Influence of interference tones on $2f_1 - f_2$ acoustic distortion products

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1 Introduction

The generation of distortion products by the cochlea involves nonlinear mechanisms that are linked strongly with preneural stages of cochlear transduction. There is evidence that the measurement of acoustic distortion can reveal objective information about cochlear frequency selectivity and filtering (Allen and Fahey, 1992; Allen and Fahey, 1993; Brown and Gaskill, 1990; Brown, Gaskill, Carlyon, Williams, and Butt, 1992). We have used external tones to influence the generation of the $2f_1 - f_2$ distortion product otoacoustic emission (DPOAE) in human subjects to characterize these cochlear mechanisms further. Two types of investigations were conducted. In the first, the amplitude of DPOAEs was measured while a third tone at a frequency below $f_2$ was progressively increased in level. The purpose was to determine the rate of suppression of DPOAE generation at the specific cochlear frequency-place sites of 1, 2 and 4 kHz. In a second series, a continuous tone was introduced at a fixed frequency and level and DPOAEs were generated across various frequency and level conditions during its presence. This paradigm was intended to identify the envelope of the cochlear frequency-place region that was perturbed by the steady-state tone.

2 Methods

Both investigations were conducted using an ER10A probe system (Etymotic Research) that was modified for delivery of three separate signals. Digitally generated pure-tones at $f_1$, $f_2$, and $f_3$ were transduced separately by ER2 earphones. For stimulation of target $2f_1 - f_2$ DPOAEs (note: "DPOAE" will refer to $2f_1 - f_2$ throughout the remainder of this article unless indicated otherwise), $f_1$ and $f_2$ were in a frequency separation ratio of 1.22:1. In the first investigation, DPOAEs were measured during the presence of a third tone ($f_3$) at either 1, 2, or 4 kHz. Stimulus frequencies for $f_1$ and $f_2$ for each condition, respectively, were: 905, 1105; 1811, 2209; 3622, 4418. Stimulus levels were 70 dB SPL for $L_1$, and $L_2$ was individually determined to produce the optimal level of $2f_1 - f_2$ for each ear and stimulus condition ($L_2$ levels ranged from 70 to 84 dB SPL). In the second investigation, DPOAEs were generated by stimuli in approximately 0.1-octave steps over a frequency range from $f_2=880$ Hz to $f_2=8800$ Hz.
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Figure 1: Rate of suppression of DPOAEs by pure-tones at either 1, 2 or 4 kHz. Frequencies used to stimulate each DPOAE are given in the methods section. Results for 2 and 4 kHz have been shifted to the right by 10 and 20 dB, respectively.

while an interference tone (IT) at either 1, 2 or 4 kHz was present continuously. Levels of each tone were: $L_1=70$ or 55 dB SPL, $L_2 = L_1$, $L_1 - 6$ or $L_1 - 12$ dB SPL and $L_2$ (IT) either 70 or 55 dB SPL, depending upon the $L_1$ condition. Baseline measurements of DPOAE amplitudes were taken for each level condition both before and after the introduction of each interference tone. Levels of DPOAEs measured during presentation of $f_2$ were then compared with the levels for the stimulus condition without the IT. Subjects for both investigations were young adults with normal hearing. Fourteen subjects participated in the first investigation, and there were 15 subjects in the second. Results from one ear of each subject were included in the data analyses.

3 Results

Results from both investigations confirmed that a tone of sufficient amplitude in the cochlear frequency-place region associated with the stimulus tones, $f_1$ and $f_2$, reduces the amplitude of DPOAEs.

In Fig. 1, the mean rate of the decrease in amplitude of three target DPOAEs as a function of increasing $L_2$ is illustrated (Note that the curves for 2 and 4 kHz have been shifted to the right by 10 and 20 dB, respectively, for better visualization). The mean slopes of these functions were approximately 2.5 (SD=.68), 2.0 (SD=.57) and 1.4 (SD=.57) dB/db for the 1, 2, and 4 kHz conditions, respectively. The differences in slopes were significant (repeated measures ANOVA, $p<.0001$). Distortion-product OAE amplitudes were suppressed by 3 dB for a mean level of the suppressor tones of 61 dB SPL and suppression to the level of the noise floor was evident for a mean level of 69 dB SPL, which is close to $L_1$ at 70 dB SPL and within approximately 5 dB of the mean.
Figure 2: Amplitudes of DPOAEs before and during presentation of an interference tone (IT) at 2 kHz for one ear. Stimuli for the DPOAEs were $L_1 = 70$ or 55 dB SPL and $L_2 = L_1$, $L_1 - 6$ or $L_1 - 12$ dB SPL. The interference tone was either 70 (leftmost panels) or 55 dB SPL (rightmost panels). The heavy solid line represents the baseline measurement (no interference tone), the circles represent DPOAE amplitudes during the interference tone and the lighter solid line is the noise floor level measured during the baseline condition. Vertical lines on each graph represent the frequency of the IT.

Results from the second investigation, in which DPOAEs were generated over a broad range of frequencies during presentation of an IT at fixed level and frequency, revealed that the generation of DPOAEs was affected only for stimuli within close proximity to the IT. The general characteristics of this effect are illustrated in Fig. 2 for results at 2 kHz for an individual ear. For both the $L_1 = 70$ and the $L_1 = 55$ dB SPL conditions, DPOAEs generated below approximately 1500 Hz and above 3000 Hz were not reduced from the baseline levels. As $L_2$ was decreased, more DPOAEs were reduced in level, the reductions were greater in magnitude, and the frequencies of maximal reduction shifted closer to the IT frequency. For the $L_1 = 55$ dB SPL conditions, baseline levels of the DPOAEs were lower than for $L_1 = 70$ dB SPL, and peak suppression frequency was closer to the IT and progressed towards frequencies below the IT as $L_2$ decreased. These trends are illustrated more clearly in the mean results in Figs. 3 and 4. In Fig. 3, the mean differences between the baseline responses...
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and those obtained during the presence of \( f_2 \) are plotted. Several trends are evident within and across \( L_1 \) conditions: (1) Maximum amplitude reductions occurred for DPOAEs generated predominantly above the IT and moved progressively towards the IT frequency as \( L_2 \) decreased. This was more obvious with \( L_1=70 \text{ dB SPL} \) than \( L_1=55 \text{ dB SPL} \); (2) The magnitude of the reductions increased as \( L_2 \) decreased and as frequency increased. This was also more obvious for the higher level stimulus conditions; (3) The range of influence was sharply limited, especially the high-frequency boundary; (4) The lower frequency cutoff of the effect moved progressively towards lower frequencies, but the higher frequency cutoff changed little as \( L_2 \) decreased in level. A notable difference with the 55 dB SPL stimuli was that maximum suppression was always

Figure 3: Mean differences between the baseline and IT conditions. Leftmost panels are results for higher levels of stimulation and panels on the right are for lower stimulus levels. The solid vertical line on each graph indicates the frequency region of the interference tone.

Figure 4: Octave 

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Figure 4: Octave span of DPOAE amplitude reductions above and below interference tones at either 2 or 4 kHz. Levels for interference tones and $L_1$ were 70 (upper panels) or 55 dB SPL (lower panels) and $L_2$ varied for each condition as listed to the left of the panels. Insufficient data were available for analysis of the $L_1 = L_2 = 55$ dB condition at 2 kHz.

at frequencies closer to the IT and shifted to frequencies below the IT for the lower stimulus levels of $L_1$. In Fig. 4, the span over which DPOAEs were reduced in amplitude is plotted as the mean distance in octaves from the IT to the high and low cutoff frequencies of the effect. Only the 2 and 4 kHz regions are considered, because it was not possible to determine a low-frequency cutoff point for most of the 1-kHz results. For both conditions of $L_1$, the span of the effect was greater for generation sites above than below the IT. As $L_2$ decreased, the overall span of the effect increased, especially during the first 6-dB reduction. The effect did not extend beyond .4 octave on the low-frequency side and .7 octave on the high frequency side of the IT.

4 Discussion

From the first investigation, it was determined that a tone just below $f_2$ at an average level of 69 dB SPL would reduce DPOAEs, produced at specific generation sites of 1, 2, and 4 kHz, to levels near the noise floor of the measuring system. This occurred with fixed stimulus levels of approximately 70 dB SPL for $L_1$ and $L_2$ within an individual ear. The follow-up investigation examined the extent over which such a tone, of fixed frequency at a level known to produce maximum suppression, would influence the generation of DPOAEs at surrounding frequencies. Results revealed that across all conditions, the effect of the third tone was confined to frequencies within less than
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an octave from its excitation region. Within this range, the distribution of reduced DPOAEs changed as \( L_2 \) was reduced in level. These results can be considered in terms of the cochlear excitation-place mechanism that is involved in suppression.

In a typical suppression tuning experiment, the amount by which a target frequency is reduced in level by an additional signal that is varied in frequency and level is measured. Our second investigation departed from this paradigm by measuring the influence of a tone of fixed level and frequency on the amplitudes of variable targets - in this case, \( 2f_1 \) – \( f_2 \) DPOAEs. Features of the results were qualitatively similar to findings typical of suppression, such as asymmetrical effects with level and frequency of the stimulus tones and confinement of amplitude reductions of the targets to regions near the suppressor. If the suppressive effects of the IT are considered in relation to cochlear mechanical displacement, then this paradigm can be viewed as simply "mapping" the excitation region of the IT.

The envelopes of the amplitude reductions that were observed were within less than an octave boundary around the IT. The distribution of these effects above and below the IT varied with \( L_2 \) within a frequency-level condition and differed for the overall 70 and 55 dB SPL paradigms. For higher levels of stimulation, peak suppression regions occurred for DPOAEs generated by frequencies that were between the IT and the high-frequency cutoff point. This corresponds to a basal distribution of DPOAE generation sites within the cochlea. The distribution moved closer to the IT place, expanded to include more frequencies below the IT and DPOAEs were reduced more in amplitude as \( L_2 \) was decreased. These results are compatible with general cochlear models that explain suppression in terms of saturation of activity sites distributed along the basilar membrane at and below the displacement maximum and that place the dominant region of the cochlear “amplifier” at a site basal to the characteristic frequency place of a stimulus tone (e.g., Brass and Kemp, 1993; Duijnhuis, 1976; Geisler, Yates, Patuzzi, and Johnstone, 1990). Based on these models, it would be expected that as \( L_2 \) was reduced, more DPOAEs would be affected or would be further reduced in amplitude because of increased saturation of the \( f_2 \) sites basal (and finally somewhat apical) to the frequency place of the IT. Additionally, there would be less influence of \( f_2 \) suppression on both \( f_1 \) and \( f_2 \). For the 55 dB SPL condition, the overall reduction in the displacement pattern of the IT would diminish the extent of its effect and the primary influence would occur near the region of maximum basilar membrane displacement. Schematic diagrams by both Kemp, Brass and Souter (Fig. 9, 1990), Brass and Kemp (Fig. 1, 1993) and Geisler et al. (Fig. 11, 1990) adequately describe the interpretation of our results.

The effects observed with reductions in \( L_2 \) - larger decreases of DPOAE amplitudes, more frequencies maximally suppressed at the “tip” regions of the IT and extension of the effect into lower frequencies illustrate the strong dependency of DPOAE generation on the \( f_2 \) cochlear-excitation place. This is a well-known property of DPOAEs (for review see Probst, 1990). The \( f_2 \) tone as suppressor exerted increasingly stronger influence as \( L_2 \) was decreased in level by 6 and then 12 dB and \( L_1 \) remained unchanged. This implies that the DPOAE generators, which are highly

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dependent on \( f_2 \), were becoming progressively more suppressed by the high-level IT as \( L_2 \) was reduced.

Our results were limited to measurements of the amplitude of \( 2f_1 - f_2 \) DPOAEs and relatively high levels were used for the interference tones. It was apparent throughout the measurements that the interactions of multiple stimuli and their byproducts created a very complex pattern for interpretation. Brass and Kemp (1993) have pointed out that DPOAE suppression experiments are not an ideal method for evaluating “pure” mechanical-suppressive effects because the paradigm includes excitation and suppression by all tones, multiple DPOAE generation and the inclusion of the stimulus-frequency otoacoustic mechanism in the final outcome. Our results must be evaluated within these limitations. Nevertheless, our findings support that cochlear mechanical properties can be evaluated using methods that exploit the OAE mechanism.

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References


