken place, whichever occurred first.

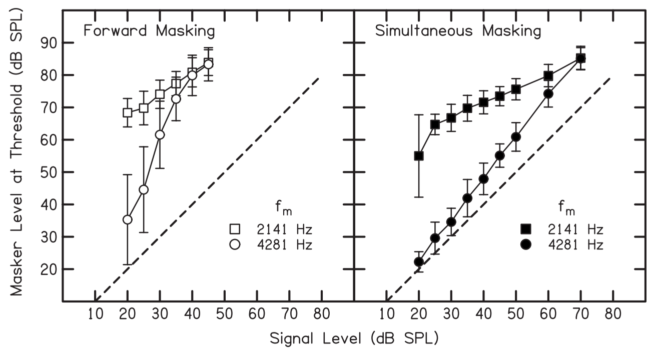

FIG. 1. Mean masker level and standard deviations based on data from all 22 subjects. Each panel shows masker level at threshold as a function of signal level for on- and off-frequency maskers, with results for FM and SM shown in left and right panels, respectively. Off-frequency (2141 Hz) masker levels are represented by open and filled squares and on-frequency (4281 Hz) masker levels are represented by open and filled circles.

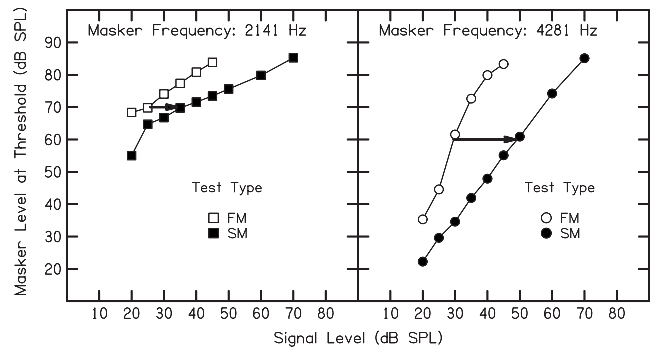

FIG. 2. Mean masker level as a function of signal level based on data from all 22 subjects, with results from on- and off-frequency maskers shown in left and right panels, respectively. Within each panel, open and filled symbols represent FM and SM, respectively. The arrows illustrate the DAM between FM and SM for fixed masker levels.

III. RESULTS

A. Masker-level functions

The mean masker levels (L_m) at threshold as a function of signal level are shown in Fig. 1, with data from FM and SM provided in left and right panels, respectively. These will be referred to as ML functions to distinguish them from growth of masking (GOM) functions, where signal level is plotted as a function of masker level. The parameter within each panel is f_m. Standard deviations for the FM thresholds were 3–5 dB for the off-frequency and 5–6 dB for the on-frequency masker, except at the lowest signal levels (20–30 dB SPL) where the standard deviations for the on-frequency condition ranged from 10 to 13 dB. For the SM conditions, standard deviations were 3–4 dB for both off- and on-frequency maskers, except for the off-frequency masker SM condition at a signal level of 20 dB SPL, where the standard deviation was 12 dB. Although there was variability among subjects, the within-subject standard deviation (based on three repeated measurements) did not exceed 3 dB for any condition.

The ML data in Fig. 1 were fitted with linear least-squares functions to allow for comparisons with previous research (Oxenham and Plack, 1997, 1998; Plack and Oxenham, 1998; Yasin and Plack, 2005). As expected, the FM ML functions were characterized by higher masker thresholds for both on- and off-frequency maskers, with the on-frequency forward masker showing the steepest function. The slopes for the off-frequency and on-frequency FM conditions were 0.6 and 2.0 dB/dB, respectively. The on-frequency ML function for the SM condition grows in a nearly linear fashion with a slope of 1.2 dB/dB; in contrast, the off-frequency ML function for the SM condition exhibits a shift in threshold of about 30 dB for the lowest signal level (20 dB SPL), compared to the same condition for the on-frequency masker, and grows at a slower rate thereafter (0.5 dB/dB). The masking data in Fig. 1 are similar to the data of Oxenham and Plack (1997, Fig. 2). However, our estimates of compression (2:1 for SM and 3:1 for FM) based on taking the ratio of on- and off-frequency GOM slopes (not shown) are not as high as their compression estimate (6:1). The difference in compression estimates might be related to the use of an on-frequency masker that was higher than the signal probe or to off-frequency listening. The use of a higher on-frequency masker (e.g., 4281 Hz) might have changed the slope of the on-frequency functions, resulting in a reduced compression estimate based on the on- and off-frequency ratio comparison. Similarly, given that no additional noise masker was used to restrict listening, the influence of off-frequency listening on the slopes of the functions cannot be ruled out.

B. Estimates of suppression based on comparison of SM and FM

In Fig. 2, the data in Fig. 1 are recast to compare ML functions under FM and SM conditions at each f_m. Because the absolute threshold for the signal is the same in SM and FM conditions, the differences in signal level shown in Fig. 2 can be viewed as differences in amount of masking (DAM). The reason for plotting FM and SM together is to visualize differences in amount of masking between FM and SM at equivalent masker levels. These differences were used as estimates of suppression. This definition is equivalent to the definition of suppression used with rate-level functions in ANF studies (e.g., Javel *et al.*, 1983) and described by Delgutte (1990a) in the context of masking. For f_m=4281 Hz and L_m=60 dB SPL (see arrow in Fig. 2, right panel), the signal levels at threshold were 29 and 48 dB SPL for FM and SM, respectively. The dB difference between these signal levels is 19 dB. A second example, f_m=2141 Hz and L_m=70 dB SPL (see arrow in the left panel of Fig. 2), estimates the amount of suppression (SM-FM difference) as 9.6 dB.

DAM between SM and FM is plotted in Fig. 3. The filled circle and square in Fig. 3 correspond to the 4281 and 2141 Hz conditions illustrated for one L_m by the arrows in Fig. 2. DAM ranged from 5 to 26 dB for masker levels of 30–80 dB SPL for the 4281 Hz masker, and from 8 to 21 dB for masker levels of 60–80 dB SPL when f_m=2141 Hz.

C. DPOAE-suppression data

Measured DPOAE levels (both with and without a suppressor tone present) are shown in Fig. 4 as input/output (I/O) functions. DPOAE level (L_d) is plotted as a function of

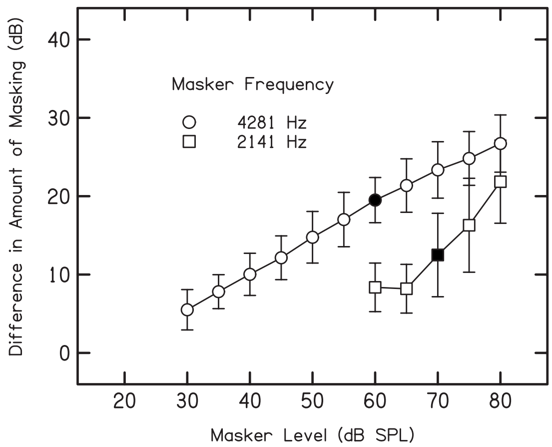

FIG. 3. The amount of suppression, estimated as the DAM for SM and FM as a function of masker level; the parameter is masker frequency. The open circles and squares represent the results for on-frequency (4281 Hz) and off-frequency maskers (2141 Hz), respectively. The filled circle and square represent the SM-FM difference illustrated by the horizontal arrows in Fig. 2.

L_2, with L_3 as the parameter. Control conditions (without a suppressor) are shown as filled symbols in Fig. 4. The I/O functions shift toward the right in the presence of suppressors. We define amount of suppression relative to L_2 by fixing L_d and determining how much L_2 must increase to maintain the same output (L_d) in the presence of suppressors. This measure of suppression is not independent of DPOAE level. Because the present study was exploratory in nature, it was necessary to empirically determine the L_d criterion output with and without suppressors that could be used to determine the L_2 levels at which this constant output (L_d) was observed. Although it was apparent from visual inspection of DPOAE I/O functions that $L_d=-3$ dB SPL was the output criterion that best agreed with the DAM results, additional analyses were performed to support this choice. The mean data were analyzed in 0.25 dB steps. The amount of suppression, calculated as the shift in L_2 as a function of L_3 (i.e., suppressor

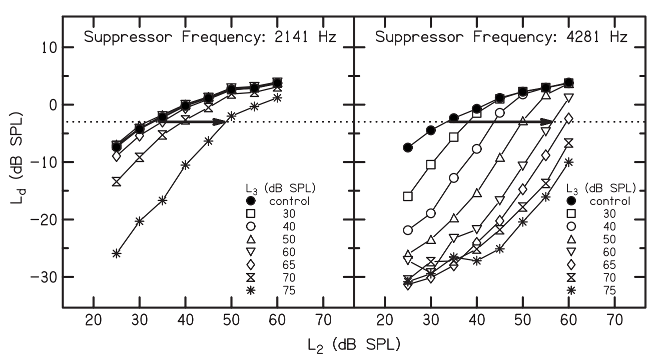

FIG. 4. Mean DPOAE level (L_d) as a function of L_2 (f_2=4000 Hz), with suppressor level (L_3) as the parameter. The filled symbols within each panel represent the DPOAE levels for control conditions, in which no suppressor was presented. The left and right panels show data for off-frequency (2141 Hz) and on-frequency (4281 Hz) suppressors, respectively. The horizontal arrows in each panel are drawn at an L_d of -3 dB SPL. They illustrate the extent to which L_2 had to be increased in order to maintain a DPOAE level of -3 dB SPL as L_3 increases from the control condition. The standard deviations (4–9 dB) are consistent with previously reported DPOAE variability.

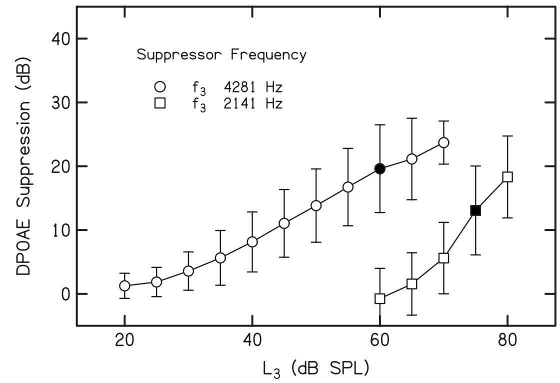

FIG. 5. Amount of DPOAE suppression in dB as a function of suppressor level. The open circles and squares represent the conditions in which f_3 =4281 Hz and f_3=2141 Hz, respectively. The filled circle and square correspond to the L_2 difference described by the arrows in Fig. 4.

level), varied by only about 2 dB for L_d between 0 and -5 dB SPL. Thus, the initial selection of $L_d=-3$ dB SPL provided the least deviation from the DAM data, while spanning the greatest number of DPOAE I/O functions. While the selection of -3 dB SPL for our definition of DPOAE suppression is somewhat arbitrary, it was sufficient for the objectives of this study to find agreement between DAM and *any* definition of DPOAE suppression.

Estimates of suppression for the DPOAE functions are plotted in Fig. 5 and ranged from 1 to 23 dB for L_3 =20–70 dB SPL for the on-frequency suppressor. The off-frequency suppressor produced suppression estimates that ranged from 0 to 18 dB for L_3=60–80 dB SPL. The filled circle and square in Fig. 5 correspond to the 4281 and 2141 Hz conditions indicated by the arrows in Fig. 4.

D. Comparison of psychophysical and physiological estimates

Figure 6 compares DAM for the on- and off-frequency maskers to the DPOAE-suppression estimates for the same frequencies. The differences between the mean DAM and DPOAE suppression were less than 3 dB for all conditions in which comparisons could be made for the on-frequency masker. For the off-frequency masker, estimates of DAM and DPOAE suppression exhibited differences of 3–9 dB for

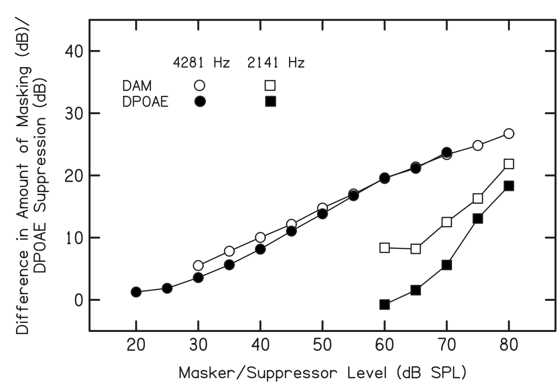

FIG. 6. Mean DAM and amount of DPOAE suppression as a function of masker/suppressor level for all subjects. Open circles and squares represent DAM for 4281 and 2141 Hz, respectively. Filled circles and squares represent DPOAE suppression for 4281 and 2141 Hz, respectively.

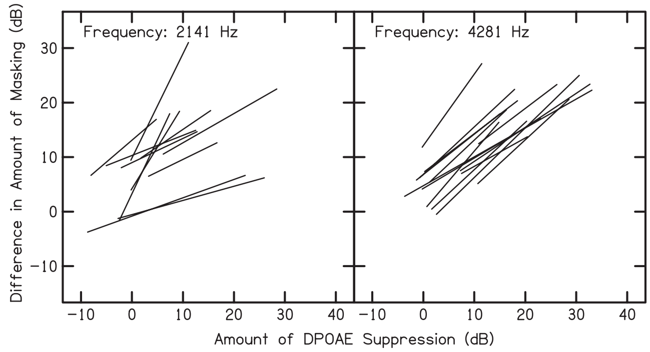

FIG. 7. Relation between DAM and DPOAE suppression represented by best-line fits to the data from individual subjects. Best-line fits for the off-frequency (2141 Hz) and on-frequency (4281 Hz) masker/suppressors are depicted in the left and right panels, respectively.

masker/suppressor levels up to 80 dB SPL. Even so, the general shapes of the DAM and DPOAE-suppression functions were similar, suggesting that suppression is at least partially responsible for the difference between SM and FM.

Figure 7 plots DAM as a function of the amount of DPOAE suppression for individual subjects, where points derived at three or more masker levels are approximated by the best-fitting straight lines shown in the figure. To evaluate this relation, pairs of values for DAM and DPOAE suppression were analyzed for all masker/suppressor levels at which they were available for individual subjects. For example, if at 60 dB SPL, the DAM was 20 dB and the DPOAE suppression was 22 dB, those two values constituted a pair (i.e., the coordinates for a data point) and were included in the analysis. If DAM and DPOAE suppression were measured at masker/suppressor levels of 50, 60, and 70 dB SPL, those three pairs were used to obtain a best-fit line. A minimum of three pairs per subject was required in order to fit a line. The relation between DAM and amount of DPOAE suppression varied across subjects for both masker/suppressor frequencies. The trends across subjects were at least qualitatively similar for the on-frequency case; greater variability was evident, however, for the off-frequency masker/suppressor condition.

Table I contains the individual results for the DAM/DPOAE-suppression correlations. As stated above, results are included only for subjects for whom three or more DAM/DPOAE-suppression pairs were available. As can be seen in Table I, three points were not available from all subjects and (not surprisingly) the number of available points for fitting a line was about twice as large for the on-frequency case, compared to the number of available points for the off-frequency case. Still, the slopes for both masker frequencies have positive correlation, and the correlation for DAM/DPOAE-suppression functions was significant at the 0.05 level, suggesting that a relation exists between these two different measures of suppression. The wide range of regression intercepts demonstrates that the DAM/DPOAE-suppression relation is variable across individuals.

The individual results shown in Fig. 7 were averaged across subjects to produce the mean data shown in Fig. 8. The mean data indicate that DAM grows at about two-thirds the rate of DPOAE suppression. The correlation between DAM and DPOAE suppression was measured separately for the on- and off-frequency conditions. Because many of the correlations were high, the individual correlations were converted to Fisher z values prior to averaging, then converted back to r values. At both frequencies, the mean correlation was positive and significant ($2141: r=0.96$, $p<0.05$; $4281: r=0.98$, $p<0.05$). These results indicate that the relationship between DAM and DPOAE suppression is independent of masker/suppressor frequency, at least for the two frequencies used in the present study.

IV. DISCUSSION

In general, the present masking results are in agreement with previously reported findings. Bacon *et al.* (1999) examined GOM using a SM task for signal frequencies between

TABLE I. Number of paired comparisons (N), slope, intercept, and correlation coefficients of the DAM/DPOAE-suppression function for individual subjects for each masker/suppressor.

	2141 Hz				4281 Hz			
Subject	Slope	Intercept	r	N	Slope	Intercept	r	N
01	0.36	10.3	0.87	3	0.74	6.7	0.99[a]	6
02	1.97	3.2	0.85[a]	7	0.55	4.2	0.91[a]	6
03	0.80	13.0	0.96	3	1.09	0.1	0.98[a]	6
04	0.63	8.7	0.88	3	0.52	3.1	0.99[a]	4
05					0.70	4.7	0.99[a]	5
06	0.26	−0.5	0.90[a]	8	0.53	4.7	0.94[a]	8
07	0.53	7.2	1.00[a]	3	0.71	7.1	0.97[a]	8
08	0.45	5.0	0.99[a]	3	0.62	2.9	0.99[a]	7
09					0.87	4.3	0.96[a]	6
10	1.91	9.8	0.88	4	1.31	12.1	0.94[a]	7
11	1.52	4.2	0.89[a]	6	0.91	−2.8	0.97[a]	8
12	0.33	−0.8	0.89[a]	5	0.86	−0.9	0.98[a]	8
13	0.44	8.9	0.65	3	0.87	6.8	0.94[a]	7
14					0.86	−4.1	0.99[a]	6

[a]$p<0.05$.

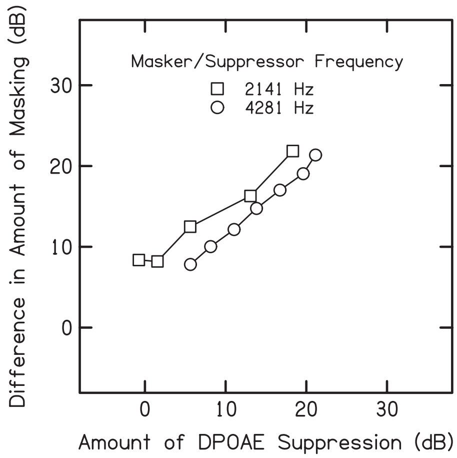

FIG. 8. Relation between DAM and DPOAE estimates of suppression. Open squares and circles represent mean values of paired DAM/suppression comparisons across subjects for 2141 and 4281 Hz, respectively.

400 and 5000 Hz in the presence of maskers about a half octave below (f_m/f_p=0.7) and ranging in level from 40 to 95 dB SPL; stimulus duration was 100 ms for f_m and 5 ms for f_p. For f_p=4300 Hz and f_m=3000 Hz, they found an average slope of 1.9 (dB/dB) for levels similar to ours (60–90 dB SPL). Bacon *et al.* (1999) concluded that for signal frequencies at or above 750 Hz, the slope of the growth of the SM function changed from a value greater than 1 (average ≈1.9) for 60–80 dB SPL signals to close to 1 at levels ≥80 dB SPL. Other studies of GOM using either a FM or FM-SM paradigm (Oxenham and Plack, 1997; Plack and Oxenham, 1998; Yasin and Plack, 2005), with f_p=4000 Hz, f_m=2400 and 4000 Hz, and stimulus parameters similar to ours, have reported that, on average, the on-frequency FM slopes were 2.4 dB/dB, a value greater than the on-frequency SM slopes when plotted as functions of signal level. Our on-frequency ML slope for the FM condition was about 2 dB/dB, which is greater than the ML slope for the SM condition (e.g., 1.2 dB/dB).

Previous research (e.g., Moore *et al.*, 1984, Delgutte, 1990a, 1990b) has suggested that the difference between SM and FM might be due to suppression; however, this hypothesis had not been directly tested against an alternative measure of suppression. The goal of this experiment was to test this hypothesis by comparing a behavioral estimate of suppression (DAM) to measures of DPOAE suppression in the same group of subjects. A primary concern of this study was to develop a set of experimental conditions that would allow comparisons between psychophysical and DPOAE data with the hope of gaining insights into the role of suppression in SM. In our previous DPOAE-suppression studies, we have kept primary levels constant while varying suppressor level. We designed the masking measurements for this study to parallel the DPOAE measurements by keeping signal level constant and varying masker level. Unfortunately, we found it difficult to compare results at constant signal levels because DPOAE generation and psychophysical masking are both only indirectly linked to the cochlear response to the probe stimulus. Equating masker levels with DPOAE suppressor levels made more sense on the assumption that the role of masker and suppressor are more similar between the two measurements. In other words, it made more sense to quantify suppression in terms of *input* levels because the *output* measures were not directly comparable. In retrospect, it would have been better to obtain masking measurements at fixed masker levels to avoid the need to interpolate between masker levels. The decision to hold suppressor level constant had less impact on the DPOAE measurement because we collected these data with suppressor levels varied in 5-dB steps.

It is worth noting that f_1, in addition to interacting with f_2 to generate distortion, also suppresses the response to f_2 (Geisler, 1998) at the “optimum” levels for DPOAE generation; the combination of f_1 with f_2 causes enough suppression that when the level of f_2 is at the subject’s audiometric threshold for f_2 in quiet, the subject is unable to detect the presence of f_2 in the stimulus. Thus, L_2 must be above the quiet threshold level for f_2 to be heard by the subject. Based on previous, unpublished measurements in our laboratory and our interpretation of the data described in this paper, we suspect that the threshold of audibility for f_2 (4000 Hz) (in the presence of f_1 at levels used to elicit a DPOAE) occurs at L_2 levels that produce L_d between −5 and 0 dB SPL. We could have chosen to define suppression at any L_d between −5 and 0 dB SPL since the same trend was observed across this range. However, the amount of suppression when L_d= −3 dB SPL was most similar to the SM-FM masking difference.

The data for SM in Fig. 2 show that, in agreement with previous studies, the slope of the off-frequency ML function is less than unity, while the slope of the on-frequency ML function is close to unity (Oxenham and Plack, 1997). Near-linear growth of SM for an on-frequency masker is expected, even though the response of the basilar membrane at a specific place is nonlinear for best-frequency tones (when cochlear function is normal), because both the masker and the signal are being processed through the same nonlinearity (Oxenham and Plack, 1997; Plack and Oxenham, 1998). Similarly, a near-linear growth in suppression (defined as the shift in L_2 necessary to maintain an L_d of −3 dB SPL as a function of L_3) was observed when $f_3 \approx f_2$ (Fig. 3), a pattern that has been observed previously (e.g., Abdala, 1998; Martin *et al.*, 1998; Gorga *et al.*, 2008). The psychophysical off-frequency masker produced a more rapid growth of masking, which also is consistent with findings previously reported in the literature (e.g., Oxenham and Plack, 1997, 1998; Plack and Oxenham, 1998; Stelmachowicz *et al.*, 1987).

In agreement with physiological data (Pang and Guinan, 1997), our off-frequency data, when f_p is plotted as a function of L_m, reveal that suppression threshold is about 55–65 dB SPL and the SM slope is 2 dB/dB. Pang and Guinan (1997), in a study of GOM in ANFs of the cat using a SM condition, found that the threshold of masking for an off-frequency masker was typically higher than 60 dB SPL and the slope of the GOM function was 2 dB/dB or higher. Our 2 dB/dB SM slope (L_p as a function of L_m) is also close to the 2.4 dB/dB slope suggested by the Allen and Sen (1998) model for the slope of an off-frequency masker.

The similarity of the psychophysical and DPOAE estimates shown in Fig. 6, to a first approximation, suggests that DAM is, at least in part, due to suppression. The correlations between these two measures of suppression shown in Table I support this view. It is likely that the absolute differences in amount of suppression between these two measures would change, depending on stimulus conditions. However, for the conditions chosen for the present study (chosen to minimize recovery from adaptation during FM), the mean difference in suppression estimates between the two paradigms is less than 3 dB at any level for the on-frequency condition, with slightly larger differences (3–9 dB) for the off-frequency case.

The individual best-line fits in Fig. 7 and their correlation coefficients in Table I provide more details concerning the relation between DAM and DPOAE suppression. This figure reveals an orderly relationship for the on-frequency condition, whereas the off-frequency case shows more scatter. As seen in Table I, the individual correlations of the DAM/DPOAE-suppression function for both masker/suppressors are ≥0.8, except for one condition. These data suggest that for a given amount of suppression, DAM may be expected to be two-thirds the suppression value for parameters similar to those used in this study. At present, we do not have an explanation for the rate of growth of DAM versus DPOAE suppression, although one possible explanation might relate to the criterion output level ($L_d=-3$ dB SPL) selected for data analysis of the DPOAE I/O functions. It is also possible that if we had used a psychophysical paradigm in which L_p was varied while L_m was held constant, we might have observed results more in alignment with the suppression function; at the very least, such a paradigm would have avoided the data transformations that were needed in the present study to compare the DPOAE and behavioral-masking data.

Our estimates of suppression (3–26 dB) are consistent with other estimates reported in the psychophysical literature. Specifically, other psychophysical studies estimating suppression as a change in signal threshold during a pulsation-threshold task (Duifhuis, 1980; Shannon, 1986) or GOM measurements (Oxenham and Plack, 1998; Yasin and Plack, 2005) have reported suppression values of 6–33 dB. Duifhuis (1980), in a study of psychophysical two-tone suppression, observed suppression estimates of about 16 dB for $f_p=1000$ Hz and $f_m=600$ Hz for L_m between 60 and 90 dB SPL using a pulsation-threshold paradigm. Shannon (1986) also used a pulsation-threshold task, and estimated about 20 dB of suppression for $f_p=1000$ Hz and $f_m=400$ Hz. Other psychophysical studies have estimated suppression as a function of signal level by subtracting interpolated masker levels for SM from the FM condition for a 2400 Hz off-frequency masker when $f_p=4000$ Hz (Oxenham and Plack, 1998; Yasin and Plack, 2005). In one case, estimates of suppression across subjects ranged from 15 to 32 dB for signal levels from 40 to 60 dB SPL (Oxenham and Plack, 1998), and, in the other case, it ranged from 6 to 17 dB for signal levels of 10–80 dB SPL (Yasin and Plack, 2005). These ranges are similar to the range observed in the present study (8–21 dB) for the off-frequency case. Using a measure of neural synchrony with $f_p=1000$ Hz and $f_m=400$ Hz, Javel (1981) reported 28 dB of suppression for the shift in neural-response functions in the presence of an off-frequency masker.

Taken together, previous data, as summarized above, suggest that the amount of suppression exhibits variability that is dependent on the relationship between signal and masker frequency, level, and test paradigm. Still, the similarity of values across studies suggests that suppression does not appear to exceed 35 dB for levels between 30 and 90 dB SPL. Thus, the values estimated for DAM in the present study are in agreement with the previously reported data for psychophysical and physiological suppression estimates.

V. CONCLUSIONS

The goal of this experiment was to examine the extent to which differences between SM and FM can be attributed to suppression that occurs during SM, but not during FM. The results for most of the signal range under study provide evidence to support the view that the difference between SM and FM (DAM) is at least partly due to suppression.

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