Growth of suppression using distortion-product otoacoustic emission measurements in hearing-impaired humans

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Growth of distortion-product otoacoustic emission suppression was measured in 65 subjects with mild-to-moderate sensorineural hearing loss (HI). Measurements were made at four probe frequencies (f_2) and up to five L_2 levels. Eleven suppressor frequencies (f_3) were used for each f_2 , L_2 combination. These data were compared to data from normal-hearing (NH) subjects (Gorga *et al.*, 2011a). In both NH and HI subjects, growth of suppression depended on the relation between f_2 and f_3 , such that the slope was close to one when $f_3 \approx f_2$, steeper than one when $f_3 < f_2$, and shallower than one when $f_3 > f_2$. Differences in growth of suppression between NH and HI subjects were not observed for fixed f_2 , L_2 combinations, however large differences were observed in suppressor “threshold” when compared at the same probe sensation level (dB SL). Smaller group differences were observed when compared at the same probe sound-pressure level (dB SPL). Therefore, the extent of these differences depended on how probe level (L_2) was specified. When the results from NH and HI subjects are compared with each other and with psychophysical studies of masking, differences are observed that have implications for the remediation of mild-to-moderate hearing loss. © 2012 Acoustical Society of America. [<http://dx.doi.org/10.1121/1.4754526>]

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I. INTRODUCTION

The purpose of this study was to describe the growth of suppression in hearing-impaired (HI) humans using measurements of distortion-product otoacoustic emissions (DPOAE), and to compare growth of suppression in these subjects to data from subjects with normal hearing (NH). How the responses of the human auditory system change with increases in stimulus level is of interest in order to understand basic properties of hearing and to better understand the changes in response growth that may accompany damage to the cochlea. Changes in response growth when hearing loss occurs (sometimes referred to as loudness recruitment) have implications for the selection of signal-processing strategies that attempt to ameliorate the loss. While cooperative adults with hearing loss can provide feedback related to loudness, infants, young children, and patients with developmental disabilities are unable to provide information about how the loudness of sound grows with intensity. Having data related to response growth that were obtained through objective measurements could provide information that eventually might be helpful in selecting signal-processing strategies (such as gain as a function of input level) for patients who are unable to provide voluntary responses related to the loudness of sound. Thus, the goal of the present study was to use DPOAE measurements of

suppression growth to describe any changes in response growth that may occur as a consequence of hearing loss. We recognize that these measurements may be applicable only in cases of mild-to-moderate hearing loss, but providing objective information in those cases would still be of value.

There are several ways in which response growth can be assessed, some of which are only possible in animal preparations while others may be applied to humans. These techniques include: measurements of basilar-membrane motion, single-unit rate-versus-level functions, growth of masking, measurements of DPOAE I/O functions and measurements of DPOAE growth of suppression, some of which show similar patterns (e.g., Sachs and Abbas, 1974; Ruggero and Rich, 1991; Ruggero *et al.*, 1992; Gorga *et al.*, 2002; Oxenham and Plack, 1997; Neely *et al.*, 2009).

The normal, nonlinear mechanical response of the basilar membrane at any particular location is frequency dependent (Ruggero *et al.*, 1992; Robles and Ruggero, 2001) and is compressive at its best frequency (BF). At BF, basilar-membrane “thresholds” are lowest and the magnitude of the response grows linearly near threshold. Compression is evident for moderate and higher input levels, at least in the normal state. When the basilar membrane is driven by a tone below BF, the lowest level at which a response occurs is increased and the response grows more linearly and rapidly with input level, compared to when it is driven by a BF tone (Ruggero and Rich, 1991; Ruggero *et al.*, 1992). Similarly, the slope of the rate-level function of auditory-nerve fibers depends on the relationship between characteristic frequency (CF) and driver frequency (e.g., Evans, 1974; Sachs and Abbas, 1974). Specifically, an auditory neuron has its lowest threshold for a CF tone (by definition), but its threshold is elevated when driven by a low-frequency tone, relative to

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CF. In addition, the slope of the rate-level function is steeper for low-frequency tones compared to the slope when the fiber is driven with a CF tone. Not surprisingly, this frequency-dependent pattern shares similarities with response-growth patterns based on measurements of basilar-membrane motion.

Similar patterns have also been demonstrated using growth of masking measurements in humans. These functions show a compressive region at moderate stimulus intensities (e.g., [Stelmachowicz et al., 1987](#); [Oxenham and Plack, 1997](#)). Growth-of-masking measurements provide evidence of compression when a probe tone of some frequency is masked by a second tone whose frequency is much lower than the frequency of the signal or probe tone. In psychophysical measurements in NH subjects, it is assumed that the probe or signal is processed nonlinearly (i.e., compressively) at its best place in the cochlea while the low-frequency masker is processed more linearly at the same place. In a masking paradigm in which probe level is the independent variable, a shallower slope of the growth of masking function is observed because increases in probe level require smaller increases in masker level in order to just mask the probe (e.g., [Oxenham and Plack, 1997](#)).

Growth of suppression based on DPOAE measurements has also been used to describe response growth. DPOAE suppression growth is frequency-dependent in much the same way as other measures of response growth ([Kummer et al., 1998](#); [Martin et al., 1998](#); [Gorga et al., 2002](#); [Abdala, 2005](#)). In these studies, suppressor tones were presented in order to reduce the response to a fixed-level pair of primary tones (f_2 and f_1 , with $f_1 \approx f_2/1.2$) that was used to elicit a response. In these measurements, it is assumed that the main generation of the distortion product whose level was being suppressed came from a place near the BF place for f_2 , even though it is known that other locations may also contribute to the ear-canal DPOAE (e.g., [Shera and Guinan, 1999](#)) and generation may also take place at regions basal to the BF location of f_2 ([Martin et al., 2010](#)). Growth of suppression when hearing was normal followed a pattern that was similar to what has been observed in measurements of basilar-membrane motion, single-unit rate-versus-level functions, and growth of masking. Specifically, suppression grew more rapidly (steeper slope) when the response was suppressed by a tone about an octave below f_2 , compared to the case when the suppressor tone was close to f_2 (e.g., [Kummer et al., 1995, 1998](#); [Gorga et al., 2002, 2008](#); [Abdala and Chatterjee, 2003](#)). This pattern, however, has not always been observed (e.g., [Porter et al., 2006](#)).

Because the mechanical response of the basilar membrane is dependent on the status of outer hair cells (OHCs) ([Ruggero and Rich, 1991](#)), either permanent or temporary damage to these structures has been shown to alter basilar-membrane responses. For example, [Ruggero and Rich \(1991\)](#) evaluated the effects of furosemide treatment (an ototoxic agent known to reduce the transduction currents in the OHCs) on the response of the basilar membrane. Furosemide treatment resulted in a temporary shift in threshold and a steepening of the slope of the basilar-membrane response to BF tones. These BF responses resembled the responses to

tones whose frequencies were below BF. The responses to low-frequency tones relative to BF were unaffected by furosemide treatment. Assuming that the response at BF represented nonlinear, compressive behavior while the response to a tone much lower than BF represented a more linear response at the place of measurement, these data demonstrate that one consequence of cochlear damage was a loss of compression and a linearization of the response for BF tones.

Although similar patterns have been observed in the responses of single auditory-nerve fibers, there are disagreements in some of the findings. For example, [Evans \(1974\)](#) observed rate-level functions at CF that had elevated thresholds and steeper slopes as a consequence of reversible hypoxia. Like the basilar-membrane data, the response to a low-frequency tone remained relatively unchanged during hypoxia. Although [Liberman and Kiang \(1984\)](#) did not specifically focus on the slopes of rate-level functions, they provided examples to suggest that these functions may become steeper following acoustic trauma. In contrast, [Heinz and Young \(2004\)](#) found no evidence to explain loudness recruitment (defined as an abnormal growth of loudness as intensity is increased) in the responses of auditory-nerve fibers following noise exposure. In fact, they observed shallower than normal rate-level functions following cochlear damage. Follow-up studies by this group suggest that loudness recruitment may be mediated by responses at higher levels of the auditory system, such as the cochlear nucleus ([Cai et al., 2008](#)).

With the exception of the observations by [Heinz and Young \(2004\)](#), basilar-membrane and auditory-nerve measurements from lower animals with cochlear damage and growth of masking measurements made in HI humans provide evidence of abnormal response growth in peripheral responses. Data from psychophysical studies in humans have shown that when growth of masking is measured for off-frequency maskers, the slope is shallower (relative to the normal case), presumably due to the changes in cochlear mechanics and loss of compressive effects from OHCs ([Stelmachowicz et al., 1987](#); [Nelson and Schroder, 1997](#); [Oxenham and Plack, 1997](#)).

[Porter et al. \(2006\)](#) described data for a wide range of f_2 frequencies in rabbits with noise-induced hearing loss that averaged between about 2 and 25 dB. Data were shown for conditions in which primary levels ranged from 45 to 70 dB SPL. Changes in suppression growth were not observed following noise exposure, although there was a tendency for the slope of the low-frequency suppression-growth function to decrease. This outcome is somewhat unexpected, given observations that the response to low-frequency tones (relative to BF) are unaffected by damage at the BF place (e.g., [Ruggero and Rich, 1991](#)).

One general problem limiting DPOAE suppression measurements is the reduced DPOAE levels in ears with mild-to-moderate hearing loss. DPOAEs, even when a suppressor tone is not presented, are sometimes absent when mild-to-moderate hearing loss exists and they typically are absent for greater degrees of hearing loss. Even when the response can be measured, it is of lower level, meaning it is

closer to the level of background noise. This results in a reduced dynamic range over which suppressive effects can be measured and potentially less reliable measurements in ears with hearing loss, especially for humans, who produce smaller DPOAE responses than other mammals.

Despite these problems, several studies have measured DPOAE suppression in HI human subjects. [Abdala and Fitzgerald \(2003\)](#) measured DPOAE suppression in children with sensorineural hearing loss and compared the results to data from NH children using the same techniques. As expected from previous data, suppression-growth functions for NH subjects revealed shallow slopes for suppressor frequencies above f_2 and steep slopes for suppressor frequencies below f_2 . In the impaired case, growth functions for suppressor frequencies below f_2 demonstrated the same steep slope as seen in NH ears. In some HI ears, steeper suppression-growth functions were observed for suppressor frequencies close to and above f_2 , which may relate to the loss of normal compressive nonlinearity, but there are few data from other studies to which these results can be compared.

[Gorga et al. \(2003\)](#) also measured DPOAE suppression in NH and HI humans, but their results differ somewhat from previous findings in humans and lower animals. In this study, both groups demonstrated steep slopes for suppressor tones below f_2 ; however, a small decrease in slope was observed in the HI case. The cause for this change in slope for low-frequency suppressors, which is similar to observations in rabbits following noise exposure ([Porter et al., 2006](#)), was not obvious. For suppressor frequencies above f_2 , only a slight increase in slope was seen in subjects with hearing loss. These observations suggest a similar growth of response for suppressor frequencies above and below f_2 in HI subjects, compared to the normal case. Unfortunately, [Gorga et al. \(2003\)](#) did not use the same long averaging times that were used in their subsequent work in subjects with normal hearing ([Gorga et al., 2011a](#)), which would have helped to increase the reliability of measurements in subjects with hearing loss by reducing the noise levels, compared to the case when only short averaging times were used. Furthermore, neither [Abdala and Fitzgerald \(2003\)](#) nor [Gorga et al. \(2003\)](#) made measurements for either a wide range of f_2 frequencies and/or L_2 levels. While the data reported by [Porter et al. \(2006\)](#) covered a wide range of f_2 frequencies, the lowest primary level for which they reported data was 45 dB SPL, a level at which estimates of gain and tuning are reduced, even in ears with normal hearing ([Gorga et al., 2011a](#)). Thus, there would be value in further exploring the growth of DPOAE suppression for a wide range of levels in humans with hearing loss, using the same time-consuming but more rigorous techniques that were used to obtain data in NH subjects ([Gorga et al., 2011a](#)).

The purpose of the present study was to determine the extent to which growth of suppression changes as a consequence of mild-to-moderate hearing loss using DPOAE measurements. Subjects were categorized into groups according to the magnitude of their hearing loss. Data were collected at four f_2 frequencies for a range of primary levels. Suppression was measured using as many as 11 suppressor

frequencies and a wide range of suppressor levels. These data were compared to growth of suppression data in humans with normal hearing that were collected with the same measurement techniques ([Gorga et al., 2011a](#)). The present study is unique in that it reports data for a relatively large sample of humans with hearing loss, it uses measurement techniques that maximize the range of levels over which reliable measurements can be made, and it evaluates suppression growth for a range of levels, including levels close to behavioral thresholds, where presumably gain is largest and tuning is sharpest.

II. METHODS

A. Subjects

Sixty-five subjects (24 males, 41 females) participated in this study. Subjects ranged in age from 15 to 80 years, with a mean age of 59.8 years. All subjects were HI, defined as an audiometric threshold of 20 dB HL or greater at any of the four f_2 frequencies (2.0, 2.8, 4.0, and 5.6 kHz) used during DPOAE suppression measurements. It was assumed that the hearing losses in these patients were of cochlear origin (based on case history and other audiometric findings), although extensive diagnostic testing to determine site of lesion was not performed as part of the selection of subjects. Depending on audiometric thresholds, subjects participated in data collection at one or more of the four test frequencies. The test frequencies ($f_2 = 2.0, 2.8, 4.0,$ and 5.6 kHz) were selected, in part, because it is common to observe hearing loss at these frequencies. Furthermore, it is more difficult to measure DPOAEs at lower frequencies in humans due to the increase in noise level that occurs as f_2 frequencies decrease, starting at about 2 kHz. Long averaging times could have been used to reduce the noise levels at lower frequencies, but many subjects would have been unable to make the additional time commitment that would have been necessary, especially since the averaging time used in the present study was already unusually long (see below). It also was decided not to collect DPOAE data at 8 kHz because our hardware was incapable of producing sufficient levels at 8 kHz and surrounding frequencies with acceptable system-distortion levels to permit reliable measurements of DPOAE suppression. The output-limitation problem was exacerbated by the fact that, because of their hearing losses, high levels of stimulation were needed to elicit responses that subsequently could be suppressed.

A 226-Hz tympanogram was measured for each subject prior to each DPOAE data were collected. This helped to ensure that middle-ear function was normal at each visit. Subjects were categorized into three groups based on behavioral threshold at the test frequency. These groups were defined by behavioral thresholds of 20–25, 30–35, and 40–45 dB HL. We attempted to collect data from subjects with slightly greater hearing loss (50–55 dB HL), but too few subjects with thresholds in this range produced DPOAE responses of sufficient magnitude in the absence of suppressors to allow for reliable suppression measurements. The categories used in the present study were selected to facilitate comparisons with normative findings reported by [Gorga et al. \(2011a, 2011b\)](#), in which data were collected from

subjects with audiometric thresholds ≤ 10 dB HL. By excluding subjects with thresholds of 15 dB HL in the previous study, it was hoped that it would be easier to observe differences in the data from impaired ears, compared to data from ears with normal hearing. Figure 1 presents the mean threshold (dB SPL) ± 1 standard deviation (SD) at each f_2 for subjects in each hearing-loss category. For comparison purposes, the mean thresholds of the NH subjects at these same frequencies, taken from Gorga *et al.* (2011a), are reproduced here. Table I provides the number of subjects that participated per hearing-loss category. No fewer than 9 subjects (and sometimes as many as 19 subjects) participated in data collection at each f_2 frequency, in each hearing-loss group. However, not all of these subjects produced reliable responses for the same wide range of stimulus levels that were possible in NH subjects (Gorga *et al.*, 2011a). Within a hearing-loss category, the same subjects did not contribute data at all four f_2 frequencies, thus making it impractical to provide average audiograms for each group in a meaningful way. For all suppression measurements, L_2 was determined based on each subject's behavioral threshold at each f_2 frequency at which data were collected. Initially, stimulus levels will be specified in dB SL, just as it was specified in the normative studies. However, comparisons will also be made between normal and impaired growth of suppression when stimulus levels were set to equivalent SPLs.

B. Stimuli

DPOAEs were elicited by pairs of frequencies (f_1 and f_2) with $f_2/f_1 \approx 1.22$. As stated above, a total of four f_2 frequencies (2.0, 2.8, 4.0 and 5.6 kHz) were used in this study. L_2 varied from 10 dB SL to as much as 50 dB SL (depending on the magnitude of the hearing loss) in 10-dB steps. The number of L_2 levels (10–50 dB SL) reliably measured for each frequency was determined by the unsuppressed level of the distortion product (L_d), which was based on DPOAE I/O functions that were measured for each subject prior to the collection of suppression data.

FIG. 1. Mean behavioral threshold (dB SPL) as a function of f_2 frequency (kHz). Error bars represent ± 1 SD. Data from 9 to 19 HI subjects were used to derive these values, although the same subjects are not represented at each frequency for a given hearing-loss category. NH thresholds, based on data from 19 to 20 subjects, are plotted for comparison purposes (Gorga *et al.*, 2011a).

TABLE I. Number of subjects included at each f_2 in each of four subject groups.

	2.0 kHz	2.8 kHz	4.0 kHz	5.6 kHz
NH	20	20	19	20
20–25 dB HL	13	19	12	11
30–35 dB HL	13	10	12	9
40–45 dB HL	10	10	11	9

In Gorga *et al.* (2011a), L_1 was set for each subject individually to produce the largest L_d for each L_2 . For frequencies ≥ 2 kHz, optimal levels were determined using an approach that we have labeled the Lissajous procedure (Neely *et al.*, 2005). This procedure was chosen because previous work in NH subjects has shown that the largest L_d results when stimulus conditions are individually optimized (Neely *et al.*, 2005, Johnson *et al.*, 2006). For the present study, we did not determine individually optimized stimulus levels for each HI subject. Instead, the y -intercept and slope, determined by the individual optimized levels used by Gorga *et al.* (2011a) for NH subjects, were averaged for each f_2 frequency and used to develop the L_1 , L_2 combinations that were used when measurements were made in HI subjects. This method avoided creating stimulus levels that compensated for changes due to hearing loss. Table II shows the L_1 , L_2 (dB SPL) combinations for each f_2 that were derived from the normative data and used in the present study. The L_1 value for a given sensation level can be determined from this table. Note that for NH subjects, the L_1 resulting in the largest L_d for a given L_2 depended on L_2 , and the differences between L_1 and L_2 were larger than previously recommended to optimize L_d (e.g., Kummer *et al.*, 1998).

Eleven suppressor frequencies (f_3) were used for each f_2 , L_2 combination. Suppressor frequencies ranged from approximately $1\frac{1}{2}$ octaves below f_2 to approximately $\frac{1}{2}$ octave above f_2 , spaced at roughly equal intervals on a logarithmic scale. The level of the suppressor (L_3) ranged from -20 to 85 dB SPL in 5-dB steps.

TABLE II. L_1 , L_2 (dB SPL) combinations used to elicit a DPOAE for each of the four f_2 frequencies.

L_2 (dB SPL)	L_1 (dB SPL) 2000 Hz	L_1 (dB SPL) 2828 Hz	L_1 (dB SPL) 4000 Hz	L_1 (dB SPL) 5656 Hz
10	45	53	46	46
15	47	55	48	49
20	50	57	50	51
25	52	59	53	53
30	55	61	55	55
35	58	63	57	57
40	60	65	59	60
45	63	67	62	62
50	65	69	64	64
55	68	71	66	66
60	71	73	69	68
65	73	75	71	71
70	76	77	73	73
75	78	79	76	75

C. Procedures

DPOAE measurements were made using EMAN (Neely and Liu, 1994) and a 24-bit soundcard (CardDeluxe, Digital Audio Labs). EMAN is a locally written computer software program that measures and displays otoacoustic emissions. This system generated the stimuli used to elicit responses from the cochlea. A probe-microphone system (ER-10C, Etymotic Research, Elk Grove Village, IL) presented the stimuli and recorded responses in the ear canal. Sound output was increased by as much as 20 dB by removing the “receiver equalization” from the ER-10C. The two primaries were presented on separate loudspeakers in the probe-microphone system, with the suppressor tone presented on the same channel as f_2 . Prior to data collection, a chirp stimulus was presented from each channel and the system response in the ear canal was measured in dB SPL. This information was then used to set the level of the stimuli for DPOAE measurements. It has been shown that standing waves may introduce errors when SPL calibrations are conducted in closed ear canals (e.g., Siegel, 1994, 2002; Siegel and Hirohata, 1994; Scheperle et al., 2008). However, this method was used in order to facilitate comparison between the present study and previous measurements in subjects with normal hearing, where SPL calibration was also used (Gorga et al., 2011a). During data collection, waveforms were alternately stored in two buffers. The waveforms were summed and the DPOAE level (L_d) was derived from the contents of the $2f_1$ - f_2 frequency bin. The contents of the two buffers were then subtracted, and the noise level was estimated from the levels in the $2f_1$ - f_2 frequency bin and the five frequency bins above and below this bin.

The set of f_2 frequencies for which each subject participated was determined, in part, on the basis of audiometric threshold. A two-alternative forced-choice, transformed up-down procedure (Levitt, 1971) was used to estimate thresholds (dB SPL) for each subject at all f_2 frequencies for which they participated. A DPOAE I/O function was then measured prior to collection of the suppression data. DPOAE I/O functions, in the absence of a suppressor, were also used in determining the f_2 frequencies and L_2 levels for which a subject could participate because they helped determine the levels (dB SL) for which reliable estimates of L_d were possible and, therefore, for which suppressive effects could be measured. Measurements of suppression were made only for those conditions under which the unsuppressed response had a signal-to-noise ratio (SNR) ≥ 10 dB.

The audiometric threshold at each frequency for which the subject qualified (meaning that audiometric threshold was within one of the hearing-loss categories described above and for which the subject produced an unsuppressed DPOAE level that was at least 10 dB above the noise floor) was selected as the reference level for determining dB SL. A suppressor frequency (f_3) was then selected and its level (L_3) was varied from -20 to 85 dB SPL in 5 -dB steps (referred to as a suppressor-level function). A control condition, in which no suppressor was presented, occurred just before and just after each suppressor-level series. If the L_d of the unsuppressed controls prior to and following any suppressor-level function differed by more than 6 dB, the condition was repeated. This was

done to control for any movement of the foam tip in the ear canal over the course of measurement of a single suppressor-level function for any f_3 frequency. Once data were collected at all 11 f_3 frequencies for a given f_2 , L_2 combination, L_2 was changed. The entire procedure was then repeated until suppression data were collected for all 11 f_3 frequencies at all L_2 levels that could be measured at a given f_2 in a given subject.

Measurement-based stopping rules were used to increase the likelihood of obtaining reliable DPOAE data for every f_2 , L_2 combination for all eleven suppressor frequencies. Specifically, data collection during DPOAE I/O function and suppression measurements continued until one of three stopping criteria was met: (1) the noise level was ≤ -25 dB SPL, (2) the SNR was ≥ 20 dB, or (3) 210 s of artifact-free averaging time had expired. These are the same rules that were used in the normative study, the data to which the present data will be compared (Gorga et al., 2011a), and were especially important here because of the reduced L_d that was a consequence of the hearing loss that existed in the present group of subjects.

System distortion was measured prior to data collection and was below -25 dB SPL for low-level stimulus conditions and -15 dB SPL for high-level stimulus conditions. Because system distortion was level dependent, a conservative constant value of ≤ -25 dB SPL was used as the noise-level stopping rule during DPOAE data collection, although high-level data were not included in analyses for conditions in which system distortion exceeded -15 dB SPL.

A total of 714 h was spent collecting the DPOAE data summarized in this paper. Data-collection time ranged from 2 h per subject to as much as 27.5 h per subject. The variation in test time among subjects was due to a number of factors which included: (1) the number of f_2 frequencies and L_2 levels completed by the subject and (2) differences in subject's internal noise, which caused averaging time to vary. Data collection proceeded rapidly when the noise floor was low and the level of the DPOAE response was high. This resulted in a favorable SNR, which was demonstrated in the unsuppressed control conditions, and was typically found in lesser degrees of hearing loss and for high L_2 levels. In contrast, more time was needed to lower the noise floor when the SNR was poor. In general, this occurred with greater degrees of hearing loss and at lower L_2 levels. However, as degree of hearing loss increased, the range of L_2 levels over which reliable L_d levels (defined as an SNR ≥ 10 dB) could be measured in the unsuppressed condition decreased. This limited the number of sensation levels that could be tested in many subjects and resulted in less data-collection time under those circumstances. The internal noise of the subject also had an impact on data-collection time regardless of degree of hearing loss. Overall, the interaction of the variables listed above determined data-collection time in each subject, and therefore, the total amount of time needed to collect these data.

III. RESULTS

A. Control conditions

All of the data from subjects with hearing loss (reported in this paper) were collected under conditions that were

identical to those used to collect previously reported normative data (Gorga *et al.*, 2011a). Accordingly, subsets of the normative data will be reproduced here for the purpose of comparison to data from subjects with hearing loss. Figure 2 plots mean DPOAE level (L_d) and noise level (± 1 SD) as a function of L_2 (dB SL) during control conditions (in which no suppressor was present) for the subjects who contributed data at each of the four f_2 frequencies for each hearing-loss category. For comparison purposes, the normative data (taken from Gorga *et al.*, 2011a) are included at these same f_2 frequencies. Control conditions were measured prior to and following each L_3 series for each f_3 frequency. Since suppression was measured for 11 f_3 frequencies for each L_2 , f_2 combination, there were 22 measurements of the control condition for each subject at each L_2 . DPOAE and noise levels for these conditions were used to obtain individual mean L_d and noise levels for each subject. These individual means were then averaged and the overall means and SDs for the four subject groups are plotted in Fig. 2. This figure provides an estimate of the mean dynamic range over which suppressive effects could be measured in both NH subjects and subjects with mild-to-moderate hearing loss. The measurement-based stopping rules, especially the averaging-time rule, resulted in noise floors that frequently were at or below -25 dB SPL, thus resulting in mean SNRs that were 15 dB or greater for control conditions. This was true for

individuals with mild-to-moderate HI and for L_2 levels as little as 10 dB above behavioral threshold. However, the range of L_2 levels (dB SL) over which reliable measurements could be made decreased with increasing degrees of hearing loss. This is due to two factors: (1) the maximum L_2 level that our measurement system was able to generate with acceptable levels of system distortion did not exceed 75 dB SPL; (2) the extent to which DPOAEs are measurable in subjects with hearing loss decreases as the magnitude of the hearing loss increases. A manifestation of the consequences of these limiters is seen in Fig. 2. Note that, for NH subjects, DPOAEs were measured for a range of L_2 levels from 10 to 60 dB SL. In contrast, the range of levels over which DPOAEs could be measured decreased as hearing loss increased, with the smallest range of L_2 levels (10 and 20 dB SL) at some f_2 frequencies for the group with thresholds of 40 and 45 dB HL.

Intersubject variability in L_d and noise levels are represented by the error bars (SD's) in Fig. 2. In almost all conditions, especially for the higher frequencies, the variability of the noise level was small enough that the error bars are hidden behind their representative symbols. This can be attributed to the combined effects of the measurement-based stopping rules and the low noise levels at high frequencies. The variability in L_d levels for the control conditions was similar for NH subjects and those with HI, regardless of degree.

FIG. 2. Mean level (dB SPL) ± 1 SD as a function of L_2 (dB SL). Open circles represent mean DPOAE level (L_d) and filled triangles represent mean noise levels. Data from NH (Gorga *et al.*, 2011a) and the three HI groups are plotted. These data represent mean levels measured during control conditions in which no suppressor was present.

While Fig. 2 provides evidence that the mean SNRs for the control conditions in all subject groups were sufficiently positive to allow for suppression measurements over a wide dynamic range, it does not describe the stability of the control conditions in individual subjects. Using the aforementioned 22 estimates of DPOAE level for the control conditions for each f_2 , L_2 combination, individual SDs were calculated. These individual SDs were then averaged (Mean_{SD}) and the standard deviations of these SDs (SD_{SD}) were calculated to provide an estimate of the variability in the control conditions. The Mean_{SD} was less than 2 dB in all but one condition (NH, $f_2 = 4.0$ kHz, $L_2 = 10$ dB SL) and these SDs did not vary by much (SD_{SD} less than 1 dB for every condition). Thus, the control conditions were stable for every f_2 , L_2 combination in individual subjects.

B. Example of decrement versus L_3 functions ($f_3 \approx f_2$, the on-frequency condition) for all f_2 frequencies and hearing-loss categories

Figure 3 plots mean DPOAE decrements as a function of L_3 . Each row represents data for a different subject group while the results for each of the four f_2 frequencies are shown in separate columns. The level of the probe (L_2) was set at 20 dB SL for the conditions shown in this figure. Since it is

not possible to use a suppressor tone at exactly the same frequency as f_2 , the “on-frequency” f_3 for each condition was selected to be slightly above the f_2 frequency. Individual data points represent the mean and SD for all subjects who contributed data for each condition shown in the figure. The open circles represent data converted into decrements. Decrements are defined as the amount by which L_d was reduced in the presence of a suppressor. To accomplish the conversion from measured L_d to decrement, the L_d for the two control conditions (one prior to and one following each suppressor-level function for a given f_3) were averaged, and the L_d for conditions in which the suppressor was present was subtracted from this average. Decrements are used here because they provide an estimate of the amount of suppression (in dB), and they reduce the influence of individual differences in absolute L_d across subjects. Data points at 0 dB decrement signify conditions in which no suppression occurred, which is evident in all 16 decrement functions. Evidence of complete suppression can be seen for high L_3 levels in the top two rows, where the decrement was large and increases in L_3 did not result in further increases in the decrement. For most of the conditions in the bottom two rows, the output limits of the hardware prevented the presentation of suppressor levels that would have resulted in complete suppression of the response, even at the highest L_3 levels.

FIG. 3. Mean DPOAE decrement (dB) as a function of suppressor level (L_3 , dB SPL). Data for the on-frequency suppressor condition is plotted for each subject group at each of four f_2 frequencies. The level of the probe (L_2) was set at 20 dB SL. Open circles represent the mean difference in L_d between control conditions and the conditions in which a suppressor was present (decrements). Error bars represent ± 1 SD. Filled circles represent the transformed decrements which were fit with a simple linear regression, shown as a line within each panel. The vertical dashed lines represent “suppression threshold” (decrement of 3 dB). These best fit lines and suppression thresholds provided the estimate of slope, provided as an inset in each panel, and were used in the construction of functions relating suppression threshold to L_2 (Fig. 6) and in the construction of STCs (Gruhlke et al., 2012).

The filled circles represent transformed decrement data, for which the transformation is described below. However, inclusion criteria were applied to the decrements prior to the transformation: (1) the decrements had to increase monotonically as L_3 increased, (2) the SNR had to be ≥ 3 dB, and (3) at least one decrement (L_{dec}) had to be within the range of 3 to 15 dB (Gorga *et al.*, 2008, 2011a). If the decrement data met these criteria, they were transformed using the formula: $D = 10 \log_{10}(10^{D_{\text{decr}}/10} - 1)$. These transformed data were then fit with a simple linear regression (SLR), from which slopes of the suppression-growth functions were obtained. These slopes are reported in each panel. There was little difference in the slope of the on-frequency decrement functions among the four f_2 frequencies, and these slopes did not change systematically with hearing loss. The vertical dashed line represents “suppression threshold,” which was defined as a decrement of 3 dB. This value was obtained by solving the SLRs for $D = 0$ in the transformed data ($D = 0$ when the decrement equals 3 dB). This suppression threshold was used to provide an estimate of suppression growth that is similar to growth of masking in psychophysical masking

functions (see Fig. 6 below) and has been used in the construction of suppression tuning curves (STCs) (Gorga *et al.*, 2011b; Gruhlke *et al.*, 2012).

C. Slopes of decrement versus L_3 functions when L_2 is fixed in dB SL and dB SPL for all f_2 frequencies and five L_2 levels

Figure 4 plots the slopes of mean decrement versus L_3 functions for NH and HI subjects for all four f_2 frequencies, as many as five L_2 levels (depending on subject group), and as many as 11 f_3 frequencies. Each row provides data for a different L_2 (specified in dB SL), while the results for each f_2 are presented in different columns. The parameter within each panel is subject group, as indicated by the inset in the upper-left panel. In this figure, f_3 (x-axis) is represented on an octave scale relative to f_2 . For the reasons described earlier, the number of measurable L_2 levels decreased as the degree of hearing loss increased.

The general trends in slope across f_2 frequency and L_2 level are similar for both NH and HI subjects. As f_3

FIG. 4. (Color online) Mean slope of the decrement function as a function of f_3 in octaves relative to f_2 . Data for each subject group is represented in each panel, as indicated by the inset in the upper left panel. Data for a different L_2 (dB SL) are shown in each row and data for a different f_2 are shown in each column.

increased, the slope of the decrement functions decreased. The on-frequency conditions ($f_3 \approx f_2$) produced a slope close to 1, regardless of subject group, f_2 frequency, or L_2 level. Although variable (see, for example, data for low L_2 levels, especially when $f_2 = 2.0$ kHz), there are no apparent differences in slope among groups.

Figure 5 plots slopes of mean decrement versus L_3 functions for NH and HI subjects, following the same conventions as were used in Fig. 4. However, in this case, data are compared at the same L_2 levels when L_2 is specified in dB SPL. Similar to Fig. 4, not every HI group provided data that could be represented in each panel. In this case, data from fewer HI categories are represented at lower L_2 levels (dB SPL) because subjects with increasing degrees of hearing loss did not produce DPOAEs of a sufficient magnitude at low stimulus levels to enable suppression measurements. As L_2 increased, so did the range of HI categories for which measurements could be made. The same trends evident in Fig. 4 are evident here. Slopes were steep when the suppressor frequency was below f_2 and shallow for suppressor frequencies above f_2 . Like the data when L_2 was held constant relative to

behavioral threshold (Fig. 4), the slopes were variable and there were no apparent differences among subject groups.

Statistical analyses were performed on slopes for each f_2 frequency for the conditions in which $f_3 = f_2 - 1$ octave, $f_3 \approx f_2$, and $f_3 = f_2 + 1/4$ octave. Separate ANOVAs were conducted when L_2 was fixed at 20 dB SL and when L_2 was fixed at 55 dB SPL with adjustments for multiple comparisons. These two L_2 conditions and three f_3 conditions were chosen because data were available from all four subject groups. For the SL comparison, statistical analyses revealed significantly more shallow slopes in NH subjects compared to the group with thresholds of 40–45 dB HL ($p = 0.018$), but not for any other group comparison. For the SPL condition, statistical analyses revealed steeper slopes in NH subjects, but only in comparison to data from the HI groups with 20–25 and 30–35 dB HL thresholds and only when $f_3 = f_2 - 1$ octave (both $p < 0.001$). Thus, there were few statistically significant differences between NH and HI subjects on this measure of suppression growth.

Figures 4 and 5 provide estimates of suppression growth for fixed L_2 levels and varied L_3 levels. An alternate

FIG. 5. (Color online) Same as Fig. 4, only here L_2 is represented in dB SPL.

description of suppression growth can be obtained by plotting the suppressor level to maintain a “threshold” response as a function of L_2 . This approach results in plots that are comparable to plots of growth of masking from psychophysical experiments in which masker level is plotted as a function of probe level. For this purpose, we defined suppression threshold as the level necessary to produce 3 dB of suppression, which was estimated by solving the SLRs for $D=0$ (which is equivalent to 3 dB of suppression; for example, see the short vertical dashed lines in Fig. 3). Figure 6 plots the mean L_3 for 3 dB of suppression as a function of L_2 , with Fig. 6(a) providing data for the case when L_2 is specified in dB SL, while Fig. 6(b) provides data for the case when L_2 was equivalent in dB SPL. Within each set of eight panels, the top row provides data for the case when $f_3 = f_2 - 1$ octave

(the low-frequency suppressor condition) and the bottom row shows the results when $f_3 \approx f_2$ (the on-frequency suppressor condition). Data for a different f_2 are shown in each column, as indicated.

When L_2 is specified in dB SL, there was a systematic shift in the functions when $f_3 \approx f_2$, although the range of sensation levels over which comparisons between the data from NH and HI subjects can be made was limited to lower levels as a consequence of hearing loss. As magnitude of hearing loss increased, these functions shifted to progressively higher levels, meaning that suppression threshold increased as behavioral threshold increased. However, the slopes of these functions are close to 1 for all subject groups. A linear relationship between L_3 and L_2 is expected when $f_3 \approx f_2$ because both the signal (f_2) and the suppressor (f_3) are close

FIG. 6. (Color online) Mean L_3 for 3 dB of suppression as a function of L_2 . Data for each of the subject groups is shown within each panel, as indicated by the inset in the upper left panel. (a) Data when L_2 is set in dB SL; (b) data when L_2 is set in dB SPL. The top row in each set of eight panels shows data for the low-frequency suppressor condition ($f_3 = f_2 - 1$ octave), and the bottom row in each set of eight panels shows data for the on-frequency suppressor conditions ($f_3 \approx f_2$).

in frequency and, thus, being processed similarly, whether or not hearing loss is present. Differences between NH and HI subjects were also observed when $f_3 = f_2 - 1$ octave, but the differences were much smaller and the slopes of the functions were always less than 1. This is the expected outcome for subjects with NH because the suppressor is presumably being processed linearly near the f_2 place, while the signal (f_2) is being processed compressively. As a result, only small increases in L_3 were needed to maintain suppression threshold as L_2 increased. The results in HI subjects, however, were not expected. Assuming that increases in L_2 resulted in more linear response growth (due to the reduction or loss of the normal compressive nonlinearity near the f_2 place), it was predicted that the slope relating suppression threshold to L_2 for the low-frequency suppressor would be more linear when hearing loss was present. However, this was not the case.

Differences between the results from NH and HI subjects were reduced when L_2 was specified in dB SPL [Fig. 6(b)]. Data were available from HI subjects only for higher L_2 levels, compared to the range of levels over which measurements were possible in NH subjects. However, at these higher levels, differences in this measurement of suppression growth were reduced, compared to the case when L_2 was specified in dB SL [Fig. 6(a)]. Furthermore, while there were small differences among subject groups when $f_3 = f_2 - 1$ octave and L_2 was specified in dB SL, those differences were all but absent when L_2 was specified in dB SPL. Like the results when L_2 was specified in dB SL, the results for this condition were not predicted. For all four subject groups, increases in L_2 required much smaller increases in L_3 in order to maintain a constant amount of suppression (3 dB). We had initially hypothesized that the slope for the condition in which $f_3 = f_2 - 1$ octave would have been more linear in HI subjects, compared to the results observed in NH subjects. This hypothesis was not supported by the data.

The slopes of the functions plotted in Fig. 6 were estimated and compared. In all but two cases (L_2 specified in dB SPL when $f_3 \approx f_2$: $f_2 = 2.8$ kHz, NH versus 20–25 dB HL, $p = 0.012$; $f_2 = 4$ kHz, NH versus 30–35 dB HL, $p = 0.005$), there were no differences in the slopes of the functions relating suppression threshold to L_2 . Separate ANOVAs were performed to compare mean L_3 for 3 dB of suppression for the conditions in which $L_2 = 20$ dB SL and $L_2 = 55$ dB SPL (with adjustments for multiple comparisons). These two level conditions were chosen because data were available for them in all four subject groups. For the condition in which $L_2 = 20$ dB SL, significant interactions were observed between hearing-loss category and f_2 and hearing-loss category and f_3 (both $p < 0.001$). In relation to the interaction between hearing-loss category and f_2 , the mean of NH subjects differed from the mean of all HI subject groups for all four f_2 frequencies ($p < 0.001$). Differences were observed between the 20–25 dB HL and 30–35 dB HL, and between the 20–25 dB HL and 40–45 dB HL groups at all levels of f_2 ($p < 0.002$). In addition, there was a difference between 30 and 35 dB HL and 40 and 45 dB HL groups when $f_2 = 2.0$ ($p = 0.025$) and no differences among these groups at the three higher f_2 frequencies. For the interaction between

hearing-loss category and f_3 , significant differences were observed for all comparisons except for the comparison between the HI groups with thresholds of 30–35 dB HL and 40–45 dB HL. Differences between groups were smaller when $f_3 = f_2 - 1$ octave than for the other f_3 condition. When $L_2 = 55$ dB SPL, there was a main effect of f_2 ($p < 0.001$) with no interaction between hearing-loss category and f_2 . As expected from an examination of the summary in Fig. 6, the effect of hearing-loss category was less in the dB SPL condition, compared to the dB SL condition. There was, however, an interaction between hearing-loss category and f_3 for the 55 dB SPL condition ($p = 0.006$). For these conditions, no significant differences between any groups were observed when $f_3 = f_2 - 1$ octave. Significant differences were observed when $f_3 \approx f_2$ for comparisons between the data from NH subjects and the data from subjects in the 30–35 and 40–45 dB HL categories, and when the data from subjects with thresholds of 20–25 dB HL were compared to the data from subjects with thresholds of 40–45 dB HL. In general, the largest and most frequently observed statistically significant effects occurred when $L_2 = 20$ dB SL and when $f_3 \approx f_2$, as would be expected from an examination of Fig. 6.

IV. DISCUSSION

The main findings of the present study include the following: (1) with the use of measurement-based stopping rules (in particular, long averaging times), it was possible to reliably measure DPOAEs at low levels and in subjects with mild-to-moderate hearing loss, (2) growth of suppression depended on the relation between probe frequency (f_2) and suppressor frequency (f_3) in HI subjects in much the same way as it did in NH subjects, (3) the growth of suppression in NH and HI subjects did not depend on the probe level (L_2) at which the comparisons were made, and (4) the way L_2 is specified influenced the extent of the differences between suppression growth in NH and HI subjects when the data were cast in a form that is comparable to that used to describe psychophysical growth of masking.

The use of measurement-based stopping rules, particularly the noise-stopping rule, coupled with long averaging times when necessary, resulted in SNRs of 15 dB or greater for the control conditions included in this study. This was true for low primary-level conditions relative to behavioral threshold in both NH and HI subjects. Thus, suppression effects could be measured over no less than a 15-dB range for any combination of f_2 and L_2 . Furthermore, these SNRs suggest that, on average, reliable measurements of suppression were possible in both NH and HI subjects for the f_2 , L_2 combinations shown in Fig. 2. The wide dynamic range over which suppression measurements could be made is perhaps unique in that it allowed us to estimate the slope of the suppression functions in subjects with mild-to-moderate hearing loss. The intersubject variability in mean absolute L_d , which is expressed by the standard deviations plotted in Fig. 2, is similar for NH and HI subjects across f_2 frequency. There was no greater variability in L_d for control conditions in HI subjects, compared to NH subjects. As a result, comparisons

of estimates of suppression growth should be unaffected by differences in intersubject variability.

While the results summarized in Fig. 2 show evidence that the intersubject variability was the same for all four subject groups, intrasubject variability may be of greater interest, as it relates to within-subject reliability in the present estimates of suppression. It was important that L_d for the control conditions for fixed f_2 , L_2 combinations remain stable for all f_3 , L_3 combinations in order to reliably measure growth of suppression for a given subject. Intrasubject variability was assessed by evaluating the reliability of control conditions. The mean SDs were small, never exceeding 2 dB, and even then, a mean SD this large occurred only once and in the data from subjects with NH ($f_2 = 4$ kHz, $L_2 = 10$ dB SL). In addition, there was little variability in the control conditions, as estimated by the SDs of the mean standard deviations (SD_{SD}), which were always less than 1 dB. Finally, there were no differences in intrasubject variability between NH and HI subjects. Combined with the SNRs shown in Fig. 2, these data suggest that the control conditions were stable for all experimental conditions, providing support for the view that the suppression measurements were reliable. The stability of the control conditions can be attributed to the use of the aforementioned measurement-based stopping rules, which allowed averaging time to vary in order to achieve a relatively constant, low noise level. A consequence of this approach is that total data-collection time for HI subjects exceeded 700 h.

Direct mechanical measurements of BM responses are not possible in humans, resulting in the need for indirect measurement paradigms if insights into cochlear processes are to be obtained. In the present context, DPOAE suppression growth was used to provide those indirect assessments. In some ways, the results we observed are consistent with previous findings in other animals. For example, suppression threshold increased as the amount of hearing loss increased (see Fig. 3). This expected result is due to the fact that as the threshold of a subject increased, L_2 had to be increased in order to elicit a DPOAE in the unsuppressed control conditions, and L_3 had to be increased accordingly for suppression to occur.

As a result of the methods that must be used in humans, evidence of compression must be inferred indirectly. Whereas response growth for a given place along the basilar membrane is compressive for BF tones, it is not possible to observe compression with on-frequency stimuli in indirect measures, such as growth of masking or growth of suppression in humans. In these conditions, both the signal and the suppressor (or the masker in psychophysical studies) are processed through the same nonlinearity. Thus, changes in signal level are accompanied by similar changes in suppressor level, even when the responses to both signal and suppressor are nonlinear. Under these conditions, suppression grows linearly, as seen in Figs. 3–6. Suppression growth for conditions in which $f_3 \approx f_2$ will be linear when hearing loss exists, regardless of the extent to which the compressive nonlinearity is affected, for the same reasons that the growth is linear in NH subjects. Both signal and suppressor are being processed similarly, thus resulting in a linear growth pattern.

The dependence of the slope of the suppression-growth functions on the relation between f_3 and f_2 was observed for all f_2 frequencies, L_2 levels, and subject groups (Figs. 4 and 5). That is, suppression grew rapidly for suppressor frequencies lower than f_2 , nearly linearly for suppressor frequencies close to f_2 , and grew slowly for suppressor frequencies above f_2 . These observations are consistent with previous (excitatory) rate-versus-level functions and estimates of suppression growth from other animals (e.g., Evans, 1974; Sachs and Abbas, 1974; Delgutte, 1990) and, for the most part, with previous DPOAE suppression data from humans (e.g., Abdala and Fitzgerald, 2003; Abdala and Chatterjee, 2003; Kummer *et al.*, 1995; Gorga *et al.*, 2002, 2008).

In some cases, the slope for f_3 frequencies below f_2 decreased when hearing loss existed (for example, Fig. 5, $f_2 = 2$ kHz), which is similar to the psychophysical results reported by Stelmachowicz *et al.* (1987) and the DPOAE suppression data of Porter *et al.* (2006). This result is explained by the reduced compressive nonlinearity in HI ears, causing the response to grow at similar rates when f_3 was less than f_2 and when f_3 approximates f_2 . However, in most cases, this did not occur and for some conditions, the slopes for low-frequency suppressors were steeper than normal in the data from HI subjects (for example, Fig. 4, $f_2 = 4$ kHz $L_2 = 10$ dB SL). Few statistically significant differences were revealed in the present data, and sometimes they occurred in opposite directions. Thus, systematic changes in slope of the decrement functions for low-frequency suppressors were not observed.

More obvious differences between the results from NH and HI subjects were observed when suppression threshold was plotted as a function of L_2 (Fig. 6). Plotted in this form, suppression growth may be more easily compared to psychophysical growth of masking than the decrement functions where L_2 was fixed. In plots of suppression threshold as a function of L_2 , significant differences were observed in the data from NH and HI subjects, with the differences most pronounced when suppression threshold was plotted as a function of L_2 when L_2 was specified in dB SL, and when $f_3 \approx f_2$. Smaller differences were observed when L_2 was specified in dB SPL. These data indicate that NH and HI subjects behaved similarly at equivalent SPLs (assuming that the stimulus was of a sufficient magnitude to elicit a response from HI subjects), but behaved differently when stimuli were presented at equivalent levels relative to behavioral thresholds. Although Oxenham and Plack (1997) reported results only when signal levels were presented at equivalent SPLs, a similar pattern would have been observed had they also plotted their data at equivalent SLs for conditions in which probe and masker frequencies were equal.

The results for conditions in which $f_3 = f_2 - 1$ octave, shown in Fig. 6, are not consistent with expectations based on psychophysical masking studies (e.g., Oxenham and Plack, 1997; Murnane and Turner, 1991; Nelson and Schroder, 1997). The slope for the low-frequency masker was more linear in the psychophysical studies of growth of masking when hearing loss existed, compared to similar stimulus conditions in NH subjects. In contrast, the slope of the functions relating DPOAE suppression threshold to L_2 in

the present study were shallow for both NH and HI subjects. Assuming that the response near the f_2 place when stimulated with an on-frequency stimulus is more linear (less compressive) when hearing loss exists, then the expectation is that the slope relating suppression threshold to L_2 would be more linear when $f_3 = f_2 - 1$ octave, which was the observation in psychophysical masking studies (Murnane and Turner, 1991; Nelson and Schroder, 1997; Stelmachowicz *et al.*, 1987; Oxenham and Plack, 1997). Clearly, this was not the case in the present set of data. There are several differences between the present experiment and the paradigm used to collect some of the psychophysical data. First, by necessity, the DPOAE suppression data were collected with the suppressor and the signal presented at the same time, whereas much of the psychophysical data were collected in a forward-masking paradigm. Differences also existed in the numbers of subjects and the degree of hearing loss for the HI subjects. For example, Oxenham and Plack (1997) reported data from 3 subjects with hearing loss, whereas 65 HI subjects participated in the present study. Perhaps more importantly, the subjects in the present study had thresholds no worse than 45 dB HL at any signal (f_2) frequency. Audiometric thresholds were not reported at the test frequency (6 kHz) in the Oxenham and Plack paper; however, the audiometric thresholds at frequencies adjacent to the probe frequency would suggest that their subjects had greater hearing loss than all of the subjects who participated in the present study. In the present study, the magnitude of the response was reduced by 3 dB, in contrast to the psychophysical experiments, in which the masker level is adjusted until the signal is no longer audible. Thus, the present paradigm might be more akin to partial masking, whereas typical psychophysical measurements are based on complete masking of the signal. That said, it is not obvious how the above factors might have influenced the differences between the present DPOAE suppression data and the previous psychophysical masking data. Further data are needed to reconcile the two sets of data.

These issues notwithstanding, the only clear difference between the data from NH and HI subjects was the impact of how signal level was specified in plots of growth of suppression that are comparable to growth of masking. Whereas large differences between NH and HI subjects were observed for the on-frequency condition when the probe was set in dB SL, those differences were reduced or absent when data were described for conditions in which the probe was specified in dB SPL. These findings highlight the fact that cochlear processing is level dependent in NH subjects, and that this level dependence potentially dominates some of the effects that are observed in subjects with mild-to-moderate hearing loss. In turn, this suggests that the observation of differences between normal and impaired ears may be more a result of level effects in cochlear processing and less due to changes as a consequence of hearing loss, at least for subjects with mild-to-moderate losses. While HI subjects, by definition, do not hear the same low-level sounds as NH subjects, the observation that they may process sound in a similar manner compared to NH subjects once level is taken into account might be consistent with the notion that there may

be value in attempts to normalize level effects (such as restoring normal loudness perceptions).

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