

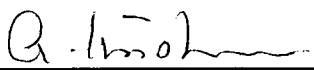
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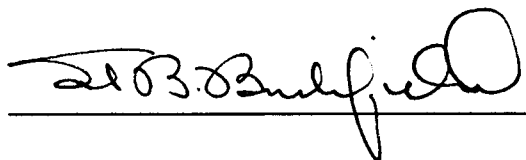
I am submitting herewith a thesis written by Ashely Whicker entitled "Growth of Distortion Product Otoacoustic Emissions: Dependence on Frequency Separation and Frequency." I have examined the final copy of this thesis for form and content and recommended that it be accepted in partial fulfillment of the requirements for the degree of Master of Arts, with a major in Audiology.



James W. Thelin, Ph.D., Major Professor

We have read this thesis and
recommend its acceptance:





Accepted for the Council:



Associate Vice Chancellor and
Dean of the Graduate School

**GROWTH OF DISTORTION PRODUCT OTOACOUSTIC
EMISSIONS:
DEPENDENCE ON FREQUENCY SEPARATION AND
FREQUENCY**

**A THESIS
PRESENTED FOR THE
MASTER OF ARTS DEGREE
THE UNIVERSITY OF TENNESSEE, KNOXVILLE**

**ASHLEY WHICKER
MAY, 1995**

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DEDICATION

This thesis is dedicated to the faculty, staff and students in the Audiology department at the University of Tennessee-Knoxville. Your support as teachers, clinicians and friends, and the genuine interest each of you expressed, turned a potentially lonely process into a truly enjoyable one. I couldn't have done it without ya'll!

ACKNOWLEDGEMENTS

Eternal thanks to my major professor, Dr. James Thelin, who went above and beyond the call of duty on a daily basis. Thank you for showing me every aspect of academia. If I can become as skilled a researcher, writer, professor and advisor as you, I will have fulfilled my ultimate goal as a professional .

To my thesis committee, thank you for guiding me through an invaluable learning experience. Dr. Ravi Krishnan, thanks for teaching me to think analytically and write efficiently. I hope to address every research project as practically and intelligently as you. To Dr. Samuel Burchfield, many thanks for your excellent skills of observation and your unfaltering ability to find good fortune in every misfortune. The person I have become has much to do with you.

Thanks to Mr. Robert Muenchen of the UT Computing Center, who took time out of his very busy schedule to explain every step of his statistical analysis until even I could understand.

To Mr. Jonathan Birck and the rest of the gang at Virtual Corporation, thank you for promptly answering my desperate pleas for help. No matter the problem I presented you, you always had a timely and practical solution. The data could not have been collected without the program you created for me.

To my subjects, Lisa Wynn, Catherine Vickers, Christy Bruggeman, Melynee Morgan, Alane Brewer, Lisa Spiroff, Audra Dulac and Michelle

White, I can not thank you enough for your time or your patience. All eight of you made data collection my favorite part of the research experience. A second round of thanks to Lisa Wynn who was an integral part of my support system and bore the brunt of my frustration without a single complaint.

A special thanks to my parents, Jim and Rebecca Whicker, who instilled in me the idea that hard work is the only synonym to success. Also to my sister and brother-in-law, Carmen and Thorne Gregory, who patiently listened to me drone on about data and statistics as if it was just as important to them as it was to me.

Last but not least, thanks to Will Weatherly. Thank you for never failing to bring me back when I needed a reality check and for also encouraging me to dream. Most importantly thank you for believing in me enough to give me the opportunity to fulfill those dreams.

ABSTRACT

The present study was conducted to determine the dependence of distortion product otoacoustic emissions (DPOAEs), specifically the $2f_1$ - f_2 distortion product (DP), on the frequency separation of the primary signals used to elicit the DPOAEs. DPOAEs were recorded in response to the experimental signals from nine human participants with normal auditory function in the test ear as determined by otoscopy, pure tone audiometry, tympanometry, ipsilateral acoustic-reflex thresholds and DPOAEs.

The signals used to elicit $2f_1$ - f_2 DP were tone pairs (the primary signals, f_1 and f_2). Both primary signals were fixed at a level of 65 dB SPL. The higher frequency primary signal, f_2 , was fixed at one of four frequencies (1000, 2000, 3000 and 4000 Hz). The lower frequency primary signal, f_1 , was varied across ten different frequency separations, for each of the four f_2 frequencies. For each experimental signal, a $2f_1$ - f_2 DP was measured in level (dB SPL). For each f_2 frequency, a DP growth function was obtained. The shapes and slopes of the DP growth functions were studied to determine if the rate of growth of $2f_1$ - f_2 DPOAEs depend upon the frequency region of the primary tones.

The results of the present study as well as those of Harris, Lonsbury-Martin, Stagner, Coats and Martin (1989) showed that the rate of growth of the $2f_1$ - f_2 DP depends on frequency separation and frequency. The onset of the DP growth functions was dependent on frequency, and the slopes of the DP growth functions increased systematically as a function of frequency. The increase in slope with frequency was the expected finding if these DPOAE phenomena are related to the interaction of the traveling wave envelopes created by the excitation of the two primary signals in the cochlea.

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CHAPTER I

INTRODUCTION

DEFINITION OF OTOACOUSTIC EMISSIONS

Otoacoustic emissions (OAE) are a release of acoustic energy from the cochlea, transmitted through the middle ear into the ear canal (Kemp, 1978). The presence of OAEs indicates a mechanically-active mechanism in the inner ear known as cochlear amplification. The cochlear amplifier results from a positive and unstable feedback system that creates reverse transmission of electromechanical energy back into the ear canal. Gold and Pumphrey (1948) suggested that the active mechanism overlays and counteracts the amount of passive mechanical damping caused by the structure and composition of the cochlea. Thus the cochlear amplifier provides greater sensitivity and frequency selectivity than would result solely from a passive system. Gold and Pumphrey's idea that this electromechanical conversion could be detected in the form of sound in the ear canal was not accepted until 1978 when Kemp developed a stimulus-generating and acoustic-response averaging system that enabled the measurement of these low-level acoustic impulses in the ear canal.

PRESUMED SOURCE OF OTOACOUSTIC EMISSIONS

Many studies using ototoxic agents and high noise levels to damage the outer hair cells of the cochlea showed a reduction or elimination of OAEs (Kim, 1980; Kemp and Brown, 1984; Lonsbury-Martin, Martin, Probst and

Coats, 1987; Martin, Lonsbury-Martin, Probst, Scheinin and Coats, 1987; Whitehead, Lonsbury-Martin and Martin, 1992). Suppression studies also support a cochlear origin (Kemp, 1979; Wilson, 1980; Zurek, 1981).

Suppression phenomena has demonstrated a reduction in the level of OAEs due to the introduction of additional tones to the cochlea. The findings of the above studies suggest a source of OAE origin with a strong correlation between OAEs and outer hair cell function (Probst, Lonsbury-Martin and Martin, 1991).

TYPES OF OTOACOUSTIC EMISSIONS

Otoacoustic emissions can be spontaneous or evoked. Spontaneous OAEs are narrow-band stimuli present without external stimulation. They are stationary and can be recorded across time. Evoked OAEs are elicited by presenting acoustic stimuli to the ear. Evoked OAEs can be further subdivided into transient (TOAE), stimulus-frequency (SFOAE) and distortion product (DPOAE) otoacoustic emissions (Probst, Lonsbury-Martin and Martin, 1991). Transient OAEs are elicited by the introduction of brief acoustic stimuli, such as clicks. They demonstrate non-linear growth, frequency dispersion, saturation potential at moderate levels and a latency with respect to the stimulus onset (Kemp, 1978). Acoustic stimuli with a low-level constant tone can generate additional acoustic energy from the cochlea at the frequency stimulated. These emissions are known as SFOAEs. Distortion product OAEs are emitted at intermodulation distortion frequencies resulting from stimulation using tonal complexes made up of two or more pure tones. The frequency of the distortion

products are related to the frequencies of the two primary stimuli. It is the nonlinear properties of the cochlea that generate this distortion. The focus of the present study will be on DPOAEs, particularly the $2f_1$ - f_2 distortion product ($2f_1$ - f_2 DP) (Probst, Lonsbury-Martin and Martin, 1991).

DISTORTION PRODUCT OTOACOUSTIC EMISSIONS

Kemp (1978) defined DPOAEs as evoked non-linear responses found at frequencies that are not present in the eliciting two-tone complex stimuli but are related to the frequency of the two primary stimuli (f_1 and f_2). The most prominent DPOAE is at $2f_1$ - f_2 ($2f_1$ - f_2 DP) which is one of the cubic difference tones. The $2f_1$ - f_2 DP is commonly measured using two procedures (Probst, Lonsbury-Martin and Martin, 1991; Whitehead, Lonsbury-Martin and Martin, 1992; Gaskill and Brown, 1990). In the first method, input/output functions are obtained by simultaneously increasing the levels of the two primary tones while maintaining a constant center frequency. In the second method, distortion-product audiograms (Lonsbury-Martin and Martin, 1990) are obtained by systematically increasing the center frequency while the levels of the two primary tones are held constant. In both methods, the frequency ratio of the two tones is fixed. Other studies have varied the frequency ratio of the primaries (f_2/f_1) by holding $2f_1$ - f_2 , f_1 or f_2 constant (Kim, 1980; Wilson, 1980; Harris et al., 1989; Gaskill and Brown, 1990; Rogers, 1994).

CHARACTERISTICS OF THE 2F1-F2 DISTORTION PRODUCT

Distortion product OAEs can be recorded with large amplitudes (30-50 dB below the amplitude of the primaries) in frequency ranges associated with the best-hearing regions for human or animal subjects (Lonsbury-Martin, Martin, Probst and Coats, 1987). The level of the 2f1-f2 DP is influenced by the intensity and the frequency separation of the primary stimuli. Input/output functions show an essentially linear relationship between an increase in the stimulus level and an increase in the level of the 2f1-f2 DP, until the point where saturation is reached (Probst, Lonsbury-Martin and Martin, 1991; Whitehead, Lonsbury-Martin, Martin, 1992; Gaskill and Brown, 1990). The effects of varying f2/f1 ratio have been described in a DP growth function (Figure 1) (Kim, 1980; Wilson, 1980; Harris et al., 1989; Gaskill and Brown, 1990; Rogers, 1994). When the frequency ratio is small the 2f1-f2 DP level is low. As the frequency separation increases, the 2f1-f2 DP level also increase until it reaches a maximum level. Wilson (1980) showed that the largest 2f1-f2 level can be elicited at an f2/f1 ratio between 1.1 and 1.2. In more recent studies the largest 2f1-f2 DP levels were obtained with an average f2/f1 ratio of 1.22 between 1 and 4 kHz (Kemp and Brown, 1983; Harris et al., 1989; Gaskill and Brown, 1990). As the ratio of the two primary stimuli is increased beyond the optimal frequency separation, the 2f1-f2 DP level declines rapidly.

ORIGIN OF 2F1-F2 DISTORTION PRODUCT IN THE COCHLEA

Suppression and cancellation techniques have been used to determine the location of the generators of the 2f1-f2 DP. Early studies by Wilson (1980)

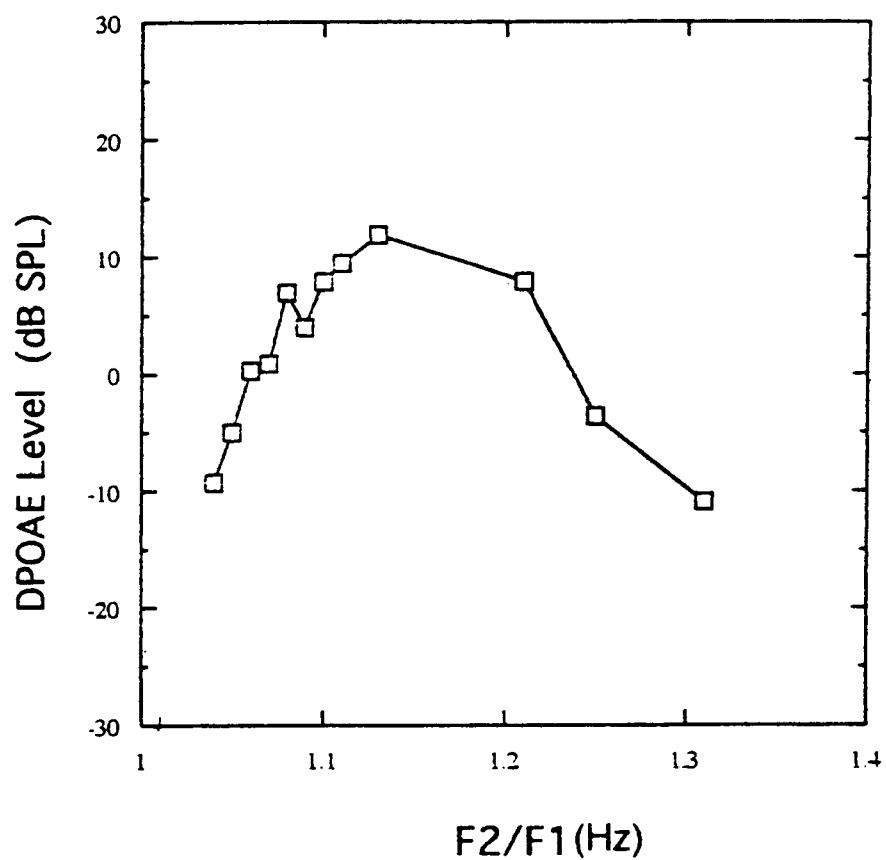


Figure1. Dependence of DPOAE level on f2/f1. Parameters of primary signals: f1 and f2 fixed in level at 65 dB SPL; f1=2000 Hz; f2 varied. (Pilot data on Participant AW).

and Kemp and Brown (1983a) have suggested a generation site associated with the frequency of the $2f_1$ - f_2 DP. Martin, Lonsbury-Martin, Probst, Scheinin and Coats (1987) found that the $2f_1$ - f_2 DP is generated at the place associated with the frequency region between the two primary stimuli. Studies by Brown and Kemp (1983b, 1984) reported that suppression of the $2f_1$ - f_2 DP was most effective when the suppressor tone was nearest to the higher frequency primary stimulus (f_2). Stover, Neely and Gorga (1994) found that $2f_1$ - f_2 DP latency estimates support a place of $2f_1$ - f_2 DP origin consistent with the f_2 place. Thus, the most convincing evidence suggests that the $2f_1$ - f_2 DP is generated near the site of f_2 .

EFFECTS OF FREQUENCY OF THE PRIMARY STIMULI ON THE GROWTH OF $2F_1$ - F_2 DISTORTION PRODUCT

There has been no systematic study of the changes in the growth of the $2f_1$ - f_2 DP as a function of the frequency of the primary stimuli. Even the studies that have reported slope measurements, at only a few frequencies, report appreciable variability in the slope measurements both across subjects and as a function of frequency. Harris et al. (1989) reported general findings that the slopes of the low frequency and high frequency leg of the $2f_1$ - f_2 DP growth function increased with an increase in the frequencies of the primary tones. Rate of growth ranged from 77-88 dB (decibels)/octave for the low leg and 102-134 dB/octave for the high leg. The investigators reported that the measurements across subjects were not stable enough to offer clinically practical information. Data from a study by Gaskill and Brown (1990) indicated

the slope of the high frequency leg of the $2f_1$ - f_2 DP growth function to be 30-420 dB/octave and a slope for the low frequency leg was not reported. A particular slope measure was not specified for a particular frequency measured. Rogers (1994) measured slopes similar in steepness to Gaskill and Brown (1990) with the steepest slope of the low frequency leg at 199 dB/octave and the steepest slope of the high frequency leg at 354 dB/octave. This measurement was made only at 2 kHz. Thus frequency dependent information for the growth of $2f_1$ - f_2 DP has not been comprehensive nor consistent within and between studies and needs to be further evaluated.

EFFECTS OF TEST METHODOLOGY ON THE GROWTH OF THE $2F_1$ - F_2 DISTORTION PRODUCT

The differences in slope information between studies may be attributed to the methodology used. Harris et al. (1989) held $2f_1$ - f_2 constant while varying the primary stimuli. Stimulus intensities ranged from 65, 75 and 85 dB sound pressure level (dB SPL). Gaskill and Brown (1990) attributed the more gradual slopes obtained by Harris et al. (1989) to the high intensity levels of the two primary stimuli. Gaskill and Brown varied f_2 while holding f_1 constant and the primary stimuli were introduced at 55-60 dB SPL. These investigators suggest that their steeper slope measures are due to the avoidance of saturation of the stimulus that may occur at high stimulus levels. Rogers (1994) used both a fixed- f_1 and a fixed- f_2 stimulus condition. The slope measurements from the fixed- f_1 condition did not differ significantly from the slopes obtained with the fixed- f_2 condition. The primary stimulus levels did not

exceed 65 dB SPL thus avoiding saturation of the stimuli. The slopes were similar in steepness to Gaskill and Brown's (1990).

METHODOLOGY OF THE PRESENT STUDY

Recent theories (Brown and Kemp 1983b; 1984; Stover, Neely and Gorga, 1994) suggest that the place associated with f_2 is the site of generation of the $2f_1$ - f_2 DP. Thus the present study will hold f_2 constant while varying f_1 . In this manner, the outer hair cells associated with the f_2 place will be consistently stimulated during the evaluation of the growth of the $2f_1$ - f_2 DP that is attributed to the specific functioning of those outer hair cells. The primary stimuli will be fixed at an intensity of 65 dB SPL. This level should be high enough to produce a measurable $2f_1$ - f_2 DP, distinct from the noise floor, but should be low enough to avoid saturation.

RATIONALE FOR THE PRESENT STUDY

The level of the $2f_1$ - f_2 DP is related in a complex manner to the frequency separation of the two primaries and the frequency region of the primary stimuli (Kim, 1980; Wilson, 1980; Harris et al, 1989; Gaskill and Brown, 1990; Rogers, 1994). There is some evidence that the slopes of the $2f_1$ - f_2 DP growth function should increase as the frequency region of the primaries increases (Harris et al, 1989; Gaskill and Brown, 1990) however there is no systematic, normative data. The present study uses the slopes of the $2f_1$ - f_2 DP growth function to describe the nature of the excitation patterns in the cochlea related to the low and high frequency regions. If the growth of the

distortion product is related to the shapes of the traveling wave envelopes, slopes of the $2f_1$ - f_2 DP growth function should increase as frequency increases. As frequency is increased, the traveling waves of the primary stimuli interact at a small range of frequency separations because the tails of the traveling waves are shorter. Thus the slope of the $2f_1$ - f_2 DP growth function is steep. At low frequencies, the traveling waves of the primary stimuli interact at a much wider range of frequency separations because the tails of the traveling waves are longer. Thus the slope of the $2f_1$ - f_2 DP growth function is more gradual.

The purpose of the present study is to compute the slope of the $2f_1$ - f_2 DP growth function at four frequencies to determine if the rate of growth of $2f_1$ - f_2 distortion product otoacoustic emissions depend upon the frequency region of the primaries. These results will be related to the interaction of the two excitation patterns created in the cochlea by the two primary tones. It will be interesting to see if the slopes of the $2f_1$ - f_2 DP growth functions are similar to other tuning in the auditory system determined by physiological methods.

CHAPTER II

REVIEW OF LITERATURE

GENERATION AND ORIGIN OF OAES

In 1979, Kemp first recorded the $2f_1$ - f_2 DP as an OAE in the external auditory canal. Subsequent investigators have demonstrated that OAEs are generated by the electromotile response of the outer hair cells which adds to the motion of the basilar membrane traveling wave (Khanna, Ulfendahl and Flock, 1990; Brownell, 1990; Probst, Lonsbury-Martin and Martin, 1991; Norton, 1992; Burch-Sims and Ochs, 1992). The enhanced basilar membrane traveling wave motion causes a reverse transduction of mechanical activity through the middle ear to the external auditory canal where it is recorded as an OAE.

Several investigators have used suppression or cancellation techniques to determine the location of the structures that generate the $2f_1$ - f_2 DP. Three explanations have been advanced as to the location of the origin of the $2f_1$ - f_2 DP. First, the data of Wilson (1980) and Kemp and Brown (1983a) provide evidence to indicate that the $2f_1$ - f_2 DP is generated at the place associated with the frequency of $2f_1$ - f_2 . Second, Martin, Lonsbury-Martin, Probst, Scheinin and Coats (1987), found that the $2f_1$ - f_2 DP is generated at the place associated with the frequency region between the primary stimuli (f_1 and f_2). Third, Brown and Kemp (1983b, 1984) showed that it was easier to suppress the $2f_1$ - f_2 DP using tones near f_2 than those near f_1 and also that the maximum suppressibility of f_2 remains constant even when stimulus

conditions are varied. In contrast, the peak suppressibility of f_1 varies as stimulus conditions are changed. Brown and Kemp could not reproduce the results of Wilson (1980) and others (first explanation) in that the suppressor tones near the $2f_1$ - f_2 DP frequency did not significantly affect the level of the $2f_1$ - f_2 DP. Thus, the most convincing evidence suggests that the $2f_1$ - f_2 DP is generated near the site of f_2 .

DPOAE FREQUENCY SEPARATION EFFECTS

Procedural considerations: Fixing or varying f_1 or f_2

The effects of frequency separation of the primary stimuli on the DPOAE depend on the frequency that is held constant as frequency separation is varied. Studies have been conducted in which the constant frequency has been f_1 , f_2 or $2f_1$ - f_2 . The rationale for holding $2f_1$ - f_2 constant is that the frequency of the response should remain invariant (Kim, 1980). Either f_1 or f_2 has been held constant in studies in which the $2f_1$ - f_2 DP is believed to have been generated in the f_1 or f_2 region (Kim, 1980; Brown and Kemp, 1983b, 1984; Stover, Neely and Gorga, 1994). Holding f_1 or f_2 constant avoids a coincidence of a spontaneous OAE close to the distortion product frequency that would create a region of abnormal excitability that would not properly represent the effects of varying frequency separation (Furst, Rabinowitz, and Zurek, 1988; Wier, Pasanen and McFadden, 1988).

Effects of frequency separation of f_1 and f_2

The $2f_1$ - f_2 DP depends complexly on the frequency separation of the primary components. The shape of the functions are similar regardless of whether f_1 , f_2 or $2f_1$ - f_2 is held constant in the experimental procedure. However the rate of growth of $2f_1$ - f_2 DP differed between some studies. The data from four different studies are described below.

Harris et al. (1989) varied the primary stimuli while holding $2f_1$ - f_2 constant. In Figure 2, the averaged data of this study are shown for $2f_1$ - f_2 DP levels in five normally functioning human ears at 1, 2.5 and 4 kHz using equal intensity primary stimuli at 65, 75 and 85 dB SPL. In each of the nine conditions, at small frequency separations, the levels of the $2f_1$ - f_2 DP decreased to some minimum usually followed by a rapid increase at greater frequency separations. After reaching a maximum level, the DPOAE decreased. This maximum level was obtained at an average f_2/f_1 ranging between 1.17-1.25 (mean=1.22) in stimulus conditions between 1 and 4 KHz. The rate of growth varied from 77-88 dB/octave for the low frequency leg and 102-134 dB/octave for the high frequency leg. In general, the slopes of the low and high frequency leg increased with frequency. These investigators reported that similar results were obtained in previous work when f_2 was held constant while f_1 was varied (Lonsbury-Martin, Martin, Probst and Coats, 1987).

Gaskill and Brown (1990) held f_1 constant while varying f_2 . Figure 3 shows average data of two normally functioning human ears at 1, 1.2, 1.5, 2, 2.5, 3.2, and 5 kHz at 55 and 60 dB SPL. The low and high frequency legs of the functions for each condition were similar in form to those described by

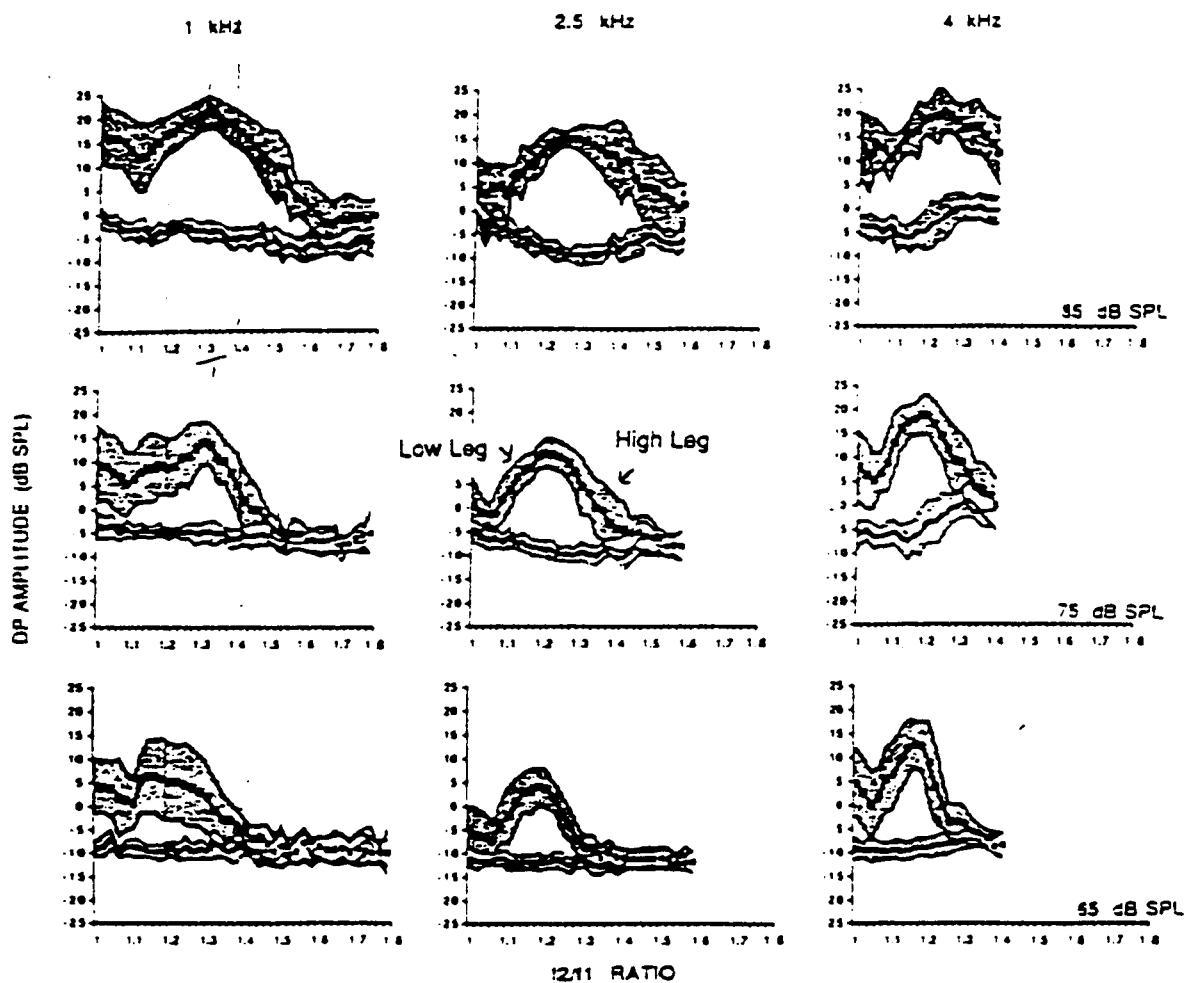


Figure 2. Mean $2f_1-f_2$ DP growth as a function of f_2/f_1 with $2f_1-f_2$ held constant (Harris, Lonsbury-Martin, Stagner, Coats & Martin, 1987).

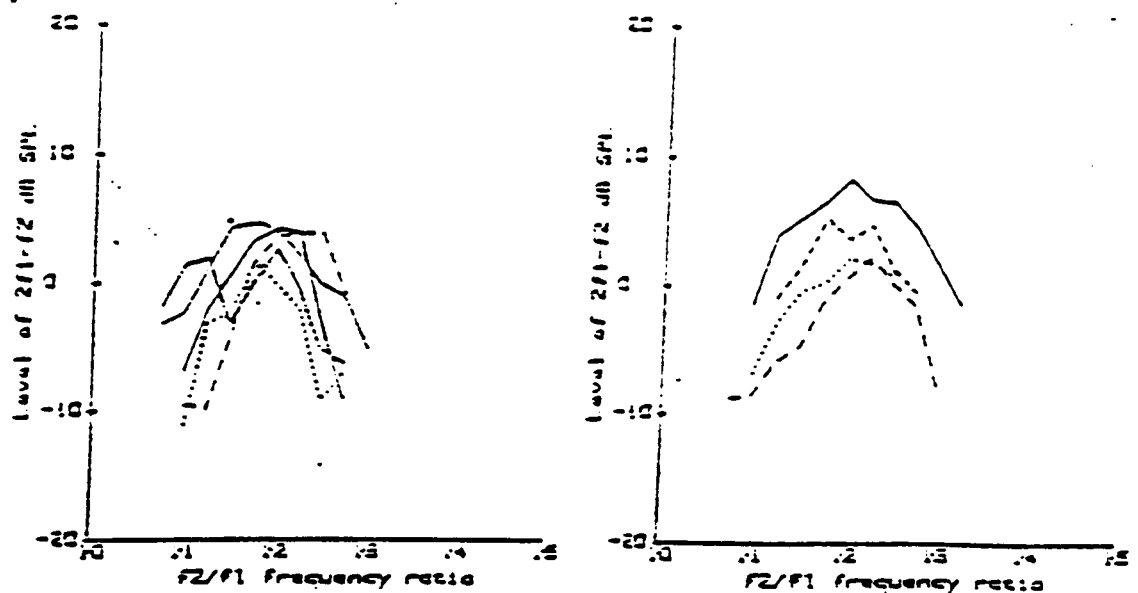


Figure 3. The growth of $2f_1-f_2$ DP as a function of f_2/f_1 (f_1 held constant). F_1 frequency code:=1000 Hz; ____=1259; _ _ _=1587; _ _ _ _=2000 Hz; ---=2519 Hz; _ _ _ _ _=3174 Hz; ____=4000 Hz;=5039 Hz (Gaskill & Brown, 1990).

Harris et al. (1989), as were the results demonstrating that the slopes of the low and high frequency legs increased with frequency. However there are several differences between the results of the two studies. First, the rate of growth of $2f_1$ - f_2 DP reported by Gaskill and Brown (1990) was 30-420 dB/octave for the high frequency leg, indicating a greater range of slopes and a steeper maximum gradient than those reported by Harris et al. (1987). Gaskill and Brown did not report slopes for the low frequency leg of the $2f_1$ - f_2 DP growth function, but they appeared to be similar in steepness to the high frequency legs of these functions. Gaskill and Brown also reported that slopes decreased in steepness at the highest level of stimulation. Thus the more gradual slopes obtained by Harris et al. (1989) may have been due to the use of higher intensity levels of f_2 . Secondly, the average optimal f_2/f_1 of 1.22 was similar in the two studies, but Gaskill and Brown's optimal f_2/f_1 did not depend on frequency or stimulus level. Gaskill and Brown suggest that the systematic dependence on frequency and stimulus level reported by Harris et al. could be due, once again, to the high-level stimulation (>65 dB SPL). Third, the $2f_1$ - f_2 DP level reversals noted at small frequency separations in the first study, were not noted in Gaskill and Brown's study. However, the f_2/f_1 in the first study were varied beginning at 1.01 while the investigators in the second study varied f_2/f_1 beginning with at 1.075. Starting with a larger f_2/f_1 may have avoided interactions reportedly causing the $2f_1$ - f_2 DP level reversals at very small f_2/f_1 .

Kim (1980) measured frequency separation effects in cats using similar procedures as were used in the two studies discussed above, with the primary

stimuli at 60 dB SPL. In general, Kim's results were in good agreement to those reported by Harris et al. (1989) and Gaskill and Brown (1990). The slopes of 2f1-f2 DP growth were not reported in Kim's (1980) study, however they appear to be similar in steepness to the slopes reported by Gaskill and Brown (1990). Reversals of 2f1-f2 DP level at small $f2/f1$ were apparent in Kim's functions under either experimental procedure.

Rogers (1994) used both a fixed $f1$ and a fixed $f2$ stimulus condition (Figure 4). The highest primary stimulus levels were 65 dB SPL. For frequency separations from 100-500 Hz, the results when $f1$ was varied were not significantly different from when $f2$ was varied. In Figure 4, the shapes of the functions reported by Rogers are shown. They were similar to those in Figures 2 and 3, but the rate of growth of 2f1-f2 DP was similar in steepness to the slopes reported by Gaskill and Brown (1990), with the steepest slope of the low frequency leg at 354 dB/octave. Reversals in the 2f1-f2 DP levels were present at small $f2/f1$.

Complex effects at small frequency separations

As $f2/f1$ is increased from the smallest values (approximately 1.01) to larger values, in some cases, DPOAE levels increase systematically and in other cases, they decrease to a minimum level and then increase systematically. Kim (1980), Harris et al. (1989) and Rogers (1994) all found reversals in the levels of the 2f1-f2 DP at small $f2/f1$ s. Rogers (1994) suggested that reversals in 2f1-f2 level at small $f2/f1$ were "enhanced" due to their location on a "pedestal" in the response spectrum as shown in Figure 5.

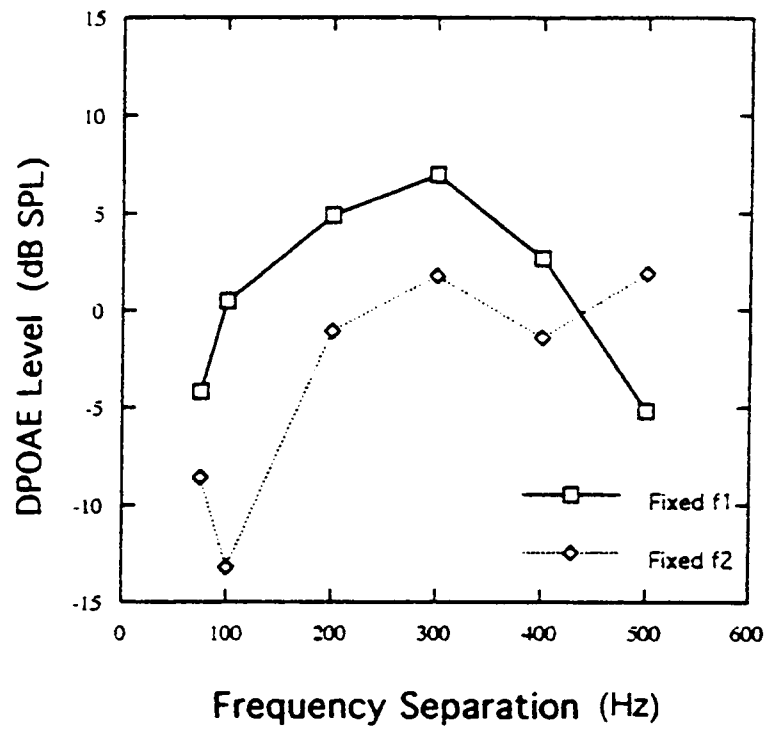


Figure 4. Response growth functions of $2f_1$ - f_2 using both fixed f_1 and fixed f_2 stimulus conditions (Rogers, 1994).

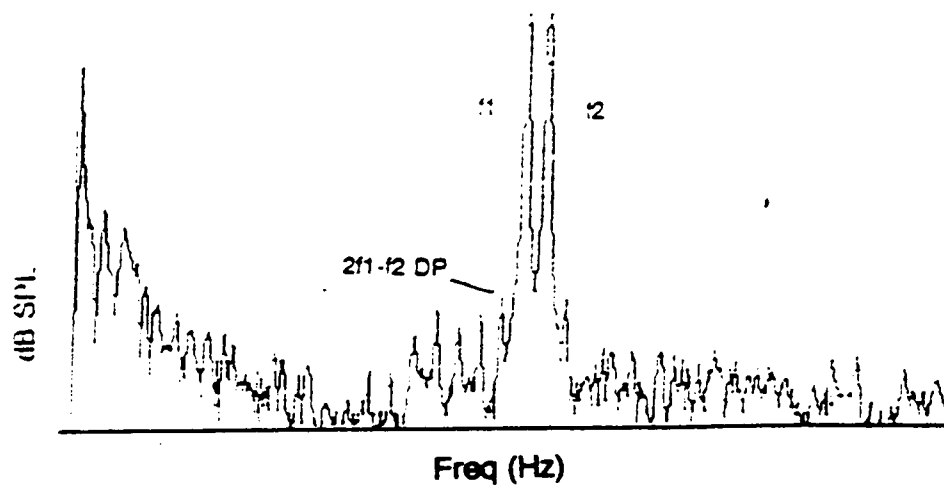


Figure 5. Response frequency spectrum showing the primary signals, f_1 and f_2 , and the $2f_1-f_2$ DP. The $2f_1-f_2$ DP is identified as enhanced due to its location on a f_1 stimulus pedestal.

The pedestal may have been part of the acoustic spectrum of one of the primary stimuli or it may have been part of the acoustic spectrum of the DPOAE. These reversals might also be due to beating and to phase relations between the stimuli as is seen in tone-on-tone masking data (Wegel and Lane, 1924; Egan and Hake, 1950) and psychophysical tuning curve data resulting from two pure tones (Thelin, Barbero, Templer and Christiansen, 1983; Nelson and Fortune, 1991). Regardless of the explanation, $2f_1$ - f_2 levels appear to have been increased due to pedestal effects.

CHAPTER III

METHODS AND PROCEDURES

PARTICIPANTS

There were 9 volunteer, female participants ranging in age from 22 to 29 years (mean = 25). Otoscopy was performed on each participant to ensure that the external ear canal was free of excessive cerumen and debris. The criterion for normal hearing sensitivity was pure-tone air-conduction thresholds at 500, 1000, 1500, 2000, 3000 and 4000 Hz of 15 dB hearing level (HL) (American National Standards Institute, 1989) or better in the test ear. The criterion for normal middle ear function was a peaked tympanogram with its maximum between ± 50 daPa of room pressure and a static admittance of the middle ear between 0.3 and 1.5 mmhos, using a probe frequency of 226 Hz. The integrity of the uncrossed acoustic-reflex arc was established by obtaining ipsilateral acoustic-reflex thresholds at 95 dB HL or less at 500, 1000 and 2000 and 4000 Hz. Audiometric data for participant qualification are shown in Appendix A.

Each participant was also required to have measurable DPOAEs for 55 dB SPL primary stimuli in one-sixth octave intervals from 1000 to 8000 Hz with $f_2/f_1 = 1.21$. DPOAEs that were at least 3-dB higher than the noise in adjacent frequency bands were considered measurable responses. DPOAE subject qualification data are shown in Appendix B.

EQUIPMENT

Experimental stimuli were generated and DPOAE measurements were made using an otoacoustic emissions test instrument (Virtual Corporation, Model 330, software version 6.5) driven by a microcomputer (Macintosh IIci). The primary stimuli were delivered to the ear through a probe assembly that was sealed in the external auditory canal using a tympanometry probe tip. Responses were measured through a microphone that was also housed in the probe assembly. Acoustic data were recorded with the microphone, amplified, and then stored on the computer hard drive. The recorded data were spectral information from 0 to 20,000 Hz in 10 Hz wide bands specified in dB sound pressure level (dB SPL re = 20 Pa). Evaluation of the DPOAE data was accomplished using custom software (Virtual Corporation) that displayed the response frequency spectrum and had a cursor that allowed determination of sound level in any of the 2000 frequency bands. Sound levels were measured using a calibration cavity provided by the manufacturer and a 1/2 inch condenser microphone (Bruel and Kjaer, Type 4134) with a sound level meter (Bruel and Kjaer, Type 2209). Sound levels were measured and adjusted at the outset of the study at frequencies ranging from 200 to 10250 Hz. The accuracy of the levels was verified at the completion of the study; levels changed by no more than 2.5 dB each frequency (Appendix C).

Data were collected with the subject seated comfortably in a double-walled, sound-treated room (Industrial Acoustics Company, Model 1203-A). The DPOAE probe assembly and preamplifier were also located in the sound-treated room. The octave-band ambient noise levels inside the sound-treated

room were 16.0 dB SPL at 250 Hz, 9.0 dB SPL at 500 Hz, 8.7 dB SPL at 1000 Hz, 9.5 dB SPL at 2000 Hz and 10.5 dB SPL at 4000 Hz. Levels were within permissible levels for testing with ears covered (ANSI S3.1, 1977).

STIMULI

The primary stimuli (f_1 and f_2) were two pure-tones held constant in level at 65 dB SPL for all experimental conditions. In Table 1, the frequencies of the experimental stimuli are shown. There were four experimental frequency regions (indicated by the frequency of f_2). In each frequency region there were 10 frequency-ratio conditions which are specified in the left-hand column of the table. The numerical values in the table are the frequencies of f_1 for each condition.

For each stimulus condition, the DPOAEs were measured from a response spectrum that was obtained using time and spectral averaging procedures. For each condition, 4 spectra were obtained. Each of the 4 spectra was computed from an averaged time waveform based on 32 stimulus presentations. The time waveforms were averaged over 32 stimulus presentations to reduce the noise floor by 15 dB before Fourier analysis was performed to obtain a response spectrum of the data. This procedure was repeated four times to obtain 4 response spectra. The four response spectra were then averaged to obtain the single response spectrum from which the DPOAE levels were measured.

Table 1

Experimental Stimulus Frequencies and Frequency Ratios

	F2=1000	F2=2000	F2=3000	F2=4000
F2/F1	F1	F1	F1	F1
1.03	970	1941	2913	3883
1.05	952	1904	2857	3810
1.07	934	1869	2804	3738
1.09	917	1834	2752	3670
1.11	900	1801	2703	3604
1.13	884	1769	2655	3540
1.19	840	1680	2521	3361
1.21	826	1652	2479	3306
1.25	800	1600	2400	3200
1.30	769	1538	2308	3076

PROCEDURES

There were three experimental trials for each participant. In each trial, data were obtained for each of the 40 experimental conditions shown in Table 1. In each trial, the presentation order of f2/f1 conditions was randomized (Appendix D).

At the start of the first session, the otoscopic and audiologic qualification previously described in the Participants section of this chapter was performed. The remainder of session 1 was devoted to data collection. The first session lasted approximately one and one half hours. Participants were given rest periods after 45 minutes or upon request. The remaining data was collected in two subsequent trials lasting forty-five minutes each.

The participant was seated in a comfortable chair in the sound-treated room. The probe assembly was held in place with velcro strips attached to a baseball-style cap that was worn by the participant.

The main source of response variability during data collection was due to the loss of the airtight seal of the probe in the external auditory canal. The investigator monitored the level and repeatability of the 2f1-f2 DP throughout the data collection process. When necessary, the test procedure was interrupted to check the probe seal if there was evidence of response variability or abnormality. When data of questionable validity were obtained, the data were discarded and the experimental conditions were repeated in a fourth test session. Raw data for all experimental conditions for all participants were shown in Appendix E.

RESPONSES

The data for each experimental trial was a single response spectrum that included the averaged sound levels of the primary stimuli, the DPOAEs, and the ambient noise in the ear canal. The spectrum was displayed on a computer screen. This permitted the measurement of sound level in each 10-Hz band from 0 to 20,000 Hz. The levels of the primaries were verified from the response spectrum. The levels of both primaries were within 3 dB of the nominal levels in 27 out of 27 stimulus presentations.

In Figure 6, an example of the response spectrum can be seen. The $2f_1$ - f_2 DP is indicated by the arrow. The measurements of DPOAE levels were also obtained from the response spectrum. When DPOAE levels were low, it was necessary to determine whether the measured level was due to stimulus or to noise. The following rule was used when the spectrum of the noise around the DPOAE was relatively unaffected by the spectra of the primary stimuli. A DPOAE was considered valid when the level of the DPOAE was at least 3 dB greater than the level of the noise in each of the two 10 Hz bands located above and in each of the two located below the DPOAE.

A second rule was established for determining the validity of the DPOAEs located on a f_1 stimulus pedestal (Figure 5). A DPOAE was considered valid when the level of the DPOAE was at least 3 dB greater than the level of the noise in three of the four adjacent 10-Hz bands above and below the DPOAE. Also, the level of the DPOAE had to be at least 3 dB higher than the average level of the noise in the two adjacent bands, 10-Hz above and below the DPOAE. With both criteria, the decisions regarding the validity

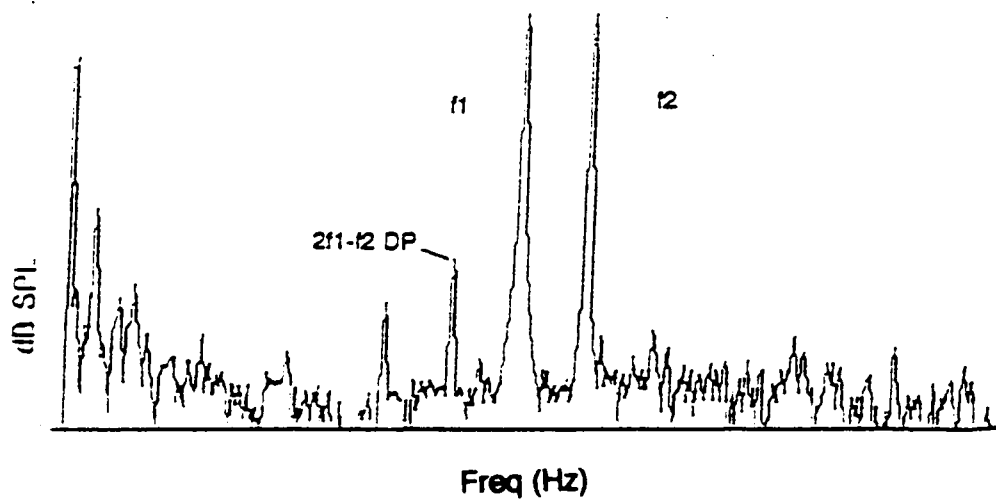


Figure 6. Response frequency spectrum showing the primary signals, f_1 and f_2 , and the $2f_1-f_2$ DP. This is an example of a strong $2f_1-f_2$ DP response.

of the DPOAE were made using the two 10-Hz bands above and below the DPOAE. When this rule was used, DPOAE datum points were identified with the letter "E" to indicate possible enhancement of the DPOAE level.

Analysis of slopes

Unless otherwise noted, the following rule was applied to select the points used in all slope computations. The minimum point was selected as the point following the lowest datum before the DP growth function began to steadily increase, reach its maximum and decrease. The maximum point was selected as the highest point in the DP growth function before it leveled off and began to decrease. The rule was developed to examine the $f2/f1$ in with the DP growth was occurring and to isolate that area from the $f2/f1$ regions in which other effects were occurring.

CHAPTER IV

RESULTS

DEPENDENCE OF 2F1-F2 DP GROWTH ON FREQUENCY

Analysis of slopes based on group medians

The results for all experimental conditions are shown in Figures 7A, 7B, 7C and 7D. At each frequency separation, there may be fewer than nine datum points because some participants did not have measurable responses above the noise floor. (Noise floor measures are not shown graphically because noise floors varied from condition to condition and trial to trial. The highest noise level was at 15.8 dB SPL and the lowest noise level was at -28.6 dB SPL with a typical noise level of approximately -15.4 dB SPL). Figures 7A through 7D permit the comparison of 2f1-f2 DP growth rate at four frequencies. The slopes of the growth functions show an apparent increase with frequency.

In Figure 8, the level of the 2f1-f2 DP is plotted as a function of frequency separation in octaves for the accurate representation of slopes as a ratio of DP changes per octave. The slopes were computed using the medians of medians shown by the square symbols in Figures 7A through 7D. The slopes based on group medians were as follows: 61.1 dB/octave at 1000 Hz, 76.9 dB/octave at 2000 Hz, 86.4 dB/octave at 3000 Hz and 101.3 dB/octave at 4000 Hz. Because only a single estimate of slope was obtained at each frequency, these data were not amenable to statistical analysis. However the results show that slope increases with frequency.

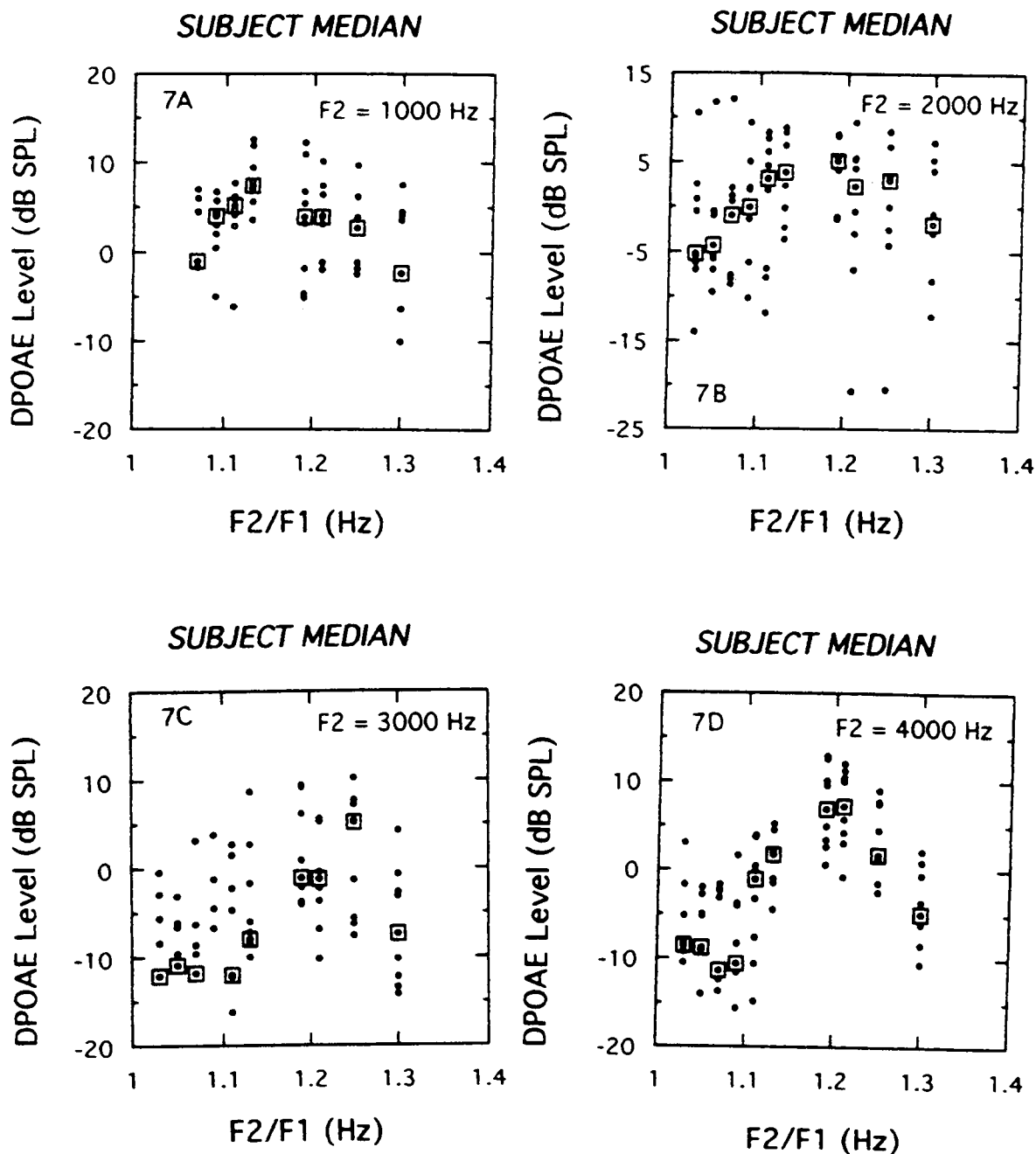


Figure 7. Median group data for all experimental conditions.
Legend: Median DPOAE amplitude (dB SPL) as a function of frequency separation (Hz). The parameter is $F2$. The square symbols represent the median of median DPOAEs at each $f2/f1$. The enclosed circles represent the median DPOAEs of each participant at each $f2/f1$.

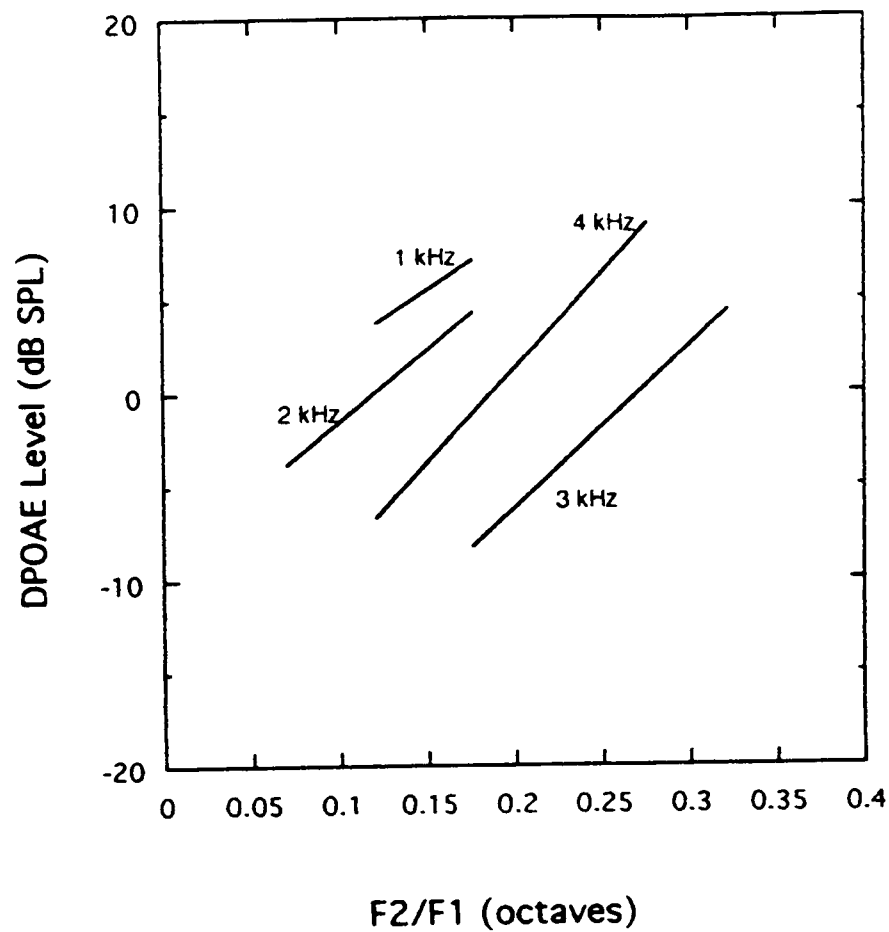


Figure 8. Group median slopes attained from individual median slopes. Legend: DPOAE amplitude (dB SPL) as a function of frequency separation (octaves). The parameter is f2.

Analysis of slopes based on individual medians

Data were analyzed by computing slopes based on individual participant data. For each participant for each experimental condition, the results were repeatable over trials. Across the nine participants and the four experimental frequencies, the patterns of the DP responses varied greatly.

In Figures 9A and 9B, representative data for $f_2 = 1000$ Hz are shown for individual participants. In Figure 9A, there was no systematic increase in the slope of the function with frequency separation. In some cases the functions were irregular in shape but showed no overall growth trend. This was characteristic of results of six of the nine participants. In Figure 9B, the DP growth function grew quickly out of the noise floor, leveled off and dropped back in the noise floor as f_1 and f_2 were separated in frequency. These results were found for three of the nine participants. The lack of a systematic increase in the flat DP growth functions of six of the participants made it impossible to apply the rule chosen to compute slope data. As a result, a meaningful estimate of slope based on individual median data could not be obtained.

In Figures 10A and 10B, representative individual participant data are shown for $f_2 = 2000$ Hz. In Figure 10A, the data are characteristic for six of the nine participants. At the smaller f_2/f_1 ($f_2/f_1 = 1.03-1.11$), the DP growth function is a series of peaks and troughs before steadily increasing, usually around an f_2/f_1 of 1.07, to a maximum at approximately $f_2/f_1 = 1.19$, leveling off and decreasing back into the noise floor. In Figure 10B, the data are characteristic of the remaining three participants. The DP growth function

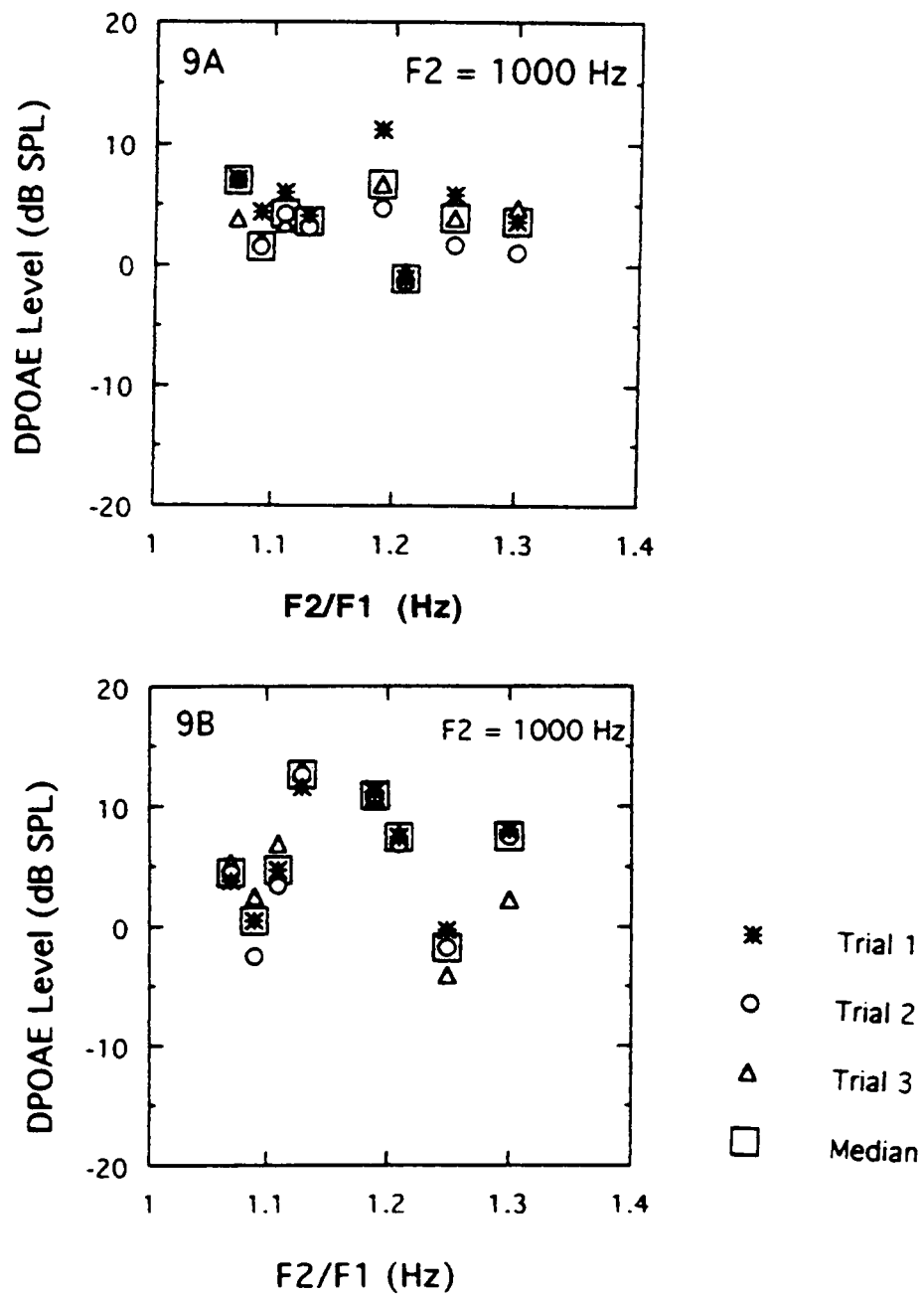


Figure 9. Sample individual participant data at $f_2 = 1000 \text{ Hz}$. Legend: DPOAE amplitude (dB SPL) as a function of frequency separation (Hz). The parameter is f_2 .

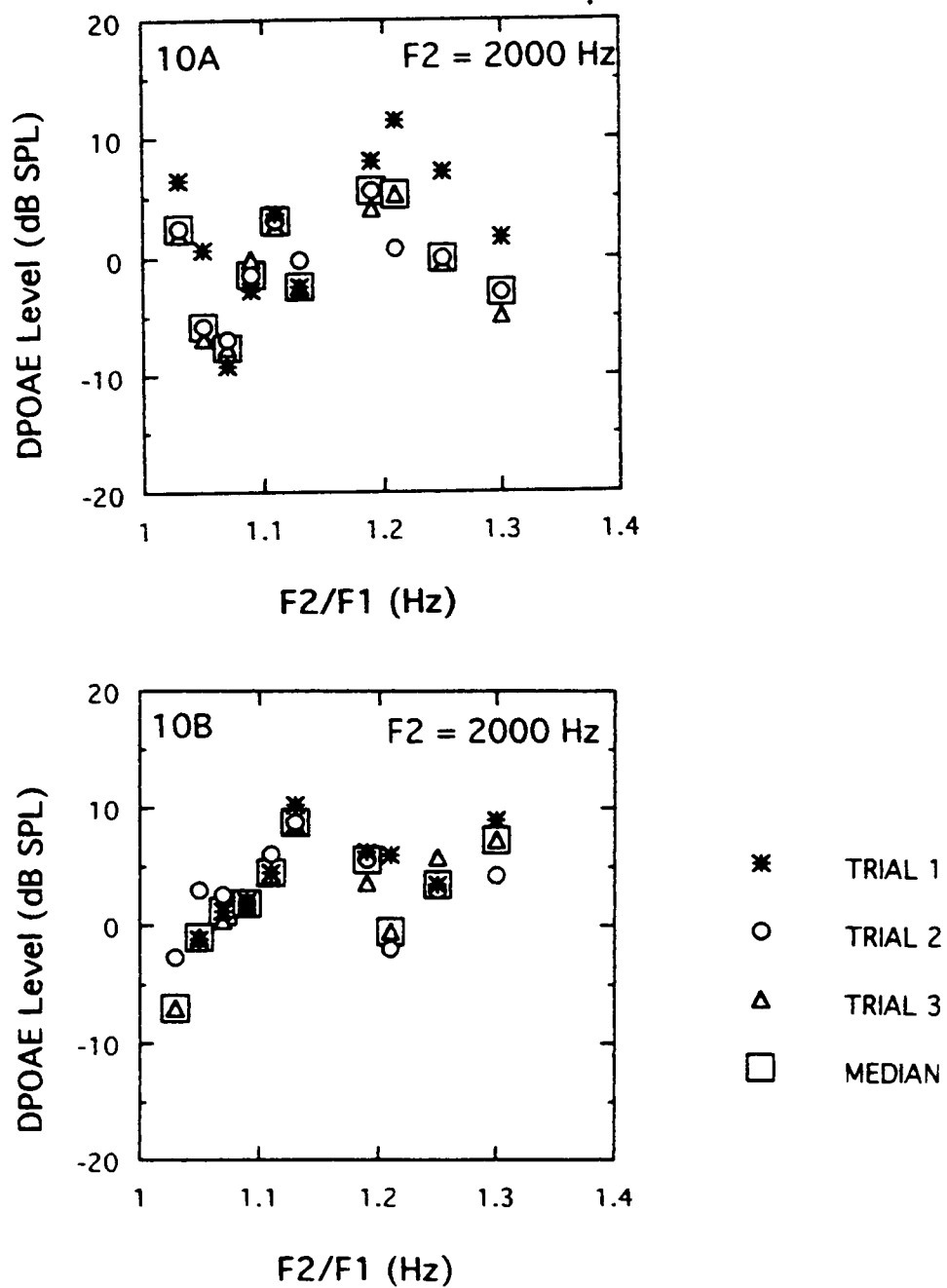


Figure 10. Sample individual participant data at $f_2 = 2000$ Hz. Legend: DPOAE amplitude (dB SPL) as a function of frequency separation (Hz). The parameter is f_2 .

increased steadily from the smallest f_2/f_1 , reached a maximum at approximately $f_2/f_1 = 1.19$, leveled off and dropped back into the noise floor. Despite the differences in the forms of the functions in Figures 10A and 10B, the growth of the DP growth function was sufficiently systematic enough that slopes could be computed. The median slopes for three trials for each participant at 2000 Hz varied between 14.7 and 110 dB/octave with a mean of 55.6 dB/octave (Table 2).

In Figure 11, representative individual participant data are shown for $f_2 = 3000$ Hz. For frequency separations up to 1.13, the DP responses were either small in amplitude or not present. For f_2/f_1 ratios greater than 1.13, the majority of DP growth functions increased rapidly to a maximum at an f_2/f_1 of approximately 1.25 and decreased quickly back into the noise floor. This is in contrast to data at 1000 Hz where responses were consistently present at small frequency separations, and at 2000 Hz where much larger responses were consistently obtained and where the majority of growth of the DP function was completed before 1.13. The individual median slopes at $f_2 = 3000$ Hz ranged from 49.7 to 142.6 dB/octave with a mean of 89.6 dB/octave (Table 2). When comparing the slopes at $f_2 = 3000$ Hz to slopes at $f_2 = 2000$ Hz, the slope increased as the f_2 frequency increased for all nine participants. It should be noted that the maximum DP level was lower for $f_2 = 3000$ Hz than for any other frequency. The reason for this decreased response level is unknown.

Table 2

Slopes of DP Growth Functions Based on Group Medians for Three
Frequencies for Nine Participants

Participants	F2 = 2000	F2 = 3000	F2 = 4000
1	110	142.6	105.3
2	30.2	49.7	85.3
3	30.7	68	78.7
4	45.9	73.6	124
5	86.6	131	116.8
6	80	108	101.8
7	57.3	57.4	158.8
8	45.5	65.3	90.9
9	14.7	110.3	127.4
Mean	55.6	89.6	109.9

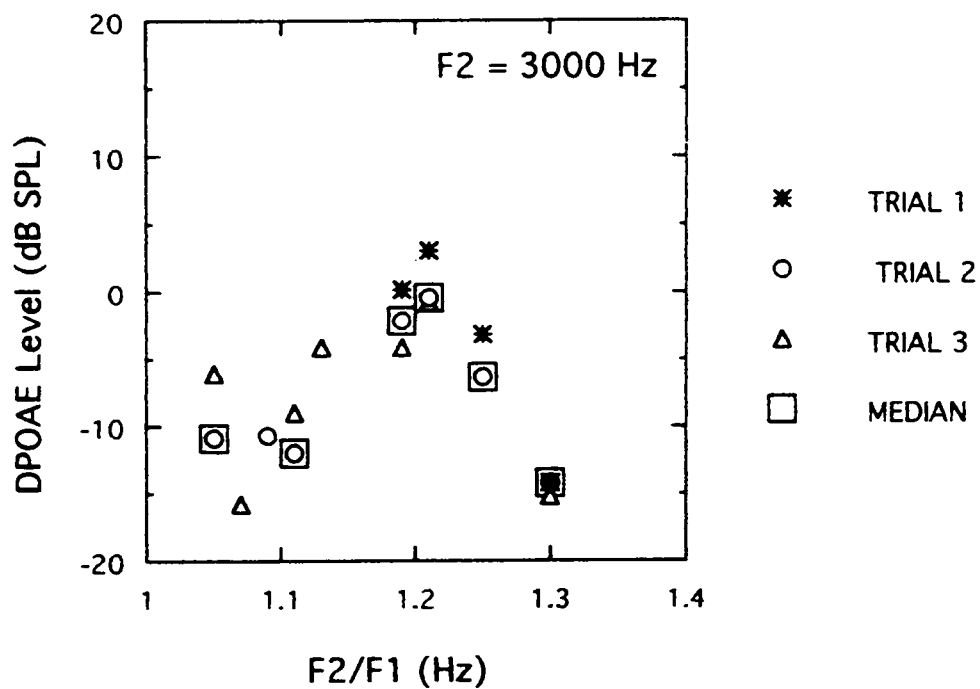


Figure 11. Sample individual participant data at $f_2 = 3000$ Hz.
Legend: DPOAE amplitude (dB SPL) as a function of frequency separation (Hz). The parameter is f_2 .

In Figure 12, representative individual data are shown for $f_2 = 4000$ Hz. The DP growth functions of all nine participants demonstrated the same rapid growth beginning around 1.09 and reaching a maximum point around 1.21, followed by a rapid decrease into the noise floor. The shape of the DP growth functions when $f_2 = 4000$ Hz was most similar across participants. Slopes were computed using the rule stated in the previous section. The slopes ranged from 78.7 to 158.8 dB/octave with a mean of 109.9 dB/octave (Table 2). For eight of the nine participants, the slope at $f_2 = 4000$ Hz was greater than the slope at $f_2 = 2000$ Hz. In six of the nine participants, the slope at $f_2 = 4000$ Hz was greater than the slope at $f_2 = 3000$ Hz.

A repeated measures analysis of variance was performed to compare growth function slopes at $f_2 = 2000$, 3000 and 4000 Hz. There were significant differences in slope as a function of frequency ($F = (2,7) = 11.75$, $p < .005$). T-tests for paired differences were conducted to make comparisons among the three frequencies analyzed. The slopes of the growth functions were significantly different for $f_2 = 2000$ Hz and $f_2 = 3000$ Hz ($t(8) = 3.86$, $p < .005$), and $f_2 = 2000$ and $f_2 = 4000$ Hz ($t(8) = 4.306$, $p < .003$). However, the slopes for $f_2 = 3000$ and $f_2 = 4000$ Hz were not significantly different ($t(8) = 1.511$, $p < .169$).

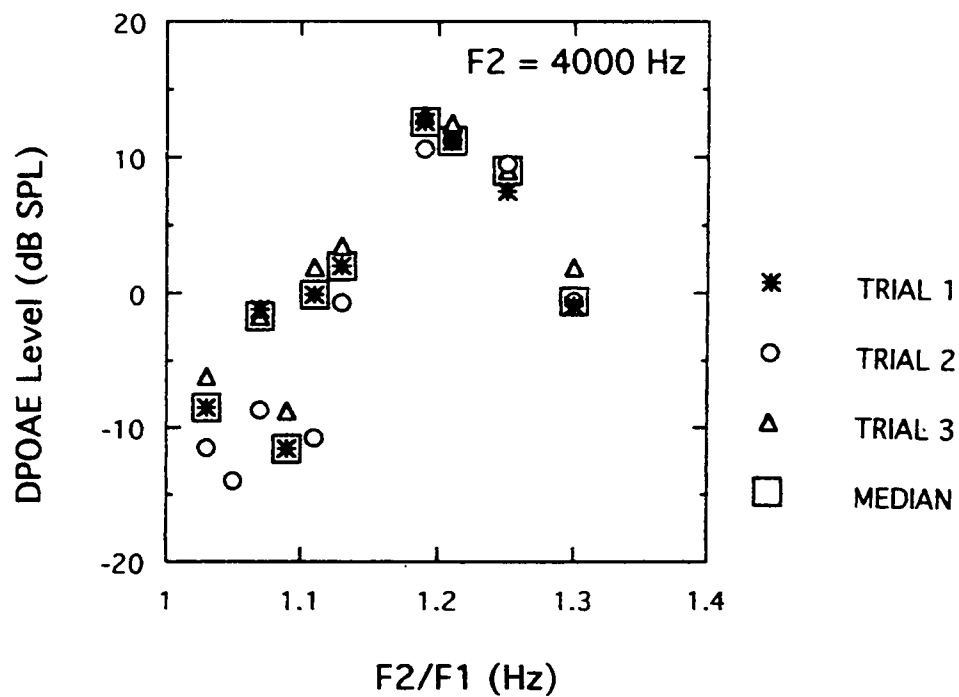


Figure 12. Sample individual participant data at $f_2 = 4000$ Hz. Legend: DPOAE amplitude (dB SPL) as a function of frequency separation (Hz). The parameter is F2.

CHAPTER V

DISCUSSION

ONSET OF DP GROWTH FUNCTION

At each frequency, there was a region of irregular fine structure present at small frequency separations in the DP growth function. However the point at which this irregular fine structure ended and systematic growth began varied for each frequency (Figure 8). When $f_2 = 1000$ Hz, the frequency separation where the irregular fine structure ended and growth began may have been larger than it was portrayed in this study due to technical difficulties separating the $2f_1-f_2$ DP from the stimulus response. For the remaining three test frequencies, the onset of the DP growth function occurred at the smallest frequency separation when $f_2 = 2000$ Hz and the largest frequency separation when $f_2 = 3000$ Hz, with $f_2 = 4000$ Hz in the intermediate range. The DPOAE amplitude was smallest for $f_2 = 3000$ Hz.

These results were compared with the results of the study by Harris et al. (1989) only, because this was the only previous human study to report DP measurements at small enough frequency separations to determine the onset of the DP growth function. The results by Harris et al. (1989) were in agreement with the results of the present study in spite of the different test methodology used (they held $2f_1-f_2$ constant, where f_2 was held constant in the present study). When $2f_1-f_2$ was 1000 Hz, the DP growth functions shown by Harris et al. (1989) were the most variable for their three frequency conditions. Also, they obtained DPOAEs at very small frequency separations

where responses could not be obtained in the present study. When their mean data were examined at 1000 Hz, there was an abrupt growth of the DPOAE that was not found in any of their other three frequency conditions or in any of the four frequencies used in the present study. These investigators may have used a different criteria for accepting a DP response as being truly separated from the noise floor or the stimulus response.

As in the present study, the amplitudes of the DPOAEs, obtained by Harris et al (1989), were decreased in regions involving 3000 Hz. Recent evidence suggested that this reduced amplitude at 3000 Hz may be due to the microphone sensitivity of the Virtual otoacoustic measurement system (Kelly, Hornsby, Kiang and Hall, 1995). However, the similar results of Harris et al. using a different measurement system (Hewlett Packard, 3326A), suggest that the decreased amplitude cannot be attributed solely to technical problems with the Virtual system. Other physiologic phenomena need to be considered. One possible cause of the DPOAE effects observed near 3000 Hz may be the resonance of the external auditory canal and tympanic membrane that occurs at approximately 2800 Hz (Shaw, 1974). The resonance could have increased the level of the primary stimuli to an amplitude that could have caused saturation of the DP response and thus a lower DP response level at 3000 Hz.

Harris et al. (1989) reported points of onset of DP growth for $2f_1-f_2 = 2500$ Hz and $2f_1-f_2 = 4000$ Hz that were comparable to the points of onset of growth in the present study. The onset of the DP growth function was at the largest frequency separation when $2f_1-f_2 = 2500$ Hz, and at an intermediate

frequency separation when $2f_1 - f_2 = 4000$ Hz. The similar results reported by two experimenters using two different test methodologies, indicate that the difference in onset as a function of frequency may be a general finding in normal hearing individuals.

SLOPES OF DP GROWTH FUNCTIONS

The slope values of the present study were comparable to slopes reported by Harris et al. (1989). Their average slopes at 1000, 2500 and 4000 Hz were 77, 82 and 88 dB/octave, respectively, and fell within the range of median slopes computed in the present study (Table 3). Gaskill and Brown (1990) reported some slopes for the high frequency leg of the DP growth function and the values were somewhat steeper than the slopes of the low frequency leg of the DP growth function reported in the present study. The more gradual slopes of the low frequency leg measured in the present study, and the steeper slopes of the high frequency legs measured by Gaskill and Brown (1990) reflect the asymmetrical shape of the DP filter. Rogers (1994), used the same test methodology used in the present study (f_2 held constant). The DP growth function generated at $f_2 = 2000$ Hz in Rogers study was very similar to the DP growth function generated at $f_2 = 2000$ Hz in the present study except at the narrowest frequency separations (Figure 13). Rogers reported a much steeper slope value (354 dB/octave) at the low frequency leg of the DP growth function when $f_2 = 2000$ Hz than was found in the present study.

Table 3

Slopes (dB/oct) of Low Frequency Legs of DP Growth Functions

Study	1000 Hz	2000 Hz	2500 Hz	3000 Hz	4000 Hz
Present study (group median)	61.1	76.9		86.4	101.3
Harris et al. (1989) (mean)	77		82		88

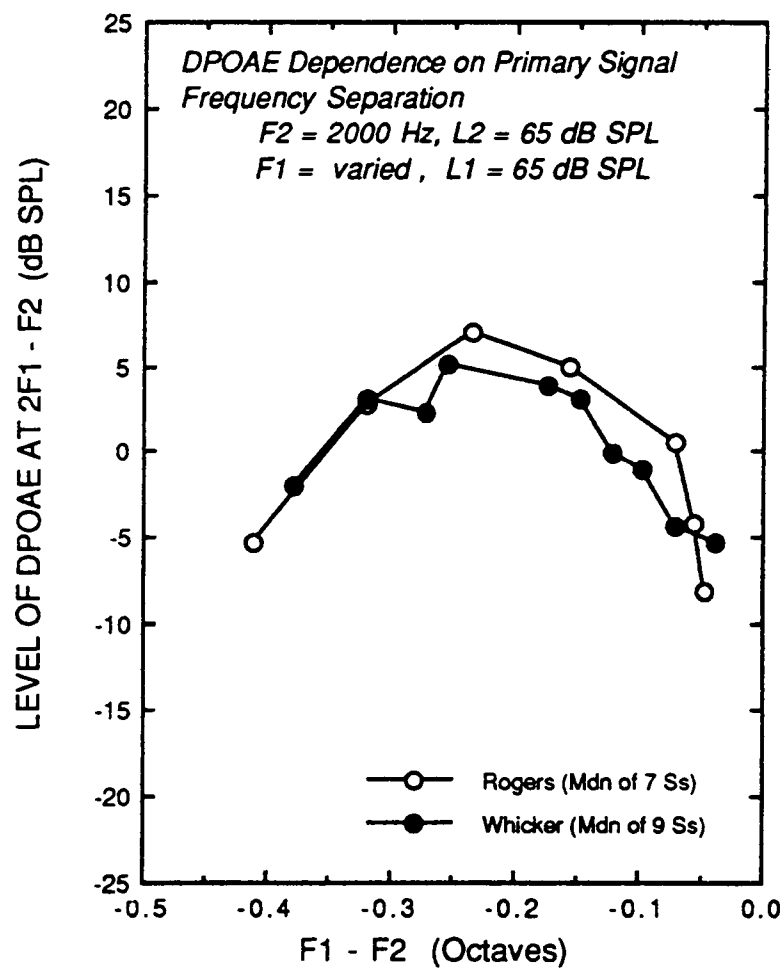


Figure 13. Comparison of two DP growth functions. Open circles represent data from Rogers (1994). Filled circles represent data from present study. Legend: Level of DPOAE (dB SPL) as a function of frequency separation (octaves). Parameter is f_2 .

In the present study, there was a systematic increase in the median values of the slopes of the DP growth functions with frequency (Figure 8). Gaskill and Brown (1990) alluded to a relationship between rate of growth and frequency, but did not describe a systematic increase in slope with an increase in frequency. The data of Harris et al. (1989) showed an increase in slope with frequency but they did not relate it to filtering in the auditory system. In the present study, data were obtained to demonstrate the growth as a function of frequency at four frequency conditions and then to describe the nature of the excitation patterns in the cochlea related to the low and high frequency regions. The increase in rate of growth of the DPOAEs, reported in the present study, is the expected finding if these DPOAE phenomena are related to the interaction of the traveling wave envelopes created by the excitation of two stimuli in the cochlea. At low frequencies, the traveling waves of the primary stimuli interact over a much wider range of frequency separations because the tails of the traveling waves are longer. Thus the slope of the DP growth function is more gradual. As frequency is increased, the traveling waves of the primary stimuli interact over a smaller range of frequency separations because the tails of the traveling waves are shorter. As a result, the slope of the DP growth function is steeper.

RELATION OF SLOPES OF THE DP GROWTH FUNCTIONS TO OTHER TUNING IN THE AUDITORY SYSTEM

It is tempting to speculate from these DPOAE data if the changes in slope are related to some aspects of neural, basilar membrane and/or hair cell

tuning. There are data for three different types of experiments that provide some information about descriptions of filtering effects found in the auditory system that are dependent upon cochlear activity.

Early studies on neural tuning demonstrate a systematic increase in the slopes of the frequency tuning curves (FTC) as a function of frequency (Kiang, 1965). Measuring the tuning of single units of the auditory nerve, estimates of the slopes of the low frequency legs of FTCs have ranged from 80 to 250 dB/octave as frequency was increased and slopes of the high frequency legs of FTCs have ranged from 100 to 600 dB/oct as frequency was increased (Evans, 1975 a & b). More recently, Sellick, Patuzzi and Johnstone (1982) demonstrated the similarities between the shapes and slopes of FTCs and isovelocity and isodisplacement basilar membrane tuning curves using the Mossbauer technique. In addition, data on inner hair cell tuning, as reported by Russell and Sellick (1977) using intracellular recording in guinea pig cochleas, are in agreement with neural FTCs. Slope computations (obtained from Russell and Sellick's Figure 3) of isoamplitude curves of a 23,000 Hz tone demonstrate slopes of the low frequency legs to be greater than or equal to 113 dB/octave and slopes of the high frequency legs to be greater than or equal to 150 dB/octave. There is substantial agreement that the asymmetric shape of the tuning curves and the steeper slopes of the tuning curves are similar for neural, basilar membrane and inner hair cell tuning methods in comparison to slopes of DP growth functions.

Slopes obtained from DP growth functions from the present study and from Harris et al. (1989) are not as steep as slopes obtained from neural,

basilar membrane or inner hair cell tuning curves. This may be due to the way the traveling waves of the primaries (f_1 and f_2) interact on the basilar membrane as they are separated in frequency. It is expected that the high frequency side of the traveling wave of f_1 interacts with the low frequency side of the traveling wave of f_2 . Thus, the rate of growth of the DPOAEs may depend on the slope of the high frequency side of the traveling wave of f_1 and the slope of the low frequency side of the traveling wave of f_2 . If DPOAE growth depended on the reduction in the overlap of the traveling waves as they were separated in frequency, the rate of growth would be somewhat less than either the high frequency slope of f_1 or the low frequency slope of f_2 . It would then be expected that slopes obtained from DP growth functions would be more gradual than slopes of neural, basilar membrane or inner hair cell tuning curves. Upon comparing slopes of DP growth functions obtained in the present and in the study by Harris et al. (1989) (Table 3) to slopes of neural FTCs over a wide range of frequencies reported by Evans (1975 a & b) and slopes of isoamplitude curves of a 23,000 Hz tone obtained by measuring intracellular receptors (Russell and Sellick, 1977), the slopes of the DP growth functions are more gradual.

In conclusion, the increase in the slopes of the DP growth functions with frequency was found by the present study and the study by Harris et al. (1989). This progression in slopes was expected if the DPOAE growth reflected the nature of the excitation patterns of the traveling waves in the cochlea. Thus, it appears that DPOAE growth may be dependent on the same traveling wave mechanisms that effect inner hair cell tuning. Also, DPOAE growth data are

adequately described by the reduction in the interaction of the high frequency side of the traveling wave of f_1 and the low frequency side of the traveling wave of f_2 as they are separated in frequency. The numerical values of the slopes of the DP growth functions from the present study and the study by Harris et al (1989) were consistent with the expected slope values of DP growth functions when comparing them to data from other physiological tuning methods in the auditory system.

CLINICAL AND THEORETICAL IMPLICATIONS

It would be interesting to extend the present research to hearing impaired individuals, specifically those with impairment due to noise exposure and/or ototoxicity. The shape and slopes of the DP growth functions could be compared to the shape and slope of the DP growth functions obtained in the present study. If the rate of DPOAE growth dependent on frequency separation and frequency truly reflects the ability of the auditory system to perform some aspect of tuning, then the resulting DP growth functions should differ substantially between normal hearing and hearing impaired individuals with damaged hair cells from noise exposure or ototoxicity. One consideration in the formulation of the present study was to develop a clinical procedure to be used as an objective measure of tuning of the auditory system in humans. However, the results indicated that individual variability was so high that clinical utility would be low. Yet, the DP growth functions that were the most systematic across individuals were seen at 4000 Hz. Since 4000 Hz is the

frequency of primary interest in hearing conservation programs, this technique may have value for assessing auditory sensitivity and tuning at this one frequency.

A second potential clinical application of this technique involves listeners with normal hearing sensitivity but poor speech discrimination ability. If the DP growth functions reflect some aspect of auditory tuning, the DP growth functions obtained by these listeners would be expected to be different from DP growth functions obtained by normal hearing individuals with normal speech discrimination ability.

One purpose of the present study was to relate frequency selectivity using DPOAE measures to frequency selectivity measured for the basilar membrane, inner hair cells and single neural units. Another way to examine the growth of the DPOAEs with frequency separation and frequency would be to use the methodology of the present study in combination with contralateral stimulation. In this way, the exact role of the outer hair cell in the growth of the DPOAEs could be studied by attempting to alter the DPOAE response using contralateral stimulation.

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REFERENCES

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APPENDICES

APPENDIX A
AUDIOMETRIC DATA FOR PARTICIPANT QUALIFICATION

	Participant Number								
	1	2	3	4	5	6	7	8	9
Age	23	22	23	22	24	23	23	24	25
Test Ear	R	R	R	R	R	R	R	R	R
PT AC Thresholds (dB HL)									
500 Hz	0	5	10	0	5	-5	5	5	0
1000 Hz	0	5	10	0	-5	0	0	0	-5
1500 Hz	0	0	5	0	-5	0	5	0	0
2000 Hz	0	0	5	0	0	-5	-5	0	-5
3000 Hz	0	0	0	0	-5	-5	0	-5	-5
4000 Hz	0	0	5	0	-5	-5	0	-5	0
Tympanometry									
Yme (mmhos)	.4	.6	.9	.5	.4	.4	.9	.5	.6
MEP (daPa)	-10	0	-25	5	-10	-5	10	-5	0
Uncrossed Acoustic-Reflex Thresholds (dB HL)									
500 Hz	85	90	75	80	80	85	80	85	85
1000 Hz	80	90	80	75	90	85	80	85	85
2000 Hz	80	95	80	80	80	95	85	80	80
4000 Hz	80	90	80	80	95	90	80	85	80

APPENDIX B
DISTORTION PRODUCT AUDIOGRAMS
FOR PARTICIPANT QUALIFICATION

Virtual Clinic
521 SW 11th
Portland, OR 97205
(503)226-3000



Name: SUBQUALI

Chart #:

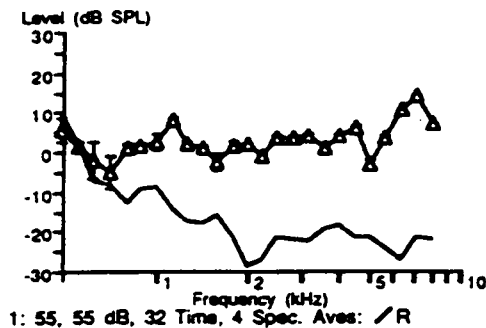
Age:

Sex:

Monday, February 13, 1995 16:56

Tester:

Distortion Product



Distortion Product Table

F1 level: 55 dB SPL F2 level: 55 dB SPL
Time Aves: 32 Spectral Aves: 4
Noise Retries: 4 Noise Tolerance: 10 dB SPL
F2 = 1.21 * F1, Fe = F2

Right

F _e (kHz)	F1 (kHz)	F1 amp (dB SPL)	F2 (kHz)	F2 amp (dB SPL)	Fdp (kHz)	Fdp amp (dB SPL)	F _n (kHz)	F _n amp (dB SPL)
0.50	0.41	54.0	0.50	55.0	0.32	5.5	0.25	9.6
0.56	0.46	55.0	0.56	53.8	0.37	1.6	0.29	1.9
0.62	0.52	53.7	0.62	53.5	0.41	-2.2	0.33	-7.3
0.70	0.58	54.9	0.70	54.0	0.46	-5.2	0.39	-8.3
0.80	0.66	53.9	0.80	54.0	0.52	1.2	0.44	-12.5
0.88	0.73	53.7	0.88	54.2	0.58	1.4	0.51	-9.3
1.00	0.83	53.7	1.00	54.0	0.66	2.6	0.58	-8.6
1.12	0.93	53.5	1.12	53.6	0.73	7.9	0.66	-14.2
1.26	1.04	54.5	1.26	55.2	0.83	2.2	0.75	-17.2
1.42	1.17	52.9	1.42	55.4	0.93	1.2	0.85	-17.9
1.59	1.31	53.3	1.59	53.9	1.03	-2.7	0.96	-15.9
1.79	1.48	52.5	1.79	54.1	1.16	1.3	1.09	-21.5
2.00	1.66	53.2	2.00	55.0	1.31	2.3	1.24	-28.7
2.24	1.85	54.4	2.24	55.0	1.47	-1.0	1.39	-27.2
2.51	2.08	54.3	2.51	54.0	1.65	3.7	1.57	-21.6
2.82	2.34	54.0	2.82	55.4	1.85	3.4	1.78	-21.9
3.18	2.63	54.0	3.18	54.7	2.08	4.1	2.00	-22.5
3.58	2.95	55.4	3.58	55.3	2.33	1.2	2.25	-19.6
3.99	3.31	54.8	3.99	55.0	2.62	4.0	2.54	-18.3
4.49	3.71	53.9	4.49	55.0	2.94	6.0	2.86	-21.2
5.04	4.17	53.9	5.04	54.0	3.30	-2.9	3.22	-21.4
5.65	4.67	54.2	5.65	54.6	3.69	3.5	3.62	-24.1
6.34	5.24	55.0	6.34	54.2	4.14	10.6	4.07	-27.0
7.13	5.89	56.1	7.13	53.5	4.65	14.0	4.58	-21.3
8.00	6.61	55.6	8.00	54.2	5.22	7.0	5.15	-21.7

Virtual Clinic
521 SW 11th
Portland, OR 97205
(503)226-3000



Name: SUB2QUAL

Chart #:

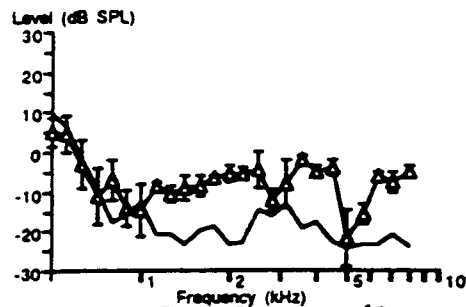
Age:

Sex:

Friday, February 17, 1995 14:41

Tester:

Distortion Product



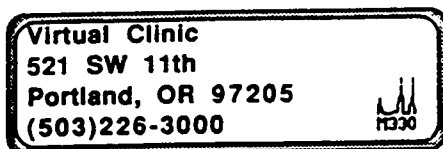
1: 55, 55 dB, 32 Time, 4 Spec. Aves: / R

Distortion Product Table

F1 level: 55 dB SPL F2 level: 55 dB SPL
Time Aves: 32 Spectral Aves: 4
Noise Retries: 4 Noise Tolerance: 10 dB SPL
 $F2 = 1.21 \cdot F1$, $F_e = \sqrt{(F1 \cdot F2)}$

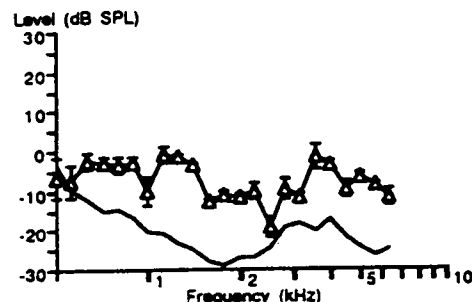
Right

F_e (kHz)	F1 (kHz)	F1 amp (dB SPL)	F2 (kHz)	F2 amp (dB SPL)	Fdp (kHz)	Fdp amp (dB SPL)	Fn (kHz)	Fn amp (dB SPL)
0.50	0.45	54.0	0.55	54.0	0.35	5.2	0.28	9.4
0.56	0.51	53.9	0.61	53.7	0.40	4.5	0.32	6.9
0.63	0.57	53.6	0.69	54.2	0.45	-3.0	0.38	-1.3
0.71	0.65	54.1	0.79	54.1	0.51	-11.4	0.43	-9.5
0.79	0.72	53.8	0.87	54.3	0.57	-6.9	0.50	-17.9
0.89	0.81	53.9	0.98	54.4	0.63	-14.2	0.56	-15.9
1.00	0.90	53.4	1.10	53.8	0.71	-14.9	0.63	-12.6
1.12	1.02	53.7	1.24	54.1	0.81	-8.8	0.73	-21.0
1.25	1.14	54.3	1.38	53.6	0.90	-10.8	0.83	-21.0
1.41	1.28	53.6	1.55	55.0	1.01	-9.1	0.94	-23.2
1.59	1.44	53.9	1.74	53.9	1.14	-8.7	1.07	-19.9
1.77	1.62	54.3	1.95	53.8	1.28	-6.6	1.21	-19.1
2.00	1.82	54.3	2.21	53.8	1.43	-5.4	1.36	-23.4
2.25	2.05	55.2	2.48	55.0	1.62	-5.7	1.54	-22.8
2.52	2.29	54.0	2.78	54.8	1.81	-4.5	1.73	-14.5
2.83	2.57	54.8	3.11	55.0	2.03	-12.1	1.96	-16.2
3.17	2.88	54.9	3.49	55.0	2.28	-8.2	2.21	-13.1
3.56	3.24	55.1	3.92	55.0	2.56	-2.0	2.49	-19.1
4.00	3.64	54.6	4.40	55.0	2.87	-5.2	2.80	-17.9
4.49	4.08	55.3	4.94	54.5	3.22	-4.2	3.14	-22.7
5.04	4.59	55.0	5.55	56.2	3.63	-22.0	3.55	-24.2
5.66	5.15	56.0	6.22	58.8	4.07	-16.0	3.99	-23.6
6.35	5.77	56.2	6.99	56.0	4.55	-6.2	4.48	-23.5
7.13	6.48	56.9	7.84	57.4	5.12	-7.8	5.05	-21.0
8.01	7.28	56.1	8.81	55.2	5.75	-5.3	5.67	-24.1



Name: sub3qual
 Chart #:
 Sex:
 Tuesday, February 14, 1995 14:30
 Tester:

Distortion Product



1: 55, 55 dB, 32 Time, 4 Spec. Aves: /R

Distortion Product Table

F1 level: 55 dB SPL F2 level: 55 dB SPL
 Time Aves: 32 Spectral Aves: 4
 Noise Retries: 4 Noise Tolerance: 10 dB SPL
 $F2 = 1.21 * F1$, $F_e = \sqrt{F1 * F2}$

Right

F_e (kHz)	F1 (kHz)	F1 amp (dB SPL)	F2 (kHz)	F2 amp (dB SPL)	Fdp (kHz)	Fdp amp (dB SPL)	Fn (kHz)	Fn amp (dB SPL)
0.50	0.45	55.0	0.55	54.0	0.35	-6.6	0.28	-3.5
0.56	0.51	53.9	0.61	53.7	0.40	-7.5	0.32	-9.8
0.63	0.57	53.6	0.69	55.2	0.45	-2.5	0.38	-12.4
0.71	0.65	54.1	0.79	54.1	0.51	-2.9	0.43	-15.4
0.79	0.72	53.8	0.87	54.3	0.57	-3.7	0.50	-14.9
0.89	0.81	54.9	0.98	54.4	0.63	-3.0	0.56	-16.6
1.00	0.90	53.9	1.10	53.8	0.71	-10.4	0.63	-20.2
1.12	1.02	54.7	1.24	54.1	0.81	-1.1	0.73	-20.9
1.25	1.14	54.3	1.38	53.6	0.90	-1.6	0.83	-23.2
1.41	1.28	53.6	1.55	54.0	1.01	-3.6	0.94	-24.9
1.59	1.44	53.9	1.74	53.9	1.14	-12.9	1.07	-28.0
1.77	1.62	54.3	1.95	53.8	1.28	-11.4	1.21	-29.1
2.00	1.82	54.3	2.21	54.8	1.43	-11.6	1.36	-27.2
2.25	2.05	55.2	2.48	55.0	1.62	-10.0	1.54	-27.0
2.52	2.29	55.0	2.78	54.8	1.81	-19.3	1.73	-24.3
2.83	2.57	55.3	3.11	54.0	2.03	-9.6	1.96	-19.5
3.17	2.88	54.9	3.49	55.0	2.28	-11.5	2.21	-18.3
3.56	3.24	55.1	3.92	55.0	2.56	-1.8	2.49	-20.4
4.00	3.64	54.6	4.40	55.0	2.87	-3.7	2.80	-17.4
4.49	4.08	55.3	4.94	55.0	3.22	-9.4	3.14	-21.9
5.04	4.59	55.0	5.55	54.2	3.63	-6.5	3.55	-24.5
5.66	5.15	55.0	6.22	54.8	4.07	-8.7	3.99	-26.6
6.35	5.77	55.2	6.99	54.5	4.55	-11.8	4.48	-25.1

Virtual Clinic
521 SW 11th
Portland, OR 97205
(503)226-3000



Name: SUB4QUAL

Chart #:

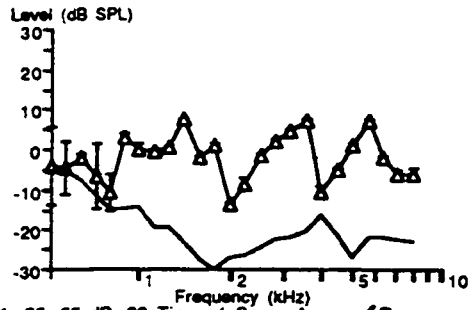
Age:

Sex:

Friday, February 10, 1995 14:46

Tester:

Distortion Product

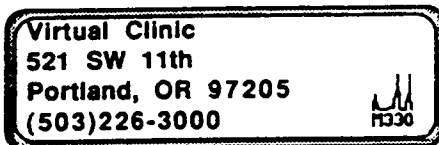


Distortion Product Table

F1 level: 55 dB SPL F2 level: 55 dB SPL
Time Aves: 32 Spectral Aves: 4
Noise Retries: 4 Noise Tolerance: 10 dB SPL
 $F2 = 1.21 \cdot F1$, $F_e = \sqrt{(F1 \cdot F2)}$

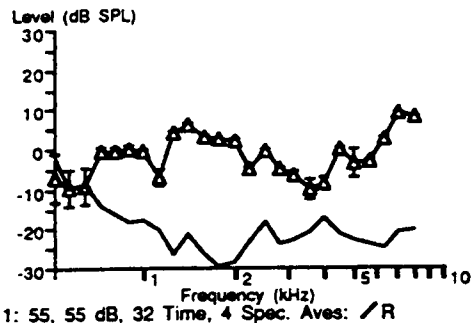
Right

F_e (kHz)	F1 (kHz)	F1 amp (dB SPL)	F2 (kHz)	F2 amp (dB SPL)	Fdp (kHz)	Fdp amp (dB SPL)	Fn (kHz)	Fn amp (dB SPL)
0.50	0.45	54.0	0.55	54.0	0.35	-4.3	0.28	-5.1
0.56	0.51	53.9	0.61	54.0	0.40	-4.5	0.32	-5.3
0.63	0.57	53.6	0.69	54.2	0.45	-2.0	0.38	-7.6
0.71	0.65	54.1	0.79	55.1	0.51	-6.4	0.43	-11.9
0.79	0.72	54.8	0.87	54.3	0.57	-10.7	0.50	-14.8
0.89	0.81	54.9	0.98	54.4	0.63	3.3	0.56	-15.0
1.00	0.90	53.9	1.10	54.3	0.71	-0.1	0.63	-14.3
1.12	1.02	53.7	1.24	55.1	0.81	-0.3	0.73	-19.4
1.25	1.14	55.3	1.38	53.6	0.90	0.7	0.83	-19.4
1.41	1.28	54.6	1.55	54.0	1.01	7.9	0.94	-23.0
1.59	1.44	53.9	1.74	53.9	1.14	-1.9	1.07	-27.6
1.77	1.62	54.3	1.95	54.8	1.28	1.1	1.21	-30.0
2.00	1.82	54.3	2.21	53.8	1.43	-13.9	1.36	-27.1
2.25	2.05	54.2	2.48	55.0	1.62	-8.5	1.54	-26.2
2.52	2.29	54.0	2.78	53.8	1.81	-1.8	1.73	-24.5
2.83	2.57	55.3	3.11	55.0	2.03	2.1	1.96	-22.3
3.17	2.88	54.9	3.49	54.3	2.28	4.5	2.21	-21.8
3.56	3.24	56.1	3.92	54.5	2.56	7.0	2.49	-20.1
4.00	3.64	54.6	4.40	55.0	2.87	-10.5	2.80	-16.4
4.49	4.08	55.3	4.94	53.8	3.22	-4.9	3.14	-21.1
5.04	4.59	55.0	5.55	54.2	3.63	1.0	3.55	-26.8
5.66	5.15	54.0	6.22	53.8	4.07	7.0	3.99	-21.7
6.35	5.77	54.2	6.99	53.0	4.55	-2.0	4.48	-21.9
7.13	6.48	52.9	7.84	54.4	5.12	-6.2	5.05	-22.3
8.01	7.28	54.1	8.81	55.2	5.75	-6.0	5.67	-22.8



Name: SUBSQUAL
 Chart #:
 Sex:
 Friday, February 10, 1995 15:48
 Tester:

Distortion Product



Distortion Product Table

F1 level: 55 dB SPL F2 level: 55 dB SPL
 Time Aves: 32 Spectral Aves: 4
 Noise Retries: 4 Noise Tolerance: 10 dB SPL
 $F2 = 1.21 * F1$, $Fc = \sqrt{(F1 * F2)}$

Right

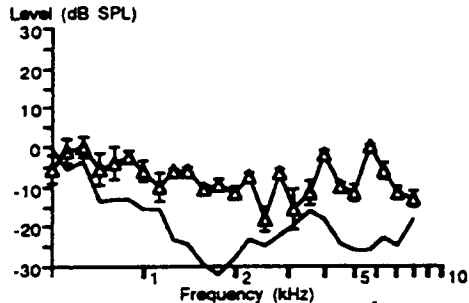
Fc (kHz)	F1 (kHz)	F1 amp (dB SPL)	F2 (kHz)	F2 amp (dB SPL)	Fdp (kHz)	Fdp amp (dB SPL)	Fn (kHz)	Fn amp (dB SPL)
0.50	0.45	55.0	0.55	54.0	0.35	-7.1	0.28	-2.1
0.56	0.51	53.9	0.61	53.7	0.40	-9.7	0.32	-9.5
0.63	0.57	53.6	0.69	54.2	0.45	-9.2	0.38	-8.9
0.71	0.65	54.1	0.79	54.1	0.51	-0.6	0.43	-14.5
0.79	0.72	54.8	0.87	54.3	0.57	-0.7	0.50	-16.3
0.89	0.81	53.9	0.98	54.4	0.63	0.0	0.56	-18.4
1.00	0.90	54.9	1.10	53.8	0.71	-0.4	0.63	-17.7
1.12	1.02	54.7	1.24	55.1	0.81	-7.3	0.73	-20.2
1.25	1.14	54.3	1.38	53.6	0.90	3.9	0.83	-26.3
1.41	1.28	53.6	1.55	54.0	1.01	6.4	0.94	-21.4
1.59	1.44	53.9	1.74	54.9	1.14	2.8	1.07	-26.3
1.77	1.62	55.3	1.95	53.8	1.28	2.6	1.21	-29.6
2.00	1.82	54.3	2.21	54.8	1.43	2.1	1.36	-28.6
2.25	2.05	54.2	2.48	54.0	1.62	-5.0	1.54	-23.5
2.52	2.29	54.0	2.78	54.8	1.81	-0.3	1.73	-18.1
2.83	2.57	55.3	3.11	55.0	2.03	-4.9	1.96	-24.0
3.17	2.88	53.9	3.49	55.0	2.28	-6.8	2.21	-23.0
3.56	3.24	55.1	3.92	55.0	2.56	-10.0	2.49	-20.9
4.00	3.64	54.6	4.40	55.0	2.87	-8.5	2.80	-17.1
4.49	4.08	55.3	4.94	55.0	3.22	0.1	3.14	-21.2
5.04	4.59	55.0	5.55	54.7	3.63	-3.5	3.55	-22.7
5.66	5.15	54.0	6.22	54.8	4.07	-3.2	3.99	-24.1
6.35	5.77	55.2	6.99	54.0	4.55	2.8	4.48	-24.9
7.13	6.48	56.9	7.84	55.4	5.12	9.0	5.05	-20.8
8.01	7.28	55.1	8.81	54.5	5.75	8.0	5.67	-20.3

Virtual Clinic
521 SW 11th
Portland, OR 97205
(503)226-3000



Name: SUB6QUAL
Chart #:
Age:
Sex:
Friday, February 10, 1995 17:55
Tester:

Distortion Product



1: 55, 55 dB, 32 Time, 4 Spec. Aves: / R

Distortion Product Table

F1 level: 55 dB SPL F2 level: 55 dB SPL
Time Aves: 32 Spectral Aves: 4
Noise Retries: 4 Noise Tolerance: 10 dB SPL
 $F2 = 1.21 * F1$, $Fc = \sqrt{(F1 * F2)}$

Right

Fc (kHz)	F1 (kHz)	F1 amp (dB SPL)	F2 (kHz)	F2 amp (dB SPL)	Fdp (kHz)	Fdp amp (dB SPL)	Fn (kHz)	Fn amp (dB SPL)
0.50	0.45	55.0	0.55	54.0	0.35	-5.8	0.28	-0.7
0.56	0.51	53.9	0.61	53.7	0.40	-1.2	0.32	-5.6
0.63	0.57	54.6	0.69	54.2	0.45	0.0	0.38	-3.7
0.71	0.65	55.1	0.79	54.1	0.51	-5.6	0.43	-13.9
0.79	0.72	53.8	0.87	54.3	0.57	-3.9	0.50	-13.0
0.89	0.81	54.9	0.98	54.4	0.63	-2.7	0.56	-13.3
1.00	0.90	53.9	1.10	53.8	0.71	-5.9	0.63	-16.0
1.12	1.02	53.7	1.24	54.1	0.81	-10.1	0.73	-15.9
1.25	1.14	54.3	1.38	53.6	0.90	-6.1	0.83	-23.3
1.41	1.28	53.6	1.55	54.8	1.01	-6.1	0.94	-24.6
1.59	1.44	53.9	1.74	53.9	1.14	-10.4	1.07	-29.3
1.77	1.62	54.3	1.95	53.8	1.28	-9.9	1.21	-32.2
2.00	1.82	55.3	2.21	53.8	1.43	-11.9	1.36	-28.0
2.25	2.05	54.2	2.48	54.0	1.62	-7.5	1.54	-23.3
2.52	2.29	54.0	2.78	54.8	1.81	-18.3	1.73	-24.9
2.83	2.57	55.3	3.11	56.0	2.03	-6.9	1.96	-22.5
3.17	2.88	54.9	3.49	56.0	2.28	-16.0	2.21	-19.7
3.56	3.24	55.1	3.92	54.0	2.56	-11.8	2.49	-16.4
4.00	3.64	54.6	4.40	55.0	2.87	-2.2	2.80	-18.2
4.49	4.08	55.3	4.94	54.0	3.22	-10.2	3.14	-24.3
5.04	4.59	55.0	5.55	54.2	3.63	-11.7	3.55	-25.8
5.66	5.15	54.0	6.22	54.5	4.07	0.0	3.99	-25.9
6.35	5.77	54.2	6.99	54.0	4.55	-6.0	4.48	-22.8
7.13	6.48	53.9	7.84	54.4	5.12	-11.8	5.05	-24.9
8.01	7.28	54.1	8.81	55.7	5.75	-13.0	5.67	-18.5

Virtual Clinic
521 SW 11th
Portland, OR 97205
(503)226-3000



Name: SUB7QUAL

Chart #:

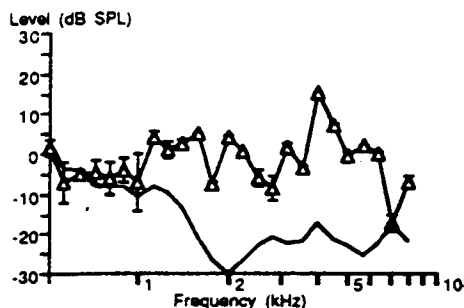
Age:

Sex:

Wednesday, February 8, 1995 19:01

Tester:

Distortion Product



1: 55, 55 dB, 32 Time, 4 Spec. Aves: / R

Distortion Product Table

F1 level: 55 dB SPL F2 level: 55 dB SPL
Time Aves: 32 Spectral Aves: 4
Noise Retries: 4 Noise Tolerance: 10 dB SPL
 $F2 = 1.21 * F1$, $F0 = \sqrt{F1 * F2}$

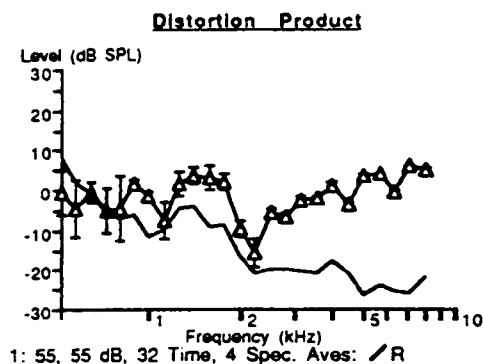
Right

F0 (kHz)	F1 (kHz)	F1 amp (dB SPL)	F2 (kHz)	F2 amp (dB SPL)	Fdp (kHz)	Fdp amp (dB SPL)	Fn (kHz)	Fn amp (dB SPL)
0.50	0.45	53.0	0.55	54.0	0.35	1.4	0.28	3.1
0.56	0.51	52.9	0.61	53.7	0.40	-7.2	0.32	-3.6
0.63	0.57	52.6	0.69	55.2	0.45	-5.2	0.38	-4.1
0.71	0.65	52.3	0.79	54.1	0.51	-4.6	0.43	-8.3
0.79	0.72	52.8	0.87	54.3	0.57	-5.9	0.50	-8.2
0.89	0.81	52.9	0.98	54.4	0.63	-4.2	0.56	-8.3
1.00	0.90	52.9	1.10	53.8	0.71	-7.4	0.63	-10.7
1.12	1.02	52.7	1.24	54.1	0.81	3.9	0.73	-8.1
1.25	1.14	53.3	1.38	54.6	0.90	0.9	0.83	-9.8
1.41	1.28	51.6	1.55	55.0	1.01	2.6	0.94	-13.0
1.59	1.44	53.9	1.74	53.9	1.14	5.3	1.07	-20.6
1.77	1.62	54.3	1.95	54.8	1.28	-7.9	1.21	-26.7
2.00	1.82	54.3	2.21	53.8	1.43	4.1	1.36	-29.8
2.25	2.05	54.2	2.48	56.0	1.62	0.3	1.54	-26.9
2.52	2.29	54.0	2.78	52.8	1.81	-6.3	1.73	-22.9
2.83	2.57	55.3	3.11	54.0	2.03	-8.6	1.96	-20.9
3.17	2.88	54.9	3.49	55.0	2.28	1.8	2.21	-22.1
3.56	3.24	56.1	3.92	54.0	2.56	-3.8	2.49	-22.0
4.00	3.64	57.6	4.40	55.0	2.87	15.0	2.80	-17.3
4.49	4.08	52.3	4.94	54.0	3.22	7.3	3.14	-21.1
5.04	4.59	53.0	5.55	54.2	3.63	-0.5	3.55	-23.1
5.66	5.15	52.0	6.22	53.0	4.07	2.3	3.99	-25.2
6.35	5.77	53.2	6.99	54.0	4.55	0.0	4.48	-22.4
7.13	6.48	52.9	7.84	54.4	5.12	-17.2	5.05	-17.8
8.01	7.28	52.1	8.81	55.2	5.75	-7.3	5.67	-21.9

Virtual Clinic
521 SW 11th
Portland, OR 97205
(503)226-3000



Name: SUB8QUALB
Chart #:
Age:
Sex:
Sunday, February 12, 1995 21:08
Tester:



Distortion Product Table

F1 level: 55 dB SPL F2 level: 55 dB SPL
Time Aves: 32 Spectral Aves: 4
Noise Retries: 4 Noise Tolerance: 10 dB SPL
 $F2 = 1.21 * F1$, $Fc = \sqrt{F1 * F2}$

Right

Fc (kHz)	F1 (kHz)	F1 amp (dB SPL)	F2 (kHz)	F2 amp (dB SPL)	Fdp (kHz)	Fdp amp (dB SPL)	Fn (kHz)	Fn amp (dB SPL)
0.50	0.45	54.0	0.55	54.0	0.35	-0.6	0.28	8.2
0.56	0.51	53.9	0.61	53.7	0.40	-4.5	0.32	1.8
0.63	0.57	53.6	0.69	54.2	0.45	-0.5	0.38	-1.0
0.71	0.65	54.1	0.79	54.1	0.51	-5.1	0.43	-5.4
0.79	0.72	53.8	0.87	54.3	0.57	-4.7	0.50	-7.2
0.89	0.81	53.9	0.98	54.4	0.63	1.5	0.56	-6.0
1.00	0.90	53.9	1.10	54.8	0.71	-1.4	0.63	-11.6
1.12	1.02	53.7	1.24	54.1	0.81	-7.8	0.73	-9.5
1.25	1.14	54.3	1.38	54.6	0.90	1.7	0.83	-4.6
1.41	1.28	53.6	1.55	55.0	1.01	3.6	0.94	-4.1
1.59	1.44	53.9	1.74	53.9	1.14	3.3	1.07	-9.2
1.77	1.62	54.3	1.95	54.8	1.28	1.9	1.21	-8.5
2.00	1.82	55.3	2.21	53.8	1.43	-9.6	1.36	-16.8
2.25	2.05	54.2	2.48	55.0	1.62	-15.7	1.54	-21.1
2.52	2.29	54.0	2.78	53.8	1.81	-5.8	1.73	-20.0
2.83	2.57	55.3	3.11	54.0	2.03	-6.6	1.96	-20.0
3.17	2.88	54.9	3.49	54.0	2.28	-2.8	2.21	-20.4
3.56	3.24	55.1	3.92	55.0	2.56	-2.3	2.49	-20.9
4.00	3.64	54.6	4.40	55.0	2.87	1.3	2.80	-17.6
4.49	4.08	55.3	4.94	55.0	3.22	-3.4	3.14	-20.6
5.04	4.59	55.0	5.55	55.2	3.63	3.8	3.55	-26.3
5.66	5.15	55.0	6.22	54.8	4.07	4.3	3.99	-23.8
6.35	5.77	55.2	6.99	54.0	4.55	-0.5	4.48	-25.2
7.13	6.48	54.9	7.84	55.4	5.12	6.0	5.05	-26.0
8.01	7.28	55.1	8.81	55.2	5.75	5.2	5.67	-21.9

Virtual Clinic
521 SW 11th
Portland, OR 97205
(503)226-3000



Name: SUB9QUALB

Chart #:

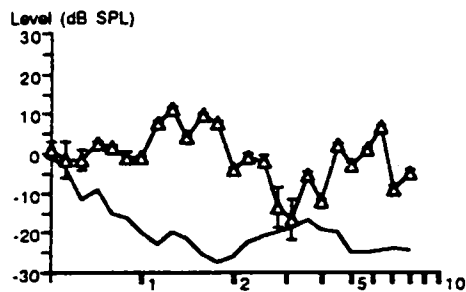
Age:

Sex:

Monday, February 13, 1995 15:57

Tester:

Distortion Product



1: 55, 55 dB, 32 Time, 4 Spec. Aves: / R

Distortion Product Table

F1 level: 55 dB SPL F2 level: 55 dB SPL
Time Aves: 32 Spectral Aves: 4
Noise Retries: 4 Noise Tolerance: 10 dB SPL
 $F2 = 1.21 * F1$, $F_e = \sqrt{(F1 * F2)}$

Right

F_e (kHz)	F1 (kHz)	F1 amp (dB SPL)	F2 (kHz)	F2 amp (dB SPL)	Fdp (kHz)	Fdp amp (dB SPL)	F_n (kHz)	F_n amp (dB SPL)
0.50	0.45	54.0	0.55	54.0	0.35	1.2	0.28	-0.6
0.56	0.51	53.9	0.61	54.7	0.40	-1.7	0.32	-3.5
0.63	0.57	53.6	0.69	54.2	0.45	-1.8	0.38	-11.7
0.71	0.65	55.1	0.79	54.1	0.51	2.4	0.43	-9.2
0.79	0.72	53.8	0.87	54.3	0.57	1.6	0.50	-15.4
0.89	0.81	54.9	0.98	54.4	0.63	-1.0	0.56	-16.3
1.00	0.90	54.9	1.10	53.8	0.71	-1.1	0.63	-19.7
1.12	1.02	53.7	1.24	54.1	0.81	7.7	0.73	-22.7
1.25	1.14	55.3	1.38	53.6	0.90	11.2	0.83	-20.0
1.41	1.28	53.6	1.55	54.0	1.01	4.1	0.94	-21.1
1.59	1.44	53.9	1.74	54.9	1.14	9.6	1.07	-25.2
1.77	1.62	55.3	1.95	54.8	1.28	7.4	1.21	-27.4
2.00	1.82	54.3	2.21	54.8	1.43	-3.9	1.36	-26.1
2.25	2.05	54.4	2.48	55.0	1.62	-1.0	1.54	-22.3
2.52	2.29	55.0	2.78	54.8	1.81	-2.0	1.73	-20.6
2.83	2.57	54.3	3.11	55.0	2.03	-13.9	1.96	-19.9
3.17	2.88	53.9	3.49	55.0	2.28	-16.8	2.21	-18.8
3.56	3.24	54.1	3.92	54.0	2.56	-5.5	2.49	-16.5
4.00	3.64	53.6	4.40	54.8	2.87	-12.2	2.80	-19.4
4.49	4.08	54.3	4.94	54.0	3.22	1.8	3.14	-19.9
5.04	4.59	55.0	5.55	54.2	3.63	-3.2	3.55	-25.2
5.66	5.15	55.0	6.22	53.8	4.07	0.8	3.99	-24.8
6.35	5.77	56.2	6.99	55.0	4.55	6.5	4.48	-24.4
7.13	6.48	55.9	7.84	55.4	5.12	-9.0	5.05	-23.7
8.01	7.28	56.1	8.81	55.2	5.75	-5.3	5.67	-24.2

APPENDIX C

CALIBRATION OF LEVELS OF PRIMARY SIGNALS

Sound levels were measured using a calibration cavity provided by the manufacturer and a 1/2 inch condenser microphone (Bruel and Kjaer, Type 4134) with a sound level meter (Bruel and Kjaer, Type 2209). Sound levels were measured and adjusted at the outset of the study at 48 frequencies in the range from 200 to 10250 Hz. The accuracy of the levels was verified at the completion of the study; levels changed by no more than 2.5 dB each frequency.

FREQUENCY (Hz)	PRE-DATA (dB SPL)	POST-DATA (dB SPL)
200	75.7	75.5
300	75	74.5
400	75	75.2
500	74.7	75
600	74.9	75.2
700	74.8	75.1
900	75.2	76
1000	75	75.5
1250	75.5	76.9
1500	75	75.5
1650	75.5	75.9
1750	75	75.1
2000	74.9	75.1
2250	75	75.9
2500	75	75.9
2750	75	75.9
3000	75.7	76
3150	74.9	75.5
3250	75.2	76
3500	75.1	76
3750	75	76.8
4000	75.5	77
4250	75	76
4500	74.9	75.5
4750	74.5	75.1
5000	75.6	76.9
5250	75	76.9
5500	75.5	77
5750	75	76.1
6000	74.9	75.8
6250	74.8	74.8
6300	75.5	76
6500	74.8	75.5
6750	75.5	76.9
7000	75	76.7
7250	75	76.8
7500	74.8	76
7750	75.1	76.3
8000	75.1	76.5
8250	74.9	76
8500	74.5	75.5
8750	75.2	76.5
9000	75.8	76.8
9250	75.5	76
9500	75.1	74.8
9750	75.1	74
10000	75.2	74.5
10250	74.8	75

APPENDIX D
RANDOMIZED ORDER OF SIGNAL PRESENTATION

Trial #1

F2/F1 (Hz)	Subject								
	1	2	3	4	5	6	7	8	9

1.03	01	05	09	03	07	04	01	02	10
1.05	02	10	01	08	05	10	03	09	06
1.07	03	03	04	09	01	09	05	01	07
1.09	04	09	03	02	10	01	09	06	02
1.11	05	08	08	06	02	05	08	08	04
1.13	06	06	07	01	04	06	02	03	01
1.19	07	01	02	10	09	02	07	07	03
1.21	08	07	06	07	03	08	10	04	08
1.25	09	02	10	05	08	03	04	05	09
1.30	10	04	05	04	06	07	06	10	05

Trial #2

F2/F1 (Hz)	Subject								
	1	2	3	4	5	6	7	8	9

1.03	09	05	04	03	08	05	10	02	09
1.05	05	10	06	07	06	04	05	04	10
1.07	08	04	10	08	03	07	06	07	08
1.09	03	07	07	02	09	10	02	01	07
1.11	01	03	02	06	04	01	07	06	06
1.13	04	08	08	05	02	06	08	08	05
1.19	02	06	09	01	10	02	03	09	04
1.21	07	01	05	09	01	09	04	03	03
1.25	06	09	03	10	05	08	01	10	02
1.30	10	02	01	04	07	03	09	05	01

Trial #3

F2/F1 (Hz)	Subject								
	1	2	3	4	5	6	7	8	9

1.03	10	04	05	04	06	07	06	10	05
1.05	06	06	07	01	04	06	02	03	01
1.07	08	07	06	07	03	08	10	04	08
1.09	01	05	09	03	07	04	01	02	10
1.11	03	03	04	09	01	09	05	01	07
1.13	02	10	01	08	05	10	03	09	06
1.19	05	08	08	06	02	05	08	08	04
1.21	09	02	10	05	08	03	04	05	09
1.25	04	09	03	02	10	01	09	06	02
1.30	07	01	02	10	09	02	07	07	03

APPENDIX E
RAW DATA FOR INDIVIDUAL PARTICIPANTS

F2/F1

	1.03	1.05	1.07	1.09	1.11	1.13	1.19	1.21	1.25	1.3
S1F1T1	N	N	7.9	5.1	8.8	14.6	12.7	11.4	11.6	5.4
S1F1T2	N	N	4.5	4	2.9	11.9	12.2	10.1	9.7	5.5
S1F1T3	N	N	4	0.7	1.9	10.1	11.4	8.4	9.2	4.5
S1F2T1	0.7	-4.2	-8	5	8.2	8.3	9.3	1	7.5	9
S1F2T2	4.3	-0.8	-3.6	5.4	8.8	8.3	4.6	-3.5	2	4.8
S1F2T3	0.8	1.7	N	N	8.3	8.3	5.1	-3	3	5.3
S1F3T1	-2.1	-3.6	N	N	-3.7	-0.5	9.4	5.6	10.2	-0.7
S1F3T2	-5.6	-6.1	N	N	-4.7	-1.7	10.7	6.8	10.2	0.3
S1F3T3	N	N	-10.8	-13.5	-6	-5.2	8.4	4.8	7.9	-0.9
S1F4T1	-5.2	-5.3	-2.7	-12.1	-9.3	-0.5	6.9	7.2	6.2	0.9
S1F4T2	-5.2	-6	-4.9	N	-6.3	-1	4.9	7.2	7.5	0.9
S1F4T3	-3	-2.5	-3.2	N	-7.6	-7.5	10.1	12	8.7	4.6
	1.03	1.05	1.07	1.09	1.11	1.13	1.19	1.21	1.25	1.3
S2F1T1	N	N	N	0.1	1.5	N	0.7	N	-5.9	N
S2F1T2	N	N	N	-7	-6.1	N	-1.8	N	N	-0.8
S2F1T3	N	N	N	-5	-6.3	-15.1	-1.8	-3.9	N	-6.3
S2F2T1	-5.5	-4	-1	1.2	N	3.8	7.8	6	7.2	0
S2F2T2	-3.5	-5.5	-2.4	-0.1	-6.7	2.3	3.9	5.3	3.5	-0.7
S2F2T3	-7	-4.3	-0.9	-0.9	-6.9	2.3	4.1	5.5	1.8	-1.7
S2F3T1	N	N	N	N	N	-10	-5.3	-8.4	-1.3	-7.4
S2F3T2	N	-8.9	N	N	N	-5.5	-2.6	-8.4	-1.3	N
S2F3T3	N	N	N	N	N	N	-4.1	-6.9	-0.6	-10.2
S2F4T1	-10.7	-9.3	N	N	N	-1.5	5.4	3.7	-2.5	N
S2F4T2	-10.5	-14	N	N	-14.8	-1.7	4.9	4.5	-3.5	N
S2F4T3	-8.5	-16.8	N	N	-7.8	-0.5	4.6	4.2	-1.5	N
	1.03	1.05	1.07	1.09	1.11	1.13	1.19	1.21	1.25	1.3
S3F1T1	N	N	7.1	5.4	7.5	3.8	3.2	1.9	-2.4	N
S3F1T2	N	N	5.3	4.2	5.2	7.4	4.9	5.6	1.2	-10
S3F1T3	N	N	6	1	4.4	5.6	2.4	3.1	-6.1	-7
S3F2T1	-6.7	N	N	-10.2	-4.7	N	-1.4	N	-1.2	-2.2
S3F2T2	-0.7	-8.5	-2.1	-8.4	-12.2	-0.5	-1.4	-8.7	N	-9.9
S3F2T3	-6.2	-9.5	-8.6	-12.6	-11.9	-3.7	-5.6	-20.7	-20.5	-8.2
S3F3T1	N	N	N	N	N	N	0.2	3.1	-3.1	-14.2
S3F3T2	N	-10.9	N	-10.7	-12	N	-2.1	-0.4	-6.3	-14.2
S3F3T3	N	-6.1	-15.8	N	-9	N	-4.1	-0.7	N	-15.2
S3F4T1	-8.7	-7.3	-11.4	-7.1	-1.1	0	4.4	4.2	2.5	-5.4
S3F4T2	-9.2	-10.3	-11.2	-9.6	-1.3	-1.5	3.4	3	1.7	-4.9
S3F4T3	-10.5	-8.8	-15.9	-8.3	-0.6	-2	2.9	2	-1	-4.1

F2/F1

	1.03	1.05	1.07	1.09	1.11	1.13	1.19	1.21	1.25	1.3
S4F1T1	N	N	7.1	4.4	6	4.1	11.2	-1.1	5.8	3.6
S4F1T2	N	N	7	1.5	4.2	3.1	4.7	-1.4	1.7	1
S4F1T3	N	N	3.8	2	3.4	3.6	6.7	-0.6	3.9	4.7
S4F2T1	6.5	0.7	-9.2	-2.7	3.7	-2.4	8.1	11.5	7.2	1.7
S4F2T2	2.5	-5.8	-6.9	-1.4	3.1	-0.2	5.6	0.8	0	-2.9
S4F2T3	2	-6.8	-7.6	-0.1	3.4	-2.5	4.1	5.3	-0.5	-4.9
S4F3T1	-0.4	-8.6	N	-4.5	1.5	0.2	6.2	4.8	6.9	-4.4
S4F3T2	-1.6	-8.4	-6.3	-4.5	1.2	2.7	6.2	5.8	9.4	-2.7
S4F3T3	1.6	-4.6	-6.3	-3.5	2.5	4.5	6.4	5.3	7.7	-1.2
S4F4T1	-8.5	N	-1.2	-11.6	-0.1	2	12.6	11.2	7.5	-0.9
S4F4T2	-11.5	-14	-8.7	N	-10.8	-0.7	10.6	11.2	9.5	-0.6
S4F4T3	-6.2	N	-1.7	-8.8	1.9	3.5	13.1	12.5	9	1.9
	1.03	1.05	1.07	1.09	1.11	1.13	1.19	1.21	1.25	1.3
S5F1T1	N	N	N	6.6	9.8	9.8	-4.8	-0.3	-1.3	-1.1
S5F1T2	N	N	-0.5	-0.5	3.7	8.6	-4.6	-1.9	-1.1	-2.3
S5F1T3	N	N	-1	3	5.9	9.4	-4.1	-3.1	1.7	-3.8
S5F2T1	N	-1.2	1.2	2	4.5	10.3	6.3	6	-1.3	-1.1
S5F2T2	-2.7	3	2.6	1.9	6.1	8.8	5.6	-2	3	4.3
S5F2T3	-7	-1	0.4	1.6	4.3	8.5	3.6	-0.5	5.8	7.3
S5F3T1	-8.4	N	-8.6	0	-2.2	-8	-3.8	-2.2	4.7	-3.2
S5F3T2	N	-11.4	-8.1	-1.2	-5.2	-5.2	-4.3	-2.9	5.2	-0.9
S5F3T3	-3.6	N	-10.1	-2.2	-1.7	-12.2	-3.1	-1.7	5.2	-3.9
S5F4T1	3	-5	-2.2	1.4	5.7	1.7	2.9	6	-0.7	-10.1
S5F4T2	2.7	-6.8	-3.9	1.6	1.9	1.2	2.6	5.2	-2	-6.1
S5F4T3	4	-3.3	-2.4	1.6	3.9	2.7	2.4	5.7	-1.5	-6.1
	1.03	1.05	1.07	1.09	1.11	1.13	1.19	1.21	1.25	1.3
S6F1T1	N	N	N	8.1	8.3	8.8	6	3.9	6.3	N
S6F1T2	N	N	N	4.5	4.9	7.9	3.4	3.9	2.2	-2
S6F1T3	N	N	N	5.7	6.2	7.4	3.9	2.9	2.7	N
S6F2T1	1	-7	-2.5	-6.2	1.2	2.6	1.6	-6.2	0.2	N
S6F2T2	-1.2	-4.8	0.6	-6.1	2.1	4.3	-1.1	-11	-4.2	-11.9
S6F2T3	-0.5	-5.5	1.9	-7.1	1.8	3.8	-3.4	-7	-4.7	-12.2
S6F3T1	-4.1	N	N	N	N	-7.2	0.9	-3.7	-5.1	-14.4
S6F3T2	N	N	-11.8	N	-9.7	-4.5	1.9	-11.2	-5.6	-12.2
S6F3T3	N	-10.9	-11.3	-10	N	N	-0.3	-10.2	-12.3	-9.4
S6F4T1	N	N	-13.7	N	-10.6	-7.2	-0.3	-6	N	-10.6
S6F4T2	-16	-13.3	-12.9	-15.6	-10.6	-4.5	0.6	-0.8	N	N
S6F4T3	N	N	-15.2	-10.8	-5.1	-4.5	1.4	0	N	-8.1

F2/F1

	1.03	1.05	1.07	1.09	1.11	1.13	1.19	1.21	1.25	1.3
S7F1T1	N	N	-1.7	5.2	5.9	4.1	N	3.1	N	N
S7F1T2	N	N	-2.5	7.7	7.7	7.4	-5.1	6.1	4.2	-4.8
S7F1T3	N	N	6.8	6.7	7.9	8.4	1.4	4.1	3.7	N
S7F2T1	-14	-8.5	-9.9	-2.6	-9.7	-0.5	4.4	3.3	0.5	-1.9
S7F2T2	N	-7	-5.6	-1.4	-7.9	-0.2	-0.9	0	-2.5	-2.4
S7F2T3	-2.2	-0.3	-7.6	0.9	4.8	7.8	4.1	2.3	-15	-0.7
S7F3T1	N	0.8	3.2	4	1.2	8.5	6.4	5.6	-3.8	N
S7F3T2	-2.1	-3.1	3.2	3.8	3.5	11	13.2	15.1	7.2	2.5
S7F3T3	-2.9	-7.4	0.7	-11.7	2.7	8.7	9.2	4.1	8.2	-7.4
S7F4T1	N	-9	N	-0.8	5.2	4.7	12.9	12	6.5	-6.4
S7F4T2	1.2	0	-2.2	-10.6	-2.1	6	15.4	10.5	14	11.6
S7F4T3	N	-12.3	-12.4	-17.8	3.7	5.2	11.4	12.5	7.7	-10.9
.	1.03	1.05	1.07	1.09	1.11	1.13	1.19	1.21	1.25	1.3
S8F1T1	N	N	N	7.9	9.3	7.1	6.4	7.4	2.5	4.2
S8F1T2	N	N	N	4	7.4	5.1	3.7	-2.4	7.4	2.7
S8F1T3	N	N	N	4.5	7.7	7.9	5.4	6.4	6.2	6
S8F2T1	-1.7	3.7	4.5	4	7.2	9.8	11.2	13.5	10	0.5
S8F2T2	-11	-2.3	-1.1	0.4	3.3	3	5.9	1	6.5	-1.9
S8F2T3	-5.2	-0.5	2.1	2.1	6.1	6.8	8.1	9.5	6.8	-4.2
S8F3T1	0.3	-4.4	-9.6	-5.5	-6	-6	1.9	0.6	2.7	-9.7
S8F3T2	N	N	N	N	-12.2	-8.7	-2.8	-7.9	-7.6	N
S8F3T3	-12.1	N	-8.8	N	-12.7	-6	-1.1	-3.7	-10.6	-13.4
S8F4T1	-0.5	0.2	-0.7	-3.6	-4.8	4.7	12.9	11.5	7.7	2.1
S8F4T2	-16.7	-10.3	-17.2	-9.6	0.4	-7.7	4.4	1.2	-6	-3.6
S8F4T3	-8	-2	-13.7	-4.1	2.4	4.5	9.6	10.5	4.5	2.6
.	1.03	1.05	1.07	1.09	1.11	1.13	1.19	1.21	1.25	1.3
S9F1T1	N	N	3.8	0.5	4.7	11.6	11.2	7.4	-0.3	8
S9F1T2	N	N	4.5	-2.5	3.4	12.6	10.9	6.9	-1.8	7.5
S9F1T3	N	N	5.3	2.5	6.9	13.1	10.7	7.6	-4.1	2.2
S9F2T1	10.5	11.7	12.1	9.4	7.1	7	8.9	2.8	8.5	3.1
S9F2T2	9.5	11.5	11.6	9.4	7.8	6.6	7.9	4.3	6.8	4.1
S9F2T3	12.5	14.5	12.4	5.1	7.6	3.8	6.1	4.8	16.5	16.1
S9F3T1	N	-9.6	N	-6.7	N	-11.2	-3.8	-1.2	5.4	4
S9F3T2	-8.4	-5.9	N	-4	-6.5	-8.5	-2.1	-1.4	4.9	4.3
S9F3T3	N	N	N	N	N	-3.7	-0.8	0.3	7.7	9
S9F4T1	-1.7	-2.8	0.1	0.1	-3.3	2.2	10.6	10	1.2	-3.6
S9F4T2	-0.7	-1	-2.2	-3.8	-3.6	1	10.1	9	2.5	-1.4
S9F4T3	-5.2	-7.5	-3.2	-4.8	-1.6	3.2	3.6	10.2	0	N

VITA

Ashley Whicker was born in Rochester, Minnesota on April 23, 1971. She received her Bachelor of Arts degree with a major in English and a minor in French from the University of North Carolina at Chapel Hill. In May of 1995, she received a Master of Arts degree in Audiology from the University of Tennessee- Knoxville. She will enter a doctoral program in Audiology and Hearing Science at the University of Texas-Austin in August of 1995 where she will also complete a Clinical Fellowship Year.