ABSTRACT

BONE CONDUCTION/AIR CONDUCTION CANCELLATION AS A FUNCTION OF INTENSITY AND FREQUENCY MANIPULATION

by Solomon Rundbaken

Research has demonstrated that it is possible to cancel a bone-conducted pure tone by an air-conducted pure tone. This phenomenon occurs when the two tones are identical in frequency and intensity, and have a 180° phase relationship.

The purpose of this study was to investigate the effects of phase conversion upon bone conduction/air conduction cancellation as a function of intensity and frequency under specified arrangements and conditions. The experimental arrangements included placement of the bone conduction oscillator on the center of the forehead, and monaural placement of the air conduction receiver (right ear occluded by the earphone; left ear open). Subjects were required to manipulate the phase and intensity of an air-conducted pure tone in one ear in an attempt to cancel a constant, identical, bone-conducted pure tone in the same ear. The experimental variables were limited to levels of 500, 1000, 2000, and 4000 cps for frequency; and to levels of 20, 30, 40, and 50 dB for intensity. Any

combination of frequency and intensity levels constituted one of sixteen treatment combinations. The specific questions asked were related to whether or not intensity differences between air-conducted and bone-conducted pure tones differed significantly during cancellation as frequency and intensity were altered.

Sixteen normal hearing adult male subjects were randomly divided into four groups and distributed throughout a 4 X 4 Latin square. Each subject was given twenty-four trials (six cancellation attempts at each of four treatment combinations) that were randomized and programmed for presentation. The intensity differences between the air-conducted and bone-conducted tones at the point of cancellation were recorded and computed as criterion scores. The reliability of the criterion scores across both frequency and intensity, as measured by correlating the first three trials of subjects in each cell against the last three trials, was found to range from .8917 to .9618.

The results of an analysis of variance test indicated that neither alterations in the intensity variable nor interaction between the intensity and frequency variables significantly affected the criterion scores. Changes in the frequency variable, however, were found to be statistically significant at the .05 level. "Critical difference" tests were employed for the frequency variable and a significant difference between means was found only between 1000 and 4000 cps at the 30 dB level. These results were discussed and reasons were presented that allowed the experimenter to assume that the statistical finding of significance for the frequency variable was of no practical value.

The results appeared to warrant the conclusion that the ratio of intensity differences between air-conducted and bone-conducted pure tones, as cancellation occurs in one ear, remains essentially constant as intensity and frequency are altered in accordance with their prescribed experimental ranges. It was further concluded that the intensity differences between air conduction and bone conduction at the point of cancellation do not change significantly as a result of inter-relationships between frequency and intensity.

On the basis of the results, recommendations for further research were discussed.

BONE CONDUCTION/AIR CONDUCTION CANCELLATION

AS A FUNCTION OF

INTENSITY AND FREQUENCY MANIPULATION

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

CHAPTER I

INTRODUCTION

It has been demonstrated that it is possible to cancel a bone-conducted pure tone by altering the phase of a binaural air-conducted pure tone of identical frequency and intensity.[1,2,3,4] This cancellation effect can be observed when the air-conducted tone is 180° out of phase with the bone-conducted tone, and the effect can be induced throughout a wide range of frequencies.[5] The present study has been focused directly upon certain observations relative to the bone conduction/air conduction cancellation phenomenon.

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[1]George von Békésy, Experiments in Hearing (N.Y.: McGraw-Hill Book Co., Inc., 1960), pp. 128-130.

[2]Merle Lawrence and Ernest Glen Wever, Physiological Acoustics (Princeton, N.J.: Princeton University Press, 1954), p. 234.

[3]Jozef Zwislocki, "Wave Motion in the Cochlea Caused by Bone Conduction," Journal Acoustical Society of America, XXV (September, 1953), pp. 986-989.

[4]Karl Lowy, "Cancellation of the Electrical Cochlear Response With Air Conduction and Bone Conduction Sound," Journal Acoustical Society of America, XIV (October, 1942), pp. 156-158.

[5]Ernest Glen Wever and Merle Lawrence, "The Place Principle In Auditory Theory," Proceedings of the National Academy of Science, XXXVIII (1952), pp. 133-138.

Purpose of the Study

The purpose of this study is to investigate the effects of the bone conduction/air conduction cancellation phenomenon as a function of intensity and frequency under certain prescribed experimental conditions.

Imposed Limitations

Because published research materials dealing with the bone conduction/air conduction cancellation phenomenon appear to be sparse as one inspects the available literature, the conclusion is drawn that this general topic is in need of detailed investigation. However, since it was neither realistic nor practical to attempt to study all aspects of the subject, the experimenter chose to channel efforts toward the study of the effects of intensity upon the bone conduction/air conduction cancellation phenomenon across a number of frequencies under carefully controlled conditions. Other areas related to the general topic that should be studied are described under Implications For Further Research in Chapter V.

Discussion

In order to effect cancellation of a bone-conducted pure tone by the modification of an identical air-conducted pure tone, it is necessary to make appropriate adjustments of intensity and phase under a binaural air conduction arrangement. The binaural presentation of the air-conducted tone is necessary due to the fact that when a bone-conducted tone (which stimulates both cochleae simultaneously) is cancelled by an air-conducted tone in only one ear, the opposite cochlea should continue to receive the auditory sensation by bone conduction. This question then arises: What would be the observable outcome if the air-conducted tone were presented monaurally?

The answer to this question was sought by one investigator,[1] who used a masking noise to prevent participation of the non-test ear as the necessary cancellation adjustments were performed on the ear under test. Complete subjective cancellations of bone-conducted and air-conducted pure tones under these monaural conditions were achieved at least 40% of the time. Very sharp nulls in the test ear were induced over the remaining 60% of the time.

What would have occurred in the experiment cited had the non-test ear been unmasked and unoccluded, thus, eliminating the problems associated with masking that have been observed and reported in the literature?[2,3] Briefly, these

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[1]Letter from Ernest L. Smith, Physicist, Sound Section, Institute For Basic Standards, National Bureau of Standards, U.S. Department of Commerce, Washington, D.C., November 23, 1965. Paper read before the Acoustical Society of America, Ann Arbor, Michigan, November, 6-9, 1963. Co-author of study, Howard S. Bowman.

[2]Gerald A. Studebaker, "On Masking In Bone Conduction Testing," Journal of Speech and Hearing Research, V (September, 1962), p. 215.

[3]Donald Dirks and Carolyn Malmquist, "Changes in Bone Conduction Thresholds Produced by Masking in the Non-Test Ear," Journal of Speech and Hearing Research, VII (September, 1964), pp. 271-272.

problems are associated with threshold shifts due to the masking noise interfering with the test ear, and the "central masking" phenomenon.

Consider a bone conduction oscillator delivering a pure tone to the forehead (midline) of a subject who has normal bilateral hearing sensitivity. The subject under this condition will experience the sensation of perceiving the bone-conducted sound image in the middle of the head,[1] or as coming from the point of contact.[2] When an air conduction receiver is placed over one ear only, the bone-conducted auditory sensation, depending upon frequency,[3] will localize toward that ear because of the effect caused by the occluded external auditory meatus (Weber effect).[4] An intracranial localization shift of the auditory sensation similar to that produced by the occlusion effect will occur when a bone conduction/air conduction cancellation effect is induced in the test ear (opposite ear unoccluded). The disappearance of the tone under this condition will not be complete because, as pointed out previously, even with perfect adjustment of frequency, intensity, and phase, the

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[1] von Békésy, op. cit., p. 135.

[2] Lawrence and Wever, op. cit., p. 337.

[3] David P. Goldstein and Claude S. Hayes, "The Occlusion Effect in Bone Conduction Hearing," Journal of Speech and Hearing Research, VIII (June, 1965), p. 137.

[4] Hallowell Davis, "Audiometry," Hearing and Deafness, ed. H. Davis (N.Y.: Holt, Rinehart and Winston, Inc., 1961), p. 169.

opposite cochlea will continue to be stimulated by the bone-conducted tone. However, there will be a definite observable effect characterized by an intracranial shift of the sound image, or at least an attenuation of the auditory sensation in the ear receiving the air-conducted tone. The cancellation effect will reach its maximum when the frequency and intensity of the two tones are identical, and when the tones are 180° out of the phase with respect to each other.

Assume that when frequency is held constant (identical bone-conducted and air-conducted tones), and intensity and phase are experimentally varied by subjects, when the two tones are exactly equal in loudness and 180° apart, the maximum cancellation effect discussed above will occur. At the point of maximum cancellation effect, there will most likely be a difference in sound pressure level between the bone-conducted and air-conducted tones. If the intensity of the bone-conducted tone is increased by a given increment, will it be necessary to raise the intensity of the air-conducted tone by an equal amount in order to induce the maximum cancellation effect? With the intensity of the bone-conducted tone adjusted to various levels across the intensity scale, will the difference between the intensities of the bone-conducted and air-conducted tones remain the same at the point of the maximum cancellation effect? Will the differences in intensity between the bone-conducted and air-conducted tones remain constant across the frequency scale?

With (1) forehead placement (midline) of the bone conduction oscillator or vibrator, (2) monaural placement of the air conduction receiver (right ear occluded by the receiver, left ear open), (3) equal loudness of bone-conducted and air-conducted pure tone stimuli, and (4) 180° bone conduction/air conduction phase relationship, the following specific questions were asked:

1. Does the intensity-difference between air- and bone-conducted pure tones (criterion scores) differ significantly at the point of maximum cancellation as <u>intensity</u> is altered?

2. Does the intensity-difference between air- and bone-conducted pure tones differ significantly at the point of maximum cancellation as <u>frequency</u> is altered?

3. Are there certain inter-relationships between frequency and intensity that affect the criterion scores?

In an attempt to answer these questions, the following null hypotheses were formulated for statistical testing in this study:

1. There is no significant difference in criterion scores as a function of intensity.

2. There is no significant difference in criterion scores as a function of frequency.

3. There is no significant difference in criterion scores as a function of interaction between frequency and intensity.

Importance of the Study

A review of the literature indicates that there is a significant lack of published materials relative to the bone conduction/air conduction cancellation phenomenon.

The basic importance of this study rests upon the assumption that the investigation will produce observations and conclusions that will contribute to a more complete understanding of the bone conduction/air conduction cancellation phenomenon.

A further justification for this investigation rests upon the possibility that the observations and conclusions drawn from the experiment will lend themselves toward the eventual clinical application of the bone conduction/air conduction cancellation effect. It is not within the limits nor the purpose of this study to determine the exact nature of its clinical potential, but the practicability of such an application will be discussed under Implications for Further Research in Chapter V.

Definitions

Several terms that appear in the literature and in this study require definitions. These terms and definitions follow.

Frequency. Aerial sound waves are produced by a vibrating body in contact with the air.[1] When the oscillations or vibrations of the body have a periodic quantity, the complete sequence of values of that quantity that occur during a period of time may be expressed by the term "cycle." "The frequency of a function periodic in time is the

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[1]Howard M. Tremaine, The Audio Cyclopedia (1st ed.; Indianapolis: Howard W. Sams and Co., Inc., 1959), p. 1.

reciprocal of the independent variable for which the function repeats itself."[1] In other words, the frequency of a sound wave is the number of cycles that occur in one second of time.

Intensity. In acoustical terminology, ". . . the sound intensity in a specified direction at a point is the average rate of sound energy transmitted in the specified direction through a unit area normal to this direction at the point considered."[2] The intensity level of a sound ". . . is 10 times the logarithm to the base 10 of the ratio of the intensity of this sound to the reference intensity."[3] The usual reference sound intensity is 10^{-16} watt per square centimeter in a specified direction.

The intensity of a sound may also be measured by determining the ratio of the sound's pressure to a standard reference pressure of .0002 dynes per square centimeter.[4]

Loudness. Loudness is a subjective or psychological measure of sound as opposed to intensity, which is a physical measure of a sound wave.[5] According to the American Standard

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[1] American Standard Acoustical Terminology (N.Y.: American Standards Association, Inc., May 25, 1960), p. 9.

[2] Ibid., p. 12.

[3] Ibid., pp. 14-15.

[4] J. C. R. Licklider, "Basic Correlates of the Auditory Stimulus," Handbook of Experimental Psychology, ed. S. S. Stevens (N.Y.: John Wiley and Sons, Inc., 1963), p. 994.

[5] Hayes A. Newby, Audiology (N.Y.: Appleton-Century-Crofts, Inc., 1958), p. 11.

definition, ". . . loudness is the intensive attribute of an auditory sensation, in terms of which sounds may be ordered on a scale extending from soft to loud."[1] Loudness depends upon the sound pressure, the frequency, and the wave form of the sound.[2]

Pure Tones. A pure tone or simple tone is a ". . . sound wave, the instantaneous sound pressure of which is a simple sinusoidal function of the time."[3] It is characterized by ". . . singleness of pitch."[4]

Phase. The phase of a periodic sound wave or quantity is the fractional part of a period through which the sound has advanced in reference from a reference point.[5] "The term phase essentially means 'time,' or the time interval between the instant when one thing occurs and the instant when a second related thing takes place."[6] In this study, the phase has been considered as the time interval between two pure tones delivered via air and bone conduction.

Phase differences can be measured by dividing the cycle into 360 parts or degrees. One phase degree may be

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[1] American Standard Acoustical Terminology, p. 45.

[2] Ibid.

[3] Ibid., p. 47.

[4] Ibid.

[5] Ibid., p. 10.

[6] Byron Goodman (ed.), The Radio Amateur's Handbook (41st ed.; Newington, Conn.: American Radio Relay League, 1964), p. 32.

thought of as 1/360 of a cycle. Phase can be controlled continuously throughout the cycle's 360° by the use of a variable phase shifter which has been described in the literature.[1]

Maximum Cancellation Effect. In the present investigation, this term represents the greatest amount of signal attenuation, or intracranial localization shift, possible as a result of the bone conduction/air conduction cancellation phenomenon under monaural air conduction conditions.

Organization of the Study

Chapter I has discussed the phenomenon of bone conduction/air conduction cancellation, the Purpose and Limitations of the study, and the Definitions of important terminology.

Chapter II consists of a detailed description of the previous literature relative to the topic. Topics of secondary interest, but pertinent to the study, are also discussed.

Chapter III is devoted to outlining in detail the experimental procedures employed in the present study. Additionally, this portion of the study discussed the subjects, apparatus, instrumental arrangement, and presentation of stimuli.

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[1]Courtney Stromsta and William L. Dawson, "A Continuously Variable 360° Phase Shifter," Journal of Speech and Hearing Research, IV (March, 1961), pp. 37-40.

Chapter IV is focused on the results of the statistical analysis and on the discussion of the findings.

The summary of the study is presented in Chapter V, and conclusions derived from the analysis are discussed. Implications for additional research also appear in the final chapter.

CHAPTER II

REVIEW OF THE LITERATURE

Because the present study is concerned with the effects of phase manipulation upon the reception of air-conducted and bone-conducted pure tones, this chapter will discuss: (1) the manner in which the experimental stimuli--pure tones--are transmitted through two media--air and bone--to the cochlea; (2) sensorineural function; (3) the physical nature of sound wave cancellation by phase interference; (4) monaural and binaural phase effects; and (5) the history of the scientific investigation of phase interference with respect to bone and air conduction.

With reference to the content of this chapter as outlined above, it should be indicated at the outset that the literature of auditory theory contains a vast amount of information with respect to air conduction, bone conduction, cochlear function, and intracranial and extracranial monaural and binaural phase effects. However, since the present study is directly related only to the air/bone cancellation phenomenon, a detailed presentation of these areas is neither practical nor necessary in view of the exact purpose and limitations of this investigation. It is felt, however, that a brief, simplified, overview of these topics would be helpful for orientation to the total nature of the study.

Air and Bone Conduction

Hearing by Air Conduction. Sound may be transmitted in various media: solids, liquids, or gasses. As sound waves travel through air, the movement of these waves, or vibrations, from the source to a given point may be considered in terms of the speed at which the sound wave travels. It has been demonstrated that sound travels in air at about 1090 feet per second at 0° centigrade.[1]

Before sound waves are converted into auditory sensations, they must travel over certain anatomical structures within the ear and undergo certain changes along the path they traverse. The process leading to the sense of hearing is initiated as the sound waves enter the external auditory meatus of the ear and impinge upon the eardrum or tympanic membrane. This impingement causes the drum to vibrate and evokes certain operations within the middle ear that are responsible for the eventual stimulation of the cochlea or sense organ of hearing.[2]

The processes that occur within the middle ear are directly related to the bones (malleus, incus, stapes) contained therein. These tiny, osseous structures extend

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[1] Newton Henry Black and Elbert Payson Little, College Physics (4th ed.; N.Y.: The Macmillan Co., 1956), pp. 572-573.

[2] Georg von Békésy and Walter A. Rosenblith, "The Mechanical Properties of the Ear," Handbook of Experimental Psychology, ed. S. S. Stevens (N.Y.: John Wiley and Sons, Inc., 1963), pp. 1075-1084.

in the form of a connected chain from the interior surface of the tympanic membrane, across the area of the middle ear or tympanic cavity, to the oval window located in the osseous wall that separates the middle ear from the inner ear (cochlea). The particular arrangement of the eardrum and the ossicular chain is such that they vibrate in conjunction with each other and, together, serve as a mechanical transformer for the purpose of transferring acoustic energy to the choclea.[1] The mechanical energy is then changed into neural energy in that part of the ear containing the sensory receptors of the auditory nerve called the cochlea. These receptors are stimulated by cochlear operations, to be discussed later, that occur as the result of the vibrations of the footplate of the stapes which is attached to the oval window. Because the total area of the oval window is about 1/20 as large as the eardrum, and due to the lever action of the ossicles, the transfer of energy across the middle ear cavity increases the sensitivity of the ear by at least 25 dB.[2]

The stapedius and tensor tympani muscles, that are also located in the middle ear, are of additional importance

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[1]Ernest Glen Wever and Merle Lawrence, "The Transmission Properties of the Middle Ear," Annals of Otology, Rhinology and Laryngology, LIX (March, 1950), pp. 5-18.

[2]Hallowell Davis, "Anatomy and Physiology of the Ear," Hearing and Deafness, ed. H. Davis (rev. ed., N.Y.: Holt, Rinehart and Winston, Inc., 1961), pp. 66-67.

to the reception of sound waves. In general, the tensor tympani maintains the eardrum or tympanic membrane in a taut condition, thus, enhancing its vibratory capabilities. The arrangement of the stapedius is such that it acts as a protective device in the presence of loud sounds by decreasing the amplitude of the vibrations of the stapes, thereby protecting the delicate structures of the cochlea.[1]

In summary, the process of hearing by air conduction involves, in simple terms, the transfer of air-borne sound vibrations from the tympanic membrane to the cochlea by way of the middle ear apparatus.

Bone-Conducted Sound Waves. A sound of sufficient amplitude may be perceived when the source, a vibrating body, is brought into contact with the bones of the head. Sounds transmitted through bone act upon the cochlear capsule in such a manner that the nerve endings within the cochlea are stimulated in a fashion similar to that induced by air conduction. The cochlear mechanism will be discussed later.

According to von Békésy and Rosenblith,[2] a vibrating body, operating at frequencies up to 800 cps, placed on the forehead, will cause the skull to displace in step with the vibrating body. This type of skull vibration may be thought of as the "translatory mode of bone conduction."[3]

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[1]W. M. Copenhaver (ed.), Bailey's Textbook of Histology (14th ed., Baltimore: The Williams and Wilkins Co., 1958), pp. 579-580.

[2]von Békésy and Rosenblith, op. cit., p. 1109.

[3]Wever and Lawrence, Physiological Acoustics, pp. 224-226.

Although, in this mode, all bony parts of the skull displace simultaneously in the same direction, it should be noted that because of the inertial forces caused by the stapes and the bony cochlear capsule, the membraneous components of the cochlea tend to move in a time-lag with reference to the enclosing capsule. This time-delay is due in part to the displacement capabilities of the membranes that cover the oval and round windows.

The inertia of the head at frequencies higher than 800 cps causes the back of the skull to displace in a direction opposite to that of the front; and beyond about 1500 cps, the skull displaces simultaneously in several sections. When parts of the skull do not displace in step with the vibrator, the "compressional mode of bone conduction" takes over. The cochlear capsule, in this form of bone conduction, is compressed from all sides and ". . . its fluid contents are pressed out, mainly taking the path of least resistance through the round window."[1]

Both modes of bone conduction, translatory and compressional, lead to movements along the cochlear partition that stimulate the nerve endings of the auditory nerve, thus inducing the auditory sensation.

Summary. The manner in which the experimental stimuli may be delivered to the cochlea has been described in a simplified presentation only for purposes of orientation.

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[1] Ibid., pp. 226-227.

It is important to note at this point that both air and bone conduction involve the same neural pathways, produce identical "patterns of displacement in the cochlea," "involve the same sensory receptor cells in the inner ear," and "combine their effects vectorially," once the auditory stimuli have reached the cochlea.[1] An explanation of the important cochlear processes that are involved with the reception of auditory stimuli will follow.

Sensorineural Function

Since Herman Helmholtz described his resonance theory in 1859, auditory researchers have accumulated a voluminous amount of knowledge that has developed essentially into two general classes of theories: place theories and frequency theories. The primary difference between the two is the manner in which pitch discrimination and perception are delineated. The place theory holds that each pitch has its specific neural representation within the cochlea. The frequency theory supports the notion that the ". . . frequency of the mechanical vibrations is communicated to the auditory nerve and thence to the higher nervous centers, and that this frequency as centrally represented provides the basis for pitch perception."[2]

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[1] Ibid., p. 234.

[2] Ernest Glen Wever, Theory of Hearing (N.Y.: John Wiley and Sons, Inc., 1949), p. 42.

Davis[1,2] sums up the current presumption regarding the perception of pitch. This account relates how the auditory nerve endings, or receptors, terminate along the flexible basilar membrane. When a specific area along the length of this membrane vibrates, the auditory receptors in that particular area are stimulated and the impulses are propagated through specific nerve fibers connected to those receptors to certain areas of the cortex. The displacement of the oval and round window membranes, and the subsequent movement of the incompressible cochlear fluid (endolymph and perilymph), are responsible for the bending of the basilar membrane and the ensuing excitation of the auditory receptors (hair cells). Acoustic stimuli of different frequencies produce basilar membrane displacements of greater amplitude in specific regions corresponding to the frequency. It is believed that a sound wave causes the nerve impulse to discharge in time with the frequency of the wave as long as the frequency is below 1000 cps. Because evidence indicates that a nerve fiber cannot discharge at rates higher than about 1000 times a second,[3] the presumption is that at higher frequencies many fibers must work together in such a manner that the impulses are discharged after the volley

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[1]Hallowell Davis, "Physics and Psychology of Hearing," Hearing and Deafness, ed. H. Davis (rev. ed., N.Y.: Holt, Rinehart and Winston, Inc., 1961), pp. 58-59.

[2]Davis, "Anatomy and Physiology of the Ear," pp. 61-78.

[3]Wever, op. cit., p. 165.

principle developed by Wever.[1] This principle holds that the pitch of sounds, at least at frequencies between 1000 and 5000 cps, is determined by the frequency of the volleys of nerve impulses reaching the brain. These volleys are carried by groups of nerve fibers; not by a single fiber. At frequencies above 5000 cps, the place theory, mentioned above, probably plays the major role.[2]

Intensity, another attribute of the sound wave, has been explained on the basis of three postulations: (1) that the number of fibers activated by the sound is proportional to its loudness; (2) that the louder the sound, the greater number of impulses in all fibers; and, (3) that certain nerve fibers possess high intensity thresholds.[3]

Physical Nature of Sound Wave Cancellation

In order to describe the physical kinematics of sound wave cancellation, it is necessary first to review briefly the basic fundamentals of acoustic energy or wave motion.

Any elastic object set into vibratory motion within an elastic medium may act as a source of sound, providing that the frequency of vibration is greater than approximately 20 cps and less than approximately 16,000 cps for the human

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[1] Ibid., pp. 166-220.

[2] Norman L. Munn, Introduction to Psychology (4th ed.; Boston: Houghton Mifflin Company, 1951), p. 382.

[3] Hallowell Davis, "Psychophysiology of Hearing and Deafness," Handbook of Experimental Psychology, ed. S. S. Stevens (N.Y.: John Wiley and Sons, Inc., 1963), p. 1139.

ear. When the sound reaches the ear, what has been transmitted and received is a longitudinal vibration or sound wave made up of alternate condensations and rarefactions. For example, assume that the sound source is a tuning fork. Each tine of the tuning fork moves in one direction, then in the other, in order to complete one cycle of vibration. A periodic compression of the particles of the surrounding medium (in this case, air), followed by a rarefaction, is produced in this manner. This process is repeated for each vibratory cycle. Only the rarefactions and condensations are propagated, not the air particles themselves. In the particular areas where a condensation occurs at a given moment, the particles within this area approach each other. In the areas where a rarefaction occurs, the particles move apart from each other. The propagating wave consists of a radial displacement of successive condensations and rarefactions from the source outward. As the vibration of each particle of the medium occurs in the same direction as the propagating wave, this type of wave is called a longitudinal wave.

Sound wave motion may be illustrated by a sinusoidal curve like that shown in Figure 1. The high points of the curve represent maximum displacements or elongations (condensations) of air particles in one direction, and the low points indicate maximum displacements (rarefactions) in the other direction. The maximum elongation (amplitude) of a wave refers to the distance each particle of air moves

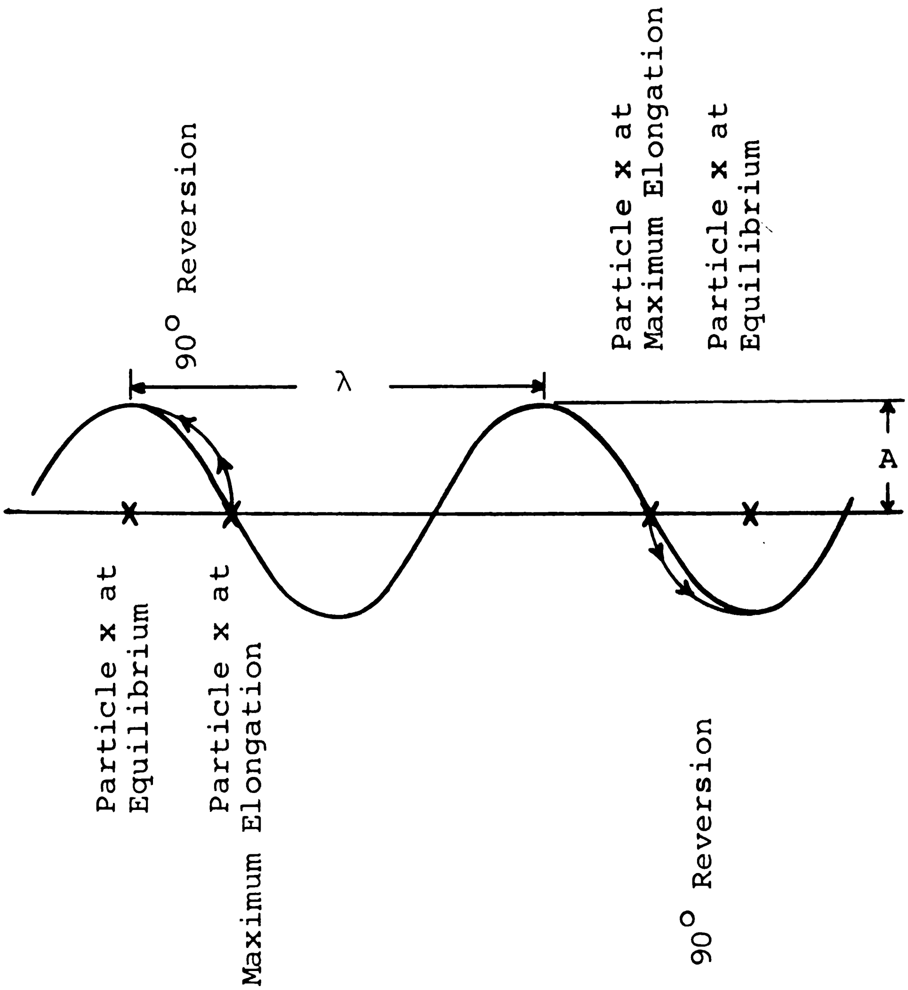

Fig. 1. A sound wave illustrating wavelength, λ, and amplitude, A. The maximum displacements or elongations of air particles are reverted 90° with respect to the actual direction of vibration for the purpose of clarification.

to and fro from its position of equilibrium. The distance between two crests or troughs in the curve in Figure 1 is the wavelength.

The vibratory motion represented by the sinusoidal curve of Figure 1 may be stated in mathematical terms. The following presentation will attempt to express mathematically the essential bases of wave motion and sound wave cancellation.

The equation[1] for a simple wave may be expressed in terms of its particle elongation in the following manner:

$$Y = A \sin 2\pi \left(\frac{t}{T} - \frac{X}{\lambda}\right),$$

where Y is the elongation of a particle at distance X from a reference point (source), t the time after the particle has left its position of equilibrium, A the amplitude of the vibration, T the period, and λ the wavelength. In order to clarify further the above equation, consider the period T of the wave to be the time required for the completion of one cycle; the wavelength the ". . . distance between the beginnings of two successive condensations or two successive rarefactions."[2] A wavelength may be computed by dividing the speed of propagation, v, by the frequency, f, as shown below:[3]

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[1]Robert A. Millikan, Duane Roller, and Ernest C. Watson, <u>Mechanics, Molecular Physics, Heat, and Sound</u> (Cambridge, Mass.: The M.I.T. Press, 1937), p. 376.

[2]<u>Ibid</u>., p. 367.

[3]Black and Little, <u>op. cit</u>., p. 577.

$$\lambda = \frac{v}{f}$$

The discussion up to this point has focused upon a single sound wave. In order to expand the presentation into the sound wave cancellation phenomenon, it is necessary to examine what occurs when two sound waves interfere with each other. Although this study is concerned with the cancellation of one sound by another, it is important to know that sound waves may also interfere in order to reinforce each other. In this case, if two waves of the same period are in phase, they reinforce each other and the amplitude is doubled. In other words, the resultant wave, or complex wave, has an amplitude which is the sum of the amplitudes of the two waves. If Y' + Y" equals the two displacements of the two waves, and Y is the resultant displacement of the complex wave, then,

$$Y = Y' + Y'' = (A' + A'') \sin 2\pi \left(\frac{t}{T} - \frac{X}{\lambda}\right),$$

where A' and A" are the amplitudes of each of the waves, T the period, t any given time with reference to the instant at which the considered particle is at a point of equilibrium, X the distance of any particle under consideration from the reference point (source), and λ the wavelength common to both waves.[1]

With reference to sound wave cancellation, under certain conditions the interference of two sounds can produce silence. When this phenomenon occurs, the two sound waves

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[1] Millikan, Roller, and Watson, <u>op. cit</u>., p. 381.

are identical in frequency and amplitude, but differ in phase by 180°. By referring to Figure 2, one can observe that when the sound waves are opposite in phase, the peaks and troughs of the waves are at opposite directions. When this condition exists, ". . . each of the particles transmitting the motion is under the action of two disturbances that tend to produce equal and opposite displacements, and as a result the particles suffer no displacement at all."[1]

The following equation[2] illustrates the combination of two waves, each one having the same direction of propagation, but opposite senses:

$$Y = Y' + Y'' = A \sin 2\pi \left(\frac{t}{T} - \frac{X}{\lambda}\right) + A \sin 2\pi \left(\frac{t}{T} + \frac{X}{\lambda}\right),$$

where the period and the wavelength are the same for both waves.

Binaural and Monaural Phase Effects

The present study was directly related only to the effects produced by phase manipulation upon air- and bone-conducted sounds; however, phase effects upon the auditory system have also been studied from bases other than those related to the conduction of sound by air and bone. A summary of these effects is presented for purposes of further orientation.

It appears, as one views the literature on binaural phase effects, that research in this area over the years

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[1] *Ibid.*, p. 383. [2] *Ibid.*, p. 385.

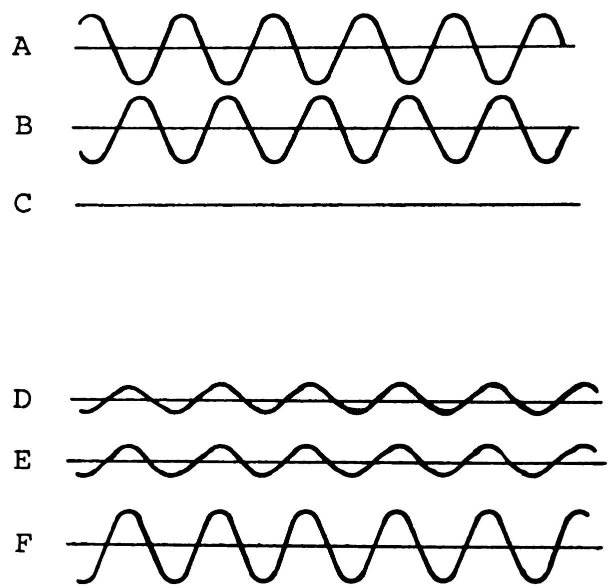

Fig. 2. Illustration of interference of sound waves. Two waves, A and B, of identical frequency but opposite in phase produce cancellation, C. Two waves, D and E, in step produce reinforcement, F.

has been directed in large measure toward investigating the effects of phase upon the localization of sound. It should be pointed out, however, that although phase has been demonstrated to be an essential factor (primarily at low frequencies)[1] in the location of sound in space, it is not the only factor responsible for localization. Intensity of the sound under consideration is also important. For this reason, the study of sound localization necessarily includes the interaction of phase and intensity upon the auditory mechanism; and, for extracranial localization, the time of arrival of the sound is also included. Furthermore, during the past few years strong evidence has been presented to indicate that the peripheral and central nervous systems also play an important role in the localization of sound.[2,3]

In general, the manner in which the two ears of a subject respond to loudness, phase, and time of arrival determine in large measure the direction of the sound.[4] The sense of direction with respect to these attributes may be explained in the following manner.

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[1] Wever, op. cit., p. 426.

[2] Mark R. Rosenzweig, "Development of Research on the Physiological Mechanisms of Auditory Localization," Psychological Bulletin, LVIII, No. 5 (1961), pp. 376-389.

[3] Joseph L. Hall, "Binaural Interaction in the Accessory Superior Olivary Nucleus of the Cat," Journal Acoustical Society of America, XXXV, No. 11 (November, 1963), p. 1908.

[4] von Békésy, Experiments in Hearing, p. 272.

If a sound comes from the right side of a subject, the sound waves reach the right ear before they do the left; furthermore, the sound is louder in the right ear because the ear acts as a buffer between the sound source and the left ear. Because the sound paths to the two ears differ in distance and direction, the phase of the sound waves, as they enter the ear canals, may also differ.

Aside from extracranial localization effects, the relationship between interaural phase differences and intracranial localization has also been studied. It has been shown that, holding amplitude constant, as interaural time differences are increased, the intracranial sound image shifts toward the ear receiving the sound that leads in phase.[1,2] With regard to this phenomenon, it appears that at frequencies above 1500 cps, the degree of intracranial lateralization decreases with increases in frequency.[3] Interaural amplitude variations will also change the interaural lateralization effect, because, holding phase constant, a tone presented binaurally appears to lateralize toward the ear receiving the louder stimulus. If the interaural phase and amplitudes are identical, assuming equalateral

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[1] B. McA. Sayers and F. E. Toole, "Acoustic-Image Lateralization Judgments with Binaural Transients," Journal Acoustical Society of America, XXXVI, No. 6 (June, 1964), pp. 1199-1205.

[2] Licklider, op. cit., p. 1028.

[3] B. McA. Sayers, "Acoustic-Image Lateralization Judgments with Binaural Tones," Journal Acoustical Society of America, XXXVI, No. 5 (May, 1964), pp. 923-926.

auditory sensitivity, the sound image will appear to be centrally located.

Binaural phase effects appear to have commanded a great deal of the attention of the investigators in auditory research; but monaural phase effects have also been considered, albeit to a lesser extent. According to some writers,[1,2] confusion relative to monaural phase effects developed as a result of Helmholtz' failure to observe these effects while experimenting with two-component sounds. Since that time, however, research on this topic has shown that monaural phase effects with two-component sounds are actually discernible.[3,4] A reason for Helmholtz' inability to record this phenomenon has been attributed to unwieldy instrumentation.[5]

The subjective sensation associated with monaural phase effects has been described in the literature as

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[1]Licklider, op. cit., pp. 1024-1026.

[2]James H. Craig and Lloyd A. Jeffress, "Why Helmholtz Couldn't Hear Monaural Phase Effects," Journal Acoustical Society of America, XXXII, No. 7 (July, 1960), pp. 884-885.

[3]Don Lewis and M. J. Larsen, "Cancellation, Reinforcement and Measurement of Subjective Tones," Proceedings of the National Academy of Science, XXIII (1937), pp. 415-421.

[4]James H. Craig and Lloyd A. Jeffress, "Effect of Phase on the Quality of a Two-Component Tone," Journal Acoustical Society of America, XXXIV, No. 11 (November, 1962), pp. 1752-1760.

[5]Craig and Jeffress, "Why Helmholtz Couldn't Hear Monaural Phase Effects," pp. 884-885.

". . . sensations of roughness or smoothness and is related to a sensation of apparent pitch."[1]

Some of the suggested mechanisms and conditions involved with monaural phase effects are: (1) that there is a phase related shift of the cochlear locus of maximal stimulation;[2] (2) that the components of the stimulus must be similar in frequency; and, (3) that there must be only a few frequency components in the stimulus.[3]

Air/Bone Cancellation

Ostensibly, Georg von Békésy, in 1932, was the first investigator to demonstrate that it is possible to cancel a bone-conducted tone by an air-conducted tone of identical frequency and amplitude. The experimental stimulus consisted of a 400 cps pure tone presented binaurally at a sensation level of 57 dB.[4] von Békésy reasoned, with reference to this experiment, the following:

> If it is possible to compensate for a bone-conducted tone by means of an air-conducted tone in such a way that nothing at all is heard, we may be sure that in bone conduction the basilar membrane moves in just the same way as it does in air conduction. That is to say, in both instances

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[1] R. C. Mathis and L. R. Miller, "Phase Effects in Monaural Perception," Journal Acoustical Society of America, XIX (1947), pp. 780-797.

[2] J. H. Craig, "The Effects of Phase on the Quality of a Two-Component Tone," Dissertation Abstracts, XXII, No. 5 (November, 1961), p. 2074.

[3] Licklider, op. cit., p. 1026.

[4] von Békésy, Experiments in Hearing, p. 129.

> the vibrations of the basilar membrane are produced by movements of the fluid near the stapes, and there is no other manner of excitation of the sensory cells.[1]

In other words, von Békésy's successful cancellation experiment indicated that the sensory apparatus within the cochlea responds in identical fashion regardless of whether the transmission pathway to the sense organ is by air or bone.

Although von Békésy's experiment ". . . clarified earlier theories and formed the basis for later experimental and theoretical investigation of the mechanism of bone conduction . . .,"[2] further direct study of the bone conduction/air conduction cancellation phenomenon for some reason does not appear in the literature until about ten years later. At this time, 1942, Lowy,[3] experimenting with cats, was able to achieve mutual cancellation of cochlear potentials caused by bone-conducted and air-conducted sounds over a frequency range extending from 250 to 3000 cps. Not only was this a verification of von Békésy's original work involving subjective evaluations on the part of subjects concerning the cancellation effect, but Lowy also appears to be the first investigator to utilize a more

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[1] _Ibid_., p. 128.

[2] Ralph F. Naunton, "The Measurement of Hearing by Bone Conduction," _Modern Developments in Audiology_, ed. James Jerger (N.Y.: Academic Press, Inc., 1963), pp. 1-3.

[3] K. Lowy, "Cancellation of the Electrical Cochlear Responses with Air- and Bone-Conducted Sounds," _Journal Acoustical Society of America_, XIV (October, 1942), pp. 156-158.

objective technique for studying the cancellation phenomenon. This technique involved measuring and comparing the electrical potentials arising from within the cochlea. As a result of his experimentation, he was able to conclude, as was von Békésy, that pure tones reaching the cochlea by bone conduction produce the same patterns of displacement as do air-conducted tones of equal intensity; and, additionally, that once cancellation has been achieved, the effect is independent of electrode placement on the cochlear capsule.

Wever and Lawrence[1,2] confirmed the above observations a few years after Lowy's experiment. However, they extended the investigation of the air conduction/bone conduction cancellation phenomenon into frequencies ranging from 100 to 15,000 cps and intensities ranging up to the point of overloading. They concluded that:

> In general it may be said that the two stimuli combine their effects vectorially, provided that their total intensity is below the level of overloading. It is therefore clear that any given tone involves the same sensory cells in the same pattern of stimulation regardless of whether it is applied by air or bone conduction.[3]

Dolch,[4] in 1954, utilized the cancellation phenomenon

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[1] E. G. Wever and Merle Lawrence, "The Place Principle in Auditory Theory," Proceedings of the National Academy of Science, XXXVIII (1952), pp. 133-138.

[2] E. G. Wever and M. Lawrence, "The Transmission Properties of the Stapes," Annals of Otology, Rhinology and Laryngology, LIX (1950), pp. 322-330.

[3] Wever and Lawrence, Physiological Acoustics, p. 234.

[4] John P. Dolch, "Phase and Intensity Relationships in the Interference of Bone- and Air-Conducted Sound," Journal of Acoustical Society of America, XXVI (1954), p. 942.

in a study and investigated the expected sensation levels as phase/intensity relationships were varied about the point of maximum cancellation. The possibilities of utilizing the air/bone cancellation technique in order to improve military interphone communication and to provide ear protection from high-level ambient noises were also briefly discussed.

More recently, 1963, Smith and Bowman,[1] in a study described in Chapter I, continued to investigate the subjective effects of air/bone cancellation. The cancellation effect in their experiment was so effective that they were led to conclude that the phenomenon might eventually be used for eliminating the contralateral ear in bone conduction testing.

The literature, as described in the preceding discussion, clearly establishes the phenomenal existence of air conduction/bone conduction sound wave cancellation. Because the phenomenon is known to exist, it is reasonable to conclude that there should be an acceptable explanation for its existence. Such an explanation is the account given by Zwislocki,[2] who, in addition to the writers cited previously, also supports the theory that the pattern of vibration of the cochlear partition is the same for air- and bone-conducted sounds.

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[1] Letter from Ernest L. Smith.

[2] J. Zwislocki, "Wave Motion in the Cochlea Caused by Bone Conduction," Journal Acoustical Society of America, XXV, No. 5 (September, 1953), pp. 986-989.

Zwislocki states that ". . . every compression of the inner ear is compensated by a volume displacement of the membranes of the oval and round windows;" and, additionally, that ". . . the displacement of the cochlear duct is proportional to the pressure difference between its two sides and in particular to the pressure difference at the windows."[1] Accordingly, Zwislocki states:

> The only time a bone-conducted tone does not lead to a vibration of the cochlear duct is when the product of the impedance of the round window and of the compression of the scala tympani is equal (in amplitude and phase) to the product of the impedance of the oval window and of the compression of the scala vestibuli plus labrynth. Under ordinary conditions, this does not occur.[2]

In order for an air-conducted tone to cancel a bone-conducted tone in the cochlea, there should be no vibration of the cochlear duct. In this case the sound pressure of the air-conducted tone must be opposite in phase and equal in magnitude to the bone-conducted tone. Assuming the proper phase relationship, Zwislocki summarizes his interpretation of air/bone cancellation in the following manner:

> The resulting pressure difference across the partition is equal to the vector sum of the pressure difference generated by bone conduction and of the pressure applied to the oval window. When the sound pressure applied to the oval window is equal to the pressure difference generated by a bone-conducted sound across the cochlear duct in the neighborhood of the windows, the resultant

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[1] Ibid., p. 987.

[2] Ibid.

> gradient is equal to zero. Thus the vibration of the cochlear duct is eliminated. . . . This should happen irrespective of the vibration pattern.[1]

With the knowledge that bone-conducted and air-conducted sounds can, through proper adjustment of frequency, phase, and amplitude be cancelled at the cochlea, Wever and Lawrence[2] proceeded to utilize the bone conduction/air conduction cancellation technique as a means by which to study phase distortion produced by properties of the middle ear apparatus. The rationale leading to the utilization of the cancellation phenomenon in the experiment about to be described was based upon the discovery made earlier by Lowy,[3] and later by themselves,[4] that stimulation by air and bone conduction produces the same patterns of effect upon the cochlea, and that the effect is constant regardless of electrode placement on the surface of the cochlear capsule.

Assuming the foregoing conclusions, Wever and Lawrence[5] observed the phase changes, as measured by cochlear potentials, with respect to air-conducted and

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[1] Ibid.

[2] E. G. Wever and M. Lawrence, "The Transmission Properties of the Middle Ear," pp. 5-18.

[3] Lowy, loc. cit.

[4] Wever and Lawrence, "The Place Principle in Auditory Theory," p. 137.

[5] Wever and Lawrence, "The Transmission Properties of the Middle Ear," pp. 9-11.

bone-conducted tones, before and after removal of the middle ear structures of cats. By recording and comparing the intensity levels and phase angles of the cochlear potentials required to produce a minimum response before and after removal of the ossicular chain, they were able to determine the phase effects created by the middle ear structures. It was determined in this manner that for frequencies up to 1000 cps, the middle ear produces an advancement in phase of about 40°. Phase changes show considerable variation at higher frequencies; however, the authors conclude, despite these phase variations that are apparently caused by the middle ear apparatus, that ". . . the middle ear is able to carry out its function as a mechanical transformer with minimum disturbance of the response pattern."[1]

Additional research[2] has demonstrated that fixation of the middle ear bones causes an advance in phase of about 70°, especially at low and middle frequencies; whereas, an increase in ossicular mass produces a phase lag which is greater than 180°. It was suggested that bone conduction lateralization effects, such as those experienced in unilateral conductive hearing losses, may be accounted for to some degree by phase shifts. This notion has been questioned,

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[1] *Ibid*., p. 18.

[2] J. P. Legouix and S. Tarab, "Experimental Study of Bone Conduction in Ears with Mechanical Impairment of the Ossicles," *Journal Acoustical Society of America*, XXXI (1959), pp. 1453-1457.

however, in a recent study.[1]

Wever and Lawrence were apparently the most frequent users of the sound-cancellation technique (air/air and air/bone) as a means of measuring phase distortion as a function of the middle ear structures. In their experimentation with cats, they were able to: (1) create a cochlear response by presenting tones simultaneously to the oval and round windows after removing everything with the exception of the stapes from the middle ear; and, (2) cancel the cochlear response by manipulating the phase and intensity of the two signals.[2] At the point of minimum response, the differences in phase and intensity of the two stimuli were recorded by means of acoustic probes. They had observed and concluded previously[3] that stimulation by way of either window involves the same receptor cells in the same pattern of activity; and that sound waves reaching and entering the cochlea by way of either window have identical intensity and phase except as altered by the stapes embedded in the oval window. The authors admit, however, that this point is probably impossible to prove because removal of

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[1]E. H. Huizing, "On the Lateralization of Bone-Conducted Sound--A Study of the Conditions Necessary for Lateralization," International Audiology, II, 1963, pp. 233-239, DSH Abstracts, IV, No. 3 (July, 1964), p. 203.

[2]Wever and Lawrence, "The Transmission Properties of the Stapes," pp. 322-330.

[3]E. G. Wever and M. Lawrence, "The Acoustic Pathways to the Cochlea," Journal Acoustic Society of America, XXII, No. 4 (July, 1950), pp. 460-467.

the footplate of the stapes from the oval window for the purpose of comparison with the round window permits the loss of cochlear fluid, thereby reducing the electrical response of the cochlea. At any rate, they were able to show that the differences in phase between the oval and round window routes, utilizing the cancellation technique, varied according to frequency. They found that the phase difference never exceeds a 15^{o} lag of the sound wave entering through the oval window at frequencies up to 5000 cps. At frequencies above 5000 cps, the phase lag increases as frequency is raised until it reaches a 180^{o} relationship at about 9000 cps. The differences in phase, as well as intensity, with respect to the oval and round windows, are ". . . mainly the result of the presence of the stapes in the oval window."[1]

Wever and Lawrence summarize their work over several experiments on the phase differences resulting from the presence of the middle ear structures by concluding that the phase variation over most of the working range of the middle ear is only moderate. The variation is usually below 40^{o} and never more than 74^{o} at frequencies below 5000 cps. The phase differences increase rapidly and are more variable at the higher frequencies.[2]

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[1]Wever and Lawrence, "The Transmission Properties of the Stapes," p. 329.

[2]Wever and Lawrence, Physiological Acoustics, p. 130.

Summary

As pointed out in Chapter I, under the section entitled Importance of the Study, it was stressed that the review of the literature revealed a sparseness of published materials on the bone/air cancellation phenomenon. However, the materials that were currently available and pertinent to the study of the topic were discussed in detail as the primary purpose of this chapter. This discussion began with von Békésy's experiment, in 1932, which appears to be the first study on phase cancellation, and traced the scientific investigation of the phenomenon up to what appears to be the most current study which appeared in 1963. A physiological interpretation of bone/air cancellation that appears in the literature was also given. Aside from the direct study of bone/air cancellation, experiments were described in which the cancellation effect was utilized as a means by which to study phase distortion in the middle ear.

Secondarily, certain supplemental topics, intended only for orientation and familiarization to the total nature of this investigation, were discussed. These included basic interpretations of air conduction, bone conduction, sensorineural function, cancellation of sound waves, and monaural and binaural phase effects.

CHAPTER III

SUBJECTS, INSTRUMENTATION, AND PROCEDURES

The psychophysical method employed in this study was the method of reproduction as described by Guilford.[1] This method allows the subject to take part actively in the experiment by controlling a comparison stimulus. According to Guilford, the method of reproduction is the most economical in terms of time, and is the "most natural" of methods.

Subjects

Selection of Subjects. Sixteen (16) subjects who met the following criteria were included in this study:

1. The subjects were male graduate students or faculty members in the Area of Speech and Hearing Science at Michigan State University. Their ages ranged from 23 to 37 years, with a mean age of 29.6.

2. All subjects possessed normal, bilateral auditory sensitivity as measured by bone conduction and air conduction audiometric threshold tests at frequencies of 500, 1000, 2000, and 4000 cps. Hearing was considered normal when audiometric thresholds were 10 dB (ASA-1951) or lower.

3. Medical history was negative with respect to ear pathology.

4. Air and bone conduction thresholds at each frequency were within 5 dB of each other. The purpose of this criterion was to minimize the extent of air/bone gap across subjects and

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[1]J. P. Guilford, Psychometric Methods (2nd ed.; N.Y.: McGraw-Hill Book Co., Inc., 1954), pp. 86-100.

frequencies. (The importance of this will be discussed in detail later.)

Instrumentation

Apparatus. The following instruments and equipment were employed:

1. Audiometer (Beltone, 12 AC)
   Calibrated to ASA-1951 Standards
2. Phase Control Unit
3. Attenuator
4. Dual Beam Oscilloscope (Tektronix, Inc., Type 502A)
5. Bone Conduction Oscillator (Radioear, Type B70)
6. Headset (Type TDH-39)
7. Earphone Cushions (Type MX-41AR)
8. Head Stabilizer Attached to Chair
   Head Stabilizer was a head-rest that was removed from a Ritter Dental Motor Chair.
9. Amplifier (Hewlett Packard, Model 450A)
10. Sound-treated Test Room

Arrangement. By referring to Figure 3, block diagram of the instrumentation, it can be observed that the bone conduction channel on the audiometer supplied the pure tone stimulus for the experiment. Voltage from this circuit was fed into: (1) the bone conduction oscillator that was placed on the forehead of each subject, and (2) the phase control that was variable throughout 360°. The output of the phase control was connected to the amplifier that supplied 20 dB of constant amplification to the attenuator. The output of the attenuator was fed into the earphone for presentation of air-conducted pure tones to the right ear of each subject. The dual beam oscilloscope simultaneously monitored: (1) the output signal of the bone conduction circuit, i.e., the voltage supplied to the bone conduction oscillator, and (2) the signal across the air conduction

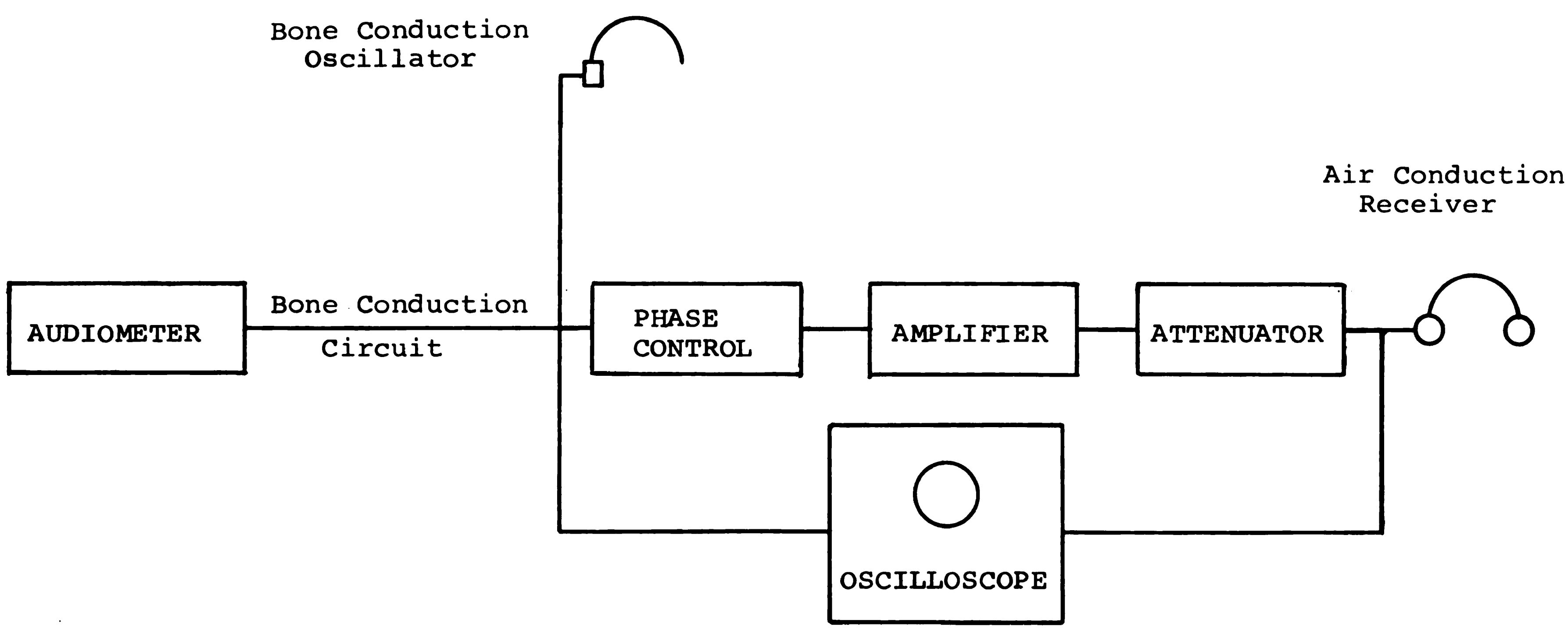

Fig. 3. Block diagram of instrumentation illustrating manner in which the pure tone stimuli were fed into various instruments.

receiver. This arrangement made it possible to monitor the signals and measure the voltage across the bone conduction vibrator and air conduction earphone. Each instrument, with the exception of the oscilloscope, was physically located on a table inside the test room. The ambient noise in the test room was between 40 and 45 dB (re .0002 dynes/cm^2). The oscilloscope was located in an adjoining room. An observation window was in the wall that separated the observation room from the test room.

Selection of Stimuli. The stimuli consisted of pure tones at frequencies of 500, 1000, 2000, and 4000 cps, with intensity ranging from 20 dB to 50 dB in 10 dB steps.

Procedures

Preparation of Subjects for Reception of Stimuli. Each subject, one at a time, was seated before a table in the test room facing the observation window. The following instructions were given to each subject:

> This experiment is concerned with observations relative to the cancellation of bone-conducted tones by air-conducted tones through phase conversion. In a moment I am going to place a bone conduction oscillator on your forehead and an air conduction receiver over your right ear. Your head will then be positioned in the head stabilizer, which is attached to the chair, in order to minimize head movement. You will then receive a bone-conducted tone and an air-conducted tone of identical frequency that may appear to be localized in your right ear. You may be completely unaware that one tone is transmitted by air and the other by bone. Your task is to cancel or at least attenuate the signal in your right ear by manually controlling the phase and intensity of the air-conducted tone. These are the controls (demonstrate to subject) that will enable you to perform this task. By slowly moving these dials, first one way

> and then the other, you are to attempt to locate a point where the signal in the right ear has reached its maximum point of attenuation. The sound may appear to shift toward the left ear or only decrease in loudness in the right ear; however, regardless of the kind of effect you may experience, when you are satisfied that you have reached a point of maximum signal attenuation in the right ear, remove your hand from the controls and say "OK." I will record this and we will move on to another tone of different frequency and intensity. Your task will remain the same throughout a series of test tones. You will also control the settings on the audiometer in front of you as I give them to you through the loud-speaker. Before we begin the experiment, you will get a chance to practice, and during this time you may ask any questions. During the entire experiment make every effort to keep your body and head as still as possible.

The instructions concerning a steady head position are important because von Békésy[1] states that head movements change the proper adjustments necessary to bring about cancellation. This was precisely the reason for the head stabilizer.

After the instructions were given, the bone conduction oscillator, held in place by the attached headband, was placed in the center of the subject's forehead. The air conduction headset was positioned over the subject's head. One receiver was over the right ear, while the other rested on the left side of the head above the left ear and did not touch the ear. The headband of the headset was isolated from the headband of the bone conduction oscillator by a foam rubber pad. After the subject's head was positioned in the head stabilizer, the subject prepared to perform the

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[1] von Békésy, Experiments in Hearing, p. 129.

tasks outlined to him. These tasks consisted of adjusting the intensity and phase of the air-conducted stimulus in the right ear until the maximum cancellation effect was achieved. There was, however, a practice period during which time the subject attempted to cancel the signal in the right ear by the prescribed procedures until five consecutive randomized tones were successfully and quickly cancelled. The experiment then began.

Experimental Presentation of Stimuli. Each subject, upon initiation of the experiment, was instructed by the experimenter (through an intercommunication system between the test room and observation room) to adjust the audiometer to deliver a bone-conducted tone at a frequency of either 500, 1000, 2000, or 4000 cps at an intensity level of either 20, 30, 40, or 50 dB, depending upon the particular treatment combination. There were sixteen (16) different treatment combinations (a combination of frequency and intensity levels) employed (see Table 1).

Once each subject had adjusted the audiometer for the appropriate bone-conducted tone, the settings remained constant until the next treatment combination. Prior to the experiment, the voltage levels at each treatment combination were recorded in order to be able to verify that the subject adjusted the audiometer precisely during the experiment. This verification was accomplished by monitoring on the oscilloscope the amplitude of the voltage across the bone conduction oscillator after each subject had adjusted

Table 1. Treatment combinations.

Intensity	Frequency
20 dB	500 cps
20 dB	1000 cps
20 dB	2000 cps
20 dB	4000 cps
30 dB	500 cps
30 dB	1000 cps
30 dB	2000 cps
30 dB	4000 cps
40 dB	500 cps
40 dB	1000 cps
40 dB	2000 cps
40 dB	4000 cps
50 dB	500 cps
50 dB	1000 cps
50 dB	2000 cps
50 dB	4000 cps

the audiometer for each setting. In no case was it necessary for a subject to re-adjust his initial setting. (The bone conduction voltage levels at each treatment combination are shown in Table 2).

As stated in the discussion of the instrumentation, the bone conduction channel on the audiometer supplied the voltage for the air conduction stimulus as well as the voltage for bone conduction. Each subject was instructed to: (1) control the intensity of the air-conducted tone by adjusting the attenuator, and (2) alter the phase of the air-conducted tone by manipulating the phase shifter. Each subject, through this procedure, was able to equate the loudness of the air-conducted tone to the loudness of the constant bone-conducted tone, and to shift the phase of the

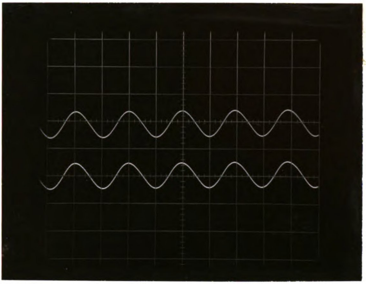
Table 2. Peak-to-peak voltage across bone conduction oscillator for treatment combinations, ASA-1951 standards (measurements in millivolts).

Intensity		Frequency: 500 cps	1000 cps	2000 cps	4000 cps
	20 dB	35.0	9.2	26.0	13.0
	30 dB	106.0	28.0	78.0	38.0
	40 dB	340.0	90.0	245.0	116.0
	50 dB	1260.0	340.0	278.0	315.0

air-conducted tone until it was 180^{o} out of phase with respect to the bone-conducted tone. By manipulating the attenuator and the phase control in this manner, each subject located the point of maximum cancellation at each of the treatment combinations. When the subject signaled that this point had been located, the intensity level of the air-conducted tone was read in peak-to-peak voltage directly from the oscilloscope and charted accordingly. The subject then moved on to the next treatment combination as instructed by the experimenter.

Procedural Management of Subjects' Responses. The subjects' responses were recorded and managed in the following steps:

1. Peak-to-peak voltage (millivolts) for each presentation of the treatment combinations were read from the oscilloscope and recorded after each adjustment had been made by subjects. (Figure 4 presents a photographic representation of the signals as they appeared on the oscilloscope).



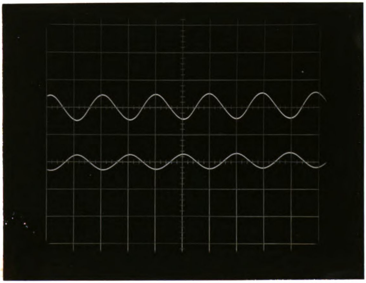


Fig. 4. Photographic representation of signals as they appeared on the oscilloscope. The bone conduction signal is on top in each picture; air conduction on bottom. The upper picture indicates that both signals are of identical amplitude and phase. The picture on the bottom indicates two signals of different amplitude about 180° apart in phase.

2. After all voltages had been recorded for all subjects, the ratio of the air-conducted voltage to the voltage across the earphone at 0 dB sound pressure level (re .0002 dynes/cm^2), at each test frequency, was computed for each treatment combination. (Table 3 presents the computed peak-to-peak voltages across the earphone at 0 dB SPL.)

3. By the use of a table[1] for the conversion of voltage ratios to decibels (re .0002 dynes/cm^2), the intensity in decibels of the air-conducted stimulus at the point of maximum cancellation was recorded for every trial or treatment combination.

4. In order to translate the recorded data into more practical measures, another table[2] was utilized that enabled the experimenter to convert the above sound pressure level measurements into audiometric equivalents (ASA-1951; Telephonics earphones, Type TDH-39). (See Table 4.) These audiometric equivalents were used in computing the criterion scores or differences in intensity between air and bone at the point of maximum cancellation.

Table 3. Voltages in millivolts across the TDH-39 earphone at 0 dB sound pressure level (re .0002 dynes/cm^2).

Frequency	Voltages
500	.00145
1000	.0014
2000	.0015
4000	.0010

[1] D. Herrington and Stanley Meachum, eds., Handbook of Electronic Tables and Formulas (2nd ed.; N.Y.: The Bobbs-Merrill Co., Inc., 1964), pp. 48-50.

[2] Instruction Manual for Model 158 Audiometer Calibrator, Bruel & Kjaer Instruments, Inc., Cleveland, Ohio, Table 5.3, p. 44.

Table 4. Table showing calibration of the TDH-39 earphone from SPL to audiometric zero.[a]

Frequency	Calibration
500	24.1 dB
1000	17.2 dB
2000	18.0 dB
4000	14.3 dB

[a] Instruction Manual for Model 158 Audiometer Calibrator, Bruel & Kjaer Instruments, Inc., Cleveland, Ohio, Table 5.3, p. 44.

(The complete display of recorded measures [raw data] and the various conversions that were described above are recorded in Appendix A).

The criterion scores, derived from the collected data, were then treated statistically. The analysis is described in Chapter IV.

Further Considerations. It should be recalled that the experimenter was interested in determining the differences, at the point of the maximum cancellation effect, between the intensities of bone-conducted and air-conducted pure tones across prescribed levels of frequency and intensity. Perhaps it would appear obvious that there should be, under the experimental conditions, an inter-subject variation in criterion scores due to inherent differences in air and bone conduction sensitivity that would seem to confound the data. However, these inter-subject variations are controlled in large measure by the statistical design that was employed.

It was reasonable to conclude that the air/bone variations, peculiar to each subject, were distributed throughout the design arrangement in such a manner as to counterbalance themselves. Furthermore, it was assumed that because these subjects represented a random sample of normal hearing subjects, the differences under consideration were randomly distributed. The experimenter elected to operate under the assumption that the above considerations adequately minimized the influence of inter-subject variations due to normal deviations in air/bone sensitivity. Note, also, that one of the criteria for subject eligibility specified that air and bone conduction thresholds had to be within 5 dB of each other at the frequencies under test. Although subject selection was based upon bone conduction tests made at the mastoid, and the experiment consisted of forehead placement of the bone conduction oscillator, the requirement of nearly identical air/bone thresholds, nevertheless, reduced the extent of air/bone variation.

CHAPTER IV

RESULTS AND DISCUSSION

The statistical design of this study is derived from Lindquist's two-factor, Type II design.[1] Lindquist refers to this design as a "mixed" design inasmuch as the design is essentially a combination of the "simple randomized" and the "treatments X subjects" designs. This design may be employed when it is desirable to control individual differences by counterbalancing these differences throughout the design. This may be accomplished by arranging the subjects and groups so that no one subject or group receives the same treatment combination more than once. The exact nature of this design will become clearer as the following discussion develops.

The sixteen subjects employed in this experiment were randomly divided into four groups, with four subjects in each group. The four groups were distributed throughout the cells in Figure 5 in order to prevent any subject or group from appearing in any one column or row more than once, as required by the Type II design.

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[1] E. G. Lindquist, Design and Analysis of Experiments in Psychology and Education (Boston: Houghton Mifflin Co., 1953), pp. 273-281.

Intensity	Frequency: 500 cps	1000 cps	2000 cps	4000 cps
20 dB	G1	G2	G3	G4
30 dB	G4	G1	G2	G3
40 dB	G3	G4	G1	G2
50 dB	G2	G3	G4	G1

Fig. 5. Manner in which the four groups (G) were distributed throughout the matrix. Each group contained four subjects.

Each subject was given six trials at each of four treatment combinations. Since there are sixteen cells in the design matrix, each cell containing four subjects, there was a grand total of 384 trials, 24 trials per subject. Each series of 24 trials per subject was completely randomized by the use of a table[1] of random numbers; additionally, each series was programmed for convenience of presentation prior to the experiment. (See Appendix B for programmed trials for each subject.)

A criterion score (intensity difference in decibels between bone and air conduction at point of maximum cancellation) was recorded for each trial (see Appendix A). The six criterion scores obtained for each subject in each cell were averaged in order to obtain a mean air/bone difference for that subject.

The reliability of subject criterion scores across both frequency and intensity was determined by correlating the mean of the first three trials per subject against the mean of the last three trials. Reliability was evaluated by Pearson product-moment correlation procedures.[2] The results of these tests, shown in Tables 5 and 6, indicate high reliability coefficients ranging from .8917 to .9618.

The Analysis of Variance. The data were analyzed

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[1]Hubert M. Blalock, Jr., Social Statistics (N.Y.: McGraw-Hill Book Co., Inc., 1960), pp. 437-440.

[2]Ibid., p. 289.

Table 5. Correlation coefficients across intensity for each level of frequency.

Frequency	Correlation Coefficient
500 cps	.8917
1000 cps	.9499
2000 cps	.9524
4000 cps	.9475

Table 6. Correlation coefficients across frequency for each level of intensity.

Intensity	Correlation Coefficient
20 dB	.9233
30 dB	.9383
40 dB	.9151
50 dB	.9618

by a two-factor analysis of variance test (Lindquist, Type II). The results of this analysis are shown in Table 7. The results indicate that the only variable showing significance at the .05 level was that of frequency. This suggests from a statistical standpoint that changes in frequency did effect the differences in criterion scores. The following null hypothesis was, therefore, rejected:

> There is no significant difference in criterion scores as a function of frequency.

There were no significant interactions between or within subjects in connection with the test variables; nor were there significant differences within subjects with respect to intensity. Therefore, the following null hypotheses were <u>not</u> rejected:

1. There is no significant difference in criterion scores as a function of intensity.
2. There is no significant difference in criterion scores as a function of interaction between frequency and intensity.

In order to identify that which contributed toward the significance found for the frequency variable, tests for "critical differences"[1] were employed across frequency for each level of the intensity variable. The results of these tests, shown in Table 8, indicate that the only significant difference between means occurred between 1000 and 4000 cps at the 30 dB level. According to the statistical analysis, this difference was an important contributor

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[1] Lindquist, op. cit., p. 93.

Table 7. Summary table for the analysis of variance.

Source of Variance	DF	Sum of Squares	Mean Square	F Statistic	Signif. at .05 Level
Between Subjects	15	1500.6774	100.0451	.8950	2.69
Frequency/ Intensity	3	159.6117	53.2039	.4759	3.49
Error (b)	12	1341.0657	111.7754		
Within Subjects	48	1428.0925	29.7519	1.2993	1.62
Frequency	3	209.5455	69.8485	3.0505*	2.92
Intensity	3	146.9855	48.9951	2.1398	2.92
Frequency/ Intensity	6	247.2797	41.2132	1.7999	2.42
Error (w)	36	824.2818	22.8967		
Total	48	2928.7699			

*denotes significance at the .05 level.

Table 8. Results of "critical difference" tests across the significant variable of frequency for each level of intensity.

	$\bar{X}$ @ 20 dB		1000	2000	4000	Significant at:
500 cps	16.225	500 cps	.4	1.825	5.45	12.3048
1000	15.825	1000		2.675	5.85	
2000	18.05	2000			3.625	
4000	21.675					
	$\bar{X}$ @ 30 dB		1000	2000	4000	
500 cps	15.375	500 cps	2.75	1.125	8.075	9.4492
1000	12.625	1000		3.875	10.825*	
2000	16.5	2000			6.95	
4000	23.45					
	$\bar{X}$ @ 40 dB		1000	2000	4000	
500 cps	12.725	500 cps	1.0	5.775	0.025	8.9533
1000	13.175	1000		5.325	0.425	
2000	18.5	2000			5.75	
4000	12.75					
	$\bar{X}$ @ 50 dB		1000	2000	4000	
500 cps	10.525	500 cps	8.625	2.175	8.375	10.3694
1000	19.15	1000		6.45	2.425	
2000	12.7	2000			4.025	
4000	16.725					

*Difference between two means significant at the .05 level.

to the significant F found in the analysis of variance.

Discussion

It has been demonstrated statistically by the analysis of variance test that as frequency was altered in this experiment, the intensity differences between air and bone conduction at the point of maximum cancellation yielded an F that was significant at the .05 level. According to the "critical difference" tests for determining the significant differences between cell means across the variable under consideration, there was only one significant difference that occurred at the 30 dB level between 1000 and 4000 cps. In an attempt to explain this variance, the raw data were inspected. It was determined that one subject at the treatment combination of 30 dB/4000 cps responded with consistent criterion scores that were considerably different from the other group members. This subject's mean criterion score was responsible for raising the cell mean sufficiently to create the significantly critical difference between the two cells under question. Had this subject's mean score been more consistent with the remainder of the subjects in that cell, the difference between the two cells would not have been significant.

Although the above observation was made as a result of inspecting the raw data for an explanation of the results of the statistical analysis, it should be pointed out that wide differences between subject criterion scores in other cells were also observed; however, these differences did not lead to statistically significant differences. The possibility exists that had a larger number of subjects been employed in each group, this type of subject variation would not have influenced the cell mean to the extent observed in this particular case.

Before departing from the above considerations, it should be indicated that the same subject referred to above also, of course, appeared in other cells in which his recorded responses were <u>not</u> significantly apart from the remainder of the group. The influence that contributed to his responses in this specific instance cannot be determined by the experimenter.

Although the particular statistical design employed to test the prescribed null hypotheses indicated statistically significant deviations in criterion scores as a function of frequency, and aside from the foregoing considerations, the experimenter is unable, in view of the total picture, to explain a reason for the significance. It hardly seems reasonable to assume that the two treatment combinations that were apparently responsible for the statistical significance could in some way be unique and different from all other treatment combinations, or that this particular combination of treatments carries some inherent influence peculiar only to that combination. It is with this in mind that the experimenter states that there appears to be a statistically significant difference, at the .05 level, in criterion scores as a function of frequency, as measured by Lindquist's two-factor, Type II design; however, it seems reasonable to assume that this statistical significance is of no practical value.

In other words, the experimenter is willing to assume, from a practical standpoint, that there is no significant difference in criterion scores as a function of frequency. This statement has been modified into a basic conclusion in the next chapter.

Further Considerations. In addition to the objective recording and analyzing of the criterion scores, the experimenter was also interested in obtaining subjective remarks from the subjects that might lend further insight into the investigation. Comments by the subjects may be summarized by two points:

1. The greater the intensity of the pure tone, the greater the difficulty in adjusting for cancellation.

2. The lower the frequency of the pure tone, the greater the difficulty in adjusting for cancellation.

These comments are verified and demonstrated by the slight trends that one observes as the means for treatment categories are plotted on graphs in Figures 6 and 7. Figure 6 shows the mean intensity differences between air and bone conduction plotted across the intensity variable. It can be seen from this graph that as intensity is increased, the greater is the difference between air and bone conduction at point of maximum cancellation. The difference,

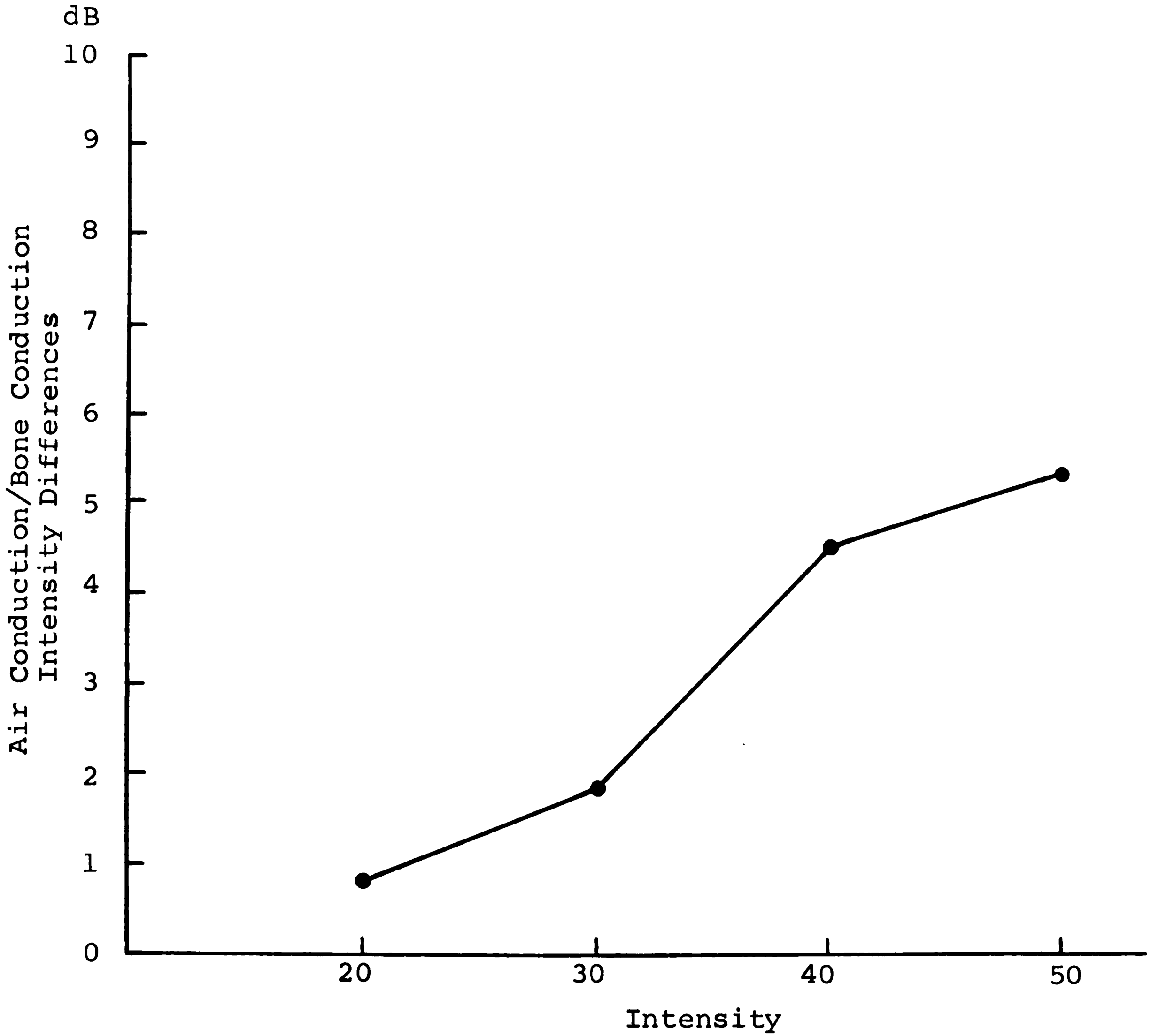

Fig. 6. Mean category intensity differences between air and bone, at point of maximum cancellation effect, plotted across the intensity scale.

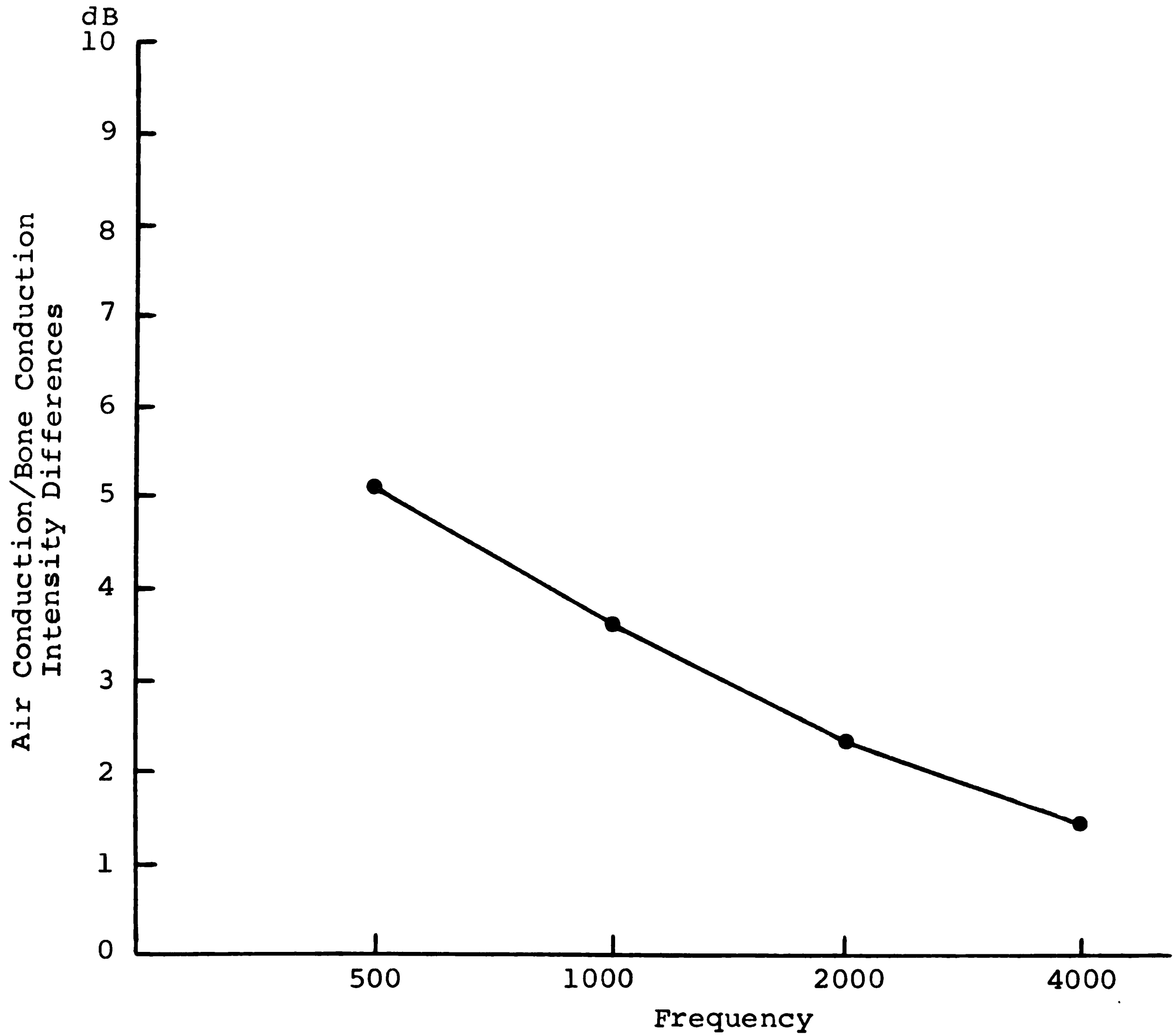

Fig. 7. Mean category intensity differences between air and bone, at point of maximum cancellation effect, plotted across the frequency scale.

however, never exceeds 5.3 dB.

Figure 7 demonstrates the mean intensity differences between air and bone as a function of frequency. The configuration on this graph indicates that as frequency is increased, the differences between air and bone conduction at the point of maximum cancellation decrease. These differences range from 1.4 to 5.1 dB.

The variation in means for treatment categories depicted in Figures 6 and 7, though not significant perhaps in light of the limited range of differences between air and bone, nevertheless, represents a slight trend that is consistent with judgments made by subjects during the experiment, and summarized by the two points outlined at the outset of this section. In this regard, one assumes that the degree of difference between air and bone conduction at the point of maximum cancellation occurs in proportion to the amount of difficulty experienced in finding this point.

Although the limitations of this experiment precluded the direct study of the degree of cancellation or intracranial shift of the sound image as a function of frequency and intensity, the experimenter was able to make observations in this respect that relate to the above discussion. It was obvious, as a result of questioning subjects, that most subjects were able to cancel tones of high frequencies at low intensities at least 90% of the time. When this complete cancellation occurred, the sound image shifted entirely to the open, non-test ear. Although tones of low frequencies and low intensities were also completely cancelled by some subjects, the percentage of complete compensation was much lower and lacking in consistency from subject to subject. The greater the intensity, the more difficult it became for subjects to achieve complete cancellation at any frequency; however, complete disappearance of a 4000 cps tone from the test ear was observed in some cases for high intensities.

In general, it may be summarized that subjects were able to cancel completely 4000 cps tones at 20 dB, as judged by a complete shift of the sound image to the contralateral ear, with very good accuracy and consistency. The percentage of complete cancellations appeared to decrease gradually as intensity was raised and frequency lowered. Some subjects were unable to achieve any degree of shift of the sound image at low frequencies of high intensities; however, in all of these cases, a distinct attenuation of the tone in the test ear was indicated. It is obvious from the discussion that the shift of the sound image, depending upon frequency and intensity, ranged in degree from none, to any point between the test ear and the contralateral ear.

In summary, the degree of cancellation observed may be described as follows:

1. There may be a complete disappearance of the tone in the test ear accompanied by a complete shift of the sound image to the non-test ear.
2. There may be a complete disappearance of the tone in the test ear accompanied by a shift of the sound

image toward the non-test ear. After the maximum cancellation effect is evoked, the sound image may appear to be localized at any point, toward the front or back of the head, between the test ear and the non-test ear.

3. The tone may not disappear nor shift from the test ear at the point of maximum cancellation; instead, there may be only an attenuation of the tone in the test ear.

4. Which one of the above circumstances may best describe a given cancellation effect depends upon the frequency and intensity combination. Generally speaking, tones of high frequencies and low intensities (within the limitations of the treatment ranges used in this experiment) are the ones most likely to be cancelled completely from the test ear. On the other hand, the lower the frequency and higher the intensity, the less likelihood of inducing a complete cancellation of the tone in the test ear, and the greater the probability of experiencing merely an attenuation of the tone. Regardless of the particular combination of frequency and intensity, however, an effect of some sort, as described above, can be induced for every trial.

Additional inspection of the data has led to the graphic representation as illustrated in Figures 8 and 9. These graphs demonstrate, respectively, the mean intensity difference between air and bone at the point of maximum cancellation, by treatment combinations, as intensity is plotted across frequency, and as frequency is plotted across intensity.

As the intensity curves in Figure 8 are observed as they cross the frequency scale on the abscissa, it appears that no practical or meaningful interpretation can be made relative to the 40 and 50 dB curves. These curves appear to slope and change directions symmetrically, but in opposition to each other. However, the observed configuration

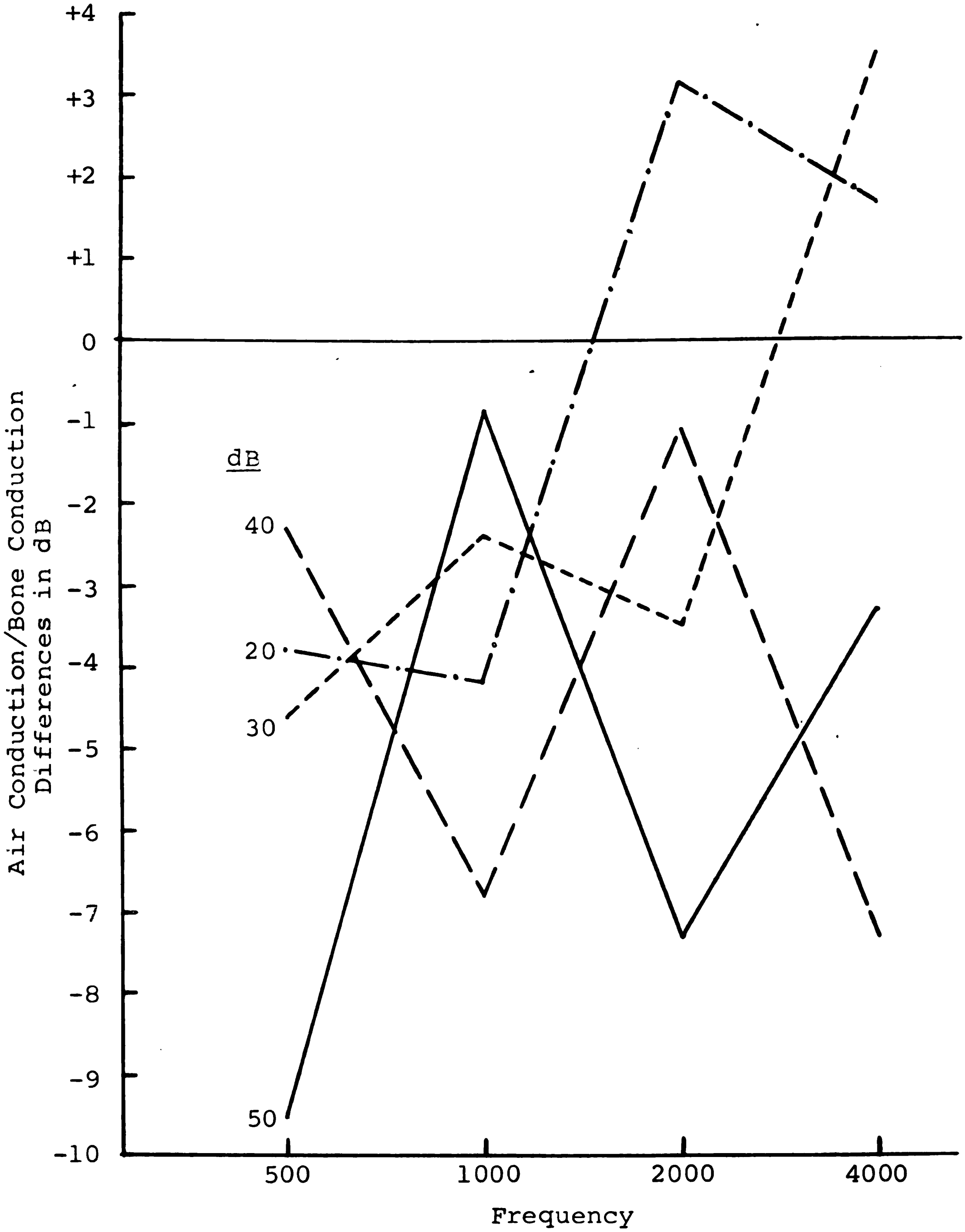

Fig. 8. Mean air conduction/bone conduction differences by treatment combination. Intensity plotted across frequency. A + sign indicates that intensity of air conduction is greater than bone conduction; a - sign indicates that the intensity of air conduction is less than bone conduction.

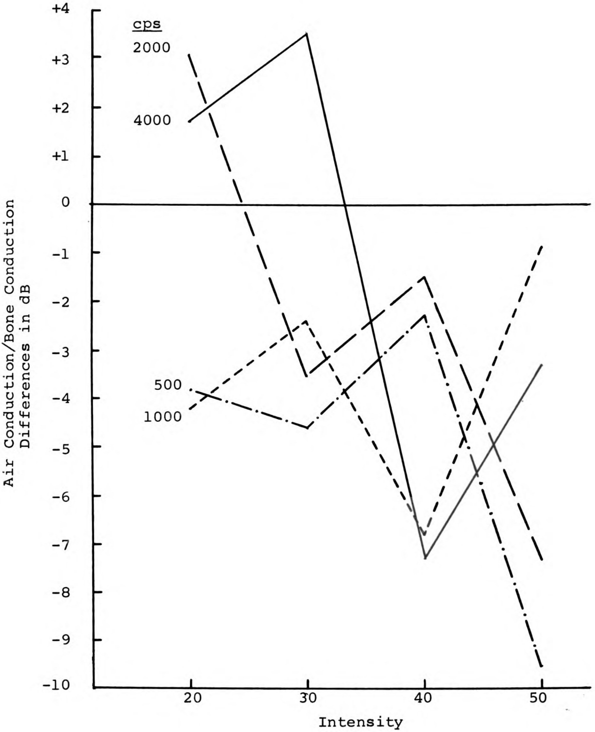

Fig. 9. Mean air conduction/bone conduction differences by treatment combination. Frequency plotted across intensity. A + sign indicates that intensity of air conduction is greater than bone conduction; a - sign indicates that the intensity of air conduction is less than bone conduction.

is judged to be a random one, having no particular significance.

The 20 and 30 dB curves in Figure 8 do appear to exhibit a trend or pattern. They both slope upward as frequency increases, extending from that part of the graph indicating that the air conduction stimulus is <u>less</u> than that of the bone conduction, to that portion of the graph indicating that the intensity of the air-conducted stimulus is <u>greater</u> than the constant bone-conducted stimulus. One might speculate from this illustration that at lower experimental levels of intensity, in combination with the higher levels of the experimental frequency scale, there is a tendency for subjects to "over-adjust" (intensity of air <u>greater</u> than bone) the air-conducted pure tone as compared to the bone-conducted tone; and to "under-adjust" (intensity of air <u>less</u> than bone) at lower frequencies at nearly all levels of intensity. It is quite clear that the subjects in this study displayed a definite tendency to "under-adjust" the air-conducted tone.

Figure 9 is similar to the preceding graph except, in this case, frequency curves at each category are plotted across the intensity variable. Again, it can be observed that there is a tendency for subjects to "over-adjust" at lower intensities and higher frequencies, and to "under-adjust" at all other treatment combinations.

<u>Additional Comments on the Results</u>. Prior to the outset of this study, the experimenter speculated over

several possible suppositions that could have accounted for significant differences in criterion scores, had they occurred, as a result of altering frequency or intensity during the experiment. Although the differences that were observed proved in the final analysis to be insignificant, from either a statistical or a practical viewpoint, the following notions are presented as reasons that led the writer to consider the possibility that the treatments might have produced significant results. These comments may also lend further insight into the results of this study.

1. The bone-conducted tones, according to the experimental conditions, at the higher intensities, could be heard by air conduction in the open, non-test ear. This arrangement should make the louder treatment levels more difficult to adjust, and subsequently produce greater variation in criterion scores. Nearly all of the subjects indicated that the louder tones, especially at low frequencies, were in fact more difficult to cancel; however, despite the greater difficulty, the subjects were able to make the proper adjustments in a consistent manner, and were not unduly hindered by the intensity of the stimuli.

2. According to von Békésy,[1] difficulties in phase adjustments vary with frequency. He states that ". . . for frequencies over 800 cps we pass into the region of resonance of the ossicles, and then the phase adjustments become

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[1] von Békésy, <u>Experiments in Hearing</u>, p. 129.

difficult." It seemed logical to assume that one could expect greater variation and differences in criterion scores as a function of difficulty in phase adjustments. The results of this study, particularly the comments made by subjects, indicate that the lower frequencies, not the higher ones, posed the greatest difficulty. Most subjects stated that they were able to detect more easily a cancellation effect at the higher frequencies, as opposed to the lower ones, although locating the effect required <u>finer</u> adjustments of phase. This can be explained by the fact that higher frequencies have shorter wavelengths, thus, causing the cancellation effect to be "sharper" as one carefully adjusts phase. In this sense, the shorter wavelengths apparently served as an asset in locating more precisely the maximum cancellation effect.

3. The possibility that variations in bone-conducted skull vibrations as a result of changes in frequency might have influenced the criterion scores was also considered. For example, it has been shown that the entire head displaces in step with the vibrating body at low frequencies; while at higher frequencies, this is not the case. For frequencies above about 1500 cps, the back of the head does not follow the vibrations of the front, apparently because at these frequencies the middle of the head is compressed.[1]

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[1] von Békésy and Rosenblith, <u>op. cit</u>., p. 1109.

It was reasoned, in light of the above example, that at low frequencies of high intensities (because at low frequencies the head vibrates like a solid body), the non-test ear would be stimulated to a greater extent than it would at higher frequencies, thus, making it more difficult to achieve a well-defined cancellation effect. This possibility was verified by most of the subjects, but the difficulties encountered were for the most part offset by careful manipulation of the phase and intensity controls, and apparently had neither statistical nor practical effects upon the criterion scores. Although the slight trend observed in treatment means, as described previously, appears to support the idea discussed in this section, it should be noted that this trend could itself be nullified by the restricted number of groups and subjects utilized in this study. Therefore, in this instance, the generalization is made with extreme caution.

4. A fourth consideration was given to the effects of the difference limen for intensity. It has been shown, depending upon frequency, that for high levels of intensity, one is able to detect smaller differences in changes in intensity as compared to lower levels of intensity.[1] It requires, across the speech frequencies, about a 3 dB change in intensity at sensation levels near zero in order

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[1]Harvey Fletcher, Speech and Hearing in Communication (N.Y.: D. Van Nostrand Co., Inc., 1953), pp. 144-146.

to detect a just-noticeable-difference; whereas, at about 40 dB, a 1 dB change may be detected.

Since one is able to detect smaller differences in intensity at higher levels of intensity, it seemed logical to assume that the range of difference between air- and bone-conducted tones at the point of maximum cancellation would be smaller at treatment levels consisting of high intensity tones. However, the results suggest the opposite, that the greater the intensity of the tone, the greater the variation between air and bone. It should be pointed out, however, that as far as the influence of the difference limen is concerned, it is doubtful that the difference limen would have significantly affected the outcome of the experiment due to its limited range at the experimental intensity levels.

5. Lastly, because of the experimental arrangement of the bone conduction oscillator and the earphone (forehead placement of the oscillator; right ear placement of the earphone, left ear open), the occlusion effect, defined and discussed in Chapter I, was considered as a potential source of variation in criterion scores. In essence, this effect is characterized by improving bone conduction thresholds at low frequencies, while having very little effect, if any, at the high frequencies.[1] The improvement of bone-conducted thresholds at the low

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[1] Goldstein and Hayes, op. cit., p. 137.

frequencies widens the gap between bone and air sensitivity. It may be recalled that the greatest degree of difference between air and bone at the point of maximum cancellation actually occurred at the lower frequencies. It is, therefore, possible that the trend suggested in Figure 7, and discussed previously, may be nullified by the influence of the occlusion effect.

Summary. This chapter has evaluated and discussed the results of this investigation from within a framework of both statistical and practical considerations with respect to the specific questions from which the null hypotheses were derived. The experimental design employed in the present study was described in detail, and the results of the analysis of variance and "critical difference" tests were presented.

Attention was also given in this chapter to observations made by the experimenter, and to subjective remarks made by subjects. These considerations were evaluated in order to determine more fully the implications of the recorded results.

Lastly, several possible reasons were discussed that could have accounted for significant differences in criterion scores, had these differences occurred.

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

The purpose of this study was to investigate bone conduction/air conduction cancellation as a function of intensity and frequency under specified experimental arrangements. The arrangements included forehead (midline) placement of the bone conduction oscillator, and monaural placement of the air conduction receiver (right ear occluded by the receiver, opposite ear open). Subjects were required to manipulate phase and intensity in an attempt to cancel a constant bone-conducted pure tone by an identical air-conducted tone.

The specific questions asked were:

1. Does the intensity-difference between air-conducted and bone-conducted pure tones (criterion scores) differ significantly at the point of maximum cancellation as <u>intensity</u> is altered?

2. Does the intensity-difference between air-conducted and bone-conducted pure tones differ significantly at the point of maximum cancellation as <u>frequency</u> is altered?

3. Are there certain inter-relationships between frequency and intensity that affect the criterion scores?

The experimenter chose to limit the experimental variables or treatments to levels of 500, 1000, 2000, and

4000 cps for frequency; and to levels of 20, 30, 40, and 50 dB for intensity. Any combination of frequency and intensity levels constituted one of sixteen treatment combinations.

Sixteen subjects were randomly divided into four groups and distributed throught a 4 X 4 Latin square in a manner that met the requirements of a Lindquist, Type II, design. Each subject was given six trials at each of four treatment combinations (total of 24 trials per subject), which were completely randomized for presentation. In order to complete a trial, each subject had to cancel (or maximize the attenuation) the bone-conducted tone in the occluded right ear by manipulating the phase and intensity of an identical air-conducted tone in the same ear. The intensity differences between air and bone conduction at the point of maximum cancellation were computed and charted accordingly as criterion scores. The reliability of the criterion scores across both frequency and intensity, as measured by correlating the first three trials of subjects against the last three trials, was found to be high. The criterion scores were then used in the statistical analysis.

The results of the analysis indicated that frequency was the only variable statistically significant in this study. Intensity changes did not appear to have any significant effect upon the criterion scores; nor were there any significant interactions between intensity and frequency.

"Critical difference" tests located what appeared to be the primary source of variation that contributed to the statistical significance. It was found that a significant difference existed between only two treatment combinations at the 30 dB category at 1000 and 4000 cps. However, there appears to be no practical value attached to the statistical finding with respect to frequency.

Conclusions

Within the experimental arrangements of this study, the following conclusions appear to be warranted:

1. Intensity differences between air and bone conduction at the point of maximum cancellation are not affected by changes in intensity. In other words, bone-conducted pure tones are cancelled in one ear by identical air-conducted tones in the same ear at any of the experimental intensity levels (20, 30, 40, and 50 dB); and the ratio of differences in intensity between the tones, when cancellation occurs, is essentially constant as intensity is increased.

2. Despite the statistically significant finding with respect to the frequency variable, the experimenter has chosen to conclude, from a practical viewpoint, that there are no significant differences between air and bone at the point of maximum cancellation as a function of frequency. That is to say, the ratio of differences in intensity between air and bone, when cancellation occurs, is essentially constant as frequency is increased over the experimental

frequency range (500, 1000, 2000, and 4000 cps).

3. The intensity differences between air and bone conduction at the point of maximum cancellation do not change as a result of interrelationships between frequency and intensity.

Implications for Further Research

The purpose of this section is to suggest certain topics related to the air conduction/bone conduction cancellation phenomenon that should be investigated.

1. The problems associated with eliminating the non-test ear during bone conduction audiometry are well known by audiologists.[1,2] The conventional method employed for this purpose is through the use of a masking noise that is fed into the non-test ear. This technique often creates further difficulties in that the thresholds in the test ear can be affected by masking the contralateral ear.[3] It appears feasible to assume that the bone conduction/air conduction cancellation phenomenon could be useful in eliminating the contralateral ear in bone conduction audiometry.[4] This possibility could be investigated with a

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[1] A. S. Feldman, "Problems in the Measurement of Bone-Conduction," Journal of Speech and Hearing Disorders, XXVI (February, 1961), pp. 39-44.

[2] Studebaker, op. cit., p. 215.

[3] James Jerger and Susan Jerger, "Critical Evaluation of SAL Audiometry," Journal of Speech and Hearing Research, VIII (June, 1965), p. 103.

[4] Letter from Ernest L. Smith.

number of subjects who have unilateral sensorineural hearing losses.

2. von Békésy[1] states that movements of the head or jaw can change the relationships between phase and intensity, thus, preventing constant cancellation of the bone conduction/air conduction tone. Observations made during this study indicate, for example, that moving the head from a frontal position to a 45° or 90° angle, either left or right, up or down, will in fact change the adjustments. It is suggested that an investigation could be undertaken whereby the changes in adjustment at various head angles or positions could be observed and compared.

3. The cancellation effects caused by changing the phase angle of the air-conducted tone to other than 180° with respect to the bone-conducted tone should also be observed. Observations as a result of this study suggest that some attenuation of the bone conduction/air conduction tone may occur at 90° or 270° at some frequencies.

4. This study was concerned with intensity differences between air and bone conduction at the point of maximum cancellation effect. It was assumed that when this effect was induced, the phase angles of the two signals were 180° apart at the cochlea. The recorded variations in intensity differences between air and bone were, for the most part, due to errors resulting from attempts to place the two

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[1] von Békésy, Experiments in Hearing, pp. 129, 134.

signals 180° apart, and to balance the loudness of the signals. The consistency or reliability of subjects in adjusting the intensity of the air-conducted stimulus has been determined by this study and found to be high; however, variations in phase adjustments were not studied in this manner. It would be enlightening to determine the reliability of phase adjustments across frequency and intensity and correlate these to the intensity reliabilities measured in the present investigation.

5. The maximum cancellation effect occurs, as described previously, when the bone-conducted and air-conducted tones are 180° apart at the cochlea. When this effect occurs, the electrical phase relationship between the two tones may not be 180° as read from an oscilloscope. This happens because the subjective experience of cancellation occurs after the signals have traveled through different media and different anatomical structures. This, of course, is not the case in physical measurements of phase. It would be useful to compare the subjective and physical measurement of phase at the point of maximum cancellation as a function of frequency and intensity. It might even be possible to determine the expected phase differences (subjective vs physical) for normal and pathological ears.

6. The experimental conditions of this study prescribed that the bone-conducted stimulus would be constant and the air-conducted stimulus variable. This question could now be asked: What would occur if air conduction is held

constant and the bone-conducted tone is varied? Would the differences between air and bone be similar to those in the present data?

7. It has been pointed out that different combinations of frequency and intensity levels produce different degrees of shift of sound image from the test ear toward the non-test ear. These shifts could be "mapped" and compared as they occur from various head positions.

8. This study could be repeated under binaural air conduction arrangements.

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APPENDIX A

RAW DATA SHOWING VARIOUS CONVERSIONS AND CRITERION SCORES

Notes on Appendix A. The data on the pages that follow show the various conversions that were necessary in order to arrive at the criterion scores listed in the last column.

1. Column 1 indicates the subjects' responses to each trial as measured on the oscilloscope in millivolts. These figures become V_1 in the ratio V_1/V_0 shown in column 2.

2. V_0 in column 2 equals the voltage necessary to produce a pressure equal to 0 dB SPL (re .0002 dynes/cm^2) across the earphones. The voltage ratios are listed in this column.

3. Column 3 takes the voltage ratios and converts them into sound pressure levels expressed in dB. This conversion was accomplished by using a table for this purpose.

4. Column 4 is the conversion of sound pressure levels into their audiometric equivalents (re ASA-1951, Telephonics TDH-39 earphones). Calibration information was taken from the Bruel & Kjaer Instruction Manual for Model 158 Audiometer Calibrator.

5. Column 5 represents the intensity differences between the air-conducted tone and the constant bone-conducted tone (levels of tone given under Treatment Combination) at the point of maximum cancellation effect. These are the criterion scores which were used in the statistical analysis.

The following is the key to the symbols and abbreviations used in Appendix A:

G = Group; S = Subject; T = Trial; AC = Air Conduction; BC = Bone Conduction; mv = Millivolts; Δ = Difference; Audiom. = Audiometric; (-) criterion score = AC less than BC; and (+) score = AC greater than BC.

GS	T	Treatment Combination	AC Volt. mv. V_1	V_1/V_0 Ratio V_0=.00145	SPL	Audiom. TDH-39 (-24.1 dB)	BC/ACΔ dB
G_1S_1	1	500 cps/20 dB	.15	103.5	40.4	16.3	-3.7
	2		.1	69.0	36.8	12.7	-7.3
	3		.1	69.0	36.8	12.7	-7.3
	4		.1	69.0	36.8	12.7	-7.3
	5		.15	103.5	40.4	16.3	-3.7
	6		.1	69.0	36.8	12.7	-7.3
G_1S_2	1	"	.1	69.0	36.8	12.7	-7.3
	2		.15	103.5	40.4	16.3	-3.7
	3		.1	69.0	36.8	12.7	-7.3
	4		.1	69.0	36.8	12.7	-7.3
	5		.15	103.5	40.4	16.3	-3.7
	6		.1	69.0	36.8	12.7	-7.3
G_1S_3	1	"	.24	165.5	44.4	20.3	+ .3
	2		.24	165.5	44.4	20.3	+ .3
	3		.22	151.7	43.6	19.5	- .5
	4		.25	172.4	44.8	20.7	+ .7
	5		.16	110.4	40.9	16.8	-3.2
	6		.1	69.0	36.8	12.7	-7.3
G_1S_4	1	"	.2	138.0	42.8	18.7	-1.3
	2		.2	138.0	42.8	18.7	-1.3
	3		.2	138.0	42.8	18.7	-1.3
	4		.2	138.0	42.8	18.7	-1.3
	5		.2	138.0	42.8	18.7	-1.3
	6		.2	138.0	42.8	18.7	-1.3

GS	T	Treatment Combination	AC Volt. mv. V_1	V_1/V_0 Ratio V_0=.00145	SPL	Audiom. TDH-39 (-24.1 dB)	BC/AC Δ dB
G_4S_1	1	500 cps/30 dB	.22	151.7	43.6	19.5	-10.5
	2		.3	207.6	46.4	22.3	-7.7
	3		.3	207.6	46.4	22.3	-7.7
	4		.35	241.4	47.7	23.6	-6.4
	5		.5	344.8	50.8	26.7	-3.3
	6		.4	276.6	48.9	24.8	-5.2
G_4S_2	1	"	.5	344.8	50.8	26.7	-3.3
	2		.35	241.4	47.7	23.6	-6.4
	3		.55	380.0	51.6	27.5	-2.5
	4		.6	414.5	52.4	28.3	-1.7
	5		.45	311.0	49.9	25.8	-4.2
	6		.5	344.8	50.8	26.7	-3.3
G_4S_3	1	"	1.0	689.7	56.8	32.7	+2.7
	2		.55	380.0	51.6	27.5	-2.5
	3		.4	275.9	48.8	24.7	-5.3
	4		.7	482.8	53.7	29.6	- .4
	5		.45	310.3	49.9	25.8	-4.2
	6		.5	344.8	50.8	26.7	-3.3
G_4S_4	1	"	.35	241.4	47.7	23.6	-6.4
	2		.35	241.4	47.7	23.6	-6.4
	3		.5	344.8	50.8	26.7	-3.3
	4		.4	275.9	48.8	24.7	-5.3
	5		.35	241.4	47.7	23.6	-6.4
	6		.3	206.9	46.3	22.2	-7.8

GS	T	Treatment Combination	AC Volt. mv. V_1	V_1/V_0 Ratio V_0=.00145	SPL	Audiom. TDH-39 (-24.1 dB)	BC/AC△ dB
G_3S_1	1	500 cps/40 dB	2.4	1655.2	64.4	40.3	+0.3
	2		2.2	1517.2	63.6	39.5	-0.5
	3		2.6	1793.1	65.1	41.0	+1.0
	4		2.2	1517.2	63.6	39.5	-0.5
	5		2.3	1586.2	64.0	39.9	-0.1
	6		1.8	1241.4	61.9	37.8	-2.2
G_3S_2	1	"	2.8	1931.0	65.7	41.6	+1.6
	2		2.0	1379.3	62.8	38.7	-1.3
	3		1.7	1172.4	61.4	37.3	-2.7
	4		2.4	1655.2	64.4	40.3	+0.3
	5		2.6	1793.1	65.1	41.0	+1.0
	6		2.6	1793.1	65.1	41.0	+1.0
G_3S_3	1	"	0.8	551.7	54.9	30.8	-9.2
	2		0.8	551.7	54.9	30.8	-9.2
	3		1.1	758.6	52.6	33.5	-6.5
	4		1.0	689.7	56.8	32.7	-7.3
	5		0.9	620.7	55.9	31.8	-8.2
	6		1.25	862.1	58.7	34.6	-5.4
G_3S_4	1	"	2.0	1379.3	62.8	38.7	-1.3
	2		1.6	1103.5	60.9	36.8	-3.2
	3		2.2	1517.2	63.6	39.5	-0.5
	4		2.0	1379.3	62.8	38.7	-1.3
	5		2.2	1517.2	63.6	39.5	-0.5
	6		2.3	1586.2	64.0	39.9	-0.1

GS	T	Treatment Combination	AC Volt. mv. V_1	V_1/V_0 Ratio V_0=.00145	SPL	Audiom. TDH-39 (-24.1 dB)	BC/ACΔ dB
G_2S_1	1	500 cps/50 dB	2.0	1379.3	62.8	38.7	-11.3
	2		1.8	1241.4	61.9	37.8	-12.2
	3		1.7	1172.4	61.4	37.3	-12.7
	4		1.8	1241.4	61.9	37.8	-12.2
	5		2.8	1931.0	65.7	41.6	- 8.4
	6		3.4	2344.8	67.4	43.3	- 6.7
G_2S_2	1	"	4.7	3241.4	70.2	46.1	- 3.9
	2		4.0	2758.7	68.8	44.7	- 5.3
	3		3.4	2344.8	67.4	43.3	- 6.7
	4		2.6	1793.1	65.1	41.0	- 9.0
	5		2.5	1724.1	64.7	40.6	- 9.4
	6		2.9	2000.0	66.1	42.0	- 8.0
G_2S_3	1	"	2.3	1586.2	64.0	39.9	-10.1
	2		5.2	3586.2	71.1	47.0	- 3.0
	3		4.0	2758.6	68.8	44.7	- 5.3
	4		4.5	3103.4	69.9	45.8	- 4.2
	5		2.8	1931.0	65.7	41.6	- 8.4
	6		4.5	3103.4	69.9	45.8	- 4.2
G_2S_4	1		1.5	1034.5	60.3	36.2	-13.8
	2		1.4	965.5	59.7	35.6	-14.4
	3		1.4	965.5	59.7	35.6	-14.4
	4		1.4	965.5	59.7	35.6	-14.4
	5		1.4	965.5	59.7	35.6	-14.4
	6		1.4	965.5	59.7	35.6	-14.4

GS	T	Treatment Combination	AC Volt. mv. V_1	V_1/V_0 Ratio V_0=.0014	SPL	Audiom. TDH-39 (-17.2 dB)	BC/ACΔ dB
G_2S_1	1	1000 cps/20dB	0.04	28.6	29.3	12.1	-7.9
	2		0.06	42.9	32.7	15.5	-4.5
	3		0.05	35.7	31.1	13.9	-6.1
	4		0.05	35.7	31.1	13.9	-6.1
	5		0.06	42.9	32.7	15.5	-4.5
	6		0.06	42.9	32.7	15.5	-4.5
G_2S_2	1	"	0.1	71.4	37.1	19.9	-0.1
	2		0.1	71.4	37.1	19.9	-0.1
	3		0.09	64.3	36.2	19.0	-1.0
	4		0.08	57.1	35.2	18.0	-2.0
	5		0.1	71.4	37.1	19.9	-0.1
	6		0.06	42.9	32.7	15.5	-4.5
G_2S_3	1	"	0.08	57.1	35.2	18.0	-2.0
	2		0.06	42.9	32.7	15.5	-4.5
	3		0.1	71.4	37.1	19.9	-0.1
	4		0.12	85.7	38.6	21.4	+1.4
	5		0.12	85.7	38.6	21.4	+1.4
	6		0.12	85.7	38.6	21.4	+1.4
G_2S_4	1	"	0.03	21.4	26.6	9.4	-10.6
	2		0.03	21.4	26.6	9.4	-10.6
	3		0.04	28.6	29.1	11.9	- 8.1
	4		0.04	28.6	29.1	11.9	- 8.1
	5		0.04	28.6	29.1	11.9	- 8.1
	6		0.03	21.4	26.6	9.4	-10.6

GS	T	Treatment Combination	AC Volt. mv. V_1	V_1/V_0 Ratio V_0=.0014	SPL	Audiom. TDH-39 (-17.2 dB)	BC/AC△ dB
G_1S_1	1	1000 cps/30dB	0.2	142.9	43.1	25.9	-4.1
	2		0.2	142.9	43.1	25.9	-4.1
	3		0.2	142.9	43.1	25.9	-4.1
	4		0.2	142.9	43.1	25.9	-4.1
	5		0.15	107.1	40.6	23.4	-6.6
	6		0.15	107.1	40.6	23.4	-6.6
G_1S_2	1	"	0.2	142.9	43.1	25.9	-4.1
	2		0.2	142.9	43.1	25.9	-4.1
	3		0.3	214.3	46.6	29.4	-0.6
	4		0.3	214.3	46.6	29.4	-0.6
	5		0.3	214.3	46.6	29.4	-0.6
	6		0.3	214.3	46.6	29.4	-0.6
G_1S_3	1	"	0.32	228.6	47.2	30.0	0.0
	2		0.32	228.6	47.2	30.0	0.0
	3		0.28	200.0	46.1	28.9	-1.1
	4		0.32	228.6	47.2	30.0	0.0
	5		0.3	214.3	46.6	29.4	-0.6
	6		0.4	285.8	49.1	31.4	+1.9
G_1S_4	1	"	0.2	142.9	43.1	25.9	-4.1
	2		0.25	178.9	45.1	27.9	-2.1
	3		0.25	178.9	45.1	27.9	-2.1
	4		0.2	142.9	43.1	25.9	-4.1
	5		0.25	178.9	45.1	27.9	-2.1
	6		0.25	178.9	45.1	27.9	-2.1

GS	T	Treatment Combination	AC Volt. mv V_1	V_1/V_0 Ratio V_0=.0014	SPL	Audiom. TDH-39 (-17.2 dB)	BC/ACΔ dB
G_4S_1	1	1000 cps/40dB	0.2	142.9	43.1	25.9	-14.1
	2		1.6	1142.9	61.2	44.0	+ 4.0
	3		0.2	142.9	43.1	25.9	-14.1
	4		0.3	214.3	46.6	29.4	-10.6
	5		0.35	250.0	48.0	30.8	- 9.2
	6		0.25	178.6	45.1	27.9	-12.1
G_4S_2	1	"	0.55	392.9	51.9	34.7	- 5.3
	2		0.45	321.4	50.2	33.0	- 7.0
	3		0.5	357.1	51.2	33.8	- 6.2
	4		0.6	428.6	52.7	35.5	- 4.5
	5		0.4	285.7	49.1	31.9	- 8.1
	6		0.5	357.1	51.1	33.9	- 6.1
G_4S_3	1		0.6	428.6	52.6	35.4	- 4.6
	2		0.6	428.6	52.6	35.4	- 4.6
	3		0.6	428.6	52.6	35.4	- 4.6
	4		0.65	464.3	53.3	36.1	- 3.9
	5		0.5	357.1	51.1	33.9	- 6.1
	6		0.5	357.1	51.1	33.9	- 6.1
G_4S_4	1		0.45	321.4	50.2	33.0	- 7.0
	2		0.45	321.4	50.2	33.0	- 7.0
	3		0.45	321.4	50.2	33.0	- 7.0
	4		0.45	321.4	50.2	33.0	- 7.0
	5		0.5	357.1	51.1	33.9	- 6.1
	6		0.5	357.1	51.1	33.9	- 6.1

GS	T	Treatment Combination	AC Volt. mv. V_1	V_1/V_0 Ratio V_0=.0014	SPL	Audiom. TDH-39 (-17.2 dB)	BC/ACΔ dB
G_3S_1	1	1000 cps/50dB	4.8	3428.6	70.7	53.5	+ 3.5
	2		4.2	3000.0	69.6	52.4	+ 2.4
	3		3.65	2607.1	68.3	51.1	+ 1.1
	4		4.25	3035.7	69.7	52.5	+ 2.5
	5		4.1	2928.6	69.3	52.1	+ 2.1
	6		4.2	3000.0	69.6	52.4	+ 2.4
G_3S_2	1	"	4.1	2928.6	69.3	52.1	+ 2.1
	2		4.3	3071.4	69.7	52.5	+ 2.5
	3		2.9	2071.4	66.3	49.1	- 0.9
	4		3.5	2500.0	68.0	50.8	+ 0.8
	5		4.4	3142.9	69.9	52.7	+ 2.7
	6		4.4	3142.9	69.9	52.7	+ 2.7
G_3S_3	1	"	0.9	642.9	56.2	39.0	-11.0
	2		0.65	464.3	53.3	36.1	-13.9
	3		0.7	500.0	54.0	36.8	-13.2
	4		0.85	607.1	55.7	38.5	-11.5
	5		0.65	464.3	53.3	36.1	-13.9
	6		0.65	464.3	53.3	36.1	-13.9
G_3S_4	1	"	4.1	2928.6	69.3	52.1	+ 2.1
	2		6.0	4285.8	72.6	55.4	+ 5.4
	3		4.6	3285.7	70.3	53.1	+ 3.1
	4		4.6	3285.7	70.3	53.1	+ 3.1
	5		8.0	5714.3	75.1	57.9	+ 7.9
	6		12.4	8857.1	78.9	61.7	+11.7

GS	T	Treatment Combination	AC Volt mv. V_1	V_1/V_0 Ratio V_0=.0015	SPL	Audiom. TDH-39 (-18.0 dB)	BC/ACΔ dB
G_3S_1	1	2000 cps/20dB	0.2	133.3	42.5	24.5	+ 4.5
	2		0.2	133.3	42.5	24.5	+ 4.5
	3		0.2	133.3	42.5	24.5	+ 4.5
	4		0.2	133.3	42.5	24.5	+ 4.5
	5		0.2	133.3	42.5	24.5	+ 4.5
	6		0.25	166.7	44.5	26.5	+ 6.5
G_3S_2	1	"	0.06	40.0	32.1	14.1	- 5.9
	2		0.04	26.7	28.7	10.7	- 9.3
	3		0.08	53.3	34.5	16.5	- 3.5
	4		0.08	53.3	34.5	16.5	- 3.5
	5		0.08	53.3	34.5	16.5	- 3.5
	6		0.08	53.3	34.5	16.5	- 3.5
G_3S_3	1	"	0.2	133.3	42.5	24.5	+ 4.2
	2		0.15	100.0	40.0	22.0	+ 2.0
	3		0.1	66.7	36.5	18.5	- 1.5
	4		0.1	66.7	36.5	18.5	- 1.5
	5		0.1	66.7	36.5	18.5	- 1.5
	6		0.1	66.7	36.5	18.5	- 1.5
G_3S_4	1	"	0.5	333.3	50.4	32.4	+12.4
	2		0.35	233.3	47.4	29.4	+ 9.4
	3		0.3	200.0	46.1	28.1	+ 8.1
	4		0.8	533.3	54.5	36.5	+16.5
	5		0.4	266.7	48.5	30.5	+10.5
	6		0.85	566.7	55.1	37.1	+17.1

GS	T	Treatment Combination	AC Volt. mv. V_1	V_1/V_0 Ratio V_0=.0015	SPL	Audiom. TDH-39 (-18.0 dB)	BC/ACΔ dB
G_2S_1	1	2000 cps/30dB	0.2	133.3	42.5	24.5	- 5.5
	2		0.2	133.3	42.5	24.5	- 5.5
	3		0.25	166.7	44.5	26.5	- 3.5
	4		0.2	133.3	42.5	24.5	- 5.5
	5		0.2	133.3	42.5	24.5	- 5.5
	6		0.25	166.7	44.5	26.5	- 3.5
G_2S_2	1	"	0.15	100.0	40.0	22.0	- 8.0
	2		0.15	100.0	40.0	22.0	- 8.0
	3		0.3	200.0	46.1	28.1	- 1.9
	4		0.2	133.3	42.5	24.5	- 5.5
	5		0.15	100.0	40.0	22.0	- 8.0
	6		0.15	100.0	40.0	22.0	- 8.0
G_2S_3	1	"	0.6	400.0	52.1	34.1	+ 4.1
	2		0.5	333.3	50.5	32.5	+ 2.5
	3		0.7	466.7	53.4	35.4	+ 5.4
	4		0.7	466.7	53.4	35.4	+ 5.4
	5		0.35	233.3	47.4	29.4	- 0.6
	6		0.4	266.7	48.5	30.5	+ 0.5
G_2S_4	1	"	0.25	166.7	44.5	26.5	- 3.5
	2		0.25	166.7	44.5	26.5	- 3.5
	3		0.2	133.3	42.5	24.5	- 5.5
	4		0.2	133.3	42.5	24.5	- 5.5
	5		0.25	166.7	44.5	26.5	- 3.5
	6		0.1	66.7	36.6	18.6	-11.4

GS	T	Treatment Combination	AC Volt. mv. V_1	V_1/V_0 Ratio V_0=.0015	SPL	Audiom. TDH-39 (-18.0 dB)	BC/ACΔ dB
G_1S_1	1	2000 cps/40dB	0.75	500.0	54.0	36.0	- 4.0
	2		0.7	466.7	53.4	35.4	- 4.6
	3		0.75	500.0	54.0	36.0	- 4.0
	4		0.75	500.0	54.0	36.0	- 4.0
	5		0.7	466.7	53.4	35.4	- 4.6
	6		0.5	333.3	50.4	32.4	- 7.6
G_1S_2	1	"	0.6	400.0	52.1	34.1	- 5.9
	2		0.8	533.3	54.5	36.5	- 3.5
	3		0.7	466.7	53.4	35.4	- 4.6
	4		0.7	466.7	53.4	35.4	- 4.6
	5		0.7	466.7	53.4	35.4	- 4.6
	6		0.8	533.3	54.5	36.5	- 3.5
G_1S_3	1	"	0.7	466.7	53.4	35.4	- 4.6
	2		0.7	466.7	53.4	35.4	- 4.6
	3		0.7	466.7	53.4	35.4	- 4.6
	4		0.8	533.3	54.5	36.5	- 3.5
	5		0.7	466.7	53.4	35.4	- 4.6
	6		0.7	466.7	53.4	35.4	- 4.6
G_1S_4	1	"	3.25	2166.7	66.7	48.7	+ 8.7
	2		3.3	2200.0	66.9	48.9	+ 8.9
	3		2.3	1533.3	63.7	45.7	+ 5.7
	4		3.1	2066.7	66.3	48.3	+ 8.3
	5		2.7	1800.0	65.1	47.1	+ 7.1
	6		2.9	1933.3	65.7	47.7	+ 7.7

GS	T	Treatment Combination	AC Volt. mv. V_1	V_1/V_0 Ratio V_0=.0015	SPL	Audiom. TDH-39 (-18.0 dB)	BC/ACΔ dB
G_4S_1	1	2000 cps/50dB	0.6	400.0	52.1	34.1	-15.9
	2		0.65	433.3	52.7	34.7	-15.3
	3		0.75	500.0	54.0	36.0	-14.0
	4		0.75	500.0	54.0	36.0	-14.0
	5		0.8	533.3	52.7	34.7	-15.3
	6		0.7	466.7	53.4	35.4	-14.6
G_4S_2	1	"	0.85	566.7	55.1	37.1	-12.9
	2		0.95	633.3	56.0	38.0	-12.0
	3		0.95	633.3	56.0	38.0	-12.0
	4		0.95	633.3	56.0	38.0	-12.0
	5		0.95	633.3	56.0	38.0	-12.0
	6		1.00	666.7	56.5	38.5	-11.5
G_4S_3	1	"	5.75	3833.3	71.7	53.7	+ 3.7
	2		4.7	3133.3	69.9	51.9	+ 1.9
	3		2.8	1866.7	65.5	47.5	- 2.5
	4		5.0	3333.3	70.5	52.5	+ 2.5
	5		3.4	2266.7	67.1	49.1	- 0.9
	6		3.0	2000.0	66.1	48.1	- 1.9
G_4S_4	1	"	2.8	1866.7	65.4	47.4	- 2.6
	2		3.5	2333.3	67.4	49.4	- 0.6
	3		3.4	2266.7	67.1	49.1	- 0.9
	4		3.0	2000.0	66.1	48.1	- 1.9
	5		2.2	1466.7	63.3	45.3	- 4.7
	6		2.0	1333.3	62.5	44.5	- 5.4

GS	T	Treatment Combination	AC Volt. mv. V_1	V_1/V_0 Ratio V_0=.0010	SPL	Audiom. TDH-39 (-14.3 dB)	BC/ACΔ dB
G_4S_1	1	4000 cps/20dB	0.03	30.0	29.6	15.3	- 4.7
	2		0.03	30.0	29.6	15.3	- 4.7
	3		0.03	30.0	29.6	15.3	- 4.7
	4		0.03	30.0	29.6	15.3	- 4.7
	5		0.03	30.0	29.6	15.3	- 4.7
	6		0.03	30.0	29.6	15.3	- 4.7
G_4S_2	1	"	0.04	40.0	32.1	17.8	- 2.2
	2		0.04	40.0	32.1	17.8	- 2.2
	3		0.04	40.0	32.1	17.8	- 2.2
	4		0.04	40.0	32.1	17.8	- 2.2
	5		0.04	40.0	32.1	17.8	- 2.2
	6		0.04	40.0	32.1	17.8	- 2.2
G_4S_3	1	"	0.2	200.0	46.1	31.8	+11.8
	2		0.15	150.0	43.6	29.3	+ 9.3
	3		0.1	100.0	40.0	25.7	+ 5.7
	4		0.1	100.0	40.0	25.7	+ 5.7
	5		0.1	100.0	40.0	25.7	+ 5.7
	6		0.1	100.0	40.0	25.7	+ 5.7
G_4S_4	1	"	0.1	100.0	40.0	25.7	+ 5.7
	2		0.1	100.0	40.0	25.7	+ 5.7
	3		0.15	150.0	43.6	29.3	+ 9.3
	4		0.1	100.0	40.0	25.7	+ 5.7
	5		0.1	100.0	40.0	25.7	+ 5.7
	6		0.1	100.0	40.0	25.7	+ 5.7

GS	T	Treatment Combination	AC Volt. mv. V_1	V_1/V_0 Ratio V_0=.0010	SPL	Audiom. TDH-39 (-14.3 dB)	BC/ACΔ dB
G_3S_1	1	4000 cps/30dB	0.25	250.0	48.0	33.7	+ 3.7
	2		0.25	250.0	48.0	33.7	+ 3.7
	3		0.3	300.0	49.6	35.3	+ 5.3
	4		0.3	300.0	49.6	35.3	+ 5.3
	5		0.35	350.0	50.9	36.6	+ 6.6
	6		0.4	400.0	52.1	37.8	+ 7.8
G_3S_2	1	"	0.2	200.0	46.1	31.8	+ 1.8
	2		0.12	120.0	41.6	27.3	- 2.7
	3		0.12	120.0	41.6	27.3	- 2.7
	4		0.1	100.0	40.0	25.7	- 4.3
	5		0.12	120.0	41.6	27.3	- 2.7
	6		0.12	120.0	41.6	27.3	- 2.7
G_3S_3	1	"	0.1	100.0	40.0	25.7	- 4.3
	2		0.15	150.0	43.6	29.3	- 0.7
	3		0.15	150.0	43.6	29.3	- 0.7
	4		0.15	150.0	43.6	29.3	- 0.7
	5		0.1	100.0	40.0	25.7	- 4.3
	6		0.1	100.0	40.0	25.7	- 4.3
G_3S_4	1	"	0.35	350.0	50.9	36.6	+ 6.6
	2		1.0	1000.0	60.0	45.7	+15.7
	3		0.65	650.0	56.3	42.0	+12.0
	4		0.85	850.0	58.6	44.3	+14.3
	5		1.1	1100.0	60.9	46.6	+16.6
	6		0.75	750.0	57.5	43.2	+13.2

GS	T	Treatment Combination	AC Volt. mv. V_1	V_1/V_0 Ratio V_0=.0010	SPL	Audiom. TDH-39 (-14.3 dB)	BC/ACΔ dB
G_2S_1	1	4000 cps/40dB	0.2	200.0	46.1	31.8	- 8.2
	2		0.2	200.0	46.1	31.8	- 8.2
	3		0.2	200.0	46.1	31.8	- 8.2
	4		0.25	250.0	48.0	33.7	- 6.3
	5		0.2	200.0	46.1	31.8	- 8.2
	6		0.2	200.0	46.1	31.8	- 8.2
G_2S_2	1	"	0.1	100.0	40.0	25.7	-14.3
	2		0.1	100.0	40.0	25.7	-14.3
	3		0.1	100.0	40.0	25.7	-14.3
	4		0.1	100.0	40.0	25.7	-14.3
	5		0.08	80.0	38.1	23.8	-16.2
	6		1.2	1200.0	61.6	47.3	+ 7.3
G_2S_3	1	"	0.2	200.0	46.1	31.8	- 8.2
	2		0.2	200.0	46.1	31.8	- 8.2
	3		0.2	200.0	46.1	31.8	- 8.2
	4		0.2	200.0	46.1	31.8	- 8.2
	5		0.25	250.0	48.0	33.7	- 6.3
	6		0.3	300.0	49.6	35.3	- 4.7
G_2S_4	1	"	0.35	350.0	50.9	36.6	- 3.4
	2		0.35	350.0	50.9	36.6	- 3.4
	3		0.4	400.0	52.1	37.8	- 2.2
	4		0.45	450.0	53.1	38.8	- 1.2
	5		0.35	350.0	50.9	36.6	- 3.4
	6		0.35	350.0	50.9	36.6	- 3.4

GS	T	Treatment Combination	AC Volt. mv. V_1	V_1/V_0 Ratio V_0=.0010	SPL	Audiom. TDH-39 (-14.3 dB)	BC/ACΔ dB
G_1S_1	1	4000 cps/50dB	0.5	500.0	54.0	39.7	-10.3
	2		0.6	600.0	55.6	41.3	- 8.7
	3		0.7	700.0	57.0	42.7	- 7.3
	4		0.5	500.0	54.0	39.7	-10.3
	5		0.5	500.0	54.0	39.7	-10.3
	6		0.6	600.0	55.6	41.3	- 8.7
G_1S_2	1	"	0.8	800.0	58.1	43.8	- 6.2
	2		0.8	800.0	58.1	43.8	- 6.2
	3		0.8	800.0	58.1	43.8	- 6.2
	4		0.9	900.0	59.1	44.8	- 5.2
	5		1.0	1000.0	60.0	45.7	- 4.3
	6		0.8	800.0	58.1	43.8	- 6.2
G_1S_3	1	"	1.4	1400.0	63.0	48.7	- 1.3
	2		1.4	1400.0	63.0	48.7	- 1.3
	3		0.55	550.0	54.8	40.5	- 9.5
	4		1.2	1200.0	61.6	47.3	- 2.7
	5		0.9	900.0	59.1	44.8	- 5.2
	6		0.8	800.0	58.1	43.8	- 6.2
G_1S_4	1	"	4.1	4100.0	72.3	58.0	+ 8.0
	2		2.0	2000.0	66.1	51.8	+ 1.8
	3		3.6	3600.0	71.2	56.9	+ 6.9
	4		3.5	3500.0	70.9	56.6	+ 6.6
	5		3.6	3600.0	71.2	56.9	+ 6.9
	6		4.0	4000.0	72.1	57.8	+ 7.8

APPENDIX B

PROGRAMMED TREATMENT COMBINATIONS PER SUBJECT AFTER RANDOMIZATION (6 TRIALS AT EACH OF 4 DIFFERENT INTENSITY/ FREQUENCY LEVELS)

	G1S1			G1S2			G1S3			G1S4	
T	Treatment	Combination	T	Treatment	Combination	T	Treatment	Combination	T	Treatment	Combination
1	20 dB -	500 cps	1	20 dB -	500 cps	1	50 dB -	4000 cps	1	50 dB -	4000 cps
2	50	4000	2	30	1000	2	20	500	2	40	2000
3	40	2000	3	50	4000	3	50	4000	3	30	1000
4	30	1000	4	20	500	4	20	500	4	20	500
5	40	2000	5	40	2000	5	20	500	5	20	500
6	50	4000	6	20	500	6	40	2000	6	20	500
7	50	4000	7	50	4000	7	40	2000	7	30	1000
8	20	500	8	30	1000	8	20	500	8	50	4000
9	50	4000	9	20	500	9	50	4000	9	30	1000
10	40	2000	10	40	2000	10	40	2000	10	30	1000
11	40	2000	11	40	2000	11	30	1000	11	40	2000
12	20	500	12	40	2000	12	40	2000	12	30	1000
13	20	500	13	20	500	13	30	1000	13	40	2000
14	50	4000	14	50	4000	14	50	4000	14	50	4000
15	30	1000	15	40	2000	15	40	2000	15	40	2000
16	30	1000	16	50	4000	16	20	500	16	30	1000
17	50	4000	17	30	1000	17	30	1000	17	20	500
18	30	1000	18	30	1000	18	30	1000	18	20	500
19	20	500	19	30	1000	19	20	500	19	50	4000
20	40	2000	20	40	2000	20	50	4000	20	40	2000
21	30	1000	21	30	1000	21	50	4000	21	40	2000
22	30	1000	22	50	4000	22	30	1000	22	20	500
23	40	2000	23	50	4000	23	40	2000	23	50	4000
24	20	500	24	20	500	24	30	1000	24	50	4000

	G2S1			G2S2			G2S3			G2S4	
T	Treatment	Combin-ation	T	Treatment	Combin-ation	T	Treatment	Combin-ation	T	Treatment	Combin-ation
1	40 dB -	4000 cps	1	20 dB -	1000 cps	1	50 dB -	500 cps	1	30 dB -	2000 cps
2	50	500	2	30	2000	2	30	2000	2	30	2000
3	20	1000	3	50	500	3	40	4000	3	50	500
4	30	2000	4	50	500	4	50	500	4	40	4000
5	40	4000	5	20	1000	5	40	4000	5	40	4000
6	50	500	6	20	1000	6	40	4000	6	50	500
7	20	1000	7	30	2000	7	50	500	7	50	500
8	40	4000	8	20	1000	8	50	500	8	40	4000
9	20	1000	9	50	500	9	20	1000	9	30	2000
10	30	2000	10	30	2000	10	20	1000	10	40	4000
11	20	1000	11	50	500	11	30	2000	11	40	4000
12	50	500	12	40	4000	12	40	4000	12	30	2000
13	20	1000	13	30	2000	13	30	2000	13	50	500
14	20	1000	14	40	4000	14	30	2000	14	20	1000
15	50	500	15	40	4000	15	40	4000	15	20	1000
16	40	4000	16	30	2000	16	50	500	16	30	2000
17	50	500	17	30	2000	17	30	2000	17	40	4000
18	30	2000	18	20	1000	18	40	4000	18	50	500
19	30	2000	19	20	1000	19	50	500	19	20	1000
20	50	500	20	50	500	20	20	1000	20	50	500
21	40	4000	21	40	4000	21	20	1000	21	20	1000
22	30	2000	22	50	500	22	20	1000	22	30	2000
23	30	2000	23	40	4000	23	30	2000	23	20	1000
24	40	4000	24	40	4000	24	20	1000	24	20	1000

	G3S1			G3S2			G3S3			S3S4	
T	Treatment	Combin- ation	T	Treatment	Combin- ation	T	Treatment	Combin- ation	T	Treatment	Combin- ation
1	30 dB -	4000 cps	18	20 dB -	2000 cps	1	30 dB -	4000 cps	1	20 dB -	2000 cps
2	20	2000	2	50	1000	2	20	2000	2	40	500
3	50	1000	3	20	2000	3	20	2000	3	50	1000
4	20	2000	4	50	1000	4	50	1000	4	50	1000
5	40	500	5	30	4000	5	20	2000	5	40	500
6	20	2000	6	50	1000	6	30	4000	6	20	2000
7	20	2000	7	40	500	7	50	1000	7	20	2000
8	40	500	8	30	4000	8	30	4000	8	50	1000
9	40	500	9	30	4000	9	20	2000	9	40	500
10	50	1000	10	40	500	10	40	500	10	30	4000
11	40	500	11	20	2000	11	20	2000	11	20	2000
12	20	2000	12	20	2000	12	40	500	12	40	500
13	40	500	13	50	1000	13	30	4000	13	50	1000
14	30	4000	14	40	500	14	50	1000	14	30	4000
15	40	500	15	40	500	15	30	4000	15	30	4000
16	30	4000	16	40	500	16	40	500	16	40	500
17	50	1000	17	50	1000	17	50	1000	17	20	2000
18	50	1000	18	40	500	18	30	4000	18	30	4000
19	20	2000	19	20	2000	19	40	500	19	30	4000
20	30	4000	20	20	2000	20	40	500	20	30	4000
21	30	4000	21	30	4000	21	50	1000	21	40	500
22	50	1000	22	50	1000	22	50	1000	22	50	1000
23	30	4000	23	30	4000	23	20	2000	23	50	1000
24	50	1000	24	30	4000	24	40	500	24	20	2000

	G4S1			G4S2			G4S3			G4S4	
T	Treatment	Combin-ation	T	Treatment	Combin-ation	T	Treatment	Combin-ation	T	Treatment	Combin-ation
1	20 dB -	4000 cps	1	20 dB -	4000 cps	1	50 dB -	2000 cps	1	20 dB -	4000 cps
2	30	500	2	20	4000	2	20	4000	2	30	500
3	20	4000	3	30	500	3	30	500	3	50	2000
4	30	500	4	20	4000	4	40	1000	4	20	4000
5	40	1000	5	40	1000	5	30	500	5	40	1000
6	40	1000	6	50	2000	6	20	4000	6	50	2000
7	20	4000	7	30	500	7	50	2000	7	30	500
8	50	2000	8	40	1000	8	30	500	8	40	1000
9	30	500	9	40	1000	9	30	500	9	40	1000
10	20	4000	10	50	2000	10	50	2000	10	30	500
11	50	2000	11	30	500	11	50	2000	11	50	2000
12	30	500	12	40	1000	12	40	1000	12	30	500
13	50	2000	13	50	2000	13	40	1000	13	40	1000
14	40	1000	14	30	500	14	40	1000	14	40	1000
15	50	2000	15	50	2000	15	50	2000	15	50	2000
16	40	1000	16	50	2000	16	20	4000	16	50	2000
17	40	1000	17	40	1000	17	20	4000	17	20	4000
18	30	500	18	40	1000	18	50	2000	18	50	2000
19	50	2000	19	20	4000	19	40	1000	19	20	4000
20	40	1000	20	20	4000	20	20	4000	20	40	1000
21	20	4000	21	30	500	21	40	1000	21	30	500
22	20	4000	22	50	2000	22	20	4000	22	20	4000
23	50	2000	23	30	500	23	30	500	23	30	500
24	30	500	24	20	4000	24	30	500	24	20	4000