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# Distortion-Product Otoacoustic Emission Input/Output Functions as a Function of Frequency in Human Adults

Robert E. Lasky*
Ellen Snodgrass*
Kurt Hecox*

**Abstract**

Two issues concerning distortion-product otoacoustic emission (DPE) input/output functions were addressed in the present study. The first was to characterize those functions from threshold to 65 dB SPL. The second concerned the extent to which DPE input/output functions vary as a function of frequency. DPE input/output functions were generated at 20 frequencies from 537 to 10,009 Hz from eight normal-hearing subjects. Replicate functions were generated within an experimental session and with more than 4 months separating sessions. Given the impressive reproducibility of the DPE measurements, the input/output functions recorded can be interpreted as the consequences of stable physiologic processes and not unimportant variability (measurement noise). These input in dB/output in dB functions were generally linear functions with slopes less than unity indicating compression of the DPE output as a function intensity of the input. The slopes of the DPE input/output functions increased as a function of frequency to approaching one at the highest frequencies tested. DPE magnitudes tended to be more similar across frequencies at high intensities. At the lower intensities, DPE magnitudes varied as a function of input frequency, explaining the difference in slope of the input/output functions. There were a small number of markedly nonmonotonic, nonlinear functions. The functions presented included a greater number of intensities and frequencies and were less susceptible to explanations implicating the variability of the measurements than previous studies. The results, however, were quite consistent with those studies.

**Key Words:** Between-session reproducibility, distortion-product otoacoustic emissions (DPE), input/output functions, within-session reproducibility

Davis (1983) has proposed two functional systems to characterize the mammalian cochlea. One of these systems is hypothesized to be metabolically active, involving mechanical feedback from outer hair cells (OHCs) enhancing local basilar membrane movement. This "cochlear amplifier" improves low-level sensitivity and tuning (Gold, 1948; Zwicker, 1979, 1983; Neely and Kim, 1983, 1986; Strube, 1985; Mountain, 1986). This active system is physiologically vulnerable to traumas such as asphyxia, aminoglycoside poisoning, aspirin, excessive noise exposure, and death. It also has a limited dynamic range, saturating at high stimulus intensity levels. The second system is relatively resistant to traumas affecting the active system, leading to the hypothesis that it is associated with the passive, macromechanical properties of the cochlea. Thus, postmortem preparations, preparations with OHC pathology, and high stimulus levels reflect activity of the second system.

Otoacoustic emissions (OAEs) are sounds emanating from the cochlea recorded in the external ear canal (Gold, 1948; Kemp, 1978). OAEs may be generated spontaneously or in response to acoustic stimulation. Intermodulation OAE distortion products are recorded in the ear canal in response to two-tone stimula-

*Department of Neurology, The University of Wisconsin-Madison Medical School, Madison, Wisconsin

Reprint requests: Robert Lasky, Department of Neurology, The University of Wisconsin-Madison Medical School, H6 - 573 Clinical Science Building, 600 Highland Avenue, Madison, WI 53792

tion. The cubic distortion product, $2f_1-f_2$ (DPE), is generally the most prominent of these distortion products and the most frequently investigated. Basilar membrane movement associated with the cubic distortion product has been directly measured using laser velocimetry (Nuttall et al, 1990; Robles et al, 1990). The cubic distortion product is hypothesized to be generated on the basilar membrane at the frequency region of the primary stimuli and propagate apically peaking at $2f_1-f_2$ (Kim et al, 1980). Suppression studies (Brown and Kemp, 1984; Martin et al, 1987) support the interpretation that the location of the primaries are the generators of the DPE. DPEs are vulnerable to the same types of insults that damage the OHCs.

DPEs have been proposed as noninvasive measures of basilar membrane movement of both the active and passive cochlear systems and of cochlear function in general (Zurek et al, 1982; Brown and Kemp, 1984; Homer et al, 1985; Brown, 1987; Lonsbury-Martin et al, 1987; Gaskill and Brown, 1990; Norton and Rubel, 1990). Input/output functions are critical to understanding the functioning of these two cochlear systems and, in particular, the active system associated with heightened sensitivity. At low to moderate intensity levels, the active cochlear system is hypothesized to affect the response of the system. At high intensity levels, the passive cochlear system is dominant. A nonmonotonicity, or notch, in the input/output function at the transition between these two systems can be explained by phase cancellation between the responses from the generators of the active and the passive systems (Wiederhold et al, 1986; Brown, 1987).

Gaskill and Brown (1990) reported that half of the human adult DPE input/output functions they recorded saturated at 60–65 dB SPL. Lonsbury-Martin et al (1990) reported saturation of human DPE input/output function at intensities above 75 dB SPL for DPEs whose primaries were above 3.5 kHz. Harris and Probst (1990) reported that linear functions best described input in dB/output in dB functions for human adults in conditions in which the intensities of the primaries were equivalent and between 25 and 65 dB SPL. This effect was more striking when the geometric mean of the primaries was at 4 kHz than at 1 or 2 kHz. With one exception, the 30–40 percent of the functions that were nonlinear at the lower frequencies did not saturate. Lasky et al (1992) reported that linear functions characterized (i.e., explained more than 90% of the variability) two thirds of the input in dB/output in dB functions of the human adults and newborns tested. No single nonlinear function characterized the remaining third of the input in dB/output in dB functions consistently.

The slopes of the input in dB/output in dB functions below 65 dB SPL seem to be less than unity indicating compression of the DPE as a function of increasing level of the primaries. Gaskill and Brown (1990) reported a mean slope of .91 (SD = .09) between 30 and 70 dB SPL. Harris and Probst's (1990) slopes ranged from .66 to .95 for 25 to 65 dB SPL input. These slopes increased with increasing frequency. The slopes of Lonsbury-Martin et al's (1990) functions between 55 and 65 dB SPL approached unity with increasing frequency. Lasky et al's (1992) slopes of adult DPE input in dB/output in dB functions between threshold and 65 dB SPL varied from .25 to .84, increasing with frequency.

Although there is some consistency in the human data concerning DPE input/output functions, significant details remain to be determined given the importance of these functions in modeling cochlear function. Two issues seem particularly relevant. The first is to characterize these functions. Below 65 dB SPL, compression functions seem to predominate, although virtually all studies report unusual nonlinearities (Harris and Probst, 1990; Lonsbury-Martin et al, 1990; Zwicker and Harris, 1990; Lasky et al, 1992). Harris and Probst (1990) attribute these nonlinearities to the fact that "...two tones are interacting not only with each other in both the forward and reverse directions, but also with multiple combination tones generated within the cochlea coincident with two-tone stimulation" (p. 183). A second issue concerns the extent to which DPE input/output functions vary as a function of frequency. With some exceptions (Whitehead et al, 1990), DPE input/output functions are reported to increase in slope with frequency. That is, the compression functions characteristic at low and moderate frequencies become more linear at high frequencies. These results, however, are based on data limited to a small number of frequencies and/or intensities.

The major obstacle to providing details of human adult DPE input/output functions concerns limitations on interpretation due to measurement errors. One measurement concern is that a sufficient variety of stimuli have been presented to adequately describe cochlear function. Thus, the full dynamic range of the system of interest should be presented. For the active cochlear system, stimulus intensities should extend from threshold to 60–65 dB SPL. Furthermore, this dynamic range must be sampled adequately to capture nonlinearities in the input/output functions, if they exist. Step sizes greater than 5 dB would seem to be too large until more is known about these functions. In this study, we attempted to characterize human adult input/output functions in 5-dB steps across a wide range of frequencies.

Another measurement concern is response reproducibility, which is critical for an adequate description of these functions. Until the reproducibility of the DPEs measures are determined, it is unclear whether observed nonlinearities characterize the input/output functions or reflect measurement error. Gaskill and Brown (1990) have presented data for one subject demonstrating impressive response reproducibility over a 9-month interval. Keeping frequency constant, the largest variability in DPE amplitude over time was 5 dB. DPE reproducibility, however, was only investigated at one intensity. Gaskill and Brown (1990) also determined the effect of probe replacement and different probes on DPEs. Reproducible measurements were made in the presence of these manipulations. Lasky et al (1992) also reported impressive within- and between-session reproducibility for a small number of subjects.

In this study, we investigated and adjusted for two different sources of measurement error in an effort to characterize DPE input/output functions as accurately as possible. One source of measurement error was noise, both transient noises and system noise. The second source of measurement error concerned the stability of the measurements over time. We attempted to account for both of these sources of error in the interpretation of our data.

## METHOD

### Subjects

Ten normal-hearing adults participated in the first data collection session; 8 of the 10 subjects returned approximately 4 months later for the second data collection session. The two sessions were identical in terms of the stimuli presented and the responses recorded. Data will be presented for the 8 subjects who attended both sessions.

Subjects were included in the study if their behavioral hearing thresholds were ≤ 20 dB HL for the octave frequencies from 250 to 8 kHz. The subjects ranged in age from 20 to 36 years of age (mean = 25.9 years, SD = 6.0 years). Six of the subjects were females. Two were males.

The study was reviewed and approved by The University of Wisconsin-Madison Medical School Internal Review Board. Informed consent was obtained from each subject prior to testing.

### Apparatus and Stimuli

The instrumentation used to collect the DPEs consisted of a probe unit housing two Etymotic ER-2 insert earphones and an Etymotic ER-10B ear canal microphone, an amplifier providing 40 dB of gain to the sound recorded in the ear canal, an Ariel DSP-16+ signal-processing board that generated the calibration stimuli, generated the primary stimulus frequencies $f_1$ and $f_2$ ($f_1 < f_2$), and digitized the sound recorded from the ear canal and an Intell 386 microprocessor-based computer. A software program written at AT&T Bell Labs by Jont Allen and his colleagues (CUBDISP™) controlled stimulus generation and response recording. In addition to other functions, the software calculated and plotted the frequency response from each of the two stimulus channels, the sound pressure level (in dB SPL) in the ear canal of the primaries, the DPEs ($2f_1–f_2$), and the noise in the vicinity of the DPEs (the mean of the three higher and the three lower Fourier transform frequency bins adjacent to the DPE).

### Procedure

Subjects were seated in a sound booth and instructed to relax and remain quiet throughout the recording session. The ER10-B probe unit was inserted into the ear canal and held in place by a Grayson-Stadler impedance probe tip. The probe was inserted in the canal, and the frequency response of each earphone in the canal was determined. The probe was repositioned until acceptable frequency responses in both channels were achieved.

The stimuli consisted of a pair of pure tones ($f_1$ and $f_2$), or primaries, presented simultaneously for 4 seconds. A total of 20 primary stimulus pairs were presented to each subject. The $f_2/f_1$ ratio was held constant at 1.2, while $f_2$ was varied in 20 steps from 537 through 10,009 Hz. The DPEs recorded to these 20 stimuli were labelled the DPE "audiogram." The DPE audiogram was generated two times at each intensity level to determine intrasession reproducibility.

After recording two DPE audiograms at 65 dB SPL, the intensity of the primaries was decreased in 5-dB steps until the DPEs were judged indistinguishable from the noise floor. Given the transfer function of the subject's ear canal and the output of the system, it was not always possible to present stimuli at all frequencies at the more intense levels.

### Data Analysis

The data was passed through two stages to eliminate DPEs that were likely to reflect noise. The first stage was to eliminate measurements made in the presence of noise transients as a consequence of subject movement or other causes unrelated to the stimuli. We eliminated noise transients by rank ordering the noise levels at each frequency associated with each DPE and identifying as noise transients noise levels that were 5 dB louder than the next softest noise level measured. A second stage was to eliminate DPEs that were not significantly greater in amplitude than the estimates of the noise. A total of 62 DPE audiograms were recorded from nine adults in a no stimulus condition (Lasky et al, 1992). We used the following criteria to define a "significant" DPE at each frequency:

1. The distributions of noises at each frequency were defined from all measurements in the intensity series (i.e., the replicates at 65, 55, 45 dB SPL, etc.) after eliminating measurements (the noise and the corresponding DPE) considered to be made in the presence of noise transients.
2. The observed SNRs were transformed to a z-score, which expressed how discrepant those SNRs were with the population of SNRs in the no stimulus condition.
3. The probability of observing the recorded z-scores was calculated. If the probability was less than .05 (one-tailed), a "significant" DPE was defined.

## RESULTS

The results will be presented in three sections. The first section considers within-session reproducibility; the second section considers between-session reproducibility; the third section presents the input/output functions recorded after considering the within- and between-session reproducibility. Specifically, the measurements analyzed had demonstrable within- and between-session reliability.

### Within-Session Reproducibility

Within-session reproducibility was evaluated in two different ways. Replicate DPEs were recorded to each intensity at each frequency. Some of the replicates had been eliminated from further analysis since they were recorded in the presence of high, transient noises or because they did not significantly differ from the noise floor. The absolute difference in dB SPL between replicates was calculated. Absolute difference scores can be misleading, since they ignore consistent differences in magnitude between replicates. Consequently, we calculated repeated measures analyses of variance to determine whether DPE magnitudes of the first replicate at any intensity or frequency were consistently larger or smaller than the DPE magnitudes of the second replicate. There were no significant replicate effects. Thus, the absolute difference scores are a direct measure of what we wanted to measure, the difference between the magnitudes of two DPE measurements separated in time but made within the same recording session.

Plotted in Figure 1 are the mean absolute differences (±1 SD) for all of the subjects as a function of intensity and frequency of the primaries for session one. Mean values were only plotted if six or more subjects had data at the intensity-frequency combination in question. Similar results were observed for the second session but will not be presented. Within-session reproducibility was high; on the average, the difference between replicate measurements was between 2 and 4 dB for both sessions one and two. Within-session reproducibility decreased with increasing frequency and decreasing intensity.

A second way of evaluating within-session reproducibility involved characterizing the input/output functions separately for the first and second replicates at each frequency for each subject. We required a minimum of three intensity values to evaluate these functions. In order to make these comparisons valid, the replicate input/output functions had to cover the same range of intensity values. For example, data

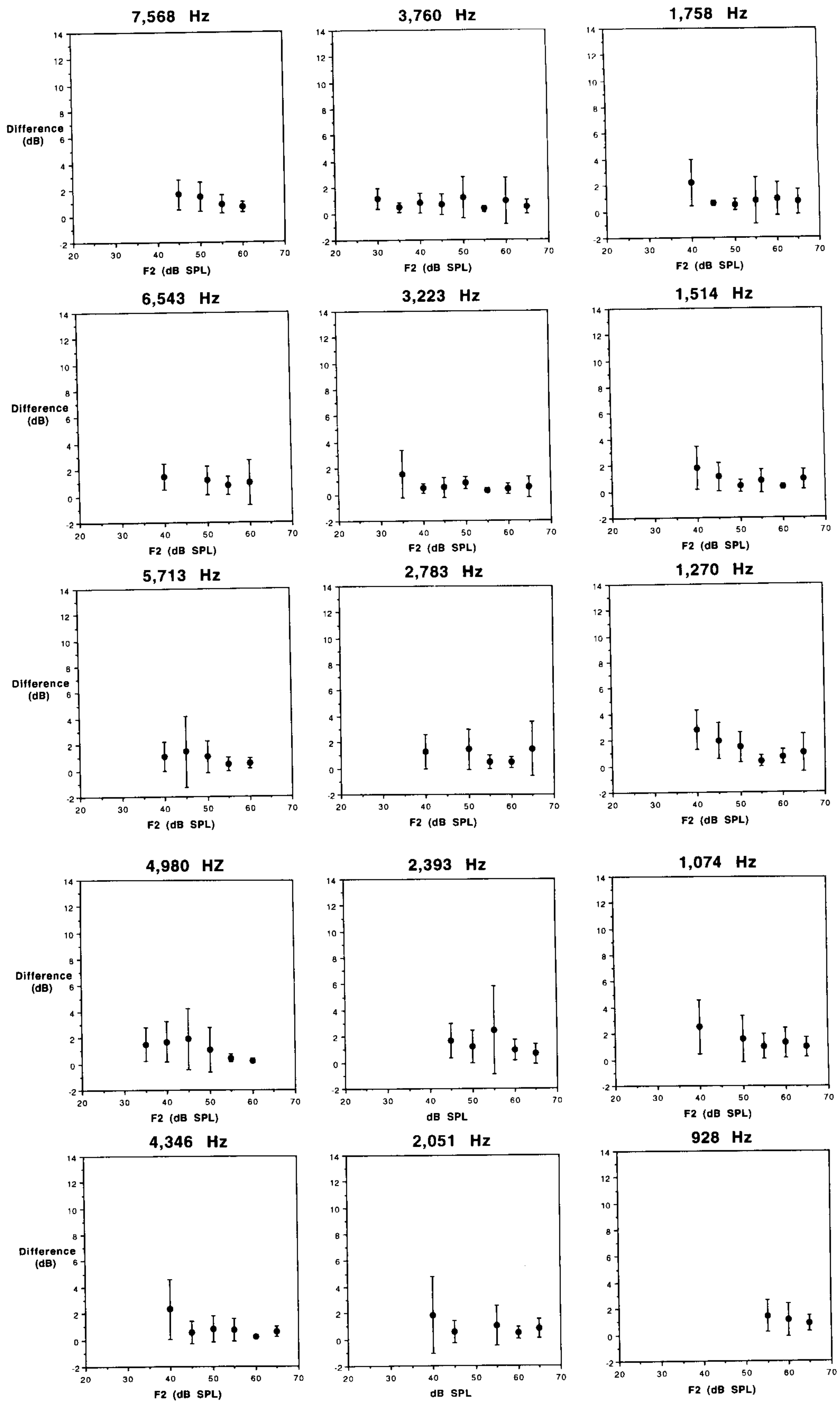


**Figure 1** Mean absolute differences between the magnitudes of the DPE replicates for session one as a function of frequency and intensity. The frequencies indicated are the $f_2$ frequencies. The error bars represent ±1 SD.

**Table 1 Comparison of the Degree of the Polynomial Fitting the Two Replicate Input/Output Functions in Session One**

| | Rep 2 | | | | |
|---|---|---|---|---|---|
| *Rep 1* | *Linear* | *2nd Order* | *3rd Order* | *4th Order* | *5th Order* |
| Linear | 62.70 | 5.6 | 1.59 | 0 | 0 |
| 2nd Order | 4.8 | 10.3 | 3.2 | 1.59 | 0 |
| 3rd Order | .79 | .79 | 2.38 | 0 | 0 |
| 4th Order | .79 | 1.59 | 1.59 | 1.59 | 0 |
| 5th Order | .79 | 0 | 0 | 0 | 0 |

The percentage of agreement as to the order of the polynomials fitting the two replicate input/output functions.

values for one replicate function were eliminated if there were no low intensity data values at the same intensities for the other replicate input/output function.

A linear function was fit by the least squares method to these replicate input in dB/output in dB data. If this function explained at least 90 percent of the variability in the data, the linear function was assumed to adequately characterize the input in dB/output in dB function. If it did not explain 90 percent of the variability, successively higher order polynomials were fit to the data until 90 percent of the variability was explained. Replicate functions were compared for each frequency for every subject for both sessions.

Table 1 compared whether or not the degree of the polynomials fitting the two replicate input in dB/output in dB functions was the same for the first session summed across frequency. Table 2 presents the same information for the second session. The main result of this analysis was that the order of the functions was highly reproducible. Specifically, the order of 77.2 percent of the functions in both of the sessions was reproducible. As expected, the majority (79.0%) of the reproducible functions were linear for both sessions. Most of the reproducible nonlinear functions were quadratic (15.6%) by the above definition; however, with a few exceptions, the nonlinearities could be described quite well by linear functions. The few exceptions were largely recorded from two of the eight subjects.

There was a discrepancy between the order of the polynomials characterizing the replicate functions at the same frequency for 22.8 percent of the frequencies. Upon visual inspection, these analyses seemed to underestimate the similarity among the input/output functions and reflect the arbitrary criterion (explaining 90% of the variance) we used to categorize functions. The actual differences between these mismatched polynomials in all cases was small. Seventy-nine percent of all mismatches were between polynomials differing in order by one.

Mismatches varied as a function of frequency. There were more mismatches at lower frequencies: 44.8 percent of the functions with $f_2$s 1514 Hz or less were mismatched while only 16.7 percent of the functions were mismatched with $f_2$s higher than that frequency. Furthermore, the fewer the intensity values sampled, the more a mismatch was likely. Thus, 38.6 percent of the small number of input/output functions based on three or four intensities were mismatches. In contrast, 20.1 percent of the functions based on more than four intensities were mismatches.

**Table 2 Comparison of the Degree of the Polynomial Fitting the Two Replicate Input/Output Functions in Session Two**

| | Rep 2 | | | | |
|---|---|---|---|---|---|
| *Rep 1* | *Linear* | *2nd Order* | *3rd Order* | *4th Order* | *5th Order* |
| Linear | 55.28 | 4.07 | .82 | 0 | 0 |
| 2nd Order | 10.57 | 17.07 | .82 | 0 | 0 |
| 3rd Order | .82 | .82 | 2.44 | 1.62 | 0 |
| 4th Order | 0 | .63 | 1.59 | 1.59 | 0 |
| 5th Order | 0 | .82 | .82 | 0 | 0 |

The percentage of agreement as to the order of the polynomials fitting the two replicate input/output functions.

## Between-Session Reproducibility

The analyses conducted to determine the between-session reproducibility paralleled the within-session reproducibility analyses. We determined the reproducibility of a single DPE after an interval of more than 4 months. Our focus was a single DPE measurement, since that has greater clinical and research relevance than the average of the two replicates, which would be a more robust measurement. Operationally, we defined this reproducibility by taking the absolute differences between the first replicates of the first and second sessions. If the first replicates were missing due to excessive noise or a nonsignificant DPE, the second replicates were used in these calculations. Again, we calculated repeated measures between-session analyses of variance. There were no significant between-session effects.

Plotted in Figure 2 are the mean (±1 SD) absolute differences for all the subjects as a function of intensity and frequency of the primaries. Mean values were plotted only if six or more subjects had data at the intensity-frequency combination in question. The mean absolute differences ranged from 2 to 7 dB. In general, the mean absolute differences and the variances associated with those differences decreased with decreasing frequency of the primaries. Not surprisingly, the between-session absolute differences were larger than the within-session absolute differences by a factor of 2 to 6, depending on the frequency and intensity considered. The variances of the between-session absolute differences were much larger than the within-session absolute difference variances.

Between-session reproducibility was also analyzed from a different perspective. The lowest order polynomial explaining > 90 percent of the variability in the recorded values was calculated to characterize the two replicate input/output functions for sessions one and two separately. A mean replicate function was generated for sessions one and two. Of these functions, 83.2 percent were of the same order in both sessions, 68.1 percent were linear, 10.6 percent were quadratic, 3.5 percent were cubic, and 0.9 percent were quartic. Of the mismatches (in order of polynomial) between the session functions, the differences were small. Furthermore, 4.4 percent of these differences could be explained by different ranges of intensities explained by the two session functions being compared.

Although more variable than the within-session reproducibility results, between-session reproducibility was impressive.

## Input/Output Functions

In this section, we considered reproducible DPE input in dB/output in dB functions and the extent to which they varied as a function of frequency. Since both within- and between-session response reproducibility were so high, the input/output functions presented were not greatly distorted by these sources of measurement error. A single input/output function was generated from the two matched reproducible session functions by averaging their parametric values.

Figure 3 presents these functions by frequency for all subjects. Again, these functions are generally linear. In addition to linear functions, nonlinear functions were recorded from some subjects at all frequencies except those (781, 635, and 537 Hz) with insufficient data. For the most part, the nonlinearities were subtle and could be explained by saturation of the DPE output. A very few functions, however, were strikingly nonlinear, even nonmonotonic (particularly at 5713 and 3760 Hz). Figure 4 presents two striking nonlinear functions in greater detail, presenting separately four input/output functions (the two replicates for each session) for each frequency. The reproducibility of these functions is apparent, indicating that random variation cannot explain these unusual functions.

In general, DPE magnitudes at the highest intensities presented were fairly similar across the frequencies sampled. The fall-off in DPE amplitude at the lowest intensities presented, however, was more dramatic at the higher frequencies sampled. This observation was quantified by the change in intercepts and slopes of the input/output functions. The few nonlinear functions were "made" linear for this analysis in order to calculate a linear function. Again, this simplification was not as drastic as it seems, since in all but a few instances linear functions described quite well the recorded nonlinear (by our definition) functions. Separate 12 (frequency) one-way repeated measures analyses of variance on the intercepts and slopes of these functions were computed for all frequencies characterized by complete data. The other frequencies were not included, since there were too many missing data at these frequen-

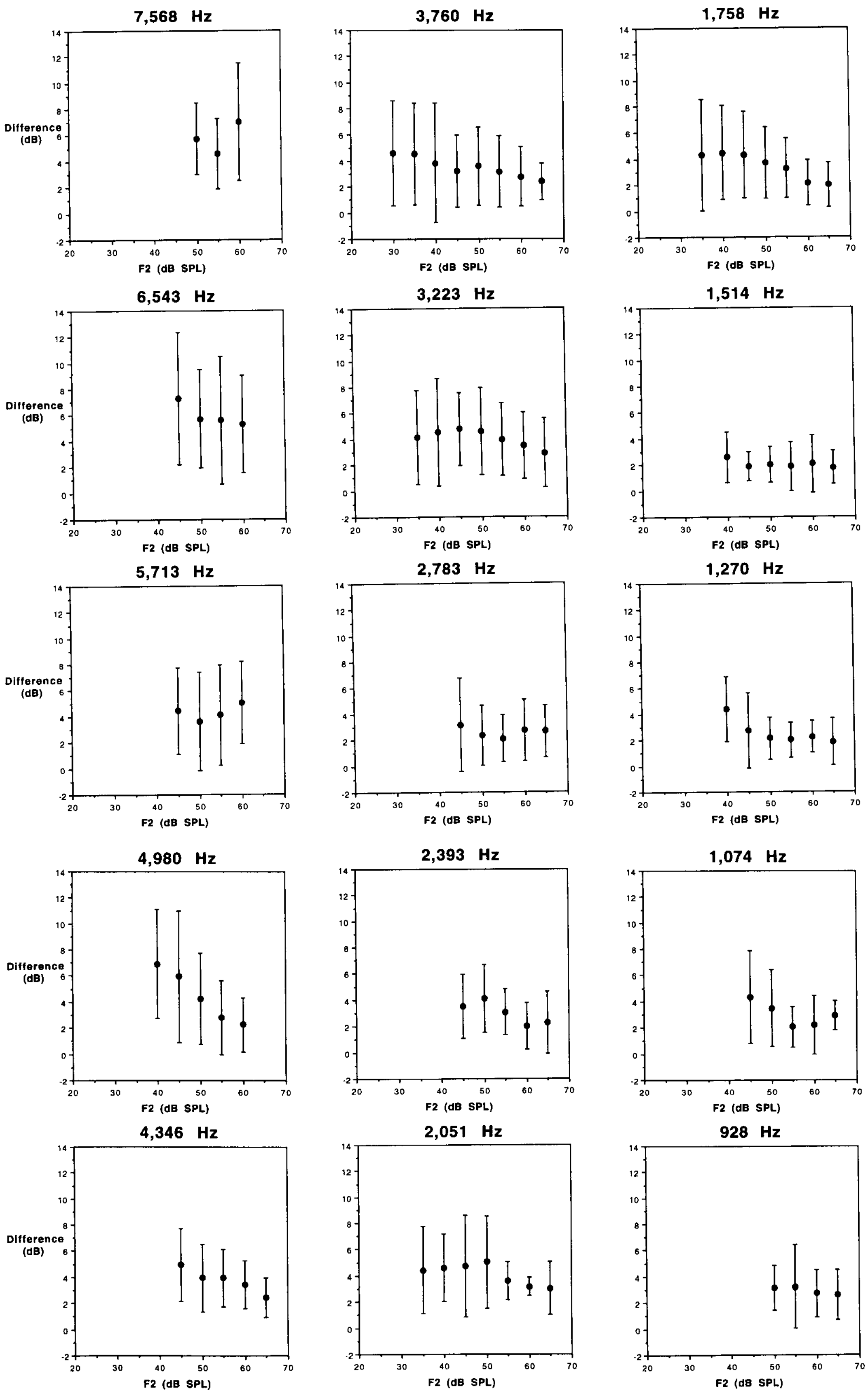


**Figure 2** Mean absolute differences between the magnitudes of the DPE measurements for sessions one and two as a function of frequency and intensity. The frequencies indicated are the $f_2$ frequencies. The error bars represent ±1 SD.

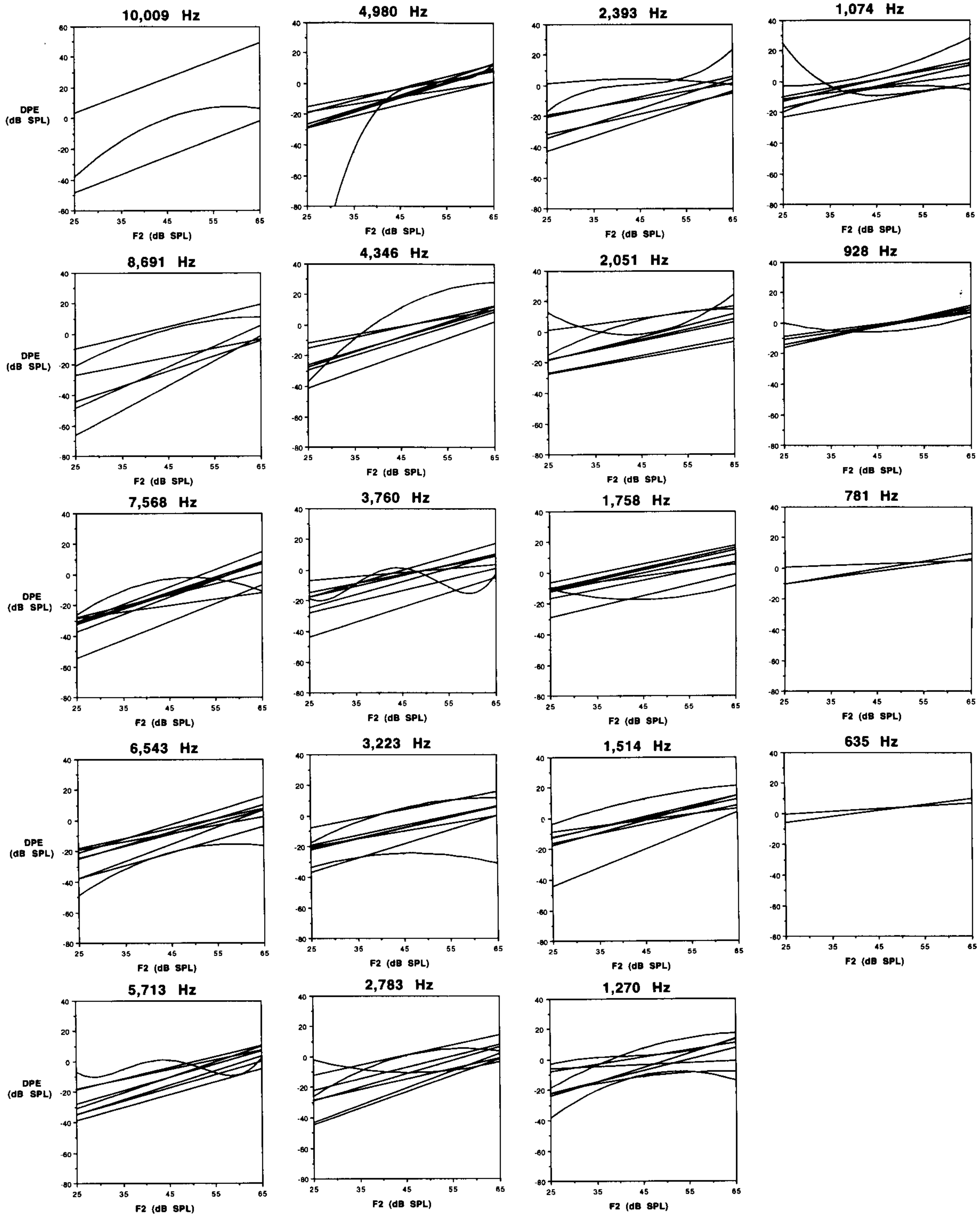


**Figure 3** Input/output functions for all subjects at all frequencies for which there were sufficient data. The frequencies indicated are the $f_2$ frequencies.

cies to be interpretable. Figure 5 presents mean (SD) intercepts and slopes of these linear functions. This figure emphasizes the significant frequency main effect for the intercepts ($F[11,77] = 3.33$; $p < .001$) and the slopes ($F[11,77] = 2.18$; $p < .024$). In particular, the slopes of these functions became steeper with increasing frequency. Linear functions adequately characterized the group intercept × frequency and slope × frequency functions over the range analyzed.

## DISCUSSION

One requisite for useful measurements of auditory function is the reproducibility of

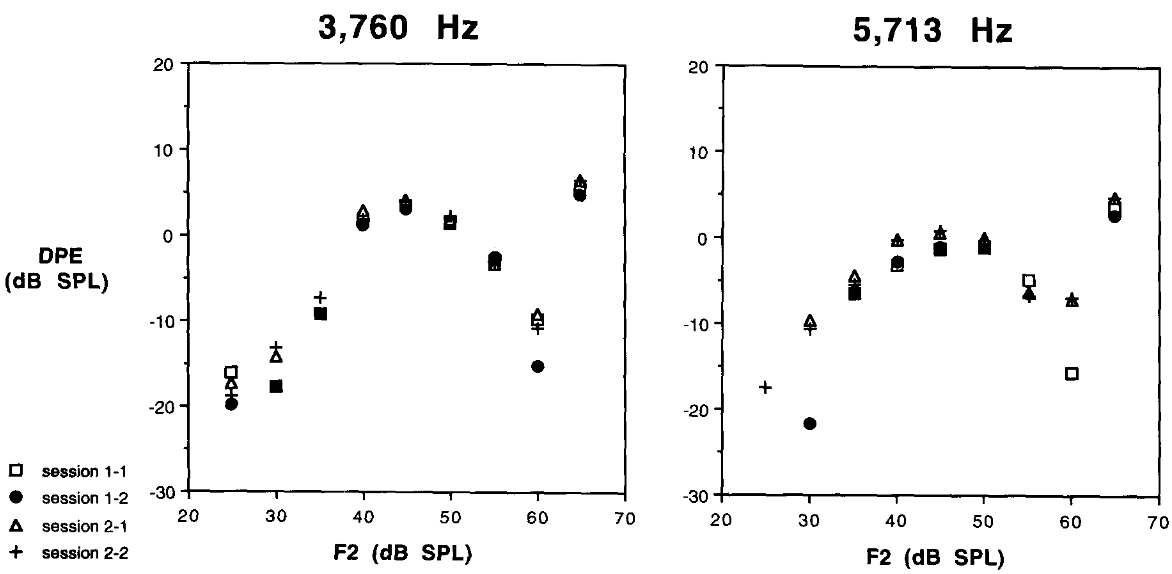


**Figure 4** Examples of two nonlinear functions recorded from the same subject. The frequencies indicated are the $f_2$ frequencies.

those measurements. In normal-hearing adults, DPEs meet that criterion of utility. Whether, however, DPEs are related to significant auditory functioning is a matter not directly addressed by this study.

The reproducibility of DPE measurements within the same recording session is impressive. This reproducibility does deteriorate at high stimulus frequencies and as the intensity of the stimulus is reduced. Nevertheless, single DPE measurements suffice for most applications as long as the background noise is kept under definable limits and only DPEs clearly above the noise (i.e., suprathreshold measurements) are considered. The reproducibility of measurements is especially critical for clinical applications where testing time is an important concern.

The reproducibility of measurements over intervals of several months (between session) was also impressive. This reproducibility is another important requisite for useful auditory measurements, indicating that the auditory functions measured remain stable. If, instead,

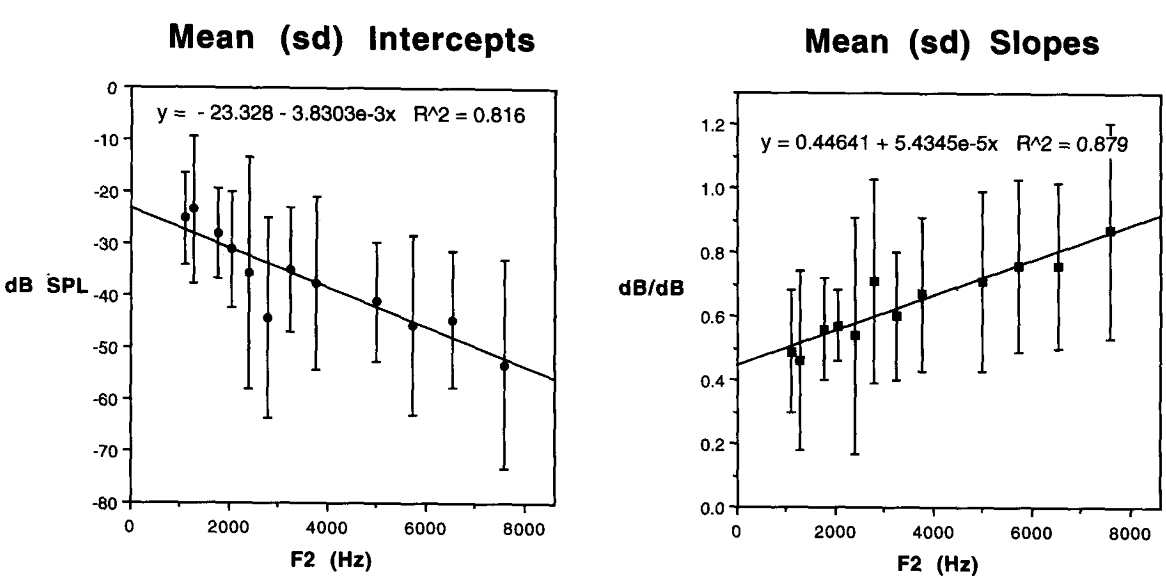


**Figure 5** Mean intercepts and slopes of the linear input/output functions as a function of $f_2$ frequency. The error bars represent ±1 SD.

these measurements demonstrated short-term reproducibility (i.e., within session) but not long-term reproducibility, they would reflect factors not considered to be indicators of important auditory function (assuming no important changes in auditory function in these normal subjects over the time intervals assessed). Again, long-term reproducibility deteriorated somewhat at the higher frequencies and low intensities. This long-term reproducibility is a critical requisite for many applications, such as clinical diagnosis and screening.

Given the impressive reproducibility of the DPE measurements, the input/output functions recorded can be interpreted as the consequences of stable physiologic or physical processes and not unimportant variability (measurement noise). Over the frequency and intensity ranges assessed, these input in dB/output in dB functions were generally linear functions with slopes less than one. There were, however, a small number of nonlinear functions that differed markedly from linear functions. Some of these functions were not only nonlinear but also nonmonotonic, alternatively decreasing and increasing in DPE magnitude as a function of increasing stimulus intensity. This complex response could reflect complex auditory processing (i.e., transitioning from the active to passive systems hypothesized by Davis, 1983), and/or complexities of the recording environment (Wiederhold et al, 1986; Brown, 1987; Harris and Probst, 1990). The observed nonlinear functions were recorded predominantly from a few subjects; the input in dB/output in dB functions of the majority of subjects were consistently linear. What distinguishes the linear from nonlinear responders is unclear but does not seem to be obviously reflected in auditory functioning, since all of the subjects had "normal" hearing. Whether DPE input/output functions can be used as indicators of psychoacoustic input/output functions is an important topic for future research.

As a number of investigators have reported (Gaskill and Brown, 1990; Harris and Probst, 1990; Lonsbury-Martin et al, 1990; Lasky et al, 1992), DPE input in dB/output in dB functions are generally linear with slopes less than unity. That is, compression characterizes most DPE input/output functions, although those functions become more linear with increasing frequency. DPE magnitudes tend to become more similar across frequencies at the highest intensities we tested. At lower intensities, DPE magnitudes vary as a function of input frequency, explaining the differences in slopes of the input/output functions. If the nonlinear amplification of the cochlear amplifier is superimposed on the passive linear amplification of the basilar membrane (Davis, 1983; Johnstone et al, 1986, Fig. 5) and the observed compression in the DPE input/output functions is due to saturation of the cochlear amplifier, these results imply that the cochlear amplifier is saturating within the observed intensity range (threshold to 65 dB SPL) at the lower but not necessarily higher frequencies, or that the DPEs recorded at the higher frequencies reflect the activity of the passive system and not the activity of the cochlear amplifier. The latter alternative assumes that the passive system generates distortion products, although the growth of those distortions as a function of intensity is linear.

DPE input/output slopes of one or less at modest intensity levels generally agree (they are somewhat shallower) with the results of psychophysical studies of the input/output functions of the same distortion product (Zwicker, 1955; Goldstein, 1967; Helle, 1969; Hall, 1972; Smoorenburg, 1972; Plomp, 1976). Otoacoustic emission $2f_1\text{–}f_2$s cannot be explained by a simple nonlinearity (e.g., $y = ax + bx^2 + cx^3 + \ldots$) of the type proposed by Helmholtz (1856) for the same reasons Helmholtz's explanation cannot account for psychoacoustic $2f_1\text{–}f_2$s. First, the low levels at which otoacoustic emission $2f_1\text{–}f_2$s can be recorded are counter to the type of overloading nonlinearity Helmholtz postulated. Second, according to Helmholtz's nonlinearity (Plomp, 1976), the amplitude of otoacoustic emission $2f_1\text{–}f_2$s would increase as the third power of the amplitude of the primaries, which it does not. A detailed exploration of the correspondence between psychoacoustic $2f_1\text{–}f_2$s and otoacoustic emission $2f_1\text{–}f_2$s would be of interest to determine the extent to which they can be explained by the same mechanisms.

The functions presented included a greater number of intensities and frequencies and were less susceptible to explanations implicating the variability of the measurements than previous studies. The results, however, were quite consistent with those other studies. The consistency and stability of these input/output functions are encouraging for researchers and clinicians. The important work of relating these functions to physiologic processes remains.

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