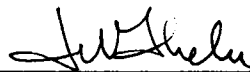


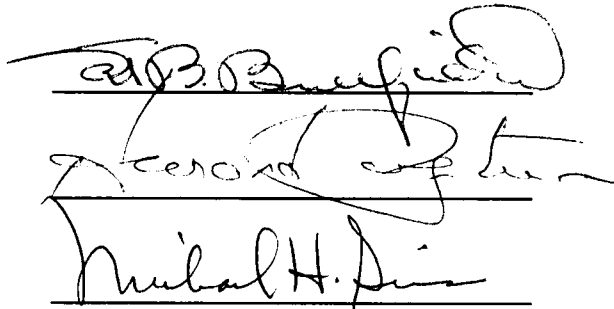
To the Graduate Council:

I am submitting herewith a dissertation written by Robert K. Rogers entitled "The Dependence of Distortion Product Otoacoustic Emissions on the Frequency Separation and the Relative Levels of the Primary Signals." I have examined the final copy of this dissertation for form and content and recommended that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Speech and Hearing Science.



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

We have read this dissertation
and recommend its acceptance:



Accepted for the Council:



Associate Vice Chancellor
and Dean of The Graduate School

DISCLAIMER

This dissertation was written by LCDR Robert K. Rogers while a student at the University of Tennessee studying for a Ph.D. in Audiology. The views expressed in this dissertation are those of the author and do not reflect the official policy or position of the Department of the Navy, Department of Defense, nor the U.S. Government.

DEDICATION

This dissertation is dedicated to my mother, Frances Rogers and in loving memory of my father, Robert L. Rogers. As a child, you taught me the importance of a good moral life style and the virtue of a hard work ethic. In return, I offer you this document as evidence of a lesson learned and the promise that my children will be raised in a similar manner.

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To the subjects, I thank each and every one of you. I am greatly aware of the inconvenience I put on you with early morning and late afternoon sessions with short notice. You were all troopers.

Last but certainly not least, thank you CAPT Ann Stokes, USAF, for allowing me to use you as a sounding board, and more importantly, allowing me to beat you up on those "special" days.

To everyone named above, Bravo Zulu.

ABSTRACT

The present study was conducted to evaluate the effects of signal conditions on distortion product otoacoustic emissions (DPOAEs). DPOAEs were recorded in response to the experimental signals from seven human subjects 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 DPOAEs were tone pairs (the primary signals): one tone (F) was fixed in level and frequency in all experimental conditions (65 dB SPL at 2003 Hz); the second tone (Fv) was presented at 45, 55, and 65 dB SPL and at seven different frequency separations above and below F (ΔF s were 65, 75, 100, 200, 300, 400, and 500 Hz). For each experimental signal, DPOAEs were measured above and below the frequencies of the primary signals at $2F - F_v$ and $2F_v - F$. The study was conducted to determine the dependence of DPOAEs on the location of Fv above and below F in frequency in conditions when F and Fv were equal and unequal in level. A second purpose was to study the dependence of DPOAE level on the location of DPOAE above and below the primary signals in frequency.

The results showed that DPOAEs located above the primary signals in frequency were suppressed in level. For DPOAEs located below the primary signals, when the variable signal (Fv) was located above the fixed signal (F) in frequency, the levels of the DPOAEs were relatively unaffected

by changes in the level of F_v or by increases in ΔF . Both effects were explained in terms of the motion of the traveling wave of the cochlear basilar membrane. DPOAE levels are reduced when they are located on the side of the primary signals with the gradually sloping traveling wave. DPOAE levels are increased when a low-level primary signal is located in the gradual slope of the traveling wave of a high-level primary signal.

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of Distortion Product Otoacoustic Emissions
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A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Robert K. Rogers
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CHAPTER I

INTRODUCTION

The cochlea is responsible for transforming mechanical energy into electrical energy. This process takes place as a result of motion of the stereocilia of the hair cells which are driven by basilar membrane movements in the Organ of Corti. These stereocilia, hair cells, and basilar membrane function together as a frequency analyzer. The commonly accepted view among researchers in the 1940's was that the cochlea was broadly tuned while retrocochlear structures were sharply tuned (Bekesy, 1960). This view was based upon studies performed on cadavers which responded passively without the addition of active cochlear processes.

The concept of a broadly tuned cochlea was questioned by Gold (1948). Gold and Pumphrey (1948) suggested that a positive and unstable feedback system in the cochlea enhanced tuning of the basilar membrane and hair cells in a manner that could account for auditory frequency selectivity without the necessity of retrocochlear filtering. They also hypothesized that this active process would form a feedback system that would create vibratory energy that would be transduced from the cochlea in a reverse direction through the middle ear to the external auditory canal. Kemp (1978) developed a signal generating and acoustic response averaging system that was capable of measuring these acoustic vibrations

(emissions) in the external auditory canal on live human subjects. These were originally called "Kemp echoes" but are now called otoacoustic emissions (OAE).

The source of the OAE is thought to be the outer hair cells on the basilar membrane (Norton, 1992; Burch-Sims & Ochs, 1992; Probst, Lonsbury-Martin, & Martin, 1991; Khanna, Ulfendahl, & Flock, 1990; Brownell 1990). Support for the outer hair cell is provided by the reticular lamina at its apical end and the basilar membrane along with nerve fibers at its basal end. Like other cells found in the body, the outer hair cell has a cytoskeleton structure. However, the cytoskeleton structure of the outer hair cell is segregated at the base and apex, allowing the body of the cell to move in response to changes in cell polarity as a result of acoustic stimulation. This active electromotile response is believed to provide a positive mechanical feedback, sometimes referred to as cochlear amplification, which increases the movement of the basilar membrane, thus increasing the sensitivity of the system. It is this addition to the motion of the basilar membrane traveling wave that travels in a reverse direction and can be recorded in the ear canal as an OAE.

OAEs can be measured as responses to click or tonal signals or as intermodulation products resulting from stimulation with two or more tones (Kemp, 1979; Probst, Lonsbury-Martin, & Martin, 1991). Intermodulation distortion products are present because the ear is a nonlinear processor of acoustic signals. When the levels of the intermodulation distortion products

are measured in the ear canal, they are called distortion product otoacoustic emissions (DPOAEs). In the present research, DPOAE procedures were used as a method for studying cochlear function.

In a nonlinear transmission system, intermodulation distortion products can be generated by presenting two pure-tones (primary signals) that are usually equal in level. Intermodulation distortion products occur at the sums and differences of multiples of the frequencies of the primary signals (e.g., $f_2 - f_1$, $2f_1 - f_2$, $2f_2 - f_1$, etc.). In Figure 1, the frequency spectra are shown for tone pairs passed through first-, second-, and third-order nonlinear systems. In the bottom spectrum of Figure 1, for the third-order nonlinear system, it can be seen that there are prominent intermodulation distortion products at $2f_1 - f_2$ (2000 Hz) and at $2f_2 - f_1$ (5000 Hz) that are equal in level. Another group of distortion products are seen from 9000 to 12000 Hz. In studies on ears, the highest level DPOAEs have been found at $2f_1 - f_2$ which is called the cubic difference tone (Kemp, 1979; Lonsbury-Marín, Martin, Probst, & Coates, 1987), and as a result, the majority of research has been conducted using the level of the cubic difference tone as the only DPOAE measure.

In studies on the signals used to elicit DPOAEs, it has been found that the levels of the distortion products at $2f_1 - f_2$ depend complexly on the frequency separation of f_1 and f_2 and the relative levels of f_1 and f_2 . When f_1 and f_2 are close in frequency, DPOAE levels are low, but as the frequency separation is increased, DPOAE levels increase rapidly until a maximum is

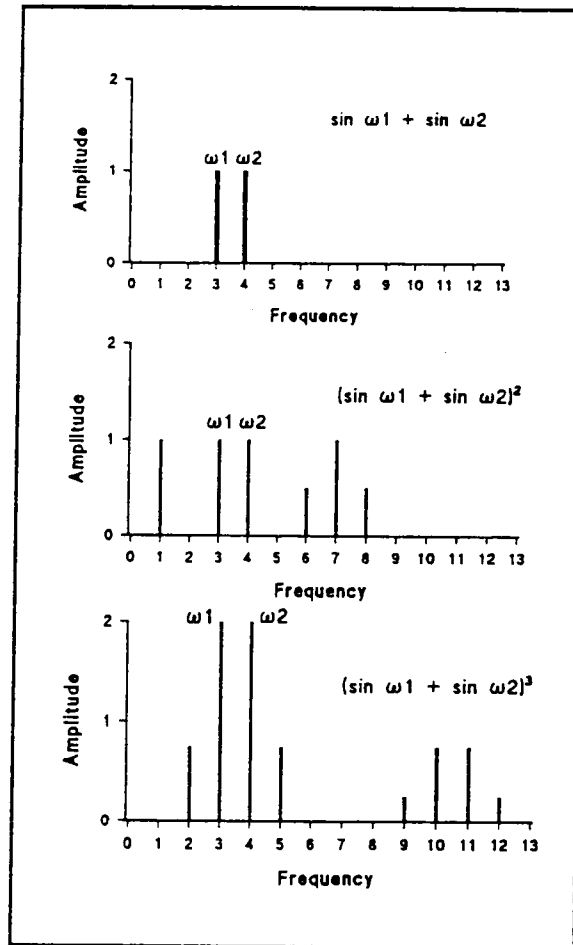


Figure 1. Frequency spectra from a two-tone signal passed through a linear system, a second-order nonlinear system, and a third-order nonlinear system (from Osterhammel & Rasmussen, 1992).

reached (Harris, Lonsbury-Martin, Stagner, Coates, & Martin, 1989; Gaskill & Brown, 1990). In most cases, the maximum is reached when f_2/f_1 is approximately 1.21 -- however this depends both on the frequencies and levels of the primary signals. At the optimal frequency separation for f_1 and f_2 , there is evidence to indicate that the highest level DPOAEs are not obtained when f_1 and f_2 are equal in level, but rather when the level of f_1 is higher than the level of f_2 by 15 dB (Gaskill & Brown, 1990).

If the cochlea functions as a third-order nonlinear system as shown in Figure 1, $2f_1 - f_2$ (2000 Hz) would be expected to be a prominent DPOAE, but the distortion products at 5000, 10000, and 11000 Hz would be expected to be equally prominent. However, the available data on DPOAEs indicate that levels of DPOAEs obtained at $2f_1 - f_2$ are substantial higher than the levels of DPOAEs at all other frequencies. In Figure 2, schematic diagrams are shown of traveling wave envelopes on the basilar membrane of the cochlea for signals used to elicit DPOAEs. The DPOAEs are indicated by lines at the frequencies at which they occur; they are not represented as traveling waves because there is ongoing discussion concerning as to whether the DPOAEs have traveling waves of their own and, if they do, where they are located on the basilar membrane (Martin, Lonsbury-Martin, Probst, Scheinin, & Coates, 1987).

The diagrams in Figure 2 illustrate that at the frequency of the DPOAE located below the primary signals is unaffected by the basilar membrane traveling wave motion. The DPOAE located above the primary signals

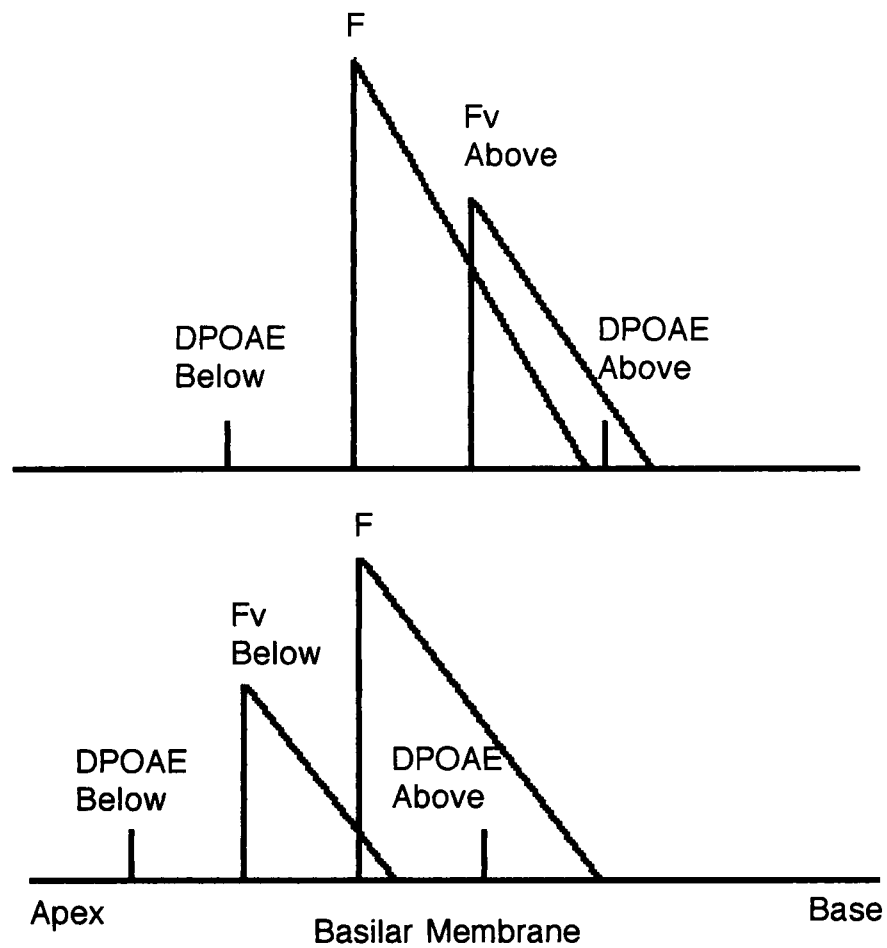


Figure 2. Schematic representation of the location of the basilar membrane traveling wave envelopes for the experimental signals F and Fv. DPOAE responses for 2F-Fv and 2Fv-F are shown as short lines.

occurs within the traveling waves of the primary signals and may be affected by the motion of the traveling wave. It is hypothesized that the traveling wave motion may account for the differences in levels of DPOAEs that fall above and below the primary signals. In the present study, the signal paradigms shown in Figure 2 were used to study the dependence of DPOAE levels on the location of the DPOAE above and below the primary signals. The primary signals were varied in two ways: primary signals were presented at seven different frequency separations, and the pairs of tones in the primary signals were presented at three different relative levels (F was fixed in level with F_v equal in level to F , 10 dB less than F , and 20 dB less than F).

With the signal paradigms shown in Figure 2, it can be seen that the location of F_v relative to F may also affect the DPOAEs. Using the signal paradigm described above, it was also possible study the effect of the location of F_v on the DPOAEs as well as to study the affects of DPOAE location on DPOAE levels.

The purpose of the present study was to determine the extent to which DPOAEs depend on the interaction of basilar membrane traveling waves from primary signals and on the location of the DPOAE above or below the primary signals. There were two research questions: 1) for any pair of primary signals, do the levels of DPOAEs that fall above and below the signals differ, and 2) when the levels of the primary signals differ, do the

levels of the DPOAEs depend on whether the primary signal that is lower (F_v) in level falls above or below the primary signal that is higher in level (F). These effects were studied as a function of the frequency separation of the primary signals and as a function of the relative levels of the primary signals.

CHAPTER II

REVIEW OF LITERATURE

General

One of the most significant findings in the area of the cochlear physiology is the discovery of the OAE. The fact that the cochlea not only receives and transmits sounds, but also emits its own sounds has offered an opportunity to evaluate cochlear function in a way never before performed. With the development of equipment capable of measuring and recording the OAE (Kemp, 1978), came the opportunity to understand and evaluate the active processes taking place within the Organ of Corti in the cochlea. This window into cochlear function has received much attention in recent years and has offered information on how the cochlea functions that previously could only be theorized. It was a major finding that the cochlea not only transmits sounds but produces its own acoustic energy and transmits this energy back through the cochlea (reverse direction) allowing recording acoustic vibrations in the external auditory canal (Brownell, 1990; Probst, Lonsbury-Martin, & Martin, 1991). This method has led to new procedures in the investigation of measurements of auditory function and sensitivity, outer hair cell function, cochlear traveling waves, and cochlear tuning.

Origins of the OAE

The source of the OAE is thought to be the outer hair cells on the basilar membrane (Khanna, Ulfendahl, & Flock, 1990; Brownell 1990; Probst, Lonsbury-Martin, & Martin, 1991; Norton, 1992; Burch-Sims & Ochs, 1992). Support for the outer hair cell is provided by the reticular lamina at its apical end and the basilar membrane along with nerve fibers at its basal end. Like other cells found in the body, the outer hair cell has a cytoskeleton structure. However, the cytoskeleton structure of the outer hair cell is segregated at the base and apex, allowing the body of the cell to move in response to changes in cell polarity as a end result of acoustic stimulation. This electromotile response is believed to provide a positive mechanical feedback, sometimes referred to as cochlear amplification, that increases the movement of the basilar membrane, thus increasing the sensitivity of the system. It is this addition to the motion of the basilar membrane traveling wave that travels in a reverse transduction manner and can be recorded in the ear canal as an OAE.

Whitehead, Lonsbury-Martin, and Martin (1991) investigated the source of the DPOAE for low-and high-level primary signals in the rabbit. In their study, low level primary signals (45 dB SPL) and high level primary signals (75 dB SPL) were used to elicit DPOAE over time while the animals were deprived of oxygen and differing levels of drugs known to destroy the cochlear outer hair cells. The DPOAEs evoked by the low level primary signals were abolished within a few minutes of induction of anoxia while

DPOAEs evoked by high level stimulation were unchanged. Also, low level emissions were temporarily abolished, with complete recovery, by an acute administration of ethacrynic acid while high level emissions were only slightly effected. A gentamicin and ethacrynic acid combination, which would be expected to produce significant hair cell damage, eliminated DPOAEs elicited by low level primary signals and greatly reduced DPOAEs elicited by high level primary signals. The authors suggested that the data indicated that low level DPOAEs may reflect the active micromechanical processes in the cochlea. However, DPOAEs elicited by high level primary signals may reflect the true passive distortion response of the cochlea.

Martin, Lonsbury-Martin, Probst, Scheinin, and Coats (1987) investigated the origin of the DPOAE. They attempted to determine if the DPOAE originated from activity at the place associated with the frequency of the distortion product versus the place associated with the area of overlap between the primary signals (f_1 and f_2). Using a suppression-tone methodology and interference-tone experiments, they found that the level of the DPOAE at $2f_1 - f_2$ was suppressed most when the suppressor or interfering tone was in the area of the geometric center of the primary signals. Though their results suggested that the geometric center of the primary signals was mostly responsible for the generation of a DPOAE at $2f_1 - f_2$, the area surrounding f_1 and f_2 also contributed to the creation of the DPOAE.

Signal Conditions that Affect DPOAEs

The effects of the frequency ratio of the primary signals and the levels of the primary signals has been studied by several investigators. Harris, Lonsbury-Martin, Stagner, Coats, and Martin (1988) investigated the effects of primary-tone separation on the level of DPOAEs. In their study, DPOAE were elicited from ten normally functioning human ears at 1, 2.5, and 4 kHz by equal level primary signals at 65, 75, and 85 dB SPL. The f_2/f_1 ratios were varied in 0.02 increments from 1.01 - 1.41 (4 kHz), 1.01 - 1.59 (2.5 kHz), or 1.01 - 1.79 (1 kHz). Their results showed that for all three primary signal levels, the larger ratios (greater separation of the primaries) were more effective at generating DPOAEs at 1 kHz than at 4 kHz. When all conditions were considered, an f_2/f_1 ratio of 1.22 yielded the largest DPOAE. When primary signal level was evaluated, the authors noted that smaller f_2/f_1 ratios were superior in generating DPOAEs in response to the primary signal at 65 dB SPL, and larger ratios elicited larger responses with primary signals at 75 and 85 dB SPL.

Gaskill and Brown (1990) also investigated the effects of primary signal separation and primary signal levels on DPOAEs. In agreement with Harris, Lonsbury-Martin, Stagner, Coats and Martin (1989), they found that, all conditions considered, the best average optimal ratio in order to obtain the largest DPOAEs is 1.225. Also, using this optimal stimulus ratio, they evaluated the effects of varying primary signal levels on the DPOAE. Their data indicated that as the level of one primary signal is increased relative to

the other primary signal, the DPOAE grew, saturated, and in most cases began to roll over. They found that for primary signal levels below 60 dB SPL, optimal DPOAE levels were obtained when the level of the first primary was 15 dB lower than the level of the second primary and that the DPOAE amplitude was approximately 30 dB below the level of the second primary. Saturation was achieved for primary signal levels slightly above 60 dB SPL. The authors concluded that with low level primary signals, DPOAE measurements are an objective measures of outer hair cell function.

Sutton, Lonsbury-Martin, Martin, and Whitehead (1994) performed a similar study investigation the dependence of the level of the DPOAE on the level of f_1 and f_2 . Using an f_2/f_1 ratio of 1.22, they obtained an input/output function by systematically decreasing f_2 while adjusting f_1 to acquire the maximum DPOAE level. They found that lowering the level of f_2 relative to f_1 resulted in an increase of the DPOAE level of 2 to 3 dB. Also, when fatiguing the auditory system by over-exposure to tones, lowering f_2 relative to f_1 greatly improved the DPOAE sensitivity. They concluded that, even though a modest increase in DPOAE level was obtained when the f_2 primary signal was lower than the f_1 primary signal, this stimulus paradigm may be better for eliciting DPOAE than using f_1 and f_2 equal in level.

Cochlear Tuning

Psychophysical Data on Cochlear Tuning. Early data available on cochlear tuning were generated from masking studies in which

one pure tone was used to mask another pure tone. Wegel and Lane (1924) evaluated the masking effects of a 1200 Hz tone at a 80 dB sensation level on tones of various frequencies ranging from 400 to 4000 Hz (See Figure 3). In this study, the 1200 Hz tone remained constant as the intensity of each of the secondary tones were varied until the masked threshold was obtained. The masked thresholds were then plotted as a function of frequency. The resulting function shows the masking produced by the traveling wave on the basilar membrane. Using primary signal levels of moderate intensities resulted in the production of aural harmonics which are seen as beats and represented graphically at frequencies that are near the frequency of the signal or the masking tone or its harmonics. The irregularities in the function in Figure 3 are due to the beating and distortion phenomena. Even still, the resulting tuning curve showed a very steep slope on the low frequency side of the 1200-Hz tone with a much more gradual slope on the high-frequency side.

Egan and Hake (1950) conducted a similar experiment but, in an attempt to overcome the beats, used a slightly different method. They used a primary tone of 400 Hz and a narrow band masking stimulus whose center frequency was 410 Hz with a bandwidth of 90 Hz. This interaction between the noise and the pure tone resulted in fewer and less pronounced beats. Similar to the Wegel and Lane (1924) study, a steep slope is evident on the low frequency side with a much more gradual slope on the high frequency side. It is suggested that the slope asymmetry may be due to the asymmetry

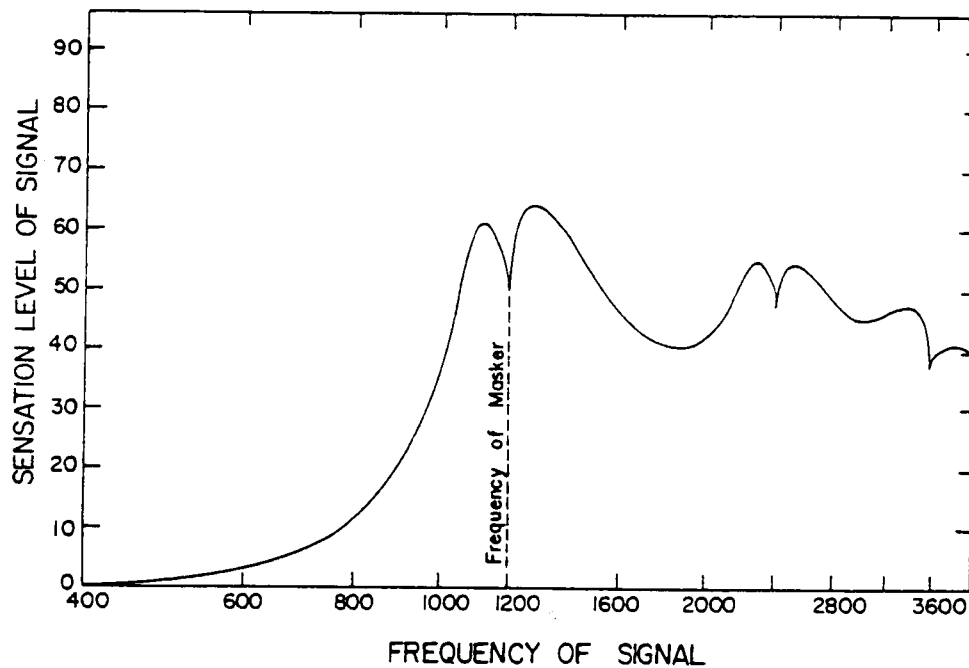


Figure 3. Masking pattern produced by an 80-dB SPL pure tone at 2000 Hz. Note the upward spread of masking above 1200 Hz due to basilar membrane traveling wave activity in the cochlea. (Adapted from Wegel & Lane, 1924)

of the basilar membrane traveling wave. Bekesy's (1960) work showed that the high frequency side of point of maximum displacement on the basilar membrane has a gradual slope while, after the maximum displacement, on the low frequency side, the slope is steep.

Physiological Data on Cochlear Tuning. Cochlear tuning has been described in numerous physiologic studies. Measures of cochlear tuning obtained from single neural units in the auditory nerve showed that filter slopes of as much as 300 dB/octave were obtained on the steepest portions of the tuning curves (Kiang, 1965). Results of studies using the Mössbauer technique indicated that basilar membrane motion alone may be sufficient to account for tuning seen in single neural unit studies (Johnstone & Boyle, 1967; Rhode, 1970).

Cochlear tuning curves have also been generated using other physiologic measures. Gibian and Kim (1982) obtained cochlear microphonic tuning curves from chinchilla's and DPOAE tuning curves at $2f_1 - f_2$ (cubic difference tone) and $f_2 - f_1$ (difference tone). The latter was performed by holding a distortion frequency constant near the characteristic frequency of the recording site and varying the f_1 and f_2 stimulus frequencies. The DPOAE responses, which were recorded in the near field using micropipettes, were found to be very similar to recordings obtained from the cochlear microphonic procedures. Kemp and Brown (1984) performed a similar study on Mongolian gerbils in which they compared iso-

suppression tuning curves measured as a cochlear microphonic response from the round window with DPOAEs recorded in the external auditory canal. In the procedure used to measure the DPOAE tuning curve, a third tone was introduced to act as a suppressor. DPOAE were recorded at $2f_1 - f_2$ for each suppressor frequency. The intensity of suppressors necessary for 6 dB suppression of both the cochlear microphonic and the DPOAE were compared and plotted at a number of different suppressor frequencies and intensities. This resulted in an iso-suppression tuning curve for each frequency tested. Good agreement was found between the tuning curves recorded by the DPOAE procedure and those obtained through cochlear microphonic recordings. The same year, Brown and Kemp (1984), using a similar stimulus paradigm, recorded the suppressibility of $2f_1 - f_2$ in the gerbil and in man. These resulting iso-suppression tuning curves using a third tone suppressor were very similar for man and gerbil.

More recent work in the area of iso-suppression tuning curves has been done by Köppl and Manley (1993). Their work, conducted on the bobtail lizard, revealed tuning characteristics that were very similar to those of mammals (Zurek, 1985; Brown & Kemp, 1984), even though the hearing-organ structure and function is significantly different between the two groups. They concluded that these findings suggest that the mechanisms responsible for the DPOAE are based on basic hair cell properties and not on accessory structures that may not be shared across species. These

investigators also concluded that iso-suppression techniques provided valid measurement of the active cochlear processes.

DPOAE Filters

Brown, Gaskill, Carlyon, and Williams (1993) noted that the cubic difference DPOAE ($2f_1 - f_2$) generated when the primary signals were progressively separated reaches a maximum when the frequency of the DPOAE falls just over half an octave below the frequency of the higher frequency primary stimulus (f_2). This peak occurs at an f_2/f_1 ratio of 1.2 which is consistent with previous research on optimal signal conditions for DPOAEs. In an effort to further investigate the idea that the maximum distortion product falls one-half octave below the higher frequency primary, DPOAEs were measured for a fixed f_2 at 4 kHz and 40 dB SPL while sweeping f_1 from 2837 to 3960 Hz at 55 dB SPL in eight human subjects with normal auditory function. For comparison, a 4000 Hz psychophysical tuning curve was generated using a notched-noise method. The authors reported a high correlation between the objectively measured tuning of the distortion peak and the equivalent tuning measured psychophysically in six of the subjects for whom good DPOAEs were obtained. The authors concluded that the peak in the DPOAE occurs one-half octave below the higher frequency primary signal due to the existence of a cochlear partition filter. This hypothesis led to speculation that the DPOAE peaks may be influenced by the tuning of the tectorial membrane. They referred to the

work of Allen (1980) which, in Allen's cochlear model, "the tectorial membrane is tuned to a frequency about half an octave below the frequency to which the basilar membrane is tuned (f_2) at any one place on the cochlear partition."

Stover, Neely, and Gorga (1994) further investigated the characteristics of the cochlear partition filter. While holding f_2 constant at half octave intervals from 2 to 8 kHz, and $f_1=f_2$ in level, f_1 was stepped from ratios of 1.02 to 1.58 in 25 Hz steps for each f_2 until a complete $2f_1 - f_2$ DPOAE filter function was obtained. They reported that the general half-octave relationship was seen. However, they found some systematic differences. As the frequency of f_2 was increased from 2 to 8 kHz, the center frequency of the filter shifted from about -0.8 octave to about -0.4 octave. They reported a similar shift as the primary stimulus levels were increased up to 75 dB SPL. The purposes of the present study was to determine the extent to which DPOAEs depend on the interaction of basilar membrane traveling waves from primary signals and on the location of the DPOAE above or below the primary signals. Also, to determine if the data in the present study provides evidence in support of the existence of a DPOAE filter. There were two research questions: 1) for any pair of primary signals, do the levels of DPOAEs that fall above and below the signals differ, and 2) when the levels of the primary signals differ, do the levels of the DPOAEs depend on whether the primary signal that is lower (F_v) in level falls above or below the primary signal that is higher in level (F).

CHAPTER III

METHOD

Overview

In the present study, DPOAEs were measured in normal-hearing subjects to examine effects related to basilar membrane traveling wave activity in the cochlea. The dependence of DPOAE levels on interactions between primary signals and on the location of the DPOAE relative to the primary signals was determined using a paradigm in which the relative levels of the primary signals and the frequency separation of the primary signals were varied.

Subjects

The subjects were seven female volunteer subjects ranging in age from 23 to 29 years with a mean age of 25 years. Otoscopy was performed on each subject 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 1000, 1500, 2000, 3000, and 4000 Hz of 15 dB 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. The

integrity of the uncrossed acoustic-reflex arc was established by obtaining ipsilateral acoustic-reflex thresholds, using a probe frequency of 226 Hz, at 95 dB HL or less at 1000 and 2000 Hz. Audiometric data for subject qualification are shown in Appendix A.

Each subject was also required to have measurable DPOAEs for 55-dB SPL primaries in one-sixth octave intervals from 1000 to 3000 Hz. The frequency ratio of the primaries was 1.21. Measurable responses were DPOAEs that were at least 3-dB higher than the noise in adjacent frequency bands. DPOAE subject qualification data are shown in Appendix B.

Equipment

Experimental signals 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 IIfx). The test instrument generated the primary signals used to elicit the DPOAEs. These signals were delivered to the ear through a probe assembly that was sealed in the external auditory canal using a tympanometry probe tip. Response measurement was accomplished through a measurement microphone that was also housed in the probe assembly. Acoustic data were recorded with the microphone, amplified, and stored on the computer hard drive. The data that was recorded was spectral information from 0 to 20000 Hz in 10-Hz wide bands. Evaluation of the DPOAE data was accomplished using custom software (Virtual Corporation)

that displayed the response frequency spectrum and had a cursor that allowed for 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 twelve frequencies in the range from 900 to 3150 Hz. The accuracy of the levels was verified at the completion of the study; levels changed by no more than 1 dB each frequency (See Appendix C).

Data were collected with the subject seated in a comfortable chair in a double-walled, sound-treated room (Industrial Acoustics Company, Model 1203-A). The DPOAE probe assembly and preamplifier were located in the sound-treated room with the subject, and the otoacoustic emissions test instrument, computer, and examiner were located outside 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.

Signals

The primary signals were composed of two pure tones. One of the tones (F) was held constant in frequency at 2003 Hz and in level at 65 dB SPL for all experimental conditions. The other primary signal in the pair (Fv) was a tone at 45, 55, or 65 dB SPL. Thus there were three sets of primary

signal pairs: 1) Fv and F equal in level; 2) Fv lower in level than F by 10 dB; and 3) Fv lower in level than F by 20 dB.

In addition to the three relative level conditions, there were fourteen frequency separation (ΔF) conditions for the primary signals. The frequencies of Fv and frequency separations between F and Fv are shown in Table 1. The frequency separations were selected so that Fv would be presented at symmetrical frequency intervals -- in Hz -- above and below F. There were seven frequency separations with nominal values of 65, 75, 100, 200, 300, 400, and 500 Hz; the actual frequency separations deviated from the nominal values by no more than 4 %.

For each ΔF condition, signals were presented in an ascending level sequence. The level of F was held constant at 65 dB SPL while the level of Fv was increased from 30 to 75 dB SPL in 5-dB steps. In the present study, the analysis was restricted to three levels of Fv: 45, 55, and 65 dB SPL. The data obtained at other levels of Fv were stored for future analysis.

The frequency spectra for the experimental signals with the smallest and largest ΔF s are shown in Figure 4; the distortion products generated by these signals are also shown. For each ΔF , there was an experimental condition in which Fv is greater than F and a corresponding condition in which Fv was less than F. In the examples shown in Figure 4, the level of Fv was lower than the level of F.

The signal conditions shown in Figure 4 permitted the comparison of DPOAE effects when Fv falls above and below F for specified ΔF s. It should

Table 1. Experimental signals: F (2003 Hz) and the different frequency values of F_v .

NOMINAL ΔF (Hz)	$F_v < F$		$F_v > F$	
	F_v (Hz)	F_v/F	F_v (Hz)	F_v/F
65	1938	0.97	2067	1.03
75	1927	0.96	2078	1.04
100	1906	0.95	2099	1.05
200	1798	0.90	2207	1.10
300	1701	0.85	2304	1.15
400	1604	0.80	2401	1.20
500	1507	0.75	2509	1.25

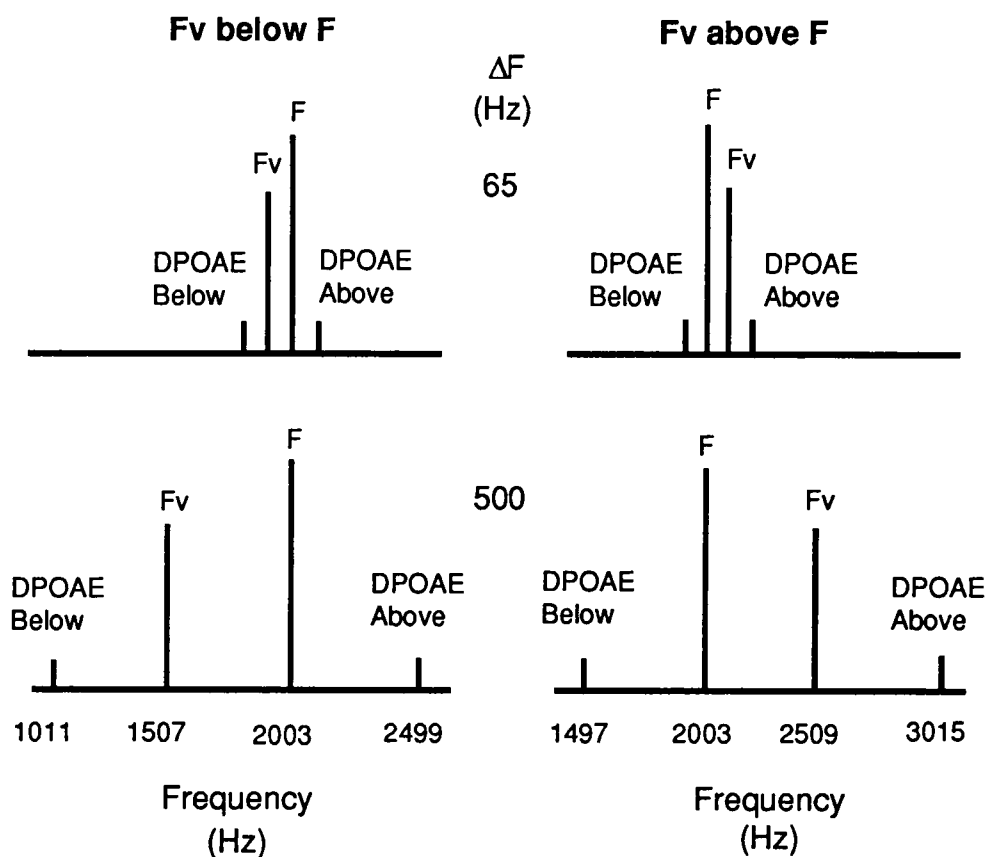


Figure 4. Theoretical spectra of selected experimental signals and the DPOAEs ($2F-F_v$ and $2F_v-F$) for each experimental signal condition are depicted. The upper portion shows the signals and the DPOAEs for the smallest ΔF condition (65 Hz) and the lower portion shows the signals and the DPOAEs for the largest ΔF condition (500 Hz) along with their corresponding frequency. ΔF conditions at 75, 100, 200, 300, and 400 Hz are not shown.

be noted that for each ΔF condition, different regions of the basilar membrane are stimulated. In the extreme case ($\Delta F = 500$ Hz), when $F_v > F$, the primaries are located at 2000 and 2500 Hz while in the corresponding condition, when $F_v < F$, the primaries are 2000 and 1500 Hz. Thus, DPOAE effects for corresponding ΔF conditions were obtained as a result of the stimulation of different regions of the basilar membrane.

For each signal condition, the DPOAEs were measured from a response frequency spectrum that was obtained using time and spectral averaging procedures. For each condition, four frequency spectra were obtained; each of the four spectra were computed from an averaged time waveform based on 64 signal presentations. The time waveforms were averaged over 64 signal presentations to reduce the noise floor by 15 dB before a Fourier analysis was performed to obtain a frequency spectrum of the data. This procedure was repeated four times to obtain four frequency spectra. The four frequency spectra were then averaged to obtain the single frequency spectrum from which DPOAE levels were measured. Averaging the frequency spectra did not reduce the noise floor, but it did give a more stable estimate of the DPOAE levels which can fluctuate over time. In preliminary studies, when DPOAE levels were unstable over time, it was found that the most stable measures of DPOAE levels were obtained using a combination of time and spectral averaging rather than using either time or spectral averaging exclusively.

Responses

The data record for each trial was a single frequency spectrum that included the averaged sound levels of the primary signals, the DPOAEs, and the ambient noise in the ear canal. The frequency spectrum was displayed on a computer screen which permitted the measurement of sound level in each 10-Hz band from 0 to 20000 Hz. An example of a response frequency spectrum is shown in Figure 5. The spectral peaks can be seen for F at 2003 Hz and Fv at 2304 Hz. The level of F and Fv were equal at 65 dB SPL. For each trial in the study, the levels of the primaries were verified from the response frequency spectrum. For 1758 of 1764 signal presentations, the levels of both primaries were within 2.0 dB of the nominal levels; in six presentations, the levels of Fv for the 45-dB SPL condition were 2.5 or 2.6 dB below the nominal level.

In Figure 5, two DPOAEs can be seen: the DPOAE above the primaries which is located at $2F_v - F$, and the DPOAE below the primaries which is located at $2F - F_v$. Notice that the DPOAE below the primaries is higher in level than the DPOAE above the primaries. The measurements of DPOAE levels was also obtained from the response frequency spectrum. When DPOAE levels were low, it was necessary to determine whether the level that was measured was due to signal or to noise. Decisions concerning the validity of the DPOAE were made using the two contiguous 10-Hz bands that fell above and the two that fell below the DPOAE. A DPOAE was considered to be valid when the level of the DPOAE was at

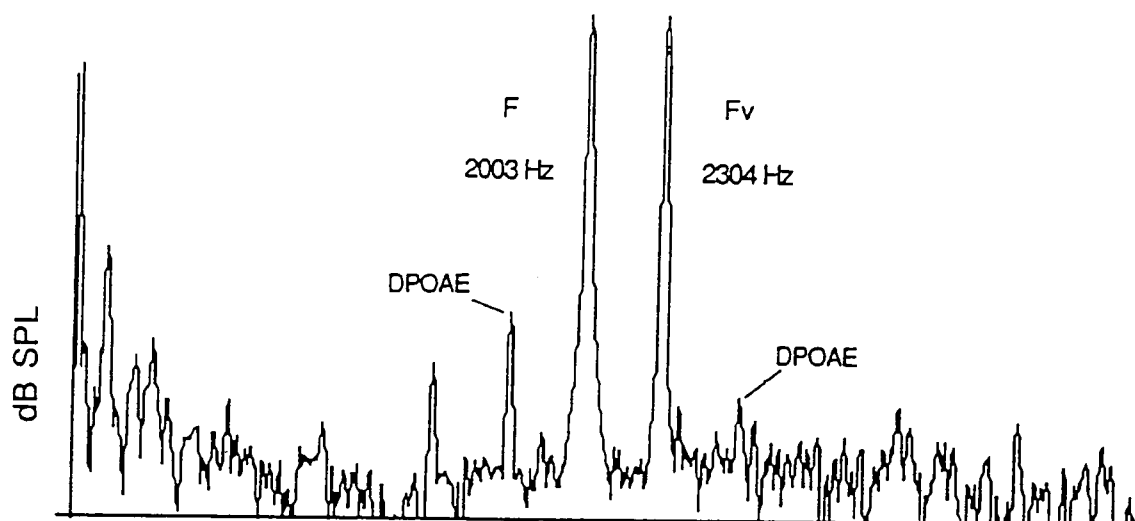


Figure 5. Response frequency spectrum showing the primary signals, F and F_v , and DPOAEs at $2F-F_v$ and $2F_v-F$. In this example, F_v is above F and ΔF is 300 Hz. These results were selected as an example of strong responses. Note that the level of the DPOAE below the primaries is higher than the level of the DPOAE above the primaries.

least 3 dB greater than the level in each of the noise in the two 10-Hz bands above and the two below. This rule was used for the analysis of a majority of the data.

For the conditions in which the ΔF was small (65, 75, and 100 Hz), there were instances in which there was an interaction of one of the primary signals and the DPOAE. An example of this is shown in Figure 6. In this example, with F_v at 2099 Hz, the DPOAE that falls above F_v is located at 2195 Hz, and is situated on a steeply sloping pedestal. For F at 2003 Hz, the DPOAE at 1907 Hz is also located on a steeply sloping pedestal. In these cases, the DPOAE appeared to be enhanced in level by the presence of the pedestal. Though the DPOAE is clearly present, it would not qualify as valid DPOAE using the rule stated above. Therefore, a second rule was established for determining the validity of the DPOAE on a pedestal. A DPOAE was considered to be valid when 1) the level of the DPOAE was at least 3 dB greater than the level of the noise in three of the four contiguous 10-Hz bands above and below the DPOAE, and 2) the level of the DPOAE had to be at least 3 dB higher than the average level of the noise in the two contiguous 10-Hz bands above and below the DPOAE. With both rules, the decisions regarding the validity 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 level of the DPOAE.

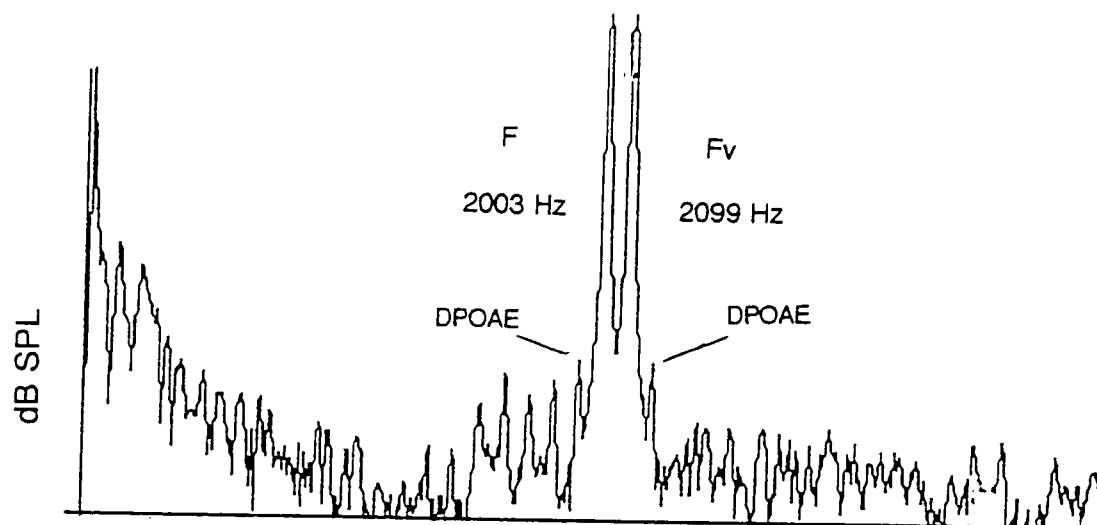


Figure 6. Response frequency spectrum showing the primary signals, F and F_v , and DPOAEs at $2F-F_v$ and $2F_v-F$. In this example F_v is above F and ΔF is 100 Hz. These results were selected as an example of pedestal effects for the DPOAEs above and below the primary signals. These DPOAE responses have been identified as being enhanced.

Procedures

There were three experimental sessions for each subject. At the beginning of the first session, the procedures were explained to the subject, and the principal investigator answered any questions asked by the subject. Subjects then read and signed the informed consent form (see Appendix D). Next, the otoscopic and audiologic qualification described in the Subjects section of this chapter was conducted. The last part of the first experimental session was spent collecting the data for Trial 1 of the study. The duration of the first session was approximately three hours. Subjects were given scheduled rest periods of 10 to 15 minutes every hour -- or more often if requested by the subject. The remaining experimental data was collected in the second and third sessions which each lasted 2 to 2.5 hours.

In each experimental session, the subject 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 subject. In each of the three experimental trials, the subject received all fourteen ΔF conditions at all three signal levels. Presentation order was randomized within each trial (See randomization table in Appendix E).

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. As a result, the examiner monitored the level and repeatability of DPOAEs throughout the data collection process and interrupted the test procedure to check the probe seal if there was evidence of response variability or

abnormality. For two of the seven subjects, there were conditions in which questionable results were obtained due to changes in the probe seal. The questionable data were discarded and the experimental conditions were repeated in a fourth experimental test session. For Subject #3, one of 42 conditions was repeated, and for Subject #4, four of 42 conditions were repeated. For both subjects, DPOAE data obtained in the fourth session were consistent with the data obtained in the first two sessions. Raw data for all experimental conditions for all subjects is shown in Appendix F.

CHAPTER IV

RESULTS

General Description of Results

The results for all experimental conditions are shown in Figures 7A and 7B and in Table 2. Each datum is a median of medians for three trials for seven subjects. In each figure, the ordinate is the level of the DPOAE in dB SPL, and the abscissa is the frequency of F_v in Hz. The parameter is the level of the variable primary signal, F_v (45, 55, and 65 dB SPL), that was paired with the fixed primary, F (held constant at 65 dB SPL). Each datum represents the median level of the DPOAE for a specific frequency separation condition. The level of the DPOAE is plotted at the frequency of F_v . Those data plotted on the left side of each figure were obtained when F_v was below F in frequency while those data plotted on the right side of each figure were obtained when F_v was above F in frequency. It is important to note that the results on the left side of Figures 7A and 7B were obtained using the signal paradigms on the left side of Figure 4 (p.25), and vice versa. Thus, the purposes of Figures 7A and 7B were to permit the comparison of DPOAE levels obtained when F_v was located below and above F as a function of the frequency and level of F_v .

Figure 7. Medians of median results for all subjects for all experimental conditions. The figure shows the dependence of DPOAE level on location of F_v relative to F , on relative level of F and F_v , on frequency separation of F and F_v , and on the location of the DPOAE.

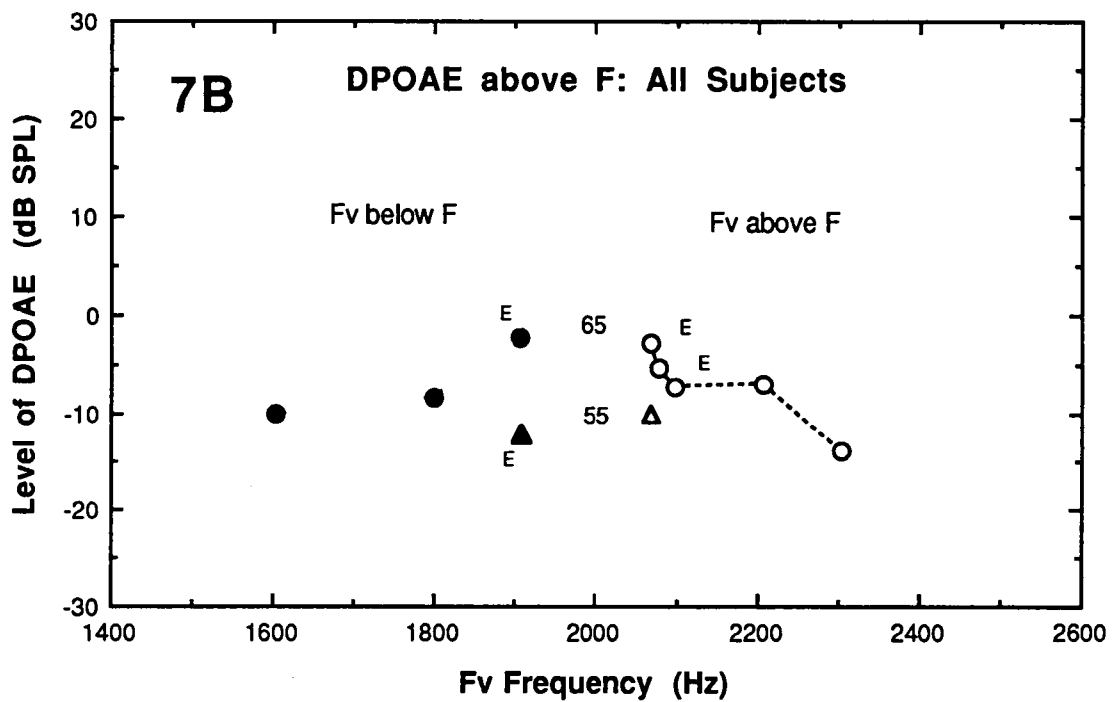
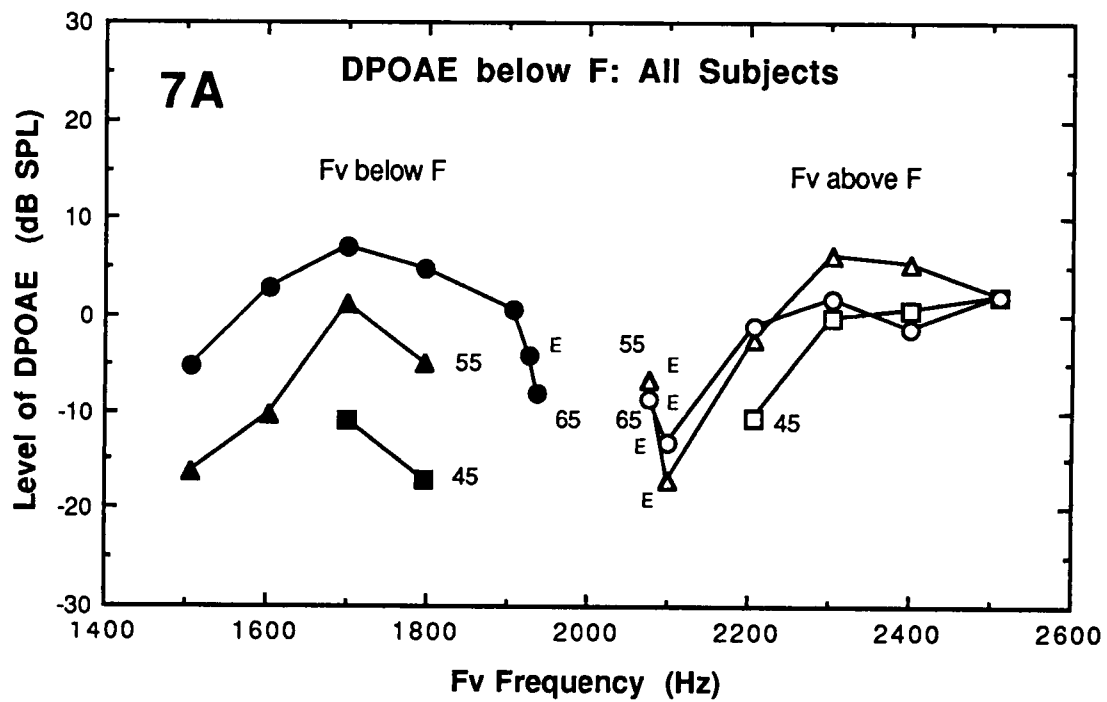


Table 2. Median DPOAE levels for all subjects taken from the medians of the three trials for each subject.

Fv Below F		Fv Stimulus Level (dB SPL)					
		<u>Fv below/dp above</u>			<u>Fv below/dp below</u>		
		45	55	65	45	55	65
Fv (Hz)	ΔF (Hz)	(dB SPL)			(dB SPL)		
1507	500	N	N	N	N	-16.2	-5.2
1604	400	N	N	-10.0	N	-10.3	2.7
1701	300	N	N	N	-11.0	1.0	7.0
1798	200	N	N	-8.3	-17.1	-5.1	4.9
1906	100	N	-12.2E	-2.2E	N	N	0.5
1927	75	N	N	N	N	N	-4.2E
1938	65	N	N	N	N	N	-8.0
Fv Above F		Fv Stimulus Level (dB SPL)					
		<u>Fv above/dp below</u>			<u>Fv above/dp above</u>		
		45	55	65	45	55	65
		(dB SPL)			(dB SPL)		
2067	65	N	N	N	N	-9.9	-2.7E
2078	75	N	-6.8E	-8.6E	N	N	-5.3
2099	100	N	-17.0E	-13.2E	N	N	-7.2E
2207	200	-10.6	-2.6	-1.1	N	N	-7.0
2304	300	-0.4	6.3	1.8	N	N	-14.0
2401	400	0.6	5.3	-1.4	N	N	N
2509	500	1.9	1.9	1.9	N	N	N

E - DPOAE level possibly enhanced due to it's location near the signal.

N - DPOAE below the noise floor.

It can be seen in Figure 7A that the levels of the responses are systematically higher and the number of plotted responses is greater than in Figure 7B. In each experimental condition for which no median response has been indicated, four or more of the subjects did not have responses that met the criterion for a valid DPOAE. In Figure 7A where the DPOAE falls below the primary signals, median responses were obtained for 29 of 42 experimental conditions while in Figure 7B where the DPOAE falls above the primary signals, responses were obtained for only 10 of 29 conditions. Because there were so few responses when the DPOAE fell above F , meaningful statistical analyses could not be performed on the data shown in Figure 7B.

Dependence of DPOAE on the Location of F_v Above and Below F

F_v and F Equal in Level. A comparison of the results was made for the conditions in which F_v fell above and below F -- and when F_v and F were both 65 dB SPL. These data are represented in Figure 7A by filled circles (F_v below F) and by open circles (F_v above F). When F_v was below F , a response was obtained at the smallest ΔF (65 Hz) and the level of the DPOAE was low. As ΔF was increased from 65 to 300 Hz, the level of the DPOAE increased. As ΔF was increased beyond 300 Hz, there was a systematic decline in the level of the DPOAE. It should be noted that the DPOAE for the 75-Hz ΔF condition was judged to be enhanced (i.e., situated on the pedestal of the signal spectrum of F_v). Since this response appears

to be monotonically related in level to the responses for the 65-Hz and 100-Hz ΔF conditions which surround it, the response for the 75-Hz ΔF condition does not appear to have been enhanced significantly.

When F_v was above F , there was no response obtained when ΔF was 65 Hz. The DPOAEs at the 75 and 100-Hz ΔF conditions were judged to be enhanced. Unlike the 75-Hz ΔF condition with F_v below F , the 75-Hz condition for F_v above F may reflect a significant enhancement of the DPOAE level due to pedestal effects. Though the 100-Hz condition was judged to be on a pedestal, its level was 4.6 dB lower than the level for the 75-Hz condition. If the level of this DPOAE was enhanced, the enhancement was not near as great as for the 75-Hz condition. The F_v -above condition was similar to the F_v -below condition for ΔF s from 100 to 400 Hz. There was an increase in the levels for ΔF s from 100 to 300 Hz after which there was a decline in level at the 400-Hz ΔF . At the 500-Hz ΔF , the highest DPOAE level was obtained. This is in contrast to the 500-Hz ΔF for the F_v -below condition, in which one of the lowest DPOAE levels was obtained for the 500-Hz ΔF condition.

A repeated measures analysis of variance was performed to evaluate the dependence of DPOAE levels on the location of F_v above and below F and on the frequency separation of F and F_v -- in the conditions where F and F_v were equal in level at 65 dB SPL. With the statistical analysis program (SAS General Linear Model Procedures) used, it was not possible to perform an analysis of variance using medians of medians with missing data

points. However, it was possible to compensate for missing data points if the analysis was based on means of individual subject medians. As a result, the analysis of variance was made using means of subject medians rather than medians of subject medians as shown in Figures 7A and 7B and in Table 2. Using means of medians for statistical analysis had the effect of reducing the differences between DPOAE levels. As a result, the statistical analysis used underestimated the magnitude of the differences when datum points were missing. This resulted in conservative estimates of the significance of DPOAE effects. The analysis of variance was performed for the ΔF conditions (100- to 500-Hz) for which only a small percentage of the responses were missing; the 65-Hz and 75-Hz conditions were excluded from the statistical analysis.

The results of the analysis, which are shown in Table 3, indicate that there is no significant effect due to the location of F_v above or below F . In this condition where F and F_v were equal in level, there could have been significant differences if the different regions of the basilar membrane that were stimulated functioned differently. The finding that the effects were not significant indicates that the different regions of the basilar membrane that were stimulated in the present study did not function differently.

Another important finding was that DPOAE level depends significantly on the frequency separation of F and F_v with no significant interaction between F_v and ΔF . This indicates that the frequency separation effects were not significantly different for F_v above and F_v below. This was the

Table 3. Analysis of variance for the dependence of median DPOAE levels on location of Fv (above or below F) and on the frequency separation of F and Fv. The signals were equal in level ($F = F_v = 65$ dB SPL). The responses were the levels of the DPOAEs that fell below the primary signals.

Source	Numerator		Denominator		F	p
	df	ms	df	ms		
Fv	1	134.29	7.71	27.03	4.97	.0576
ΔF	4	99.98	28.04	17.50	5.71	.0017*
S	6	229.84	1.31	15.31	15.01	.1341
Fv X ΔF	4	22.36	19.00	28.62	.78	.5513
Fv X S	6	26.82	19.00	28.62	.94	.4917
ΔF X S	23	16.76	19.00	28.62	.59	.8894

* Significant ($p < .01$)

expected finding if different regions of the basilar membrane were functioning similarly.

The results of the analysis in Table 3 also indicate that there were no effects due to subject differences. Also, there was no significant interaction between Fv and S conditions and between ΔF and S conditions.

Fv Lower in Level than F. The experiment described above was repeated with the exception that Fv was lower in level than F. There were two relative level conditions: 1) F at 65 dB SPL / Fv at 55 dB SPL, and 2) F at 65 dB SPL / Fv at 45 dB SPL. In Figure 7A, for the 55-dB SPL condition with Fv below F (filled triangles), there were no valid median DPOAEs obtained at the 65-, 75-, and 100-Hz ΔF conditions. For the ΔF conditions from 200- to 500- Hz, the increases and decreases in DPOAE level were similar in magnitude to those obtained in the 65-dB SPL condition. However, the levels of the DPOAEs for the 55 dB SPL condition were systematically lower than for the 65-dB SPL condition.

In Figure 7A, for the 55 dB SPL condition with Fv above F (open triangles), responses were obtained for the same ΔF conditions as the 65-dB SPL condition with Fv above F. The shape of these two functions were very similar except that the DPOAE levels were higher for the 300-Hz and 400-Hz ΔF conditions at the 55-dB SPL condition than at the 65-dB SPL condition. The results for Fv above F for the 55- and 65-dB SPL conditions are very different from those when Fv was below F. When Fv was below F, reducing the level of Fv by 10 dB decreased the levels of the DPOAEs. However,

when F_v was above F , reducing the level of F_v by 10 dB increased the levels of the DPOAEs at some ΔF s and decreased the levels of the DPOAEs at other ΔF s. Thus, changing the level of F_v from 65 to 55 dB SPL had a relatively small effect on the levels of the DPOAEs. For the 65- and 55-dB SPL conditions for F_v above F , the same DPOAEs (75-Hz and 100-Hz conditions) were judged to be enhanced.

The same analysis of variance used to compare F_v above and below F for the 65- dB SPL conditions was used for the 55- dB SPL condition. As in the previous analysis, results were compared for ΔF conditions from 100 to 500 Hz. The results of this analysis are shown in Table 4. As in the previous analysis, ΔF effects were significant. However, in contrast to the previous analysis, there was a significant dependence on the location of F_v . In the 65- dB SPL condition, when F_v fell above and below F , there was no significant difference in the levels of the DPOAEs. In the 55- dB SPL condition, the levels of the DPOAEs when F_v was above F were significantly greater than when F_v was below F . There were no significant effects attributable to subjects or two-way interactions of main effects.

Dependence of DPOAE Level on the Relative Levels of F and F_v

F_v below F . The data discussed in this section are the three functions on the left-hand side of Figure 7A (p. 34). The functions show that there is a systematic reduction in DPOAE level when the level of F_v was decreased from 65 to 55 dB SPL and from 55 to 45 dB SPL. With each

Table 4. Analysis of variance for the dependence of median DPOAE levels on location of Fv (above or below F) and on the frequency separation of F and Fv. The signals were unequal in level (F = 65 dB SPL and Fv = 55 dB SPL). The responses were the levels of the DPOAEs that fell below the primary signals.

Source	Numerator		Denominator		F	p
	df	ms	df	ms		
Fv	1	600.93	10.85	25.54	23.53	.0005*
ΔF	4	140.03	23.68	22.35	6.26	.0014*
S	6	166.60	2.82	22.23	7.49	.0710
Fv X ΔF	4	44.50	15.00	25.53	1.74	.1931
Fv X S	6	25.54	15.00	25.53	1.00	.4604
ΔF X S	20	22.09	15.00	25.53	.87	.6253

* Significant ($p < .01$)

reduction in the level of F_v , there was a decrease in the median levels of the DPOAEs and an increase in the number of conditions for which no valid DPOAE could be obtained.

A repeated measures analysis of variance was performed to compare the DPOAE levels obtained in the 65- and 55- dB SPL conditions when F_v was below F . The comparison was made for ΔF conditions from 100 to 500 Hz. The 45- dB SPL condition was not included in this comparison because there were insufficient data for most of the ΔF conditions. The results of the analysis, which are shown in Table 5, indicate that when F_v is below F , the levels of the DPOAEs depend significantly on the relative levels of F and F_v . As in both of the statistical analyses discussed above, DPOAE levels depended significantly on ΔF . In contrast to the previous analyses, subject differences were significant. Interactions between main effects were not significant.

F_v above F . The data discussed in this section are the three functions on the right-hand side of Figure 7A (p.34). The functions show that the DPOAE levels depend complexly on the relative levels of F and F_v . In three out of six ΔF conditions, DPOAE levels increased where F_v was decreased from 65 dB SPL to 55 dB SPL resulted in increases in median DPOAE levels, in two conditions the DPOAE levels decreased slightly, and for one condition the DPOAE level did not change.

The same analysis of variance that was performed in the section immediately preceding this section was performed to compare the results for

Table 5. Analysis of variance for the dependence of median DPOAE levels on the level of Fv (65 dB SPL and 55 dB SPL) and on the frequency separation of F and Fv. The primary signal Fv was below F. The responses were the levels of the DPOAEs that fell below the primary signals.

Source	Numerator		Denominator		F	p
	df	ms	df	ms		
Fv SPL	1	961.38	7.97	14.03	68.52	.0001*
ΔF	4	115.69	25.15	23.57	4.91	.0046*
S	6	232.13	9.90	25.52	9.10	.0015*
Fv SPL X ΔF	4	3.29	16.00	12.71	.26	.8998
Fv SPL X S	6	14.27	16.00	12.71	1.12	.3930
ΔF X S	22	25.14	16.00	12.71	1.98	.0829

* Significant ($p < .01$)

the 65- and 55- dB SPL conditions for F_v above F . The results of the analysis are shown in Table 6. In contrast to the results when F_v was below F , the DPOAE levels were not significantly different for the 65- and 55- dB SPL conditions when F_v was above F . There were no significant effects attributable to subjects or two-way interactions of main effects.

In the 45-dB SPL for the ΔF s at 200, 300, and 400 Hz, the DPOAE levels were systematically lower than the DPOAE levels for the 55- dB SPL condition. For the 200- and 300-Hz ΔF conditions, DPOAE levels decreased by 8.0 and 6.7 dB respectively when the level of F_v was decreased from 55 to 45 dB SPL. This was a smaller decrease than the 12 dB decrease that was obtained for the same ΔF conditions with F_v below F . However, it should be noted that when F_v was above F in the 500- Hz condition, the median levels of the DPOAEs remained constant as the level of F_v was decreased from 65 to 55 to 45 dB SPL.

Dependence of DPOAE Levels on the Location of the DPOAE Above and Below the Primary Signals

The results shown in Figure 7A (p.34) represent the levels of DPOAEs that were below the primary signals while the results in Figure 7B show the levels of DPOAEs that were above the primary signals. When the DPOAEs were above the primary signals, the median DPOAE levels were obtained for so few conditions that connecting lines could be drawn for only one of the six possible ΔF functions. Thus, it was difficult to make any generalizations about effects related to ΔF with the exception that the highest level DPOAEs

Table 6. Analysis of variance for the dependence of median DPOAE levels on the level of Fv (65 dB SPL and 55 dB SPL) and on the frequency separation of F and Fv. The primary signal Fv was above F. The responses were the levels of the DPOAEs that fell below the primary signals.

Source	Numerator		Denominator		F	p
	df	ms	df	ms		
Fv SPL	1	55.46	13.19	9.48	5.85	.0307
ΔF	4	189.96	22.42	27.52	6.90	.0009*
S	6	217.77	1.96	11.60	18.78	.0537
Fv SPL X ΔF	4	11.71	18.00	23.11	.51	.7315
Fv SPL X S	6	7.13	18.00	23.11	.31	.9243
ΔF X S	21	27.70	18.00	23.11	1.20	.3517

* Significant ($p < .01$)

were obtained at small ΔF s when there was the possibility of enhancement due to pedestal effects. However, since 8 of 10 datum points were obtained in the 65- dB SPL condition, 2 in the 55- dB SPL condition, and none in the 45- dB SPL condition, there appears to be a clear dependence on the level of F_v . When DPOAEs were above the primary signals in frequency, DPOAE levels appeared to decrease slightly as ΔF was increased.

Examples of Results for Individual Subjects

In Figures 8A and 8B, results are shown for the subject with the highest level DPOAE responses among the seven experimental subjects. In Figure 8A, the patterns of results are similar to the median results shown in Figure 7A. For F_v below and above F , the results depend on ΔF . For F_v below, there is a systematic decrease in DPOAE levels with decreases in the level of F_v . And for F_v above F , DPOAE levels vary complexly with changes in the level of F_v .

In Figure 8B, as in Figure 7B (p.34), the DPOAE levels were substantially lower and there were fewer valid DPOAE responses when the DPOAE was above (rather than below) the primary signals. When datum points for which enhancement was suspected are disregarded, the results suggest that DPOAE levels may decrease slightly as ΔF is increased.

In Figures 9A and 9B, the results are shown for the subject with the lowest level DPOAE responses of the seven experimental subjects. In general, the effects that were described for Figure 7 (p.34) and Figure 8

Figure 8. Median results for the subject with the highest level DPOAE responses for all experimental conditions. The figure shows the dependence of DPOAE level on location of F_v relative to F , on relative level of F and F_v , on frequency separation of F and F_v , and on the location of the DPOAE.

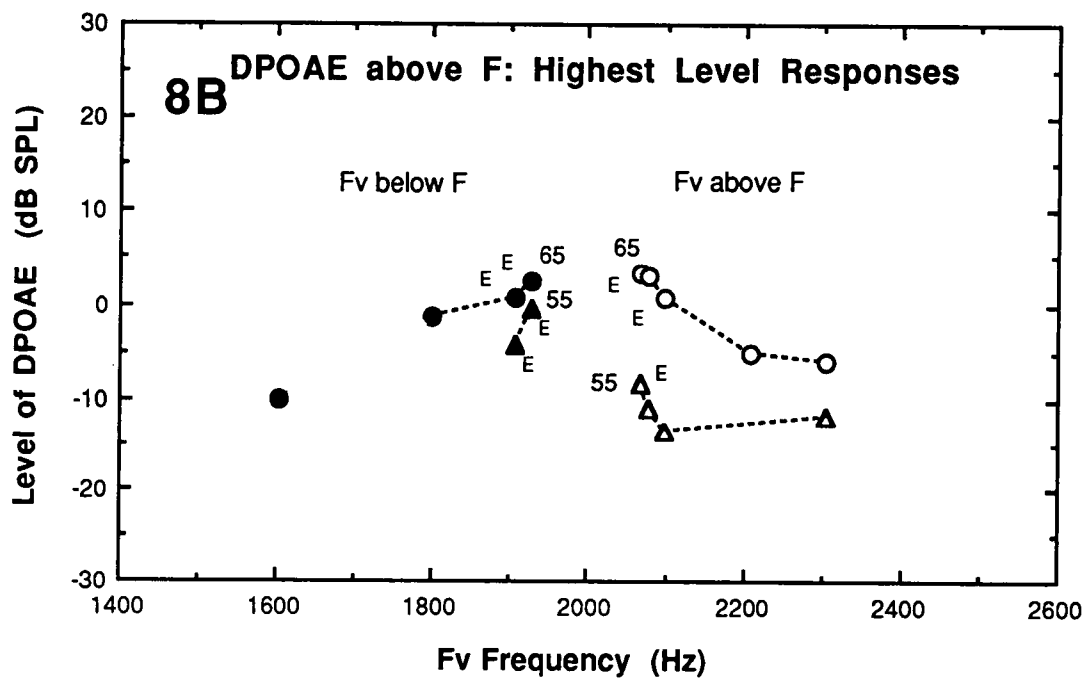
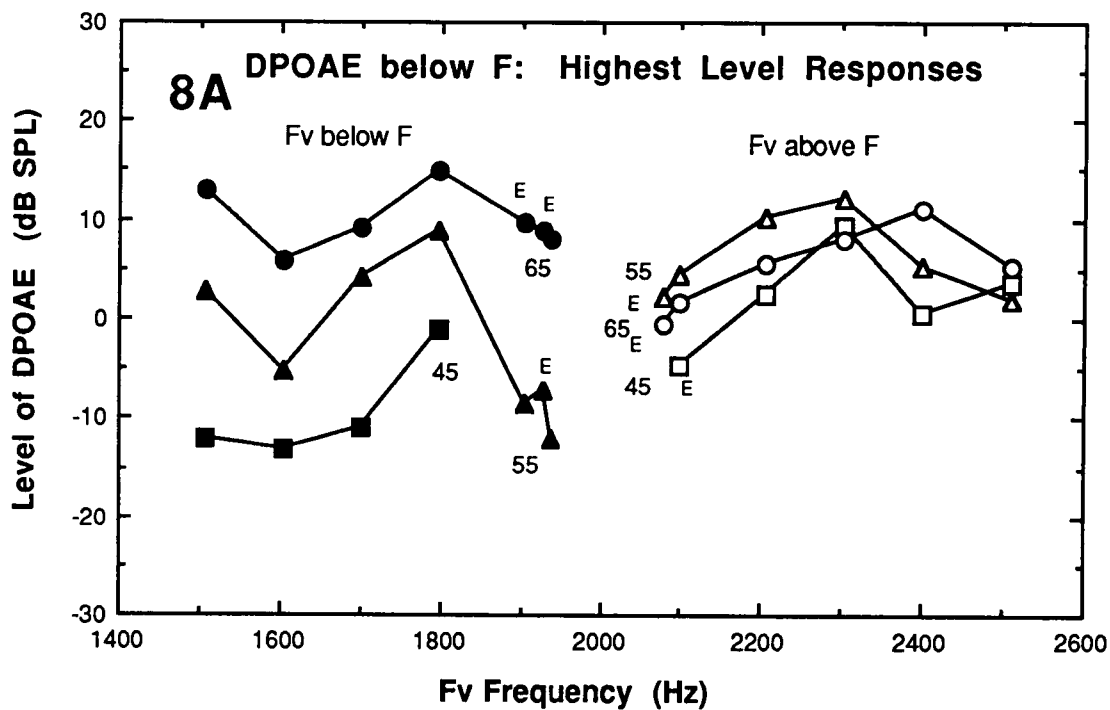
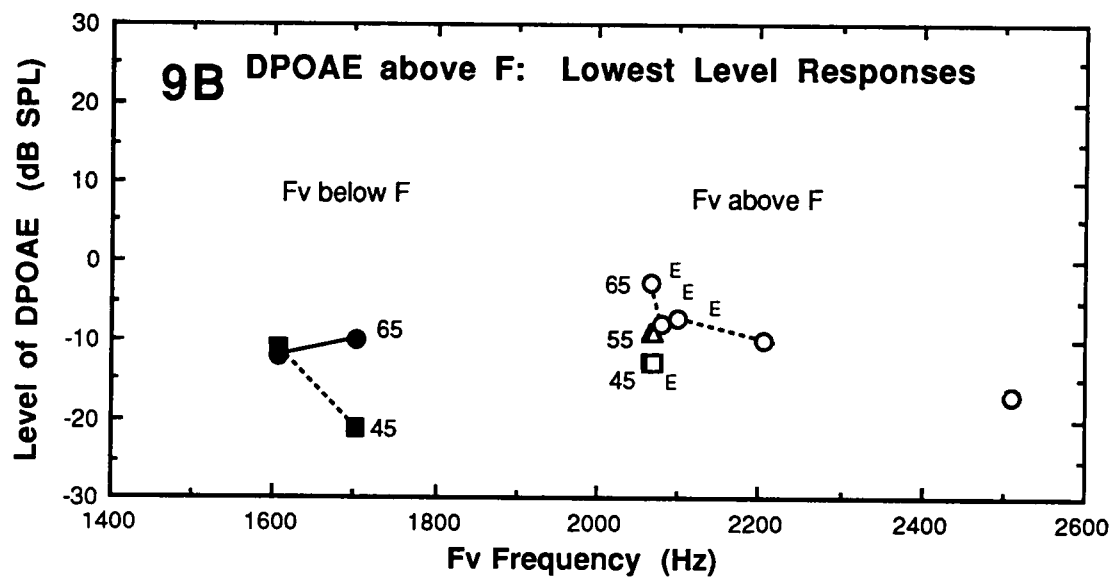
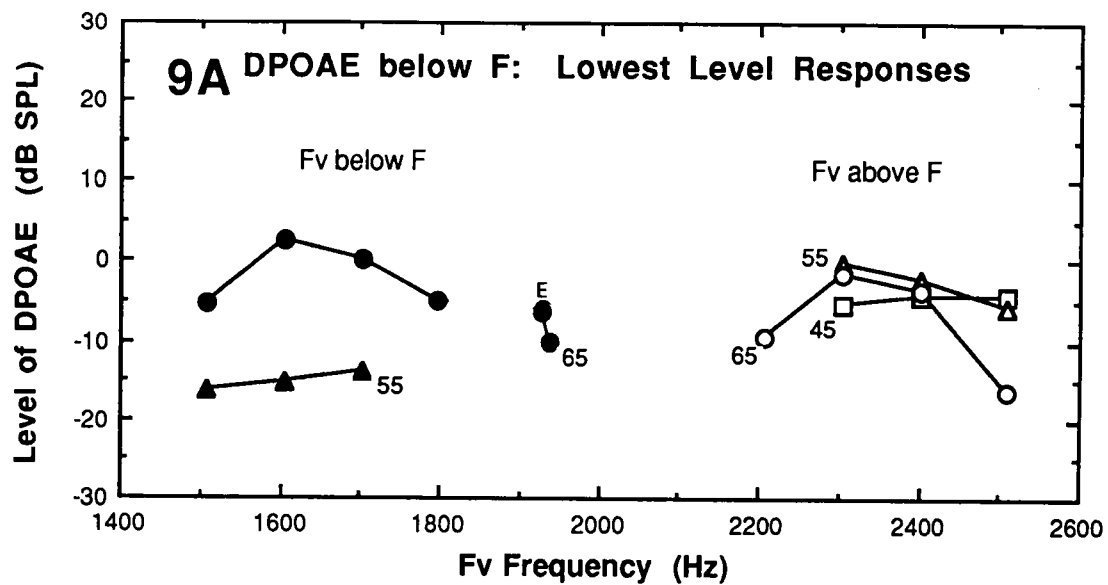


Figure 9. Median results for the subject with the lowest level DPOAE responses for all experimental conditions. The figure shows the dependence of DPOAE level on location of F_v relative to F , on relative level of F and F_v , on frequency separation of F and F_v , and on the location of the DPOAE.



apply to Figure 9 as well. However, there is one aspect of these data that deserves special consideration. When F_v was below F and the DPOAE was below the primary signals, the levels of the DPOAEs decreased a much greater amount as the level of F_v was decreased from 65 to 45 dB SPL. In contrast, when F_v was above F , the levels of the DPOAEs were much less affected by changes in the level of F_v .

CHAPTER V

DISCUSSION

DPOAE Instability at Small Frequency Separations of the Primary Signals

When frequency separations between primary signals were small ($\Delta F = 65, 75, \text{ and } 100 \text{ Hz}$), there was more response instability than at greater frequency separations. This may have been due to technical factors related to response measurement and also to physiologic phenomena related to the interaction of the primary signals at small ΔF s. From the examination of tone-on-tone masking data (Wegel & Lane, 1924; Egan & Hake, 1950) and psychophysical tuning curve data obtained with two pure tones (Thornton & Abbas, 1980; Thelin, Barbero, Templer, & Christiansen, 1983; Nelson & Fortune, 1991), there are effects that create nonmonotonic functions near the frequency of the signal. These effects, which are related to beating and phase relations between signals, were possible sources of the nonmonotonic functions observed for some of the conditions at small frequency separations. Since signal phase was not controlled in the present study, it is possible that some response instability could be attributed to phase or beating effects.

Another possible explanation for the unstable results at small frequency separations in the present study was the enhancement of DPOAE levels. A significant number of DPOAEs were classified as being enhanced

(Figure 7, p.34) because the DPOAE on the response frequency spectrum was situated on a pedestal that did not appear to be attributed to ambient noise. There were two possible causes for the pedestal. First, the pedestal may have been part of the acoustic spectrum of one of the primary signals, and second, it may have been part of the acoustic spectrum of the OAE originating from the primary itself. In both cases, the DPOAE levels would have been increased by amounts that would be difficult to estimate. As a result, DPOAE levels may have been elevated substantially either due to technical error or a physiologic phenomenon.

With the design of the present study, it was not possible to evaluate the data in a manner that would permit the identification of the causes of the response instability and the nonmonotonic response functions observed at small frequency separations. Thus, it could not be determined whether the effects at small frequency separations are due to significant physiologic phenomena or to technical factors.

DPOAEs Located on the Basal Side of the Traveling Wave

In the present study, when there were DPOAEs located above the frequencies of the primary signals (Figure 7B, p.34) that were not enhanced, there was only one condition in which the level of the DPOAE was higher than the levels of the DPOAEs that were located below the primary signals. The DPOAEs that are below the frequencies of the primary signals are located on the steep side of the traveling waves created by the primary

signals. For the DPOAEs located in this region, there is no expectation that their levels would be affected by the traveling wave activity. However, for the DPOAEs located above the frequencies of the primary signals, the gradual slopes of the traveling waves may extend into the frequency regions of these DPOAEs. This finding is supported by data that indicates that the DPOAEs above the primary signals have origins on the basilar membrane that are in this region above the frequencies of the primary signals (Martin, Lonsbury-Martin, Probst, Scheinin, and Coats, 1987; Köppl & Manley, 1993). For DPOAEs located below the primary signals, DPOAE levels appear to depend on factors other than the traveling wave. For DPOAEs located above the primary signals, the traveling wave appears to be the dominant factor in the determination of the level of the DPOAE. It is a major finding of the present study that the effect of the traveling wave is to reduce the levels of the DPOAEs above the frequencies of the primary signals for a wide range of signal conditions. However, it is unclear whether the reduction is due to the masking of a DPOAE that is present, the suppression of a DPOAE that was present, or de-enhancement (Zwicker, 1986) that prevented the development of a DPOAE.

DPOAEs Located on the Apical Side of the Traveling Wave

In the preceding section, it was noted that there is some evidence to suggest that the DPOAEs located on the basal side of traveling waves (usually low level DPOAEs) originate in a frequency region or at a location on the basilar membrane that is basal to the region activated by the

primary signals. In contrast, the origin of DPOAEs located on the apical side of the traveling waves (the high level DPOAEs) has been studied by several investigators with the consensus that it originates in the frequency region near or between the frequencies of the primary signals (Brown & Kemp, 1984; Martin, Lonsbury-Martin, Probst, Scheinin, & Coats, 1987; Köppl & Manly, 1993). Though the present study was not designed to address the issue of the origins of the DPOAEs, the data shown in Figure 7A (p.34) do suggest that DPOAE levels are affected by interactions of the primary signals that could occur near or between the locations of the traveling waves of the primary signals on the basilar membrane.

Dependence of DPOAEs on the Interaction of the Primary Signals

In the present study, the dependence of DPOAEs on the interaction of the primary signals was examined by varying the relative levels and frequency separations of the primary signals. The data on the left hand side of Figure 7A, p.34 (signal paradigms shown in the upper part of Figure 2, p.06 and on the left hand side of Figure 4, p.25) show the effects of varying the primary signal that is lower in frequency. They indicate that DPOAEs depend on ΔF in the following manner: DPOAE levels were highest when ΔF was 300 Hz and they decreased systematically at smaller and larger ΔF s. When the level of the lower frequency primary signal was decreased by 10 dB and 20 dB, there was a systematic reduction in the levels of the DPOAEs at all ΔF s.

In contrast, when the level of the higher frequency primary signal was decreased (right hand side of Figure 7, p.34), some DPOAE levels decreased but others increased or remained the same. In general, when the primary signal that was varied was located above the fixed signal, the DPOAE levels were affected minimally by changes in the level or the frequency separation of the signal that was varied. These findings indicate that when traveling wave of a small primary signal is located in the traveling wave of a larger primary signal that is lower in frequency, the DPOAE level is determined by complex interaction effects. Similar findings have been reported by Gaskill and Brown (1990) and by Sutton, Lonsbury-Martin, Martin, and Whitehead (1994).

Dependence of DPOAEs on the Frequency Separation of the Primary Signals

The results shown on the right hand and left hand sides of Figure 7A (p.34) have been described by some investigators as filters related to the mechanisms that generate DPOAEs (Harris, Lonsbury-Martin, Stagner, Coats, & Martin, 1989; Brown, Gaskill, Carlyon, & Williams, 1993; Stover, Neely, & Gorga, 1994). The results describe filtering because there is only a limited range of frequency separations for which optimal DPOAE levels are obtained. These investigators used primary signals that were equal in level or primary signals in which f_2 was lower in level (similar to the data on the right hand side of Figure 7A, p.34). Though the methods used to plot

frequency separation data varied significantly from study to study, there has been a general finding that the filter is centered at approximately one-half octave below the higher frequency primary signal. Using that method of specifying frequency separation, the highest DPOAE level on the right hand side of Figure 7A (p.34) is located at the ΔF of 300 Hz which is 0.44 octaves below f_2 . This is in agreement with the findings of previous investigators.

The results on the left hand side of Figure 7A (p.34) were obtained using signals that have not been used by previous investigators: signals with f_1 lower in level than f_2 . The findings were similar to those reported in the preceding paragraph in that the center of the filter was located at the ΔF of 300 Hz which is 0.51 octaves below f_2 ; the findings differed in that the filtering effects reduced DPOAE levels greater amounts at larger ΔF s.

Brown, Gaskill, Carlyon, and Williams (1993) have proposed that the existence of the DPOAE filter may be due to one-half octave differences in the tuning characteristics of the basilar and tectorial membranes (Allen, 1980). If the filtering action were due to tuning curves, it would be expected that slopes of the filter skirts would be very steep. The steepest slopes of DPOAE filter skirts were computed using the data in the present study for primary signals that were close in frequency:

354 dB/octave for the F_v below F condition
($F = F_v = 65$ dB SPL; between $\Delta F = 65$ Hz and $\Delta F = 100$ Hz)

199 dB/octave for the F_v above F condition
($F = 65$ dB SPL and $F_v = 55$ dB SPL; between $\Delta F = 100$ Hz and $\Delta F = 200$ Hz).

These filter slopes are sufficiently steep to provide evidence to support the hypothesis that the DPOAE filter is due to basilar membrane and tectorial membrane tuning.

Conclusions and Considerations for Future Research

The results of the present study indicate that the generation of DPOAEs is complexly related to tuning in the cochlea. As other investigators have found but have not stated in this manner, DPOAE levels are reduced significantly when they are located on the basal side of the traveling waves of the primary signals. A second major finding of the present study was that DPOAE levels are affected complexly by the interaction of the traveling waves of the primary signals on the basilar membrane. At high levels of the primary signals, the interaction may result in small reductions in DPOAE levels while at lower signal levels the interactions may result in significant enhancement of DPOAE levels. The third major finding of the present study was evidence to support the concept of the existence of a DPOAE filter that was dependent on tuning in the cochlea.

Future research needs to be conducted to determine the mechanisms by which the traveling waves of the primary signals interact to enhance or suppress DPOAE responses. Similarly, there is the need to understand the mechanisms responsible for the suppression of the DPOAEs that are located on the basal side of the traveling waves of the primary signals. When these phenomena are understood more fully, the information that can be obtained

with DPOAE measurement techniques about tuning and filtering may have applications for the differential description and diagnosis of ear disorders and hearing loss.

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APPENDICES

APPENDIX A
AUDIOMETRIC DATA FOR SUBJECT QUALIFICATION

	Subject Number						
	1	2	3	4	5	6	7
Age	24	29	25	23	25	28	24
Test Ear	L	R	L	L	L	L	L
PT AC Thresholds (db HL)							
1000 Hz	00	00	05	05	10	05	-05
1500 Hz	05	00	05	05	05	00	-05
2000 Hz	-05	05	05	00	00	00	-10
3000 Hz	00	00	05	05	05	-05	05
4000 Hz	05	05	00	00	00	00	00
Tympanometry							
Yme (mmhos)	0.4	1.0	1.3	0.6	0.4	0.4	0.5
MEP (daPa)	05	05	05	05	00	05	10
Vec (mmhos)	0.9	1.3	1.6	1.0	1.2	1.3	1.0
Uncrossed Acoustic-Reflex Thresholds (dB HL)							
1000 Hz	95	85	85	75	85	85	80
2000 Hz	95	85	90	80	85	80	85

APPENDIX B
DISTORTION PRODUCT AUDIOGRAMS
FOR SUBJECT QUALIFICATION

University of Tennessee
Audiology Laboratory
Knoxville, TN 37996
(615) 974-1796



Name: S1, Qualifier

Chart #:

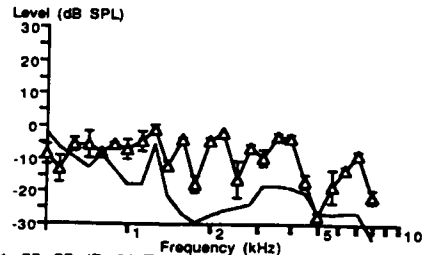
Age:

Sex:

Tuesday, May 17, 1994 9:37

Tester:

Distortion Product



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

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
 $F2 = 1.21 * F1$, $F_0 = \sqrt{(F1 * F2)}$

Right

F ₀ (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	53.5	0.35	-8.9	0.28	-2.2
0.56	0.51	54.9	0.61	53.7	0.40	-13.2	0.32	-6.4
0.63	0.57	55.3	0.69	54.2	0.45	-5.8	0.38	-9.4
0.71	0.65	54.1	0.79	54.1	0.51	-5.8	0.43	-12.9
0.79	0.72	53.8	0.87	54.3	0.57	-8.2	0.50	-8.7
0.89	0.81	53.9	0.98	54.4	0.63	-5.5	0.56	-13.3
1.00	0.90	53.9	1.10	54.4	0.71	-7.4	0.63	-17.6
1.12	1.02	53.6	1.24	54.2	0.81	-4.3	0.73	-18.0
1.25	1.14	54.7	1.38	53.6	0.90	-0.8	0.83	-5.7
1.41	1.28	53.6	1.55	54.0	1.01	-12.2	0.94	-21.6
1.59	1.44	53.9	1.74	53.9	1.14	-4.0	1.07	-26.8
1.77	1.62	54.2	1.95	54.1	1.28	-17.6	1.21	-29.4
2.00	1.82	53.6	2.21	54.7	1.43	-4.6	1.36	-27.4
2.25	2.05	54.4	2.48	54.0	1.62	-1.8	1.54	-26.1
2.52	2.29	55.0	2.78	54.8	1.81	-16.3	1.73	-24.9
2.83	2.57	55.0	3.11	55.0	2.03	-6.5	1.96	-23.7
3.17	2.88	54.9	3.49	55.0	2.28	-9.8	2.21	-18.2
3.56	3.24	55.1	3.92	54.7	2.56	-3.2	2.49	-18.5
4.00	3.64	55.0	4.40	54.4	2.87	-3.5	2.80	-18.6
4.49	4.08	54.4	4.94	54.0	3.22	-16.9	3.14	-20.2
5.04	4.59	54.0	5.55	54.8	3.63	-27.2	3.55	-26.6
5.66	5.15	55.0	6.22	54.9	4.07	-18.3	3.99	-26.8
6.35	5.77	55.1	6.99	55.0	4.55	-13.0	4.48	-26.2
7.13	6.48	54.1	7.84	55.0	5.12	-8.5	5.05	-26.2
8.01	7.28	54.1	8.81	55.0	5.75	-21.2	5.67	-33.8

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Knoxville, TN 37996
(615) 974-1796



Name: S2,Qualifier

Chart #:

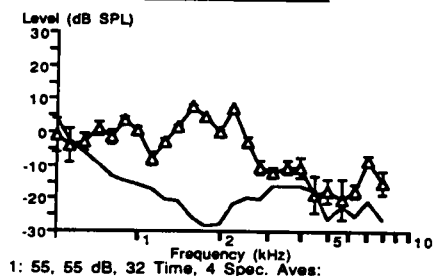
Age:

Sex:

Tuesday, May 17, 1994 13:37

Tester:

Distortion Product

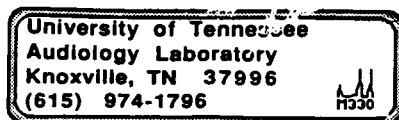


Distortion Product Table

F1 level: 55 dB SPL F2 level: 55 dB SPL
Time Aves: 32 Spectral Aves: 4
Noise Retries: 4 Noise Tolerance: 10 dB SPL
 $F2 = 1.21 * F1$, $F_0 = \sqrt{F1 * F2}$

Right

F ₀ (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	53.5	0.35	-1.1	0.28	4.3
0.56	0.51	54.9	0.61	53.7	0.40	-4.2	0.32	-2.5
0.63	0.57	55.3	0.69	54.2	0.45	-3.2	0.38	-6.2
0.71	0.65	54.6	0.79	54.1	0.51	0.9	0.43	-9.8
0.79	0.72	53.8	0.87	54.3	0.57	-1.5	0.50	-13.1
0.89	0.81	53.9	0.98	54.4	0.63	3.8	0.56	-14.6
1.00	0.90	53.9	1.10	54.4	0.71	0.6	0.63	-16.0
1.12	1.02	53.6	1.24	54.2	0.81	-8.3	0.73	-17.5
1.25	1.14	54.7	1.38	54.6	0.90	-3.1	0.83	-20.4
1.41	1.28	54.6	1.55	55.0	1.01	1.6	0.94	-21.1
1.59	1.44	54.9	1.74	53.9	1.14	7.5	1.07	-25.7
1.77	1.62	54.2	1.95	53.6	1.28	4.6	1.21	-28.7
2.00	1.82	53.6	2.21	53.7	1.43	-0.1	1.36	-27.8
2.25	2.05	54.4	2.48	54.0	1.62	7.2	1.54	-21.7
2.52	2.29	54.0	2.78	53.8	1.81	-3.0	1.73	-19.6
2.83	2.57	54.2	3.11	55.0	2.03	-10.7	1.96	-20.4
3.17	2.88	54.9	3.49	55.0	2.28	-12.0	2.21	-16.3
3.56	3.24	55.1	3.92	53.7	2.56	-10.8	2.49	-16.1
4.00	3.64	55.0	4.40	55.4	2.87	-10.7	2.80	-16.4
4.49	4.08	55.4	4.94	55.0	3.22	-18.7	3.14	-18.0
5.04	4.59	55.0	5.55	54.8	3.63	-18.0	3.55	-26.4
5.66	5.15	54.0	6.22	54.9	4.07	-20.6	3.99	-22.3
6.35	5.77	55.1	6.99	56.0	4.55	-17.8	4.48	-25.3
7.13	6.48	54.1	7.84	56.0	5.12	-8.8	5.05	-20.8
8.01	7.28	55.1	8.81	55.8	5.75	-15.2	5.67	-26.4



Name: S3,Qualifier

Chart #:

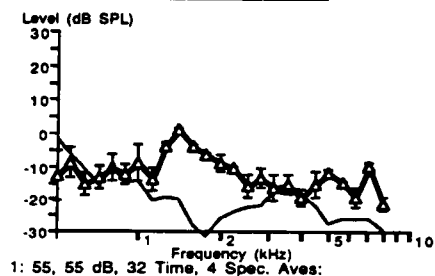
Age:

Sex:

Wednesday, May 18, 1994 9:03

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
 $F2 = 1.21 * F1$, $Fc = \sqrt{F1 * F2}$

Left

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	53.5	0.35	-12.9	0.28	-1.3
0.56	0.51	54.9	0.61	53.7	0.40	-8.7	0.32	-6.0
0.63	0.57	55.3	0.69	54.2	0.45	-15.5	0.38	-10.9
0.71	0.65	55.1	0.79	54.1	0.51	-13.3	0.43	-15.6
0.79	0.72	54.8	0.87	54.3	0.57	-10.0	0.50	-10.1
0.89	0.81	53.9	0.98	55.4	0.63	-12.0	0.56	-14.7
1.00	0.90	54.9	1.10	54.4	0.71	-8.6	0.63	-14.4
1.12	1.02	53.6	1.24	54.2	0.81	-13.8	0.73	-20.6
1.25	1.14	54.7	1.38	54.6	0.90	-3.3	0.83	-19.5
1.41	1.28	54.6	1.55	54.0	1.01	1.3	0.94	-19.7
1.59	1.44	53.9	1.74	53.9	1.14	-3.8	1.07	-28.0
1.77	1.62	54.2	1.95	54.6	1.28	-5.9	1.21	-31.4
2.00	1.82	53.6	2.21	54.7	1.43	-8.6	1.36	-26.0
2.25	2.05	55.4	2.48	55.0	1.62	-10.1	1.54	-24.1
2.52	2.29	55.0	2.78	54.8	1.81	-15.5	1.73	-22.6
2.83	2.57	55.0	3.11	55.0	2.03	-13.5	1.96	-21.8
3.17	2.88	53.9	3.49	55.0	2.28	-16.5	2.21	-17.8
3.56	3.24	55.1	3.92	54.7	2.56	-15.2	2.49	-17.9
4.00	3.64	55.0	4.40	54.4	2.87	-19.5	2.80	-18.3
4.49	4.08	54.4	4.94	54.0	3.22	-15.4	3.14	-21.9
5.04	4.59	55.0	5.55	53.8	3.63	-11.5	3.55	-27.3
5.66	5.15	55.0	6.22	53.9	4.07	-14.8	3.99	-25.9
6.35	5.77	55.1	6.99	54.0	4.55	-19.2	4.48	-26.2
7.13	6.48	55.1	7.84	55.0	5.12	-9.8	5.05	-25.9
8.01	7.28	55.1	8.81	55.0	5.75	-21.5	5.67	-29.7

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Name: S4, Qualifier

Chart #:

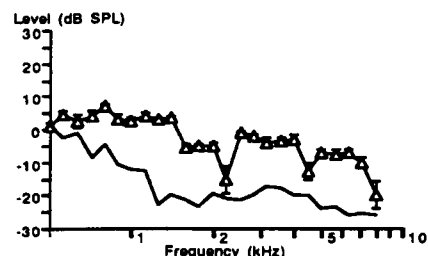
Age:

Sex:

Tuesday, May 24, 1994 13:53

Tester:

Distortion Product



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

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
 $F2 = 1.21 * F1$, $Fo = \sqrt{F1 * F2}$

Right

Fo (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	53.5	0.35	1.1	0.28	1.5
0.56	0.51	53.9	0.61	53.7	0.40	4.8	0.32	-2.5
0.63	0.57	54.3	0.69	54.2	0.45	2.8	0.38	-1.1
0.71	0.65	54.1	0.79	54.1	0.51	3.9	0.43	-8.5
0.79	0.72	54.8	0.87	55.3	0.57	7.3	0.50	-4.6
0.89	0.81	54.9	0.98	55.4	0.63	3.3	0.56	-10.7
1.00	0.90	53.9	1.10	55.4	0.71	2.4	0.63	-12.2
1.12	1.02	53.6	1.24	54.2	0.81	3.9	0.73	-12.6
1.25	1.14	53.7	1.38	54.6	0.90	2.9	0.83	-22.9
1.41	1.28	53.6	1.55	55.0	1.01	3.3	0.94	-19.9
1.59	1.44	53.9	1.74	54.9	1.14	-5.5	1.07	-21.5
1.77	1.62	54.2	1.95	53.6	1.28	-5.1	1.21	-23.4
2.00	1.82	53.6	2.21	53.7	1.43	-4.9	1.36	-19.3
2.25	2.05	54.4	2.48	55.0	1.62	-15.3	1.54	-20.6
2.52	2.29	55.0	2.78	54.8	1.81	-1.0	1.73	-21.5
2.83	2.57	55.0	3.11	55.0	2.03	-2.0	1.96	-19.9
3.17	2.88	54.9	3.49	55.0	2.28	-4.0	2.21	-17.2
3.56	3.24	55.1	3.92	54.7	2.56	-3.8	2.49	-17.6
4.00	3.64	54.0	4.40	55.4	2.87	-3.2	2.80	-19.6
4.49	4.08	55.4	4.94	55.0	3.22	-12.9	3.14	-19.6
5.04	4.59	55.0	5.55	54.8	3.63	-7.0	3.55	-23.7
5.66	5.15	54.0	6.22	53.9	4.07	-7.8	3.99	-23.5
6.35	5.77	55.1	6.99	54.2	4.55	-7.2	4.48	-26.1
7.13	6.48	55.1	7.84	55.0	5.12	-10.0	5.05	-25.5
8.01	7.28	54.1	8.81	55.0	5.75	-19.7	5.67	-25.8

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Name: S5, Qualifier

Chart #:

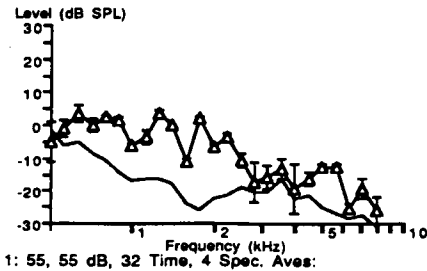
Age:

Sex:

Wednesday, May 25, 1994 7:51

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
 $F2 = 1.21 * F1$, $F_0 = \sqrt{F1 * F2}$

Right

F ₀ (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	53.5	0.35	-5.1	0.28	-1.6
0.56	0.51	53.9	0.61	53.7	0.40	-1.0	0.32	-6.2
0.63	0.57	54.3	0.69	54.2	0.45	3.8	0.38	-5.1
0.71	0.65	54.1	0.79	54.1	0.51	0.2	0.43	-8.4
0.79	0.72	53.8	0.87	54.3	0.57	2.5	0.50	-10.7
0.89	0.81	53.9	0.98	55.4	0.63	1.3	0.56	-14.2
1.00	0.90	53.9	1.10	54.4	0.71	-5.9	0.63	-16.9
1.12	1.02	53.6	1.24	55.2	0.81	-3.6	0.73	-16.3
1.25	1.14	53.7	1.38	53.6	0.90	3.7	0.83	-16.4
1.41	1.28	54.6	1.55	54.0	1.01	-0.2	0.94	-18.0
1.59	1.44	54.9	1.74	53.9	1.14	-11.0	1.07	-23.8
1.77	1.62	55.2	1.95	53.6	1.28	1.9	1.21	-26.1
2.00	1.82	53.6	2.21	53.7	1.43	-6.4	1.36	-22.5
2.25	2.05	54.4	2.48	54.0	1.62	-3.6	1.54	-21.3
2.52	2.29	54.0	2.78	54.8	1.81	-10.5	1.73	-18.6
2.83	2.57	54.0	3.11	55.0	2.03	-17.2	1.96	-20.6
3.17	2.88	53.9	3.49	55.0	2.28	-16.0	2.21	-20.2
3.56	3.24	55.1	3.92	54.7	2.56	-13.0	2.49	-16.3
4.00	3.64	55.0	4.40	54.4	2.87	-19.2	2.80	-22.4
4.49	4.08	55.4	4.94	54.0	3.22	-16.2	3.14	-21.3
5.04	4.59	55.0	5.55	54.8	3.63	-12.8	3.55	-25.0
5.66	5.15	54.0	6.22	53.9	4.07	-12.6	3.99	-27.1
6.35	5.77	54.1	6.99	54.0	4.55	-25.2	4.48	-28.5
7.13	6.48	54.1	7.84	54.0	5.12	-19.5	5.05	-27.5
8.01	7.28	55.1	8.81	56.0	5.75	-25.7	5.67	-31.3

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Name: S6, Qualifier

Chart #:

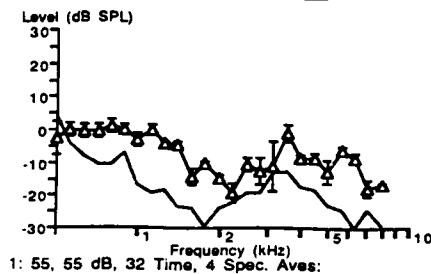
Age:

Sex:

Wednesday, May 25, 1994 12:46

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
 $F2 = 1.21 * F1$, $Fc = \sqrt{F1 * F2}$

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	53.5	0.35	-2.4	0.28	4.1
0.56	0.51	53.9	0.61	53.7	0.40	0.0	0.32	-3.9
0.63	0.57	55.3	0.69	54.2	0.45	-0.8	0.38	-8.2
0.71	0.65	55.1	0.79	54.1	0.51	-0.3	0.43	-10.9
0.79	0.72	54.8	0.87	54.3	0.57	0.8	0.50	-10.5
0.89	0.81	53.9	0.98	54.4	0.63	-0.2	0.56	-7.1
1.00	0.90	54.9	1.10	54.4	0.71	-2.9	0.63	-16.7
1.12	1.02	53.6	1.24	54.2	0.81	-0.1	0.73	-19.1
1.25	1.14	54.7	1.38	53.6	0.90	-4.1	0.83	-18.4
1.41	1.28	53.6	1.55	54.0	1.01	-4.4	0.94	-23.5
1.59	1.44	53.9	1.74	54.9	1.14	-14.0	1.07	-24.0
1.77	1.62	54.2	1.95	53.6	1.28	-10.4	1.21	-29.4
2.00	1.82	53.6	2.21	53.7	1.43	-14.6	1.36	-23.9
2.25	2.05	55.4	2.48	55.0	1.62	-19.6	1.54	-22.5
2.52	2.29	54.0	2.78	53.8	1.81	-10.5	1.73	-19.3
2.83	2.57	55.0	3.11	55.0	2.03	-12.5	1.96	-19.5
3.17	2.88	54.9	3.49	55.0	2.28	-11.2	2.21	-13.1
3.56	3.24	55.1	3.92	54.7	2.56	-1.2	2.49	-12.8
4.00	3.64	55.0	4.40	54.9	2.87	-8.5	2.80	-17.0
4.49	4.08	54.4	4.94	55.0	3.22	-8.7	3.14	-18.1
5.04	4.59	54.0	5.55	54.8	3.63	-12.8	3.55	-22.8
5.66	5.15	55.0	6.22	53.9	4.07	-6.3	3.99	-24.4
6.35	5.77	55.1	6.99	55.0	4.55	-8.5	4.48	-30.0
7.13	6.48	54.1	7.84	55.0	5.12	-17.8	5.05	-24.5
8.01	7.28	54.1	8.81	55.0	5.75	-17.0	5.67	-29.6

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Name: S7, Qualifier

Chart #:

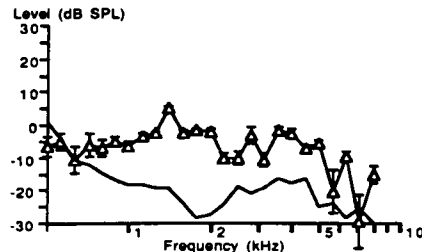
Age:

Sex:

Monday, May 30, 1994 13:54

Tester:

Distortion Product



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

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	53.5	0.35	-6.4	0.28	1.1
0.56	0.51	53.9	0.61	53.7	0.40	-5.2	0.32	-3.8
0.63	0.57	55.3	0.69	54.2	0.45	-10.8	0.38	-10.6
0.71	0.65	54.1	0.79	54.1	0.51	-6.1	0.43	-12.1
0.79	0.72	53.8	0.87	54.3	0.57	-7.2	0.50	-14.8
0.89	0.81	54.9	0.98	54.4	0.63	-5.2	0.56	-16.6
1.00	0.90	53.9	1.10	55.4	0.71	-6.9	0.63	-18.3
1.12	1.02	53.6	1.24	54.2	0.81	-3.3	0.73	-18.2
1.25	1.14	53.7	1.38	53.6	0.90	-2.3	0.83	-19.2
1.41	1.28	53.6	1.55	54.0	1.01	5.1	0.94	-19.2
1.59	1.44	54.9	1.74	54.9	1.14	-2.5	1.07	-24.1
1.77	1.62	54.2	1.95	53.6	1.28	-1.4	1.21	-28.5
2.00	1.82	53.6	2.21	53.7	1.43	-2.1	1.36	-27.7
2.25	2.05	54.4	2.48	54.0	1.62	-10.3	1.54	-24.2
2.52	2.29	54.0	2.78	54.8	1.81	-10.3	1.73	-18.7
2.83	2.57	55.0	3.11	55.0	2.03	-3.0	1.96	-21.0
3.17	2.88	53.9	3.49	55.5	2.28	-10.5	2.21	-19.5
3.56	3.24	55.1	3.92	54.7	2.56	-1.8	2.49	-16.4
4.00	3.64	55.0	4.40	54.4	2.87	-2.5	2.80	-17.6
4.49	4.08	54.9	4.94	54.0	3.22	-6.9	3.14	-16.3
5.04	4.59	54.0	5.55	54.6	3.63	-5.8	3.55	-24.9
5.66	5.15	54.0	6.22	53.9	4.07	-20.3	3.99	-23.9
6.35	5.77	54.1	6.99	54.0	4.55	-9.5	4.48	-28.3
7.13	6.48	54.1	7.84	55.0	5.12	-29.2	5.05	-25.2
8.01	7.28	54.1	8.81	55.0	5.75	-15.5	5.67	-29.9

Page 1 of 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 twelve frequencies in the range from 900 to 3150 Hz. The accuracy of the levels was verified at the completion of the study; levels changed by no more than 1 dB each frequency

Frequency (Hz)	Pre-data Collection (dB SPL)	Post-data Collection (dB SPL)
900	75	75
1000	74.5	75
1250	75	75.5
1500	74.5	74.5
1600	74.5	74.5
1750	75	75
2000	75.5	74.5
2250	74.5	74.5
2500	75	75
2750	75	75
3000	75.5	75
3150	75	74.5

APPENDIX D
INFORMED CONSENT FORM

**THE DEPENDENCE
OF DISTORTION PRODUCT OTOACOUSTIC EMISSIONS
ON THE
FREQUENCY SEPARATION AND
RELATIVE LEVELS OF THE PRIMARY SIGNALS**

Project Objectives

The objective of this project is to determine if cochlear tuning can be measured using distortion product otoacoustic emission input/output (DPOAE I/O) functions. The data will be collected using the Virtual Corporation Model 330 Otoacoustic Emission Measurement System for which the DPOAE I/O function is FDA approved for research purposes only. The project has been approved by the University of Tennessee Committee on Research Participation.

Qualifying Criteria to Participate

You will have to meet the following criteria in the test ear as determined by the principal investigator to participate in the study:

1. No external ear pathology, cerumen impaction, or foreign body in the ear canal determined by otoscopy.
2. Normal middle ear function determined by tympanometry.
3. Normal pure tone hearing thresholds and ipsilateral acoustic reflex thresholds.
4. Normal DPOAE audiogram.

Distortion Product Otoacoustic Emission Input/Output (DPOAE I/O) Function Measurement

1. You will be seated in a comfortable chair inside a sound treated room.
2. A measurement probe which has a soft plastic tip will be inserted into your ear canal.
3. You will hear a series of sounds that will be used to activate your inner ear. The ear's responses to each sound will be measured by the probe in your ear canal and processed by a computer. This response is the DPOAE. You will be asked to remain still without talking during the 10 minutes required to obtain each I/O function.
4. DPOAE I/O functions will be recorded in 5 dB steps ranging from 30 to 75 db SPL. None of these signals pose a hazard to the ear. They range in loudness from soft to moderately loud.
5. Each DPOAE I/O function will take approximately 10 minutes. In each trial, DPOAE functions will be obtained for 14 different frequency conditions. There will be 3 complete trials (for a total of 30 minutes per frequency). In order to accomplish this, your participation will be spread out over four 2-hour sessions. The four sessions will be conducted over a period of two weeks or less. Total testing time will be approximately 8 hours.

Risk and Benefits

There are no significant risks associated with this project. The benefit of the project is that you will be contributing to the knowledge base of DPOAE which has great promise as a clinical measure of cochlear function. The results of the research will be presented at scientific meetings and published in scientific journals. Your research data will be identified by number only.

Privacy of Records

Your research data record will be identified by an assigned research number. Your name and research number will be kept confidential in a locked file. The research data record will include:

1. Your age and gender
2. Results of the qualifying tests:
 - a. Pure tone thresholds
 - b. Tympanometry
 - c. Acoustic reflex thresholds
 - d. DPOAE audiogram
3. Results of the experimental DPOAE I/O function tests.

YOUR PARTICIPATION IS COMPLETELY VOLUNTARY.

YOU MAY TERMINATE YOUR PARTICIPATION AT ANY TIME.

WHO TO CONTACT IF YOU HAVE CONCERNS:

If you have any concerns, please contact either of the principal investigators; Robert K. Rogers, M.S., 615/974-4758 or James W. Thelin, Ph.D., 615/974-1796.

PERMISSION TO PARTICIPATE

I agree to participate in this study.

Signature of Participant

Signature of Witness

Date

APPENDIX E
RANDOMIZED ORDER OF SIGNAL PRESENTATION

Trial #1

Fv (Hz)	Subject						
	1	2	3	4	5	6	7
1507	09	03	03	06	08	08	09
1604	03	08	01	13	05	09	05
1701	10	13	09	02	12	11	06
1798	04	05	07	09	14	05	11
1906	07	12	12	11	04	10	01
1927	11	02	06	07	09	03	12
1938	08	06	14	10	10	14	13
2067	01	14	10	01	02	06	08
2078	12	11	13	05	13	13	07
2099	05	07	05	08	11	12	03
2207	06	09	08	04	03	07	14
2304	02	01	04	03	07	04	04
2401	14	10	11	12	06	02	02
2509	13	04	02	14	01	01	10

Trial #2

Fv (Hz)	Subject						
	1	2	3	4	5	6	7

1507	01	04	06	14	01	07	11
1604	11	13	04	11	08	14	07
1701	03	05	01	06	11	04	02
1798	09	03	13	01	04	13	12
1906	14	08	08	04	09	05	05
1927	12	02	11	08	06	03	14
1938	06	12	10	10	12	11	06
2067	07	09	14	07	03	12	01
2078	05	01	05	03	05	02	08
2099	13	10	12*	09	14	08	03
2207	08	06	03	13	13	09	09
2304	10	07	09	05	10	10	10
2401	02	11	02	12	02	01	04
2509	04	14	07	02	07	06	13

* Condition repeated due to loss of probe seal in the ear canal.

Trial #3

Fv (Hz)	Subject						
	1	2	3	4	5	6	7

1507	08	04	03	03	08	06	10
1604	05	06	13	11*	07	14	01
1701	13	02	06	13*	12	10	07
1798	09	14	09	14*	05	13	08
1906	10	07	05	09	06	11	04
1927	02	03	12	07	10	02	09
1938	03	13	07	08	03	05	05
2067	14	12	04	02	14	07	13
2078	11	11	11	06	13	03	12
2099	12	01	14	10	04	08	02
2207	07	10	08	12*	01	04	06
2304	06	05	02	05	11	01	03
2401	01	09	01	01	02	09	11
2509	04	08	10	04	09	12	14

* Condition repeated due to loss of probe seal in the ear canal.

APPENDIX F
RAW DATA FOR INDIVIDUAL SUBJECTS

Subject Raw Data

Subject #1 - Fv Below F

Fv (Hz)	ΔF (Hz)		Fv Stimulus Level (dB SPL)					
			<u>Fv below/dp above</u>			<u>Fv below/dp below</u>		
			45 (dB SPL)	55 (dB SPL)	65 (dB SPL)	45 (dB SPL)	55 (dB SPL)	65 (dB SPL)
1507	500	T1-	N	-14.0	-13.0	N	-16.2	-0.2
		T2-	N	-19.0	-13.0	N	-14.2	-0.2
		T3-	N	N	N	N	-13.2	-1.2
1604	400		-6.0	-8.0	-4.0	N	N	-5.3
			N	-5.0	-5.0	N	-12.3	-3.3
			N	-10.0	-4.0	N	-11.3	-5.3
1701	300		-12.0	N	-8.0	-13.0	-11.0	8.0
			N	N	N	-17.0	-10.0	6.0
			N	-10.0	N	-19.0	-10.0	7.0
1798	200		N	-12.3	-7.3	-5.1	3.9	9.9
			-12.3	-10.3	-3.3	-6.1	2.9	10.9
			-13.3	-9.3	0.7	-8.1	1.9	10.9
1906	100		-8.2E	-2.2E	0.8E	-17.5	-8.5	-5.5
			-7.2	-2.2E	-1.2E	N	-4.5	-7.5E
			-8.2E	-0.2E	0.8	N	N	-2.5
1927	75		N	-2.4E	-1.4E	N	-7.2	-2.2E
			N	-2.4E	-4.4E	-19.2	-8.2E	-3.2
			N	-4.4E	N	N	-10.2	-4.2
1938	65		N	N	N	N	N	N
			N	-3.5E	N	N	N	-13.0
			N	-3.5E	-1.5E	N	N	N

E - DPOAE level possibly enhanced due to it's location on the stimulus.

N - DPOAE below the noise floor.

Subject Raw Data

Subject #1 - Fv Above F

Fv (Hz)	ΔF (Hz)		Fv Stimulus Level (dB SPL)					
			<u>Fv above/dp below</u>			<u>Fv above/dp above</u>		
			45 (dB SPL)	55 (dB SPL)	65 (dB SPL)	45 (dB SPL)	55 (dB SPL)	65 (dB SPL)
2067	65	T1-	N	1.5E	2.0E	N	-9.9	2.8E
		T2-	-4.7E	0.2E	2.0E	-11.7	N	2.3E
		T3-	-5.0E	1.0E	1.5E	-12.7E	-7.4	2.0E
2078	75		-7.8E	-0.8E	2.7E	N	-11.8	1.5E
			-6.6E	-0.3E	2.7E	N	N	1.0
			-6.1E	-0.6E	0.9E	N	N	0.7E
2099	100		-9.2	-1.7E	2.0E	N	N	1.3
			-11.0E	-3.2E	-0.5E	N	N	2.6E
			N	-4.2E	1.0E	N	-11.9	-0.7E
2207	200		-13.4	-1.9	8.1	-10.0	N	-3.0
			N	-4.4	7.6	-13.0	N	2.0
			N	-6.4	7.4	-8.0	N	1.0
2304	300		1.6	7.8	-6.4	N	-16.0	N
			1.3	7.1	-13.9	N	-18.0	N
			-1.1	6.6	-8.4	N	N	N
2401	400		11.1	14.1	11.1	N	-10.4	-4.4
			7.3	12.1	11.8	N	N	-3.4
			8.8	10.3	6.8	N	N	-4.4
2509	500		2.2	4.4	3.9	-18.0	N	-9.0
			-1.1	2.2	3.2	N	N	-13.0
			1.9	3.7	2.9	N	-11.0	-7.0

E - DPOAE level possibly enhanced due to it's location on the stimulus.
N - DPOAE below the noise floor.

Subject Raw Data

Subject #2 - Fv Below F

Fv (Hz)	ΔF (Hz)		Fv Stimulus Level (dB SPL)					
			<u>Fv below/dp above</u>			<u>Fv below/dp below</u>		
			45 (dB SPL)	55 (dB SPL)	65	45 (dB SPL)	55 (dB SPL)	65
1507	500	T1-	N	N	N	-12.2	2.8	12.8
		T2-	N	N	N	-15.2	0.8	12.8
		T3-	N	-8.0	N	N	3.8	14.8
1604	400		N	-8.0	N	-19.3	-4.3	5.7
			N	N	-6.0	-15.3	-5.3	6.7
			-7.0	N	-10.0	-13.3	-11.3	2.7
1701	300		-13.0	N	N	-7.0	5.0	10.0
			N	-10.0	N	-11.0	4.0	9.0
			N	N	-6.0	-11.0	4.0	9.0
1798	200		N	-11.3	-1.3	-1.1	8.9	14.9
			-8.3	N	-0.3	-0.1	7.9	13.9
			N	N	-1.3	-1.1	8.9	14.9
1906	100		-12.2E	-4.2E	0.8E	N	-5.5	7.5E
			N	-1.2E	4.8E	N	-8.5	9.5E
			N	-6.2E	0.8E	N	-10.5	9.5E
1927	75		N	-1.4E	2.6E	N	-7.2E	6.8E
			N	0.6E	1.6E	N	-8.2E	8.8E
			N	-0.4E	2.6E	N	-6.2E	8.8E
1938	65		N	N	N	N	N	6.0
			N	N	N	N	-9.0	10.0
			N	N	N	N	-12.0	8.0

E - DPOAE level possibly enhanced due to it's location on the stimulus.

N - DPOAE below the noise floor.

Subject Raw Data

Subject #2 - Fv Above F

Fv (Hz)	ΔF (Hz)		Fv Stimulus Level (dB SPL)					
			<u>Fv above/dp below</u>			<u>Fv above/dp above</u>		
			45 (dB SPL)	55 (dB SPL)	65 (dB SPL)	45 (dB SPL)	55 (dB SPL)	65 (dB SPL)
2067	65	T1-	N	N	N	N	-8.7	3.3E
		T2-	N	3.0E	N	-13.9	-8.4E	3.8E
		T3-	N	N	N	N	-6.7	3.0E
2078	75		N	-0.3E	-1.8E	-15.5	-11.0	3.0
			N	2.9E	1.2E	N	N	3.2E
			N	2.2E	-0.6E	N	-9.5	2.0
2099	100		-8.7E	2.5E	2.0	N	-10.7	-0.9E
			-4.7E	5.2	1.7	N	N	0.8E
			-4.5E	4.5	1.0	N	-13.7	1.8E
2207	200		1.9	9.1	4.9	N	N	-1.0
			2.6	10.4	6.4	N	N	-5.0
			2.4	10.1	5.6	-13.0	N	-8.0
2304	300		8.3	11.3	7.6	N	-12.0	-7.0
			9.3	12.1	8.1	N	N	-6.0
			9.3	13.3	10.1	N	-11.0	-5.0
2401	400		0.6	4.3	10.1	N	N	-19.4
			0.1	5.3	13.1	N	N	N
			0.8	6.1	11.1	N	N	N
2509	500		7.9	6.9	4.9	N	N	N
			2.9	0.9	6.9	N	-16.0	N
			3.7	1.9	5.2	N	N	N

E - DPOAE level possibly enhanced due to it's location on the stimulus.
N - DPOAE below the noise floor.

Subject Raw Data

Subject #3 - Fv Below F

Fv (Hz)	ΔF (Hz)		Fv Stimulus Level (dB SPL)					
			<u>Fv below/dp above</u>			<u>Fv below/dp below</u>		
			45 (dB SPL)	55 (dB SPL)	65 (dB SPL)	45 (dB SPL)	55 (dB SPL)	65 (dB SPL)
1507	500	T1-	N	N	N	N	N	-0.2
		T2-	N	N	N	N	-16.2	N
		T3-	N	N	N	N	-15.2	-5.2
1604	400		N	N	-15.0	N	-15.3	2.7
			-11.0	N	-12.0	N	N	-3.3
			-8.0	N	-4.0	-18.3	-10.3	2.7
1701	300		N	N	N	N	-14.0	2.0
			-21.0	N	-10.0	N	-17.0	-0.0
			-12.0	-12.0	-10.0	N	-14.0	-2.0
1798	200		N	N	N	N	N	-5.1
			N	N	N	N	N	-7.1
			N	-15.3	-9.3	-13.1	-17.1	-4.1
1906	100		N	N	N	N	N	N
			-11.2E	N	-6.2	N	-15.5E	N
			N	N	N	-13.5	N	-7.5E
1927	75		N	N	N	N	N	-3.2E
			N	N	N	-16.2	N	-10.2E
			N	N	N	N	-18.2E	-6.2E
1938	65		N	N	N	N	N	-10.0
			N	N	N	-14.0E	N	-2.0
			N	N	N	N	N	-13.0

E - DPOAE level possibly enhanced due to it's location on the stimulus.
N - DPOAE below the noise floor.

Subject Raw Data

Subject #3 - Fv Above F

Fv (Hz)	ΔF (Hz)		Fv Stimulus Level (dB SPL)					
			<u>Fv above/dp below</u>			<u>Fv above/dp above</u>		
			45 (dB SPL)	55 (dB SPL)	65 (dB SPL)	45 (dB SPL)	55 (dB SPL)	65 (dB SPL)
2067	65	T1-	N	N	N	-12.9E	-9.4	-2.7E
		T2-	N	N	N	N	-8.9E	-6.9E
		T3-	N	N	N	-11.9E	-8.7E	-2.7E
2078	75		N	N	N	N	N	-8.0E
			N	N	N	-15.8	N	-10.8E
			N	N	N	N	N	-6.5E
2099	100		N	N	N	N	-13.9	-4.9E
			N	N	-9.5E	N	N	-7.2E
			N	N	N	N	N	-7.2E
2207	200		-13.9	N	-6.6	N	N	-10.0
			N	-14.6	-12.4	N	N	N
			N	N	-9.4	-10.0	-17.0	-10.0
2304	300		-5.4	-2.1	-11.9	N	-9.0	-7.0
			-5.6	-0.1	-1.6	N	N	N
			-4.6	2.3	0.6	N	N	N
2401	400		-4.4	-1.9	-2.9	N	N	-11.4
			-4.9	-2.4	-3.7	N	N	N
			-4.2	-2.2	-4.2	-13.4	-16.4	N
2509	500		-4.3	-5.8	-18.3	N	N	-15.0
			-1.1	-1.8	-11.6	N	N	-17.0
			-11.3	N	-16.3	N	-15.0	-20.0

E - DPOAE level possibly enhanced due to it's location on the stimulus.

N - DPOAE below the noise floor.

Subject Raw Data

Subject #4 - Fv Below F

Fv (Hz)	ΔF (Hz)		Fv Stimulus Level (dB SPL)					
			<u>Fv below/dp above</u>			<u>Fv below/dp below</u>		
			45 (dB SPL)	55 (dB SPL)	65 (dB SPL)	45 (dB SPL)	55 (dB SPL)	65 (dB SPL)
1507	500	T1-	N	N	N	N	-12.2	N
		T2-	N	N	N	N	N	N
		T3-	-10.0	-10.0	-9.0	-18.2	N	N
1604	400		-10.0	N	-12.0	-15.3	-7.3	N
			N	N	N	N	-7.3	-2.3
			N	N	-18.0	-14.3	-6.3	-0.3
1701	300		-16.0	N	N	-6.0	2.0	2.0
			N	-11.0	-10.0	-3.0	6.0	3.0
			-17.0	N	N	N	3.0	5.0
1798	200		N	N	-8.3	-17.1	-1.1	8.9
			N	N	N	-14.1	-0.1	7.9
			-20.3	-11.3	-12.3	N	-9.1	6.9
1906	100		-11.2	-11.2E	-2.2E	N	N	1.5E
			N	-12.2E	-2.2E	N	N	0.5E
			N	N	N	N	-11.5	N
1927	75		N	N	N	N	-14.2	N
			N	N	N	-2.2	N	-1.2E
			N	N	N	N	N	N
1938	65		N	N	N	N	N	-8.0
			N	N	N	N	-10.0E	-8.0
			N	N	N	-15.0	-13.0	N

E - DPOAE level possibly enhanced due to it's location on the stimulus.

N - DPOAE below the noise floor.

Subject Raw Data

Subject #4 - Fv Above F

Fv (Hz)	ΔF (Hz)		Fv Stimulus Level (dB SPL)					
			<u>Fv above/dp below</u>			<u>Fv above/dp above</u>		
			45 (dB SPL)	55 (dB SPL)	65 (dB SPL)	45 (dB SPL)	55 (dB SPL)	65 (dB SPL)
2067	65	T1-	-6.7E	-1.7E	-2.2E	N	N	N
		T2-	N	-2.0E	-5.0E	N	N	N
		T3-	N	-2.0E	N	-11.7E	-10.7E	-5.7E
2078	75		-8.1E	-2.6E	-4.6E	N	N	-7.0
			N	-2.6E	-8.6E	N	N	-5.0
			N	-10.6E	N	N	N	-6.0
2099	100		-12.5	-4.2E	N	N	N	N
			N	-17.0E	N	N	N	N
			N	N	N	N	-10.9	N
2207	200		-2.6	4.9	-4.1	N	-9.0	0.1
			-3.4	4.9	-4.9	-6.0	N	N
			-4.1	1.4	-3.4	N	N	-6.0
2304	300		-14.9	1.1	8.1	N	N	N
			N	1.8	8.1	N	N	-5.0
			-13.1	2.8	6.3	N	-7.0	-5.0
2401	400		7.8	10.1	-1.4	N	-4.4	-9.9
			3.1	1.3	-3.2	-6.4	N	N
			4.3	8.1	-0.4	N	N	N
2509	500		6.9	7.2	3.4	N	N	-14.0
			6.2	6.7	1.9	N	N	N
			6.9	7.2	2.9	N	-16.0	N

E - DPOAE level possibly enhanced due to it's location on the stimulus.
N - DPOAE below the noise floor.

Subject Raw Data

Subject #5 - Fv Below F

Fv (Hz)	ΔF (Hz)		Fv Stimulus Level (dB SPL)					
			<u>Fv below/dp above</u>			<u>Fv below/dp below</u>		
			45 (dB SPL)	55 (dB SPL)	65	45	55	65 (dB SPL)
1507	500	T1-	N	N	N	N	-4.2	0.8
		T2-	N	N	N	N	-4.2	-0.2
		T3-	N	N	-17.0	N	-3.2	-1.2
1604	400		N	N	N	-8.3	-11.3	7.7
			N	-13.0	N	-9.3	0.7	11.7
			N	N	N	-9.3	-1.3	10.7
1701	300		-8.0	-8.0	N	7.0	5.0	8.0
			N	N	-10.0	5.0	-2.0	10.0
			N	N	-9.0	4.0	1.0	10.0
1798	200		N	-9.3	-11.3	-10.1	-6.1	3.9
			N	N	N	-12.1	-7.1	4.9
			N	N	-10.3	N	-6.1	4.9
1906	100		N	N	-3.2E	N	N	0.5
			N	N	-2.2E	-11.5	N	N
			N	N	N	-4.5	N	0.5E
1927	75		N	N	N	N	N	-2.2E
			N	N	N	-14.2	N	-4.2E
			N	N	N	N	N	N
1938	65		N	N	N	N	N	-4.0
			N	N	N	N	N	-3.0
			N	N	N	N	N	-2.0

E - DPOAE level possibly enhanced due to it's location on the stimulus.

N - DPOAE below the noise floor.

Subject Raw Data

Subject #5 - Fv Above F

Fv (Hz)	ΔF (Hz)		Fv Stimulus Level (dB SPL)					
			<u>Fv above/dp below</u>			<u>Fv above/dp above</u>		
			45 (dB SPL)	55 (dB SPL)	65 (dB SPL)	45 (dB SPL)	55 (dB SPL)	65 (dB SPL)
2067	65	T1-	N	-5.2E	-4.7E	N	-12.4E	N
		T2-	N	N	N	N	N	N
		T3-	N	N	N	-10.2	N	N
2078	75		N	N	N	N	N	-9.5
			N	N	N	N	N	-9.0
			N	N	N	N	N	N
2099	100		N	-11.2E	-13.2E	N	-15.9E	N
			N	-10.0	-10.2E	N	N	N
			N	N	N	N	N	N
2207	200		-9.9	-9.6	-0.4	N	N	N
			N	-11.6	-1.1	N	N	N
			-16.4	N	N	N	-12.0	-8.0
2304	300		-0.4	6.3	5.3	N	N	-14.0
			-1.9	3.8	1.1	-13.0	N	N
			-0.1	6.8	4.3	-9.0	-9.0	-13.0
2401	400		-6.9	-0.7	-6.4	-14.4	N	-14.4
			-3.7	1.3	-4.9	-14.4	N	N
			-4.9	0.6	-3.2	N	N	N
2509	500		-6.8	-2.6	-1.3	N	N	N
			-5.1	0.2	0.2	N	N	-12.0
			-6.3	0.4	0.9	N	N	N

E - DPOAE level possibly enhanced due to it's location on the stimulus.
N - DPOAE below the noise floor.

Subject Raw Data

Subject #6 - Fv Below F

Fv (Hz)	ΔF (Hz)		Fv Stimulus Level (dB SPL)					
			<u>Fv below/dp above</u>			<u>Fv below/dp below</u>		
			45 (dB SPL)	55 (dB SPL)	65 (dB SPL)	45 (dB SPL)	55 (dB SPL)	65 (dB SPL)
1507	500	T1-	N	N	N	N	N	-11.2
		T2-	N	N	-14.0	N	N	-11.2
		T3-	N	N	N	N	N	N
1604	400		N	-7.0	-10.0	N	-10.3	-7.3
			N	N	N	N	-12.3	-8.3
			N	N	-5.0	N	-8.3	N
1701	300		-10.0	-16.0	N	N	-7.0	-1.0
			N	-11.0	-9.0	-17.0	-7.0	-6.0
			N	N	N	N	-6.0	7.0
1798	200		N	N	-8.3	N	-14.1	-0.1
			N	N	-6.3	N	-13.1	-1.1
			N	-11.3	N	N	N	-2.1
1906	100		N	N	-7.2E	N	N	-10.5E
			N	N	N	-13.5	N	N
			N	N	-7.2E	N	-13.5	-12.5E
1927	75		N	N	N	-15.2	-12.2E	N
			N	N	0.6E	-5.2	N	N
			N	N	N	N	N	N
1938	65		N	N	-6.5	N	N	-8.0
			N	N	N	N	N	-10.0
			-4.5E	-7.5E	-4.5E	N	N	N

E - DPOAE level possibly enhanced due to it's location on the stimulus.

N - DPOAE below the noise floor.

Subject Raw Data

Subject #6 - Fv Above F

Fv (Hz)	ΔF (Hz)		Fv Stimulus Level (dB SPL)					
			<u>Fv above/dp below</u>			<u>Fv above/dp above</u>		
			45 (dB SPL)	55 (dB SPL)	65 (dB SPL)	45 (dB SPL)	55 (dB SPL)	65 (dB SPL)
2067	65	T1-	N	N	N	N	N	N
		T2-	N	N	N	N	N	N
		T3-	N	N	N	N	N	N
2078	75		N	-8.1E	N	N	N	-5.5
			N	-5.3E	-5.8E	N	N	-4.0
			N	-6.8E	-7.6E	N	N	-5.3
2099	100		N	N	-7.2	N	N	N
			-14.0E	-9.5E	N	N	N	-5.4
			N	N	N	N	N	N
2207	200		-5.1	-0.4	-8.6	N	N	N
			-12.4	-2.6	-5.4	N	-6.0	-12.0
			-10.6	-3.9	-6.9	-9.0	-11.0	-10.0
2304	300		-2.1	0.1	-1.6	N	N	-17.0
			-3.9	-0.6	-3.4	N	-14.0	N
			-5.6	-2.1	-4.6	N	N	N
2401	400		-0.9	-4.9	-7.9	N	N	N
			1.8	0.3	-4.7	N	N	N
			-0.9	-2.7	-9.4	-12.4	N	N
2509	500		-10.1	N	-18.6	-15.0	-16.0	-11.0
			-5.3	-11.3	N	N	-17.0	-14.0
			-5.8	N	N	N	N	-9.0

E - DPOAE level possibly enhanced due to it's location on the stimulus.

N - DPOAE below the noise floor.

Subject Raw Data

Subject #7 - Fv Below F

Fv (Hz)	ΔF (Hz)		Fv Stimulus Level (dB SPL)					
			<u>Fv below/dp above</u>			<u>Fv below/dp below</u>		
			45 (dB SPL)	55 (dB SPL)	65	45 (dB SPL)	55 (dB SPL)	65
1507	500	T1-	N	N	N	N	N	3.8
		T2-	N	N	N	N	N	-10.2
		T3-	-12.0	N	N	N	N	-6.2
1604	400		N	-12.0	-5.0	N	-5.3	10.7
			N	N	-11.0	N	-11.3	1.7
			N	N	-5.0	N	-11.3	2.7
1701	300		-9.0	N	-8.0	-8.0	2.0	10.0
			-13.0	N	N	-8.0	1.0	8.0
			N	N	N	-9.0	2.0	8.0
1798	200		N	-8.3	-3.3	-2.1	-4.1	4.9
			-12.3	-10.3	-1.3	N	-5.1	6.9
			-6.3	N	-6.3	N	-5.1	3.9
1906	100		N	-3.2E	0.8E	N	N	2.5E
			-9.2	-3.2E	-2.5E	N	-6.5	2.5E
			-11.2	-6.2	0.8E	N	-9.5	1.5
1927	75		N	-4.4E	N	N	N	2.8E
			-6.4E	-2.4	1.6E	N	N	3.8E
			N	-0.4E	-2.4E	N	-12.2	3.8E
1938	65		N	N	N	-16.0	N	-4.0
			N	N	0.5E	N	N	-1.0
			N	N	-0.5E	N	N	-1.0

E - DPOAE level possibly enhanced due to it's location on the stimulus.

N - DPOAE below the noise floor.

Subject Raw Data

Subject #7 - Fv Above F

Fv (Hz)	ΔF (Hz)		Fv Stimulus Level (dB SPL)					
			Fv above/dp below			Fv above/dp above		
			45 (dB SPL)	55 (dB SPL)	65 (dB SPL)	45 (dB SPL)	55 (dB SPL)	65 (dB SPL)
2067	65	T1-	N	N	-3.0E	-14.4E	-7.7	4.0E
		T2-	N	-4.5E	N	N	-8.4	3.3E
		T3-	N	-4.2E	N	N	-9.9	2.5E
2078	75		N	N	-6.3E	N	-10.3E	2.5
			N	-7.8E	-9.1E	N	N	1.0E
			N	-7.3E	-9.1E	-12.5	N	1.5
2099	100		N	N	-5.7E	N	N	-3.9E
			N	N	-4.5E	N	N	-1.9E
			N	N	-4.5E	N	-15.2E	-2.4E
2207	200		-6.4	3.1	7.4	N	N	-13.0
			-10.1	-0.1	6.4	N	N	-7.0
			-6.6	2.9	6.9	N	N	-7.0
2304	300		5.1	10.3	0.6	N	-13.0	-11.0
			1.1	8.3	1.8	N	N	-6.0
			1.6	8.6	2.1	N	N	-4.0
2401	400		7.6	9.1	3.8	N	N	-8.4
			5.1	9.8	4.8	N	N	-10.4
			5.8	9.1	3.3	N	N	-9.4
2509	500		5.4	3.9	1.4	N	N	N
			6.2	6.9	3.9	N	N	N
			5.4	4.9	1.9	N	N	N

E - DPOAE level possibly enhanced due to it's location on the stimulus.

N - DPOAE below the noise floor.

VITA

Robert K. Rogers was born in Cartersville, Georgia on October 20, 1954. After graduating from High School in 1972, he attended Truett McConnell College for two years. Upon consecutive quarters on academic and disciplinary probation, he was promptly dismissed from the school. For the following year, he worked at odd jobs, finally enlisting in the U.S. Navy in 1975. While in the Navy, a major attitude adjustment was undertaken resulting in the Associate of Arts degree in General Education from Los Angeles City College in October of 1978. In December of 1979, he left the Navy to return to school on the GI Bill, all-the-while remaining in the Naval Reserves. He received his Bachelor of Science degree with a major in Psychology from East Tennessee State University in May of 1981 and the Master of Science degree with a major in Audiology in 1984. With a great desire to return to the military, he was commissioned in the U.S. Army (no openings in the Navy) in February 1985 as a Medical Service Corps Audiologist. After three years serving as a staff audiologist at Walter Reed Army Medical Center, he completed an inter-service transfer back to the U.S. Navy with a three year tour of duty as the Head, Audiology Department, Naval Hospital Long Beach. In 1991, he was selected for the Out-Service Training Program to be sponsored by the Department of the Navy for the Ph.D. degree in Audiology. In August of 1994, he received the Ph.D. from the University of Tennessee. LCDR Rogers is currently under orders to report to the Naval Medical Center Portsmouth, VA no later than September

1994 with duty as the Head, Audiology Department, Occupational Health Directorate. Future plans include clinical as well as greater administrative responsibilities within the Navy Medical Department.