ABSTRACT

AN INVESTIGATION OF THE TRANSMISSION OF RELATIVE SOUND PRESSURES OF PHONATED VOWEL SOUNDS AT SELECTED LOCATIONS OF THE HEAD AND NECK

By

Charles Lonegan

Many investigators have examined the nature of vibration through tissues of the body of a speaker. Research in this area indicated that vibrations were more intense at some anatomical locations than others. There has not been consistent agreement in results of investigations.

The purpose of this investigation was to examine the relative sound pressures of vowel sounds uttered by a speaker as they were transmitted through the tissues of his head and neck. The study was directed at investigating, experimentally, the difference in the transmitted relative sound pressures among twelve vowel sounds picked up at sixteen anatomical locations, employing subjects with three distinctly different body types.

Six adult male speakers were employed. Two subjects were selected to represent each of three different body

physiques: ectomorphs, mesomorphs, and endomorphs. The subjects all utilized the General American English dialect. Twelve vowels were selected for this study. Sixteen anatomical locations were specified as sites to be investigated. These were at various distances from the larynx, representing differences in tissue composition. Sound pressure levels and fundamental frequencies of all utterances were held constant by all speakers, monitored at 12 inches from the mouth.

A helmet and shield which had minimal contact with the surface of the head and neck was designed to secure four accelerometers brought into contact with the anatomical locations.

The accelerometers employed were integrated-circuit-piezoelectric quartz transducers sensitive to subtle vibrations, with an almost linear frequency curve response throughout the speech range. The accelerometers transmitted the vibrations picked up to a tape recorder; simultaneous responses from four anatomical locations were recorded. The four accelerometers were shifted to other positions in the helmet and the procedure repeated until sixteen locations had been recorded.

Relative sound pressures of tissue transmitted vibrations were analyzed by means of a power level recorder; a graphic display of each sample was obtained from which mean relative sound pressures were determined.

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These data were treated by a three factor analysis of variance in which the factors were: vowels, positions, and body types to test for significances. In addition, the resonance characteristics of the helmet and shield and the frequency response curves of the accelerometers attached to the helmet and shield were obtained experimentally.

Conclusions

1. The vowels /i/ and /u/ were transmitted through the tissue of the head and neck with higher relative sound pressures than any other vowels. The vowels /a/ and /æ/ were transmitted through these tissues with lower relative sound pressures than any other vowels.

2. The anatomical positions at the top-center of the skull, the forehead, the neck near the larynx, and the mandible transmitted vowel sounds with higher relative sound pressures than any other locations.

3. On the basis of the relative sound pressures transmitted, the sixteen anatomical locations fell into two basic groups: Group I--locations toward the midline and front of the skull; Group II--sites remote from the larynx.

4. Highest relative sound pressures were transmitted for the vowels /i/ and /u/ at the positions on the top-center of the skull and on the forehead.

5. Differences between results obtained by this experiment and previous studies may be attributed to refinements in instrumentation and procedures employed, as well

as to possible interactions between transmitted signals and resonance characteristics of the supporting system which held the accelerometers.

6. Results suggest that contact microphones are questionable as efficient means of transmitting speech signals. However, further research is needed to determine the interactions of signals with the supporting system and spectral characteristics of transmitted signals through various tissues. Intelligibility of tissue transmitted signals should be also studied in the future.

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CHAPTER I

INTRODUCTION

Speech scientists have long been interested in the characteristics of speech sounds and the contribution of resonation and forced vibration to the overall characteristics of speech. In general, most of the research has been focused upon the measurement of communication systems such as the telephone and the radio.

Speakers often note that certain structures of the body vibrate during speaking and singing. Singing teachers, speech pathologists, and teachers of the deaf have instructed their pupils to use these vibrational sensations as a feedback aid in achieving specific sounds and vocal qualities. This has generally been attempted with little understanding of the nature of the phenomenon of tissue vibration.

Simon and Keller note that many investigators in the last one hundred years became interested in the nature of tissue vibration during speech.[1] This interest stemmed

[1]Clarence T. Simon and Franklin Keller, "An Approach to the Problem of Chest Resonance," _Quarterly Journal of Speech Education_, XIII (1927), p. 433.

from early research into the nature of vocal cord vibration and the resonance characteristics of the cavities of the vocal tract.

Early investigators believed that the vibration of bones and skin surfaces during voice production resulted from resonance factors in the vocal tract. It was generally concluded that vibration of tissue during voice production contributed to the overall quality of the voice. Bones and skin of the thorax, neck, and head were thought to vibrate because the cavities underlying these structures had resonant frequencies similar to the frequency of vibration of the vocal cords.

As refinements in measurement procedures and instrumentation were made, near the turn of the century, investigators began to suspect that tissue vibration during speech was the result of forced virbation and not resonance. These investigators supported the view that the vibration pattern of bone and skin tissue probably added little to the overall quality of the voice. The pattern of tissue vibration of the thorax, neck, and head during voice production appeared to be different in nature from the pattern of vibration of the laryngeal source, thus indicating that tissue near the larynx was forced to vibrate because of its proximity to the original source and not because of similar resonance frequencies.

The present study was designed to investigate further the transmission of the relative sound pressure of vowels through various tissues of the head and neck using more refined procedures and equipment than was available to former researchers.

Purpose of the Study

The purpose of this study was to examine the overall relative sound pressures of vowel sounds produced in the vocal tract as they were transmitted through tissues of the head and neck. The study was directed at investigating, experimentally, the differences in relative overall intensity among twelve vowels recorded at sixteen anatomical locations, employing subjects with three different body types. The sound pressure level and the fundamental frequency of all vocal utterances were kept constant. The following questions were posed for this investigation:

1. Is the relative overall sound pressure transmitted through tissue for each vowel dependent on body type and anatomical location?
2. Is relative overall sound pressure transmitted through tissue for each body type dependent upon the vowel and anatomical location?
3. Is the relative overall sound pressure transmitted through tissue for each anatomical locations dependent on specific vowel and body type?

Importance for the Study

The present study examines the differences among the relative sound pressure of twelve vowels as they are transmitted through sixteen anatomical locations of subjects representing three different body types. This study could provide additional information concerning the use of contact microphones. Indeed, Snidecor notes that in some military, government, and scientific operations, the use of a contact pick up transducer would be more desirable than the conventional type of microphone held in front of the mouth.[1] In aviation, space exploration, and ocean diving, conventional microphones are likely to pick up and transmit not only speech signals but also competing noises such as the hissing of the oxygen supply equipment. The speech signal is often masked out or distorted by this noise. A contact microphone would be sensitive only to tissue vibration and not to competing environmental noises.

A contact microphone would also free the mouth area from obstruction, allowing greater movement of the articulators. In addition, with the mouth no longer blocked by a microphone, observers would be able to read

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[1]John C. Snidecor, Irving Rehman, and David D. Washburn, "Speech Pickup by Contact Microphone at Head and Neck Positions," Journal of Speech and Hearing Research, II (1959), pp. 277-281.

lips as well as to employ sound cues in situations, such as extreme noise, in which both visual and auditory cues would aid communication.

Neely and Forshaw suggested that in diving operations, for example, a contact microphone would be less sensitive to damage by sudden changes in air pressure or shock waves.[1] Also, a contact mircophone would be less likely to damage the mouth, teeth, and other facial structures in the case of sudden shock resulting from falls, crashes, etc.

Moser and Oyer summarized previous investigations which had been conducted concerning the relative intensity of speech sounds transmitted through human tissue.[2] Work in this area has indicated that some anatomical locations of the head and neck are more efficient than others in transmitting speech sounds. However, much of the early work in this area employed contact transducers that were imprecise for speech transmission. In addition, some early procedures employed relied upon subjective evaluation, poor control of application of the transducer to the

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[1]Keith K. Neely and S. E. Forshaw, "Speaking and Listening through the Head: I. The Intelligibility of Speech Recorded in Quiet and at Different Positions of the Head and Throat," Journal of Auditory Research, V (1965), pp. 151-157.

[2]Henry M. Moser and Herbert J. Oyer, "Relative Intensities of Sounds at Various Anatomical Locations of the Head and Neck during Phonation of the Vowels," Journal of the Acoustical Society of America, XXV (1958), pp. 275-278.

surface of the skin, investigation of few anatomical sites, use of one or two subjects without regard for differences in body physique. This has resulted in considerable lack of agreement in results.

Early investigations have indicated that certain refinements in instrumentation and procedures may result in more valid and reliable data. It would appear that a sensitive transducer attached to the proper location could provide an efficient method of transmission of speech sounds from a speaker to a listener.

The present study is an attempt to control the variables indicated above and to obtain data resulting from refinements in instrumentation and procedures previously employed.

Definitions

Certain terms employed in this report are defined in this section for purposes of clarity. Attempt is made to indicate how each of these terms is used in regard to the procedures and instrumentation involved in the present study.

Vowel

The vowels employed in this study are the twelve vowels /i/, /I/, /e/, / /, /a/, / /, /Λ/, / /, /ε/, /o/, /u/, and / / which are found in the General American English dialect. No diphthongs were included.

Transducer

A transducer is a device used to convert the mechanical vibrations of the head and neck into electrical signals. In the present study, the transducer employed was an integrated-circuit-piezoelectric quartz transducer referred to herein as an accelerometer.

Relative Sound Pressure

The sound pressure of a signal determined by its relationship to a calibration tone which has a known sound pressure. The calibration tone is referred to as zero decibels and acts as the reference point for comparison. The reference tone employed in this study was a 1000 Hz pure tone of 10 milivolts. In the present study, relative sound pressure could range from -30.0 dB to +20.0 dB because the graph paper employed for graphic analysis had a grid whose range was 50 dB.

Body Type

Body type refers to classification of the physique of each subject according to the somatotyping system devised by Sheldon.[1] Subjects were classified into the general body types of ectomorph (thin, frail physique),

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[1] W. H. Sheldon, Atlas of Men (New York: Harper and Brothers, 1954). W. H. Sheldon, The Variations of Human Physique (New York: Hafner Publishing Company, 1963).

mesomorph (muscular, solid physique), and endormorph (soft, round physique).

CHAPTER II

REVIEW OF THE LITERATURE

This chapter represents a review of the theoretical and research literature relevant to this investigation. A discussion of early considerations of the concept of "chest resonance" is presented initially. A brief history of the contemporary interest in the transmission of sound through living human tissue is included. The discussion then focuses on recent research into the precise measurement of vocal sound picked up at various anatomical locations of the human body. This review also includes a consideration of refinement in pick up, filter, and amplification equipment that led to the present investigation. The chapter concludes with a summary of the review in terms of the development of the present investigation.

CHEST RESONANCE

During the early part of the twentieth century, voice and speech scientists were interested in the investigation of the concept of "chest resonance." The relationship between this phenomenon and the intelligibility of speech and the quality characteristics of speech was of particular interest.

Throughout the nineteenth century, voice scientists in general had attributed great importance to the contribution of vibration of the walls of the chest to voice quality. It was not until the work of Helmholtz that researchers began to divide into opposing camps regarding the importance as well as the existence of chest resonance.[1] Simon and Keller reported that

> After these many years of bandying terms, the division of opinion is rather sharply marked; writers either accepted chest resonance enthusiastically as a fortunate and much-to-be-desired phenomenon, or else reject it flatly as an anatomical and acoustical impossibility.[2]

<u>Early Support</u>

Many early investigators vigorously supported the existence and importance of chest resonance. In 1909, Curtis supported the view that the chest cavity helped to fortify the original vocal tone and to improve overtone production.[3] Fillebrown, 1911, believed that the largest

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[1] Simon and Keller, ". . .the Problem of Chest Resonance," p. 433.

[2] *Ibid.*, p. 433.

[3] H. H. Curtis, *Voice Training and Tone Placement*, (New York: Appleton Company, 1909), p. 66.

air chamber in the body was the chest which also acted as a principal resonating cavity.[1] In the face of considerable controversy, Scott concluded in 1915 that while chest resonance was difficult to prove scientifically, his own senses of "hearing and feeling" testified to its existence.[2]

Early Opposition

Many investigators argued that chest resonance was nonexistent. Muckey felt that the chest was a closed cavity during voice production and could not act as a resonator.[3] Aiken supported the same notion and stated that only open cavities such as the mouth, nose, and pharynx could act to resonate vocal sound.[4] Woolbert and Weaver in 1922 stated that chest resonance was impossible because the function of the thorax was to provide the breath stream for speech and could not, at the same time, contribute toward vocal sound resonation.[5] Early investigations into chest inhalation lead later researchers to examine the vibration of bones and tissue remote from the chest.

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[1]Thomas Fillebrown, Resonance in Singing and Speaking (Boston: Oliver Diston Company, 1911), pp. 49-50.

[2]John R. Scott, The Technique of the Speaking Voice (Missouri: Stephens Company, 1915), p. 214.

[3]Floyd S. Muckey, Natural Method of Voice Production (New York: Scribner's Sons, 1915), p. 59.

[4]W. A. Aiken, The Voice (London: Longmans, Green, and Company, 1920), p. 36.

[5]M. Woolbert and A. Weaver, Better Speech (New York: Harcourt, Brace, Company, 1922), p. 83.

Early Experimental Studies

In 1927, Simon and Keller conducted the first experiment designed to pick up and record the patterns of vibration of the bones during voice production. The experiment was designed primarily to settle the long-standing controversy concerning chest resonance.

Simon and Keller felt that much of the controversy stemmed from ambiguity and misunderstanding of the term "resonance."[1] Physicists do not mean that resonance occurs only in a cavity or chamber, but in any elastic system such as air or elastic fluid. Resonance requires an elastic system which is tuned to the sound being amplified, whereas forced vibration occurs with a solid mass which has no tuned relationship to the sound being amplified. Simon and Keller suggested that while the chest probably does not act as a resonator, it might be an area of forced vibration.[2]

Simon and Keller used a special carbon button stethoscope which was constructed to be sensitive to vibrations picked up from contact with a surface and not to be sensitive to air-conducted vibrations. The stethoscope was placed against seven anatomical locations

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[1]Simon and Keller, ". . .the Problem of Chest Resonance," pp. 432-439.

[2]*Ibid.*, p. 436.

(right wing of thyroid cartilage, sternum at second rib, medial sections of the left and right seventh ribs, sternum at the sixth rib, medial portion of the clavicle on left and right sides) while the subject intoned the vowel /o/. The sound was electrically converted to light waves which were photographically recorded. These photographs were measured carefully and plotted on graphs. From the graphs the following general conclusions were made. Chest vibration

> consists of forced vibrations, caused by mechanical shaking of the vocal cords; forced vibrations whose frequency corresponds to the frequency of the fundamental of the cord tone, and which are in no way to be considered as indicative of any resonance occurring with the cavity.[1]

In 1931, Wise became concerned with the problem of chest resonance and set out to determine how the thoracic cavity was caused to vibrate during voice production. Preliminary studies were concerned with the conductivity of various forms of body tissue and the routes that sound waves travelled through the body. Wise employed a form of the stethoscope called a phonendoscope which picked up only vibrations of the surface it was placed against. By sounding a tuning fork and placing it at one point of the body (or by having the subject sing vowel sounds) and placing the phonendoscope at another point, it was found

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[1] Ibid., p. 439.

that vibrations were conducted for long distances through the body. All forms of tissue were found to conduct sound but with varying degrees of efficiency.

On the basis of subjective aural judgments, the conductile efficiency of various tissues was ranked-ordered from most efficient to least efficient as follows: (1) bone, (2) tendon, (3) tense muscle, (4) lax muscle, (5) non-muscular tissue.

Wise concluded that sound vibrations reach the thoracic cavity through several diverse paths, the vertebral column being the most significant. Each sound path adds to the total vibration which is given off in the form of measurable sound. The overall pattern of vibration of the chest cavity results from forced vibration and not from resonance.[1]

Lindsley investigated the psychophysical determinants of voice quality. A vibration microphone was employed to pick up signals from the chest. These signals were then amplified, recorded, and superimposed upon the subjects' own air-conducted speech sound, thus adding chest vibration to normal speech. On the basis of subjective judgments of voice quality, it was discovered

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[1]Claud M. Wise, "Chest Resonance," Quarterly Journal of Speech, XVIII (1932), pp. 446-452.

that some voices were improved by the technique. The conclusion reached was that the pattern of thoracic vibration was the result of forced vibration.[1]

Early research in the area of chest resonance and the transmission of sound through the body tissue indicates that the walls of the chest as well as other more remote body structures vibrate during the production of vocal sound. The research cited indicates that the thoracic cavity vibrates as the result of forced vibration rather than resonance.

Transmission of Sound through Body Tissue

Over a period of several decades, Georg von Bekesy conducted many investigations into the conductile efficiency of living body tissue. In 1932, Bekesy noted that the bones of the head vibrate in three different patterns depending upon the frequency of the tone applied to the bone. Below 200 Hz, the skull behaves as a rigid body and is displaced in a direction parallel to that of the vibrating body which initiated the displacement. Various parts of the skull vibrate in simple parallel movements. At 800 Hz, the forehead vibrates in the opposite direction from the back of the skull because of

[1]C. F. Lindsley, "Psychophysical Determinants of Voice Quality," Unpublished Ph.D. Dissertation, University of Southern California, 1934.

the inertia of the back of the skull. The middle of the head becomes compressed, creating a system that resonates at a certain frequency. Thus, the forehead moves forward as the back of the head moves backward, and vice versa. At 1500 Hz, the skull vibrates in sections separated by nodal lines; this vibration pattern is similar to that of a bell.[1]

In 1937 Bekesy investigated the relative amplitude of the surface of the skin during phonation. He concluded that skin throughout the body vibrates as the result of phonation, but amplitude of vibration of the skin decreases as the distance fromt he laryngeal source increases. The displacement amplitude of the skin in the area of the ear, for example, is only one-twentieth of the amplitude recorded near the larynx.[2]

Bekesy felt that it was important to know the magnitude of the vibration of various parts of the head so that an understanding of air-conducted and bone-conducted sound could be applied clinically to cases of partial deafness. He found that it was difficult to measure vibration of bony structures because soft tissue covering them is an inefficient transducer of vibration from the

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[1]Georg von Bekesy and Walter A. Rosenblith, Mechanical Properties of the Ear," in <u>Handbook of Experimental Psychology</u>, ed. by S. S. Stevens (New York: Wiley and Sons, 1963), pp. 1108-1109.

[2]<u>Ibid</u>., p. 1111.

bone to the pick-up device. Investigation revealed that the vibrations of the back of the head were about as large as those of the front of the head at 1800 Hz. It was concluded that 1800 Hz appears to be the resonant frequency of the skull.[1]

Bekesy determined that it was possible to measure the amplitude of vibration of different parts of the body. He employed a vibration pick-up device whose output was proportional to acceleration and which registered vibration only of the surface against which it is placed.[2] Bekesy concluded that laryngeal sound produced vertical vibrations and rotation of the bones of the skull.

> . . . the vibration component of the skull is caused not only by vertical vibration of the edges of the vocal cords, but also by sound pressure in the mouth. This sound pressure does not produce a lateral symmetry of the head, but it produces vertical vibrations of the lower jaw and skull.[3]

In 1967 Bekesy indicated that loss of vibrational amplitude of the skin may result from the skin being composed of several soft, fatty layers, whose structure varies from individual to individual and which vary at different anatomical locations. Because of tissue

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[1] Georg von Bekesy, "Vibration of the Head in a Sound Field and its Role in Bone Conduction," Journal of the Acoustical Society of America, XX (1948), pp. 749-760.

[2] Georg von Bekesy, "The Structure of the Middle Ear and the Hearing in One's Own Voice by Bone Conduction," Journal of the Acoustical Society of America, XXI (1949), pp. 217-232.

[3] Ibid., p. 221.

composition, vibration of the skin occurs in complex and irregular patterns.[1]

Mullendore[2] reported relative amplitudes of vibration of three vowels at ten locations of the body for five male subjects with similar physiques. He employed a contact microphone which was held by hand against the selected locations by the subjects. The signal was picked up, converted into electrical impulses, and recorded on magnetic tape. Tape loops for each vowel were analyzed by a frequency analyzer for relative intensity levels. The vowels employed were /i/, /a/, and /u/. In addition to these, the six vowels /o/, /I/, / /, / /, / /, and / / were used to investigate the spectrum characteristics of vowel sounds picked up at various locations of the human body.

Analysis of 440 vowel samples revealed differences of relative intensity (amplitude) of vibration among the ten anatomical locations. Mullendore rank-ordered the locations from greatest amplitude to least amplitude of vibration as follows: (1) thyroid cartilage, (2) mandible, (3) nose, (4) top of skull, (5) clavicle, (6) vertebrae,

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[1]Georg von Bekesy, Sensory Inhibition (New Jersey: Princeton University Press, 1967), p. 119.

[2]James M. Mullendore, "An Experimental Study of the Vibrations of the Bone of the Head and Chest During Sustained Vowel Sounds," Speech Monographs, XVI (1949), pp. 163-176.

(7) sternum--superior end, (8) sternum--inferior end, (9) mastoid, (10) fifth rib.

Mullendore summarized by stating that

> . . . measurable variations in intensity of the framework vibration were present among the various locations studied for all subjects, with the head vibration more intense than the thoracic . . . there was a significant variation in the absolute intensity of the bone-conducted sound even though the air-conducted sound intensity was held constant for all . . .[1]

The following overall conclusions were reached regarding the spectral characteristics of the eight vowels employed when picked up at each location: (1) all points tested vibrated during production of vowel sounds, (2) the nature of vibration was complex enough to provide a reasonable basis for discrimination of the various vowels, (3) the pattern of vibration varied from location to location, (4) the wave composition differences in bone-conducted sound varied considerably from those of air-conducted sound. Bone-conducted sound has less total energy.[2]

Moser and Oyer investigated the relative intensities of twelve sustained vowels at sixteen locations ranging from the larynx to the top of the skull.[3] The investigators used three male speakers selected to represent

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[1] _Ibid_., p. 174.

[2] _Ibid_., p. 172.

[3] Moser and Oyer, "Relative Intensities of Sounds . . .," pp. 275-278.

three distinct body types: heavy, medium, and thin build. It was assumed that differences in body types would influence relative intensity measurements. The subjects hand-held a bone oscillator while producing the vowels /i/, /I/, /e/, / /, /ε/, /a/, / /, /ʌ/, / /, /o/, / /, and /u/.

The signals were recorded on magnetic tape and later analyzed by a power level recorder for overall relative intensity. The investigators concluded that the head and neck could be mapped into four distinct regions according to relative intensity of vowel sounds. The regions are presented in order from most intensive to least intensive:

Region I. Neck--left, right; angle of mandible--left, right; larynx.

Region II. On and below occipital protuberance; nasalis; center of mandible.

Region III. Top center of skull.

Region IV. Sphenoid--left, right; temporal--left, right; frontal bone; above occipital protuberance.

The general conclusion was reached that

> . . . except for the region at the top and center of the head, the relative intensity of tissue-conducted sound produced by the vocal mechanism is decreased as distance from the larynx is increased, . . .[1]

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[1] Ibid., p. 277.

Snidecor, Rehman, and Washburn[1] investigated the use of a pick-up microphone at various anatomical sites to determine the relative power of the vowels /i/, /ε/, / /, and /u/. At each location, five recordings were made of each of the five vowels. Results indicated the following rank ordering of locations from greatest to least relative intensity level: (1) larynx, (2) mandible, (3) chin, (4) nose, (5) mastoid, (6) forehead, (7) ear canal, and (8) zygoma.

These results correlated closely with the findings of Moser and Oyer. On the basis of power, judged intelligibility, and listener preference, the forehead, mastoid, and larynx appear to be the most suitable pick-up positions for situations involving no-lip or free-field microphone use.

Using a sound-treated box to protect the ears from air-conducted sound and by loading the ear drum with metal, Kirikae, Sato, Oshima, and Hirose[2] found that bone-conducted sound contributes to a subject's hearing his own voice with different levels of loudness for different vowels. Air-conduction feedback of one's own voice appears to play an important part in hearing the vowels

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[1] Snidecor, Rehman, and Washburn, "Speech Pickup . . .," pp. 277-281.

[2] I. Kirikae, T. Sato, H. Oshima, and H. Hirose, "An Experimental Study of Hearing One's Own Voice," Practica Oto-Rhino-Laryngologica, XXIII (1961), pp. 56-71.

/a/ and /e/, whereas the bone-conduction element is most important in hearing the vowels /i/, /u/, and /o/. This would indicate that the bones and tissue of the head vary in conductile efficiency of vowel sounds according to variation in frequency distribution or formant components of each of the vowels.

Neely and Forshaw investigated the intelligibility of bone-conducted speech picked up in quiet by transducers at six locations of the head and neck, including the frontal bone, the top and center of the skull, above and below the external occipital protuberance, the temporal bone, and the side of the neck. Four trained male speakers hand-held the pick-up transducer against the selected locations while reading twenty-four multiple-choice intelligibility lists. Four different types of transducers were used for each speaker at each location for all lists. The lists were tape-recorded and judged by sixteen listeners for speech intelligibility. Speech signals were judged to be most intelligible from on the forehead; speech recorded at the back of the head ranked second in intelligibility.[1]

A similar study investigated the intelligibility of bone-conducted speech picked up in white and pink noise

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[1]Neely and Forshaw, "Speaking and Listening through the Head: I . . . ," pp. 151-157.

of 120 dB SPL by transducers placed on the upper lip and on the throat near the larynx. Strong, Chant, Forshaw, and Neely[1] found that listeners rated speech recorded on the lip to be significantly more stable and intelligible than that recorded on the throat. Different pressures of application of the transducer was found to have no influence on judged speech intelligibility.

Development of Instrumentation

Research between 1900 and 1925 into the transmission of vibrations through the human body tissue relied heavily upon the tactile sense and subjective judgment of the investigator to determine the nature and location of tissue vibration.

Simon and Keller[2] attempted the first instrumental experiment in this area. They employed a carbon-button stethoscope which was sensitive to tissue-transmitted vibration but not to air-transmitted vibration. The investigators were able to convert the original sound waves into light waves. These in turn were recorded on photographic film and measurements of the vibrations were made from this source.

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[1]R. A. Stong, V. G. Chant, S. E. Forshaw, and Keith Neely, "Speaking and Listening through the Head: III. The Intelligibility of Speech Recorded in Noise," Journal of Auditory Research, VI (1966), pp. 385-391.

[2]Simon and Keller, ". . . the Problem of Chest Resonance," pp. 432-439.

The investigation of Wise[1] marked an advance in instrumentation design. A stethoscope which permitted vibration to be picked up and recorded electrically was employed. This permitted more accurate and more sensitive collection of data.

Research in this area between 1934 and 1966 employed a variety of contact crystal microphones or refinements of bone conductor oscillators driven in reverse to obtain the tissue-transmitted vibration signal. As refinements in these varieties of instruments were made, data which were more accurate were reported. All of these instruments were incapable of transmitting all of the complex components of the patterns of vibration picked up from the skin. A certain amount of information was lost because of limitations in the sensitivity of the pick-up device.

In 1969, the Piezotronics Company developed a quartz transducer (accelerometer) with an integrated circuit designed for dynamic pressure measurements of pulsations and vibration environments. The accelerometer is a high frequency response, dynamic pressure, measuring instrument. An amplifier mounted inside the transducer converts the high impedance output from the crystals into

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[1]Wise, "Chest Resonance," pp. 446-452.

a low impedance system of less than one-hundred ohms. The instrument is sensitive to extremely small pressure changes. The accelerometer is powered by a compact eighteen volt, battery pack which provides a constant two milliampere current with low system noise.[1]

The accelerometer and battery power unit provide for extremely sensitive pick-up and transmission of pressure changes due to vibration. The unit can be connected directly to an oscilloscope, sound level meter, or recorder. The advantages of compact size, sensitivity, and accuracy resulted in the selection of this system for use in the present investigation.

Summary

This review has indicated that in the last one-hundred years a considerable amount of investigation has been conducted into the transmission of sound through the tissues of the human body. Early researchers in voice science and music believed that the chest acted as a resonating chamber and contributed to the overall quality and tone characteristics of the human voice during speaking and singing. The concept of chest resonance was derived from empirical observation of the vibration of the thorax during phonation.

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[1] "ICP Transducer Data and Information Manual," (New York: PCB Piezotronics Incorporated, 1969).

During the late nineteenth century at about the time of the work of Helmholtz into resonation, opinion began to differ concerning the importance of, and even the existence of, chest resonance. Some investigators believed that chest resonance was a real and measurable phenomenon which contributed noticeably to voice characteristics. Others believed that the chest was incapable of acting as a resonating chamber and that vibration felt during phonation was the result of forced vibration and not resonation.

Early experimental research relied on one or another form of the stethoscope which was held against the skeletal framework and transmitted sound to a listener's ear or to a photographic or sound recording device. Measurements were roughly quantitative but based mostly on listener judgments.

Refinement in instrumentation resulted in the development of bone conduction transducers, magnetic tape recorders, and equipment for spectral and power analysis of sound waves. Measurements of sound transmitted through tissue became less subjective.

The research in this area over several decades has consistently indicated that vibration of the thorax during phonation is primarily the result of forced vibration. In general, it has been concluded that vibration of the bones and tissue of the head and neck during phonation is primarily the result of forced vibration, with some resonation from the mouth and nasal cavities contributing to the overall pattern of vibration to a lesser extent. Table 1 presents an outline and summary of early experimental investigations into tissue-transmitted sound.

Researchers since the early days of Bekesy's research have, in general, found that amplitude or intensity of the vibration of tissues of the head and neck during phonation decreases in proportion to the remoteness of the structure from the sound source. Some research, however, has indicated that the top and back of the skull vibrates with greater intensity than some other structures closer to the larynx. Table 2 presents an outline and summary of more recent research into relative intensity of vibration of the skin during speech production.

Differences in recent research findings may result from the following:

1. Lack of control for differences in body physique, *i.e.*, height, weight, fatty tissue composition.
2. Differences in stimulus materials employed, *i.e.*, singing versus speaking; vowels versus connected discourse.

TABLE 1.--Outline and summary of early research in tissue-transmitted sound.

	Simon-Keller (1927)	Wise (1931)	Bekesy (1932-1967)
Pick up Transducer	carbon-button stethescope	phonendoscope	bone conduction oscillators
Speech Signal	/o/	singing vowels tuning fork	vowels and connected discourse
Subjects	1 trained male speaker	1 trained male singer	1 trained male speaker
Conclusions	chest vibrates as result of forced vibration which correspond to frequency of vocal cord vibration	all tissues conduct sound but with varying efficiency; chest vibrates as result of forced vibration	head vibrates in 3 patterns; smaller amplitude of vibration of skin as distance from larynx increases; resonant frequency of head 1800 Hz; bones vibrate vertically and also rotate; under-lying fatty tissue determines manner of vibration of skin.

3. Failure to secure the placement of pick-up transducer against skin to assure that data collected fo not contain noise and distortion created by movement of the transducer.
4. Use of instrumentation that lacked sensitivity to complex and subtle patterns of tissue vibration.

TABLE 2.--Comparison of results of pertinent studies which investigated relative amplitude of vibration of skin during speech production.

Summary	Mullendore (1949)	Moser-Oyer (1958)	Snidecor (1959)
Subjects	5 males - similar physiques	3 males - 3 different physiques	1 male
Transducer	contact crystal microphone; hand held	bone oscillator; hand held	3 different bone oscillators; hand held
Speech Signal	/i/ /a/ /u/	/i/ /a/ /u/ /I/ /ʌ/ / / /e/ / / /o/ /ɛ/ / / / /	/i/ /u/ /ɛ/ / /
Locations-Ranked Most to Least Amplitude of Vibration	thyroid cartilage mandible nose top of skull clavicle vertebrae sternum-superior sternum-inferior mastoid 5th rib	neck, left-right mandible, l.r. larynx near occipital protuberance top skull sphenoid, l.r. temporal, l.r.	larynx mandible chin nose mastoid forehead ear canal zygoma
Conclusions	much variation in tissue conducted sound wave composition	less amplitude of vibration farther away from source	forehead, mastoid larynx best pick up sites

TABLE 2.--Continued.

Summary	Kirikae (1961)	Neely (1965)	Stong (1966)
Subjects	1 male	4 males	2 males
Transducer	not given	2 bone oscillator 1 contact mic. 1 noise cancelling mic.	4 different contact mic.
Speech Signal	/i/ /a/ /u/ /e/ /o/	24 multiple choice intell. lists in quiet	10 multiple choice intell. lists in white noise
Locations-Ranked Most to Least Amplitude of Vibration	not given - - - - vowels differ in levels of loudness they transmit tissues of head vary in conductile efficiency	forehead back of head center skull occipital protuberence throat ear canal	upper lip larynx (3 different pressures of application)
Conclusions		speech most intelligible at forehead	speech most intelligible at upper lip. different pressures of application had no effect.

CHAPTER III

EXPERIMENTAL PROCEDURES

This chapter includes a description of the subjects participating in this study and the recorded samples of the twelve vowel sounds at the sixteen anatomical locations of the head and neck. The chapter also describes the design and construction of the experimental helmet and shield as well as a discussion of the equipment employed to record and analyze the data. Procedures employed to obtain the data and instructions given to the subjects are described. The method of analysis of the recorded samples is also presented.

Subjects

The subjects were six male graduate students ranging in age from 23 years 0 months to 35 years 0 months. Subjects were selected from the Department of Audiology and Speech Sciences at Michigan State University and had a mean age of 27 years 8 months. During their undergraduate careers, all subjects had taken a course in the understanding and use of the International Phonetic Alphabet. They were able to transcribe spoken language into written phonetic symbols as well as being able to produce speech sounds when presented with written phonetic cues. All subjects used the General English American Dialect of speech.

To account for differences in the conductibility of sound through the bones and skin of individuals with different body characteristics, the general body morphology classification system devised by W. H. Sheldon was employed in the selection of subjects.[1]

For the purposes of the present study, the broad categories of endomorph, mesomorph, and ectomorph were used for the selection of subjects. The specific techniques and measurements devised by Sheldon to determine body classification were not used in this study; however they are discussed in Appendix A. Two subjects were selected to represent each of the three body classifications. Body classification, for this study, was based upon the dimensions of height in inches and weight in pounds, as well as on over-all suitablity to one particular category according to the descriptive terms (solid, fragile, square) provided by Sheldon and discussed previously in this section.

1

Appendix B presents the pertinent descriptive data relative to each of the subjects employed in this study as well as the body classification for each. Appendix C presents the mean age, height, and weight for each body classification.

Equipment and Materials

The equipment and materials reported below were used in the various phases of this experiment to be described in the following sections of this chapter.

Equipment

Tape Recorders: Speed 7½ inches/second

(Ampex, Model AG 500-2)
(Ampex, Model AG 600-2)
(Scotch Brand Magnetic Tape 201)

Microphone:

(Bruel-Kjaer, Model 4145)

Sound Level Meter:

(Bruel-Kjaer, Model 2203)

Power Source:

(ICP Piezotronics Battery Power Unit 480A)
(Bruel-Kjaer, Model 2805)

Accelerometers (four):

(ICP Piezotronics Quartz Transducers, Model 111A21)

Filters:

(ICP Piezotronics special 6000 Hz Low Pass Filter)

Oscillator:

(Hewlett-Packard, Model 4204 A)

Power Level Recorder:

(Bruel-Kjaer, Model 2305)
(Bruel-Kjaer, Paper QP 1102)

Impedance Head:

(Bruel-Kjaer, Model 8801)

Helmet:

(Astro-Cell Helmet, Model RAC-H2)

Shaker:

(Bruel-Kjaer, Model 4801)

Preamplifier:

(Bruel-Kjaer, Model 2625)

Amplifier:

(Bruel-Kjaer, Model 2107)
(Bruel-Kjaer, Model 2603)

Generator:

(Bruel-Kjaer, Model 1024)

Phonetic Material

Twelve American English Vowels

Frequency Response Curves of the Transmission Instrumentation

The frequency response curves of the Ampex Tape recorders were found to be reasonably linear and flat for both recording and reproduction. These curves are presented in Appendix D.

The relationship between pressure inputs of different intensities and the output measured in millimeters was shown to be linear by the manufacturer. Some response curves of the accelerometers to variable frequencies of constant r.m.s. accelerations was determined experimentally. Results indicated nonlinear responses throughout the speech range. Four of the obtained curves are presented in Appendix E.

Construction of Helmet and Shield

A standard football helmet was modified to provide a stable means of attaching the four accelerometers to the sixteen sites on the head and neck for each subject. The inner, foam rubber padding of the helmet was removed leaving the fiberglass shell. Four solid brass rods which were one-eighth inch in diameter and six inches long were threaded on the outside and inserted through threaded holes in the helmet shell. This provided four legs which rested on the skull. The legs provided a stable means of resting the helmet on the head with minimum contact to the head by anything other than the accelerometers. Thus the helmet itself did nto touch the head at any point but was suspended above the head. Foam rubber tips were placed on each leg for comfort. The legs could be adjusted to raise or lower the helmet to account for individual differences in head size.

Twelve of the sixteen anatomical sites to be investigated were on the head and could be reached through the helmet. Provision had to be made so that four accelerometers at one time could be attached through the helmet to the surface of the skull. Eight holes, each one inch in diameter, were drilled through the helmet at various locations which corresponded to the cranial anatomical sites to be studied. By turning the front of the helmet to the back of the head, thus repositioning the relationship of the holes to the anatomical sites, several holes could be used to pinpoint more than one anatomical site.

Aluminum tubing with a three-quarter inch overall diameter and a one-quarter inch core was threaded on the outside and on the inside and cut into four, eight inch lengths. Each of these tubes could be attached through a hole in the helmet by means of nuts and washers. The accelerometers were threaded into the inner core of each tube and the tubes adjusted so that the accelerometer touched the surface of the skull at the precise point required. In this manner, four accelerometers could be attached to the helmet at one time.

Because of the method of fixing the accelerometers to the helmet, it was found impossible to measure the pressure of application of the transducers against theskin.

For this reason, it was decided that the accelerometers would be positioned so that solid contact against the anatomical location was made. No mechanical measurement of the pressure of contact by the transducers to the skin was attempted. The original holes in the helmet were one inch in diameter and the aluminum tubes were three-quarters of an inch in diameter. This provided additional room to move the tubes containing the accelerometers. This margin for adjustment plus the ability to adjust the position of the helmet on the head by means of four legs proved to be sufficient to allow the use of one helmet to collect the data for all six subjects.

The four remaining anatomical sites were located on the mandible and neck. These regions could not be reached easily with the use of the helmet. Therefore a plexiglass shield molded to fit around the neck in a fashion similar to a neck brace was constructed and fitted to the helmet. Four holes, each one inch in diameter, were drilled in the plexiglass to provide attachments for the remaining anatomical sites. The accelerometers were attached to the shield in the same manner as they were attached to the helmet. Figure 1 presents a photograph of the experimental helmet and shield and together comprised the supporting system.

FIGURE 1.--Photograph of helmet and shield with accelerometers in position.

Frequency Responses of Accelerometers Attached to Helmet

The transmitting instrumentation (tape recorders and accelerometers) were found to have reasonably flat frequency response curves; however it was decided to investigate experimentally the response curve of the accelerometers when attached to the helmet. It was found that the helmet itself present relative peak resonances up to 20 dB at 80 Hz and at 120 Hz following the transverse and posterior-anterior axis. These resonances were found by shaking the helmet with input of constant r.m.s. acceleration and different frequencies in several points of the helmet and recording the output from opposite directions through a linear read-out system.

The responses of the accelerometer to inputs of different frequencies and constant r.m.s. acceleration were also obtained. These measurements were performed by shaking the base of the accelerometers, which were mounted in the helmet, with a shaker yielding a constant r.m.s. acceleration of a variable frequency, and recording the electrical output of the accelerometers. A block diagram of the system used for the measurement is presented in Figure 2.

The results of these measurements are presented in Table 3. It will be seen that significant resonances occurred in the speech frequency range. Thus, the response of the accelerometers was no longer linear when they were attached to the helmet.

TABLE 3.--Resonance responses of accelerometers attached to helmet.

Input in Tenths of r.m.s. acceleration (g)	Peak Output Response in Relative Decibels of Sound Pressure Level	Frequency of Peak Output Response
0.1 g	9 dB	850 Hz
0.3 g	13 dB	380 Hz
	15 dB	900 Hz
0.5 g	13 dB	380 Hz
	16 dB	850 Hz

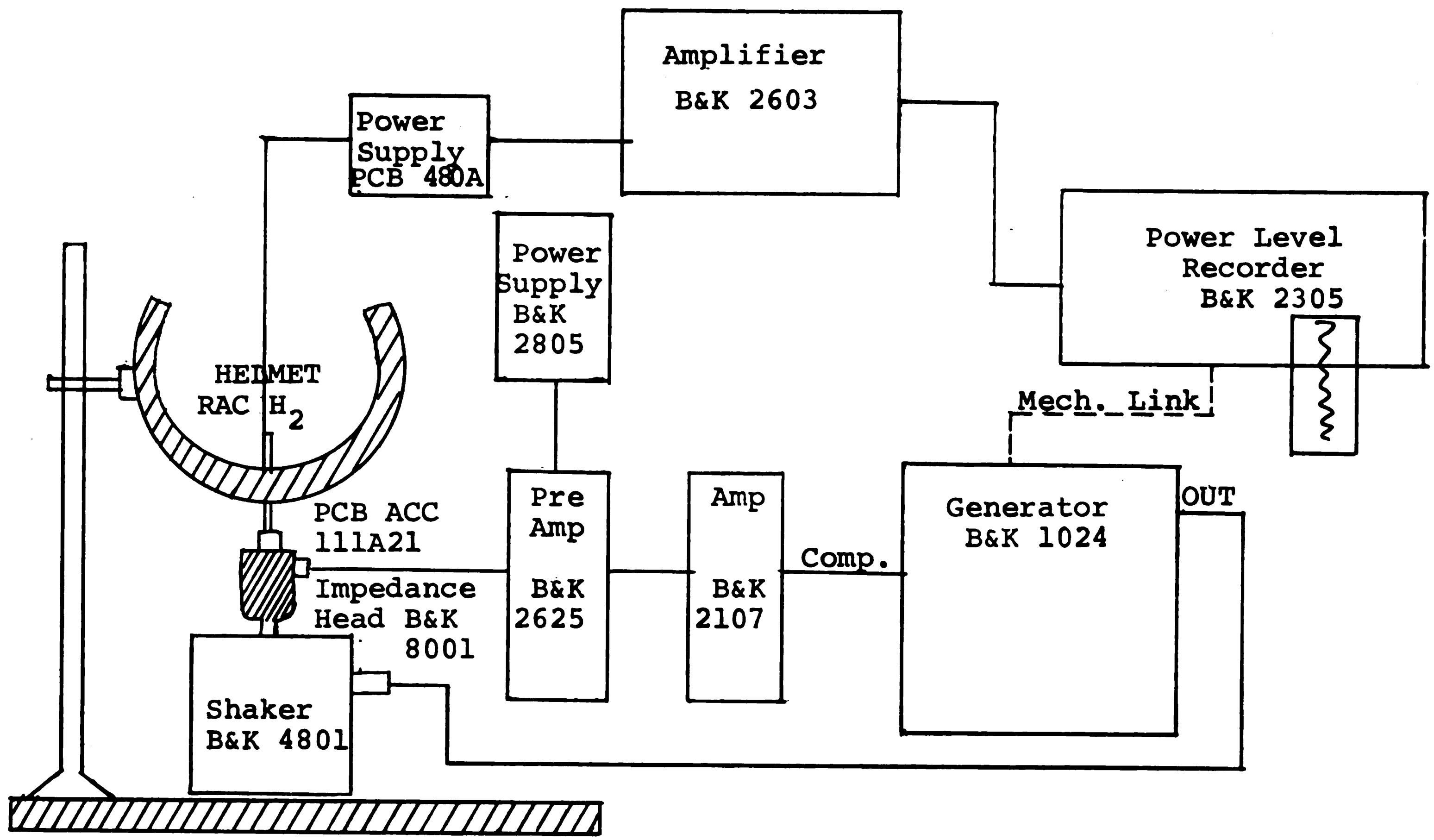

Figure 2.--Block diagram of system used to test response of accelerometers.

Vowel Sounds and Anatomical Locations

The twelve vowel sounds selected to be recorded and later analyzed for the investigation were: /i/, /I/, /e/, /ɛ/, / /, /a/, / /, /ʌ/, / /, /O/, /u/, / /. These sounds are the same as those used in the Moser and Oyer study.[1]

The sixteen anatomical locations (also duplicates of those used by Moser and Oyer) examined in this study are listed in Table 4 and are coded according to the order in which each of the locations was recorded for the six subjects. This order was determined primarily by the limitations imposed by the predrilled holes in the fiberglass helmet and shield. Figure 3 presents an illustration of the sixteen anatomical locations.

Recording of Experimental Data

The data were collected in a sound treated room (IAC 1400 Series). Six adult male speakers acted as subjects. At a later time, all subjects were re-recorded so that measurements of reliability could be made. The sound pressure level and the fundamental frequency of all vocalized utterances were kept constant by all speakers. At a later time, all subjects were re-recorded so that measurements of reliability could be made.

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[1]Moser and Oyer, "Relative Intensities of Sounds . . . ," pp. 275-278.

TABLE 4.--Anatomical locations examined.

Code	Location
A 1	One inch below occipital protuberance
A 2	Two inches above occipital protuberance
A 3	Frontal bone, one inch above nasalis
A 4	Coronal suture, on top and center of skull
B 1	Nasalis bone
B 2	External occipital protuberance
B 3	Left wing sphenoid
B 4	Right wing sphenoid
C 1	Lower border, left ramus of mandible
C 2	Lower border, right ramus of mandible
C 3	Right temporal, one inch above auditory meatus
C 4	Left temporal, one inch above auditory meatus
D 1	Mental protuberance of mandible
D 2	Below notch of thyroid cartilage
D 3	Left side neck, on plane with larynx
D 4	Right side neck, on plane with larynx

Practice

Each subject practiced sustaining each vowel for a minimum of five seconds at a constant level of 76 dB which he monitored visually on scale C of the sound level meter. Subjects sat with their lips approximately twelve inches from a table-mounted microphone connected to the sound level meter. Each subject practiced maintaining a constant fundamental pitch for all utterances of all vowels investigated. Only after each subject was able to sustain the same fundamental pitch at a constant sound pressure level of 76 dB, were the data collected.

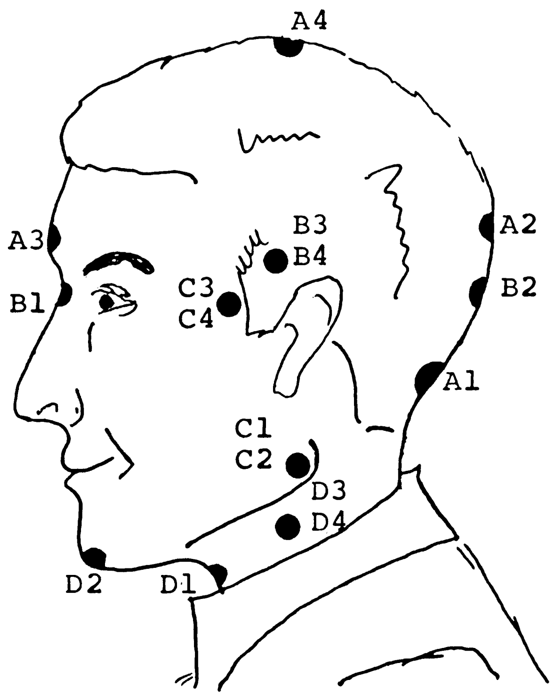

Figure 3.--Schematic representation of anatomical locations.

Equipment

The modified helmet was placed on the head of each subject so that the four adjustable legs touched the skull but the surface of the helmet did not. The legs were adjusted so that the helmet rested confortably and securely on the head and so that the first four anatomical sites were located under the appropriate holes. The helmet was repositioned so that the holes necessary for the second and third sets of cranial recordings could be made. For the fourth set of recordings, the plexiglass shield was attached to the helmet and the four holes it contained were aligned over the required anatomical locations.

Four integrated-circuit-piezoelectric quartz transducers were used to pick up tissue vibration during voice production. These transducers were designed to obtain dynamic measurements of vibration environments, and they contained a tiny integrated circuit amplifier which converts a high impedance from the quartz crystals into a low impedance signal. Each accelerometer was attached to its own battery-supplied electrical source and to one of four available tape recorder channels. Attached to the output of each accelerometer system prior to the tape recorder input was a specially designed 6000 Hz low pass filter that prevented passage of high frequency noise in the system. A complete description of the transducers was presented earlier in this report.

Procedures

The four accelerometers were affixed to the helmet (or shield) until recordings were obtained from each of the sixteen locations. The accelerometers were placed with sufficient pressure to depress the surface of the skin slightly at each location. Each time the subject uttered the vowel sounds, the signals received by each of the four accelerometers were picked up and fed to the four channels of two tape recorders. Recordings of vibrations at four locations were made simultaneously. The positions of the four accelerometers were changed four times until sixteen anatomical locations had been recorded. Figure 4 presents a block diagram of the equipment employed in recording the data.

Prior to recording, a 1000 Hz pure tone was fed into each channel at a level of 100 milivolts. Input gain was set to read -10 on each VU meter. Thus a constant gain setting was established. This same tone acted as the reference tone for the determination of relative intensity for each recorded signal.

Each subject was read the following instructions prior to recording the data:

> There will be four recording periods, each separated by a rest period. These procedures will be followed during each recording period. When you are signalled to do so, intone the vowel sound which you will see printed on a card placed in front of you. You are to sustain the vowel for five seconds and you will be signalled when five seconds have elapsed.

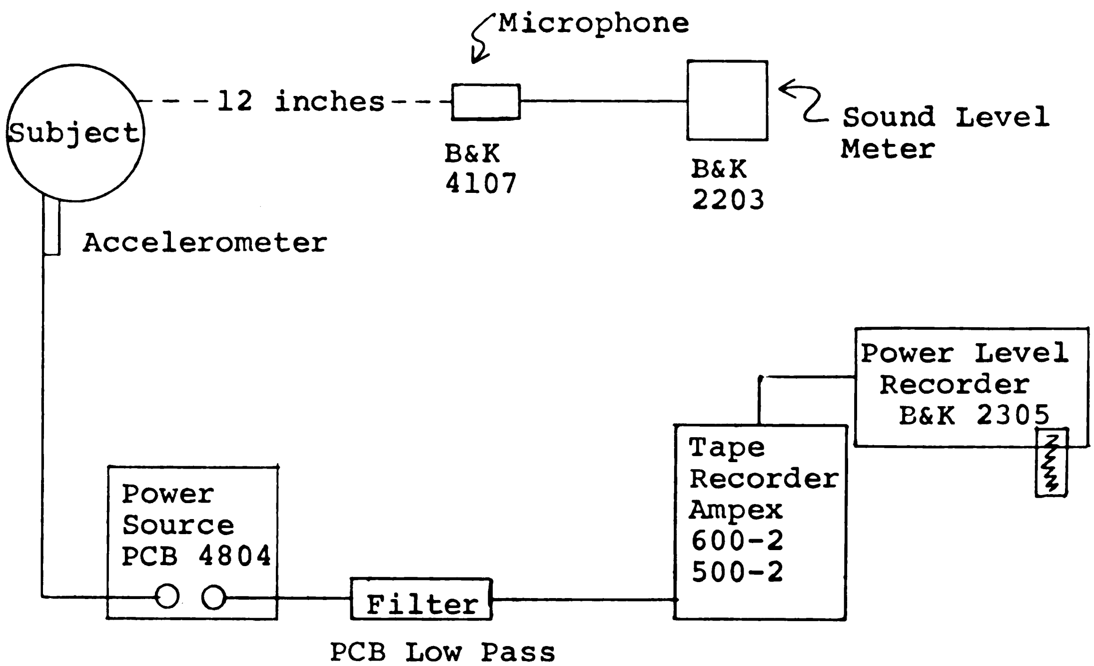

Figure 4.--Block diagram of accelerometer and recorder equipment.

> Please attempt to keep the level of your voice at the point indicated by the sound level meter in front of you (76 dB). Also try to maintain the same fundamental pitch for each utterance. There will be a five second pause after which you will be presented with a new vowel sound to be produced in the same manner. This procedure will be continued until twelve vowels have been recorded from sixteen different points on the head and neck. Are there any questions?

Table 5 presents the fundamental frequencies of the six subjects. It can be seen that none of the fundamental frequencies differs significantly from the mean of 130.8 Hz.

TABLE 5.--Fundamental frequency for each subject.

Subject		Fundamental Frequency
S 1		130 Hz
S 2		135 Hz
S 3		130 Hz
S 4		125 Hz
S 5		135 Hz
S 6		130 Hz
	Mean Fundamental Frequency	130.8 Hz

Analysis of Experimental Data

Magnetic tape recordings were made of each of the vowel samples obtained in the manner described in the previous section. Twelve vowels for six subjects at sixteen anatomical locations were recorded for a total of

1152 vowel samples. Each vowel signal was fed into the power level recorder directly from the magnetic tape. The power level recorder plotted a graphic display of relative sound pressure level for each vowel on the graph paper type QP 1102. The grid on this paper consists of fifty parallel lines. The space between each line represents one decibel of pressure so that a range of fifty decibels can be plotted.

Prior to recording the signals on magnetic tape, a 1000 Hz pure tone was recorded on each channel at a level of 100 millivolts at a constant gain setting. This tone was fed into the power level recorder directly from the magnetic tape. The tracing pen of the power level recorder was set to rest on the thirtieth line of the graph paper when the reference tone was fed into it. The thirtieth line of the graph paper was then considered to be zero decibels and became the reference point for future graphic tracings.

All the 1152 vowel signals were plotted on the graph paper. Each sound pressure graph was identified according to subject, vowel, and recording site. Each vowel was represented graphically as a series of peaks and valleys which represented changes in relative pressure of the signal transmitted.

An average relative sound pressure score in decibels was obtained for each of the 1152 vowel graphs. For each sample, the relative sound pressure level of each peak was determined, and an arithmetic mean of the relative sound pressures of all peaks for the sample was taken. These mean relative sound pressures became the data to be analyzed statistically for the investigation.

CHAPTER IV

RESULTS AND DISCUSSION

There were three independent variables of interest in the present study. These included body type, vowel, and anatomical recording site. The dependent variable under consideration in the experiment was relative sound pressure transmitted through tissue.

The raw original and retest scores for all subjects and vowels are found in Appendix G. The original scores for all subjects and vowels were averaged according to body type; these data can be found in Appendix H. Appendix I contains the mean scores for all subjects and each vowel, regardless of body type. Examination of these data provided descriptive information relevant to the goals of the study.

In addition, statistical tests were performed to examine the significance of these data. The results of these tests are included in Tables 6 through 11. A discussion of the statistical tests employed in this study is included in Appendix F.

Descriptive Analysis of Results

Observation of the data yielded by this study suggested that the vowel sounds /i/ and /u/ are transmitted through tissue with the greatest relative sound pressure through all locations in all body type groups of subjects. The vowels /æ/ and /a/ are transmitted with the least relative sound pressure. The different spectral characteristics of each vowel as well as the resonance characteristics of the body structures the helmet and accelerometers may have been responsible for these differences encountered in the overall sound pressure transmitted through tissue by each vowel.

Of major interest was the interaction of body type and vowel, body type and location, vowel and location, and body type-vowel-location in the relative sound pressure transmitted through tissue.

The mean relative sound pressures for each vowel used in this study, regardless of position, were plotted for the three subject groups of ectomorphs, mesomorphs, and endomorphs as well as for all subjects combined. These plots are presented in Figure 5. Vowels have been ranked in descending order according to mean relative transmitted sound pressure.

Examination of Figure 5 reveals that the mean scores from each vowel for ectomorphs and endomorphs were very close. The mesomorph subjects, show mean relative sound pressure scores which are consistently below the score for either of the other groups, although the analysis of variance test indicated that there was no significant

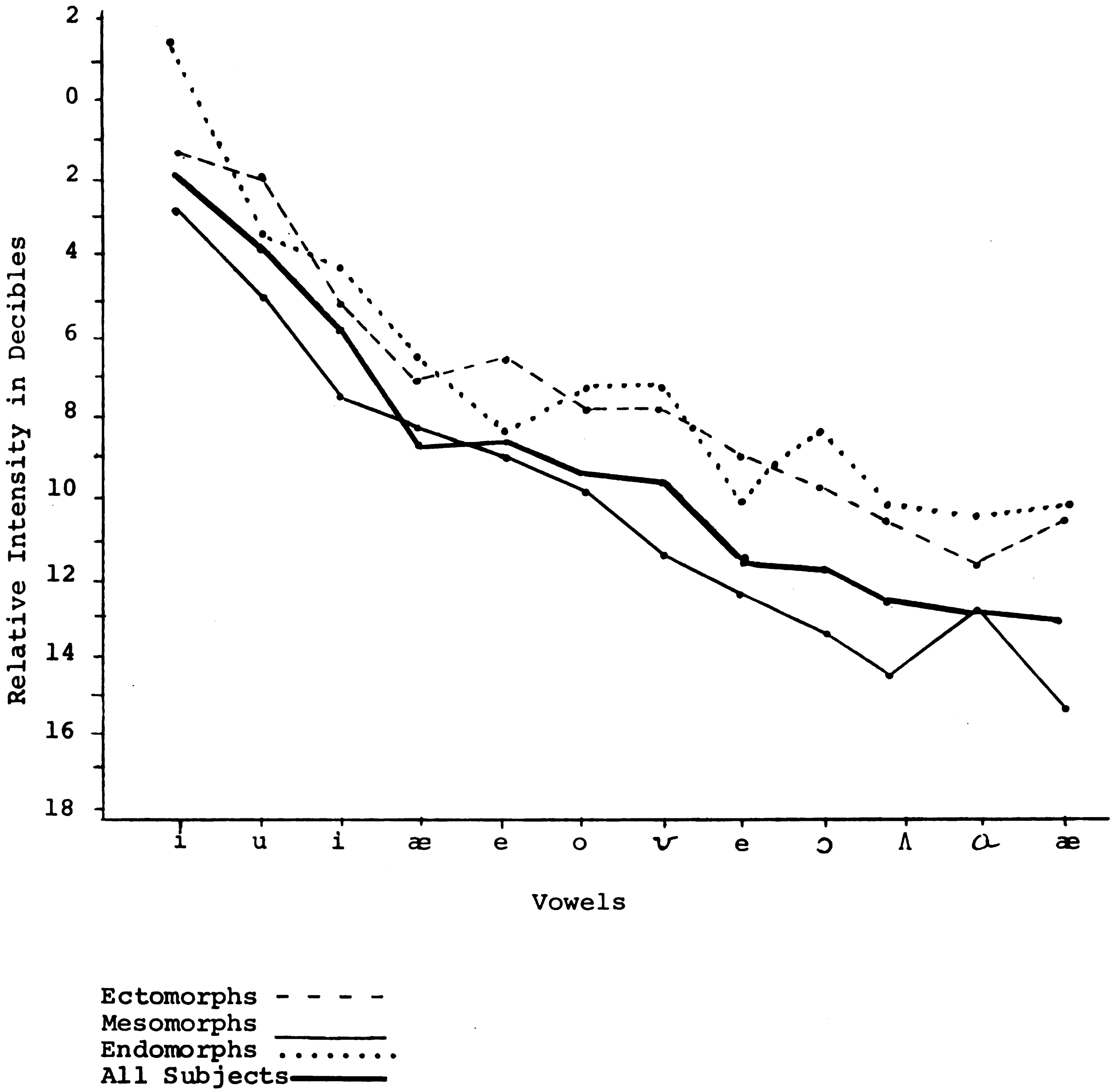

FIGURE 5.--Mean relative sound pressures transmitted for each vowel for the groups of ectomorphs, endomorphs, mesomorphs and all subjects, regardless of Position.

difference among the three groups. However, a trend can be seen in which mesomorphs appear to transmitt lower relative sound pressure scores than other subjects. Mean relative sound pressure scores at the sixteen locations failed to show any trends among the other two body types.

Figure 6 presents the mean relative sound pressures transmitted for each of the groups of ectomorphs, mesomorphs, and endomorphs as well as for all subjects regardless of vowel. The positions are ranked in descending order according to relative sound pressure. Examination of Figure 6 reveals that there is considerable intra-body-type-group of subjects variability and inter-body-type-group of subjects variability. None of the three body type groups approached the smooth descending slope of the means of all subjects. Each body type group is represented by a markedly jagged curve. There does not appear to be any trend for any particular body type with respect to mean relative sound pressures transmitted at the various anatomical locations.

It would appear that when vowel sounds are uttered by male subjects and vibrations picked up by transducers placed at a variety of anatomical locations of the head and neck, the sound pressure is transmitted with the greatest intensity through the top-center of the skull (A4), the frontal bone (A3), the neck near the larynx (D4), and the mandible (D1).

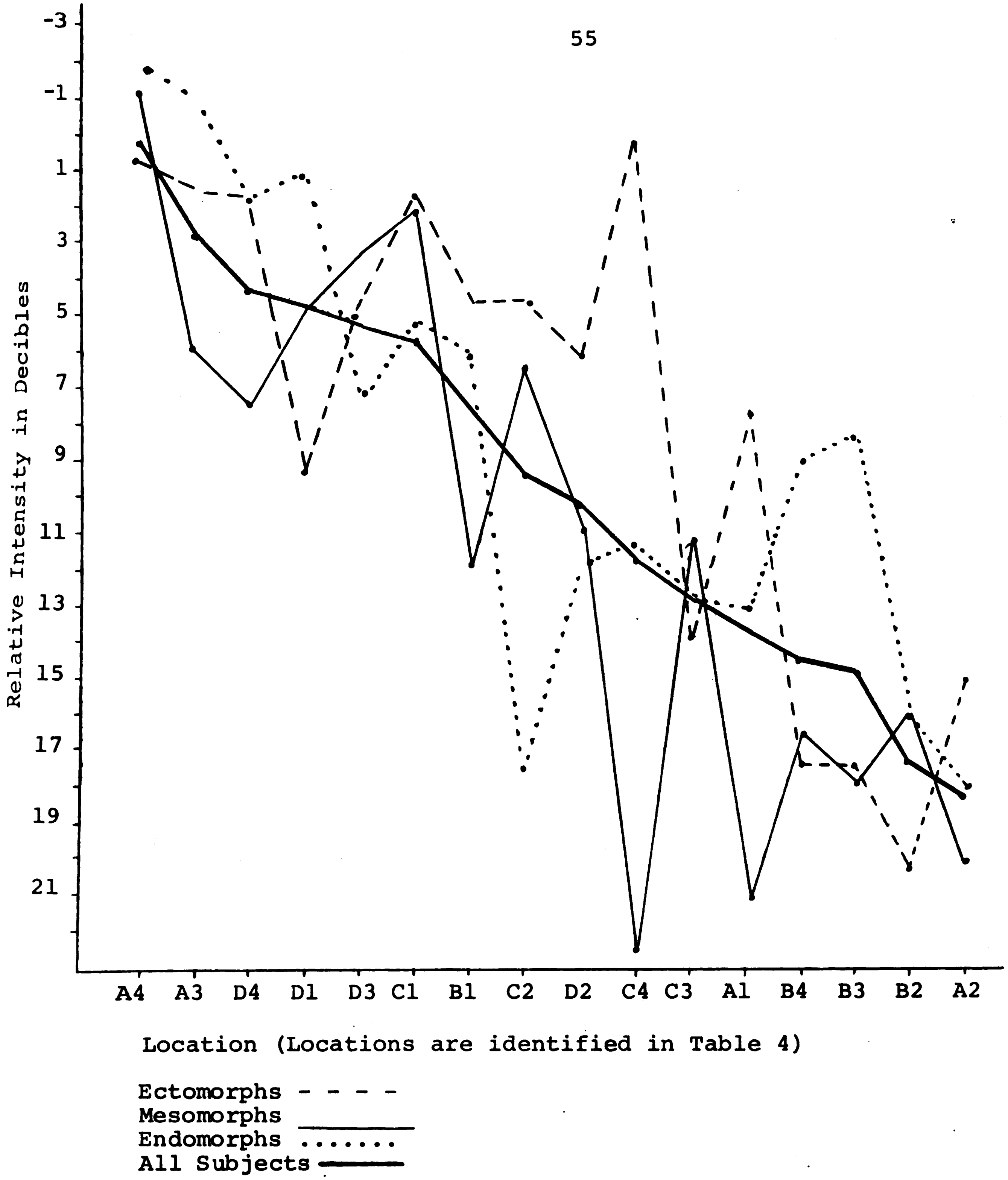

FIGURE 6.--Mean relative sound pressures transmitted for each position for the groups of ectomorphs, endomorphs, mesomorphs and all subjects, regardless of vowel.

Results of Statistical Tests

All of the statistical computations for this study were conducted on the Control Data Corporation 3600 Digital Computer at the Computer Center of Michigan State University. An analysis of variance of the three main levels used in this experiment and four of their interactions was conducted according to the STAT Series Program provided by the center.[1]

Table 6 provides a summary of this analysis of variance and shows that three of the seven F-statistics are significant, at the level of confidence of 0.05%, namely: vowels, positions, and interactions of vowel and positions. All other levels tested (body type and interactions of body type with vowels and positions) showed no significant differences.

These outcomes suggested that the questions asked in Chapter I should be answered as follows:

1. The relative overall sound pressure transmitted through tissue for each vowel is independent of body type and anatomical location.

2. The relative overall sound pressure transmitted through tissue for each body type is dependent upon each vowel and anatomical location.

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[1]Agricultural Experiment Station, "STAT Series Description No. 14: Analysis of Variance with Equal Frequency in each Cell," (East Lansing: Michigan State University, 1968).

TABLE 6.--Summary of analysis of variance comparing vowel, positions, and body type.

Source of Variance	Sum of Squares	DF	Mean Square	F Statistic
(A) Vowel	12366.207	11	1124.200	68.929#
(AxC) Vowel-Body Type	302.930	22	14.087	0.863
Z=ACD+AD	538.208	33	16.309	
(B) Positions	36801.099	15	2453.406	5.308#
(BxC) Positions-Body Type	18275.524	30	609.184	1.318
Z=BCD+BD	20795.944	45	462.132	
(C) Body Type	2445.836	2	1222.918	0.676
Z=D+CD	5419.613	3	1806.537	
(AxB) Vowel-Positions	2492.427	165	15.105	2.011#
(AxBxC) Vowel-Position-Body Type	2530.645	330	7.668	1.021
Z=ABCD+ABD	3716.834	495	7.508	
Total	105692.271	1151		

= significant beyond 0.0005 level

3. The relative overall sound pressure transmitted through tissue for each anatomical location is independent of vowel and body type. In any anatomical position, the vowels can be similarly ranked.

4. There is not any significant interaction among vowel, anatomical location, and body type with respect to overall sound pressure transmitted through tissue.

The result of this analysis suggested that vowels could be ranked from highest relative transmitted sound pressure to lowest in the following manner: /i/, /u/, /I/, /ɝ/, /e/, /o/, /v/, /ε/, / /, /ʌ/, /a/, /æ/. See Table 7). This was valid for all subjects regardless of anatomical position. Table 8 presents the array of comparisons of mean sound pressure transmitted of each vowel to all the others. This was determined by the use of Duncan's Multiple Range Test.[1] The (x) symbol represents entries in the rows which differ significantly from the entries listed in the columns. It should be noted that the relative sound pressures of the two most intensely transmitted vowels, /i/ and /u/, are significantly different from all the remaing vowels, with /i/ having the highest relative transmitted sound pressure.

Further, Duncan's test suggested that positions could be ranked from highest relative transmitted sound pressure to lowest. (See Table 9). The position at the top-center of the skull had the highest relative sound

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[1]Agricultural Experiment Station, "AFS MISC Series . . ."

TABLE 7.--Means of twelve vowels ranked in descending order of relative transmitted sound pressure level.

Vowel	Mean Relative Intensity of dB re: 0 Reference
i	-1.833
u	-4.385
I	-7.149
ɝ	-7.959
e	-8.038
o	-9.165
v	-9.725
ε	-11.354
ɔ	-11.567
ʌ	-12.262
a	-12.601
æ	-12.773

TABLE 8.--Display of transmitted sound pressure of each vowel as compared to every other vowel.

Comparison Vowel	æ	a	ʌ		ε	v	o	e		I	u	i
æ					X	X	X	X	X	X	X	X
a						X	X	X	X	X	X	X
ʌ						X	X	X	X	X	X	X
ɔ						X	X	X	X	X	X	X
ε	X					X	X	X	X	X	X	X
v	X	X	X	X	X		X	X			X	X
o	X	X	X	X	X					X	X	X
e	X	X	X	X	X	X					X	X
ɝ	X	X	X	X	X	X					X	X
I	X	X	X	X	X	X	X				X	X
u	X	X	X	X	X	X	X	X	X	X		X
i	X	X	X	X	X	X	X	X	X	X	X	

X = difference between mean transmitted sound pressure was significant at 0.05 level.

TABLE 9.--Means of sixteen positions ranked in descending order of relative sound pressure.

	Position	Mean Relative Intensity in dB re: 0 reference
A4	Top-center of skull	0.343
A3	Frontal Bone	-2.833
D4	Neck-right	-3.330
D1	Mental protuberance of mandible	-3.415
D3	Neck-left	-4.080
C1	Ramus of mandible-left	-4.367
B1	Nasalis bone	-4.976
C2	Ramus of mandible-right	-9.569
D2	Notch of thyroid-below	-10.368
C4	Temporal-left	-11.187
C3	Temporal-right	-12.700
A1	Occipital protuberance-one inch below	-14.144
B4	Sphenoid-right wing	-14.218
B3	Sphenoid-left wing	-14.589
B2	Occipital protuberance	-17.635
A2	Occipital protuberance-above two inches	-17.974

pressures transmitted, while the position below the occipital protuberance in the back of the skull had the lowest relative sound pressure transmitted. Table 10 presents the array of comparisons of each position to all other positions. The (x) symbol represents entries in the rows which differ significantly at the 0.05% level of confidence from the entries listed in the columns. The mean relative sound pressures transmitted at the top-center of the skull is significantly different from nine of the remaining fifteen positions.

Retest Results

Analysis of variance of data yielded by retest of every subject was conducted to determine the reliability of the original measurements. An analysis of variance test of the retest data helped to determine the significance of the main levels tested and their interactions. Table 11 presents the summary of this analysis of variance. It confirmed the significance of the same two factors, vowel and position, and the interaction between these two factors as encountered in the original test. The probability of the F-statistic was, once again, less than 0.05% for all three significant statistics.

A Pearson product-moment correlation procedure was conducted to test the correlation between the original scores and the retest scores for the six subjects. A positive

TABLE 10.--Display of each position compared to every other position for differences between their means.

Comparison Positions	A2	B2	B3	B4	A1	C3	C4	D2	C2	B1	C1	D3	D1	D4	A3	A4
A2										X	X	X	X	X	X	X
B2										X	X	X	X	X	X	X
B3										X	X	X	X	X	X	X
B4										X	X	X	X	X	X	X
A1										X	X	X	X	X	X	X
C3											X	X	X	X	X	X
C4																X
D4																X
C2																X
B1	X	X	X	X	X											
C1	X	X	X	X	X	X										
D3	X	X	X	X	X	X										
D1	X	X	X	X	X	X										
D4	X	X	X	X	X	X										
A3	X	X	X	X	X	X										
A4	X	X	X	X	X	X	X	X	X							

X = difference between mean significant at 0.05 level.

TABLE 11.--Summary of analysis of variance comparing vowel, positions, and body type for retest data.

Source of Variance	Sum of Squares	DF	Mean Square	F Statistic
(A) Vowel	10873.489	11	988.499	44.867#
(AxC) Vowel-Body Type	380.918	22	17.314	0.785
Z=ACD+AD	727.042	33	22.031	
(B) Position	30264.368	13	2017.624	4.714#
(BxC) Position-Body Type	9634.102	30	321.137	0.705
Z=BCD+BD	19258.828	45	427.973	
(C) Body Type	5906.209	2	2953.104	2.178
Z=D+CD	4066.489	3	1355.497	
(AxB) Vowel-Positions	1799.366	165	10.905	2.286#
(AxBxC) Vowel-Position-Body Type	1559.340	330	4.725	1.034
Z=ABCD+ABD	2261.614	495	4.568	
Total	83731.769	1151		

= significant beyond 0.0005 level.

correlation of 0.546, significant at the 0.01 level, was obtained. Thus, the scores obtained on test and retest sessions were found to be statistically similar.

Discussion

The results of examination of the data collected for this experiment indicate both specific conclusions and trends which are note-worthy. The analysis of variance treatment points out that there are statistically significant differences among the mean relative transmitted sound pressures for each vowel, anatomical position, and for the interaction between vowels and anatomical positions.

Further statistical analysis indicates that the vowels /i/ and /u/ were transmitted through tissue significantly more intensely than any of the other vowels employed in the study. The least intensely transmitted vowels were the /ʌ/, /a/, and /æ/. It should be noted that the /i/ and /u/ are both high vowels, whereas the /ʌ/, /a/, and /æ/ are central and low vowels. Apparently the high front and back vowels are transmitted more easily through the tissues of the head and neck than any of the other vowels.

Re-examination of Table 9 indicates two distinct general groupings of the mean relative transmitted sound pressures through the different anatomical sites, when the means for all locations are compared to each other. Group I, the high relative sound pressure region, consisted of the eight locations showing the highest mean relative sound pressures transmitted. Included in this group are the following positions: top-center of the skull, frontal bone, nasalis bone, left and right side of neck, and left and right ramus of the mandible.

Group II, the low relative sound pressure region, consisted of the eight locations showing the lowest mean relative intensities. Included in this group are the following positions: below the notch of the thyroid, left and right temporal bone, left and right wing of the sphenoid, and the area near the occipital protuberance. Although there are significant differences among the means of transmitted sound pressures within each group, the grouping suggested above appears to be a meaningful one. An interesting finding was that the relative sound pressure at the thyroid notch of the larynx was not in the high intensity group. This may have been due to the vertical movement of the larynx during phonation resulting in unstable positioning of the accelerometer.

Interactions between vowel and position proved to be, for the most part, a random function. It was observed that the mean relative sound pressures of the interactions of the vowels locations with the highest relative sound pressures transmitted were ranked highest in the list of such interactions. Thus, the vowels /i/ and /u/ when transmitted through the top-center of the skull and the frontal bone had greater mean relative sound pressures than any other vowels at any other locations. It was also noted that the vowels /a/ and /æ/ when transmitted through the occipital protuberance region had lower mean relative sound pressures than any other vowels at any other locations.

Additionally, it would be recalled that there may possibly have been an interaction of the resonances created by the helmet with the sound pressures transmitted. It is possible that some of the differences of the transmitted sound pressures obtained may have been due to these resonance factors rather than to the anatomical characteristics of the positions from which the measurements were taken.

Further statistical analysis of the positions indicates that the anatomical sites of the top-center of the skull and the frontal bone had significantly higher transmission of relative sound pressure than any other positions. The positions through which the relative sound pressures of the vowels were transmitted less efficiently were the occipital protuberance and the point two inches below the occipital protuberance; both of these positions are located in the back of the skull.

Results of previous research in this area do not show close agreement concerning which anatomical sites transmit speech sounds most efficiently with respect to relative sound pressure. Mullendore[1] found that the thyroid

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[1]Mullendore, "An Experimental Study . . . ," pp. 163-176.

cartilage, the mandible, the nose, and the top of the skull transmitted vowels with greatest intensity. Snidecore, Rehman, and Washburn[1] found that the larynx, mandible, chin, and nose were most efficient; and Neely and Forshaw[2] found the forehead, back of head, and top of skull to be the most efficient sites.

The study by Moser and Oyer[3] employed the same anatomical sites and the same vowels as the present study. Moser and Oyer used three subjects who hand-held a bone oscillator to the anatomical locations while phonating. Table 12 presents a random ordering of the results of the Moser and Oyer study and the results of the present study.

The Moser and Oyer results were grouped into four different anatomical sites according to relative intensity. It was concluded that "except for the region at the top and center of the head, the relative intensity of tissue-conducted sound . . . is decreased as the distance from the larynx is increased, . . ."[4] The position at the top and center of the skull is found in Group III which is a relatively low group.

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[1]Snidecor, Rehman, and Washburn, "Speech Pickup by . . . ," pp. 277-281.

[2]Neely and Forshaw, "Speaking and Listening . . . ," pp. 151-157.

[3]Moser and Oyer, "Relative Intensities of . . . , " pp. 275-278.

[4]*Ibid*., p. 178.

TABLE 12.--Comparison of the results of the Moser and Oyer Study to the results of the present study. Positions ranked in descending order of relative sound pressures.

Moser and Oyer Results	Present Results
Angle of Mandible-Right	Top and Center of Skull
Larynx	Frontal Bone
Angle of Mandible-Left	Neck-Right
Neck-Right	Mental Protuberance
Neck-Left	Neck-left
Mental Protuberance	Angle of Mandible-Left
Nasalis Bone	Nasalis Bone
Occipital Protuberance-Below	Angle of Mandible-Right
Occipital Protuberance	Larynx
Top-Center of Skull	Temporal Bone-Left
Occipital Protuberance-Above	Temporal Bone-Right
Temporal Bone-Left	Occipital Protuberance-Below
Sphenoid Bone-Right	Sphenoid Bone Right
Temporal Bone-Right	Sphenoid-Left
Frontal Bone	Occipital Protuberance
Sphenoid Bone-Left	Occipital Protuberance-Above

Solid Underling indicates divisions between groupings achieved in each study.

The present study indicated that the position at the top and center of the skull was the most efficient transmitter of vowel sounds. The anatomical sites fell into two groups on the basis of their relative sound pressures Group I consisted of locations toward the top and front of the skull. Group II consisted of those sites on the sides and back of the skull, except for the larynx itself.

Examination of Table 12 indicates that while there is not a one-to-one correspondence in the rank orderings of the results of the Moser and Oyer study and the present study, the findings of the two studies basically agree. Inspection of Table 12 reveals that there is a seventy-five percent agreement between the two studies with respect to the transmitted relative sound pressure of vowels at those anatomical locations that appeared above or below the mid-point in the ranking. Both studies indicate that as distance from the larynx increases, the transmitted relative sound pressure of the vowel decreases. An exception was noted in the case of the position beneath the thyroid notch on the larynx. The relative sound pressure of this position was found in the low pressure group. This may have resulted from unstable placement of the accelerometer against the larynx which tended to move during phonation. The present study suggests that locations near the larynx and overlying broad, flat bones transmit vowel sounds with greater pressure than locations remote from the larynx and overlying irregularly shaped bone or no bone at all.

CHAPTER V

SUMMARY AND CONCLUSIONS

This study was concerned with the investigation of the relative sound pressures of vowel sounds as they are intoned by male subjects of different body types and transmitted through tissues of the head and neck.

Summary

Speech scientists have recognized that tissue which is remote from the larynx vibrates during voice production. Tissue vibration was thought to contribute to the overall quality of the voice during speech and singing. Later investigators, aided by the development of electronic instrumentation for sound analysis, concluded that tissue vibration during voice production was the result of forced vibration, and probably did not contribute significantly to voice quality.

Many investigators have examined the nature of vibration of speech sound through tissues of the human body. Research in this area indicated that sounds are more intense at some anatomical locations of the body than others. However, there has not been consistent agreement in results. The early investigators have indicated that certain refinements in instrumentation and procedures might provide more precise and consistent measurements and might result in data which are more valid and reliable.

The purpose of this investigation was to examine the relative sound pressures of vowel sounds as they were uttered and transmitted through the tissues of the head and neck. The study was directed at investigating, experimentally, the difference in relative sound pressure among twelve vowel sounds picked up at sixteen anatomical locations employing subjects with three distinctly different body types.

Six adult male speakers were employed in this investigation. The subjects were selected to represent three different body physiques: ectomorph, mesomorph, and endomorph. Two subjects were placed in each body classification. The subjects all utilized the General American Dialect and were familiar with the International Phonetic Alphabet. Twelve vowels were selected for the investigation. Sixteen anatomical locations of the head and neck were specified as sites to be investigated that were at varied distances from the larynx and that represented differences with respect to tissue compositions. In some instances positions on both sides of the head were included.

A special helmet and shield which had minimal contact with the surface of the head and neck were designed. The helmet and shield provided holes through which four accelerometers could be anchored. In this way, control was exerted over the security of application of the accelerometers against the surface of the head and neck.

The accelerometer employed was an integrated-circuit-piezoelectric quartz transducer that was sensitive to very subtle vibrations and had a linear frequency curve throughout the speech range. The four transducers were applied to the anatomical site under investigation through the helmet and shield, and the subjects intoned the vowels while monitoring the intensity of their voices. Through the use of a sound level meter, the sound pressure level of all utterances was held constant by all speakers. Subjects also practiced maintaining a constant fundamental pitch for each utterance. The transducers transmitted the signals picked up at the skin surfaces to a tape recorder. In this way, responses from four anatomical locations were recorded simultaneously. The four transducers were moved and the procedure repeated until the output from all sixteen locations had been recorded.

The investigator analyzed the tape recorded vowel signals by means of a power level recorder according to relative sound pressure patterns, and a graphic display of each sample was obtained. Mean relative sound pressure measurements were made from each of the graphic displays; these measurements provided the data for this investigation.

The dependent variable under consideration was relative sound pressure. The data obtained from the subjects were treated by a three factor analysis of variance in which the factors were (1) vowels, (2) positions, and (3) body type. A Pearson product-moment correlation was used to compare original data to retest data for all subjects.

Conclusions

Within the limitations of this experiment, there are certain conclusions that can be drawn from the hypotheses tested and from observations made of the outcomes of the research.

1. The vowels /i/ and /u/ are transmitted through the tissue of the head and neck with significantly higher relative overall sound pressure than any other vowels. The vowels /a/ and / / are transmitted through these tissues with significantly lower relative overall sound pressure than any other vowels.

2. The anatomical positions at the top-center of the skull, the forehead, the neck near the larynx, and the mandible transmit vowel sounds with higher relative than any other locations.

3. On the basis of relative sound pressure the sixteen anatomical locations fell into two basic groups. Group I-The Central Region--consisted of locations toward the midline and front of the skull, near the larynx. Group II-The Peripheral Region--consisted of those sited remote from the larynx.

4. Highest relative sound pressures are obtained for the vowels /i/ and /u/ at the positions on the top-center of the skull and on the forehead. It is possible to hypothesize that these vowels at these positions were better transmitted than any other vowels at any other positions because of the spectral characteristics of the vowels as well as the density and solidity of the anatomical structures. The spectral characteristics of the vowels /i/ and /u/ may be such that they are more easily transmitted through the bones of the skull than any of the other vowels investigated.

5. When the accelerometers were attached to the supporting system, it was found that a non-linearity in frequency response of the transducers occurred. With a constant pressure of application of 0.1 gravitational acceleration there was a 10 dB increase in responses of frequencies below the speech range. This did not appear to have a significant effect on the relative sound pressure levels of the ten vowels. However, as pressure of application

was increased, the non-linearity of transducer response curves increased so that relative sound pressure levels, of transmitted vowels, of 10 to 16 dB were found in the speech frequencies. Thus vowels at various anatomical locations may have been transmitted with different sound pressures because of the interaction within the supporting system. The obtained data must be considered with this possibility in mind.

6. No statistically significant differences were found among relative intensities among body types. However, mesomorph subjects showed a trend toward lower relative sound pressures across all vowels than did nother subjects. This may be related to the solid muscles and tissue structure associated with the mesomorph physique.

7. The measurements obtained by the procedures employed in this experiment were shown to be reliable by results of comparison to retest data.

8. Differences between results obtained by this experiment and previous studies may be attributed to differences in instrumentation and procedures employed.

Suggestions for Future Research

From the results of the study and from observations of the procedures used, several suggestions for future investigation can be made.

1. While the helmet and shield provided a secure means of attaching the transducers to the head and neck, they also introduced considerable subject discomfort and difficulty in manipulating and changing the location of the transducers, and nonlinearity of the frequency response curves of the accelerometers.

Further research in this area may attempt to create a method of attaching the transducers in such a way that the entire surface of the head and neck is uncovered. The transducers could, for instance, be attached to arms which could be moved toward the surface of the head and neck from the sides. In this way, adjustments in location site and pressure of application could be made more easily and with greater precision. This would also reduce the discomfort experienced by the subjects.

In addition, refinement in attaching the transducers to the body surface might overcome the nonlinear responses when the accelerometer was attached to the supporting system.

2. It would seem that several studies similar to the present one could be replicated meaningfully using the same equipment, but with certain refinements in procedure. Controlling for differences in pressure of application of the transducers to the surface of the head and neck would provide a clearer understanding of the effect of varied pressure on the measurements.

3. In addition, any replication of this study should attempt to investigate larger groups of ectomorphs, mesomorphs, and endomorphs to determine whether the trend indicated by the data is a significant one.

4. A similar study to the present one could be developed in which the obtained samples were judged by a panel of listeners for intelligibility. In conjunction with this, a spectral analysis of the frequency components of each sample could be made. In this way, significant relationships may be found between intelligibility, frequency characteristics, and anatomical location.

5. Significant information could be obtained through a study similar to the present one but employing subjects with widely different fundamental pitches.

6. Initially it was stated that contact microphones used in military, government, and scientific operations might be better employed if optimal anatomical positioning was discovered. The present investigation suggests that the top-center of the skull and the forehead were areas at which certain vowels were best transmitted. Various contact microphones should be examined carefully to determine if their frequency response curves may tend to amplify vowel sounds, consonant sounds, and even connected speech in different ways. A contact microphone may possibly be designed which, when placed on the top-center of the skull or on the forehead would pick up

tissue transmitted speech signals whos intelligibility would be appropriate for communication purposes. Thus a contact microphone might be employed in place of an air conduction microphone and result in safer as well as more efficient transmission of speech of astronauts, deep sea divers, mine workers, and aircraft personnel.

It is not clear what effect, if any, the nonlinearity of response curves of the supporting system may have upon the transmission of vowel sounds. However, the nonlinearity suggests that perhaps contact microphones may not be an accurate means of transmitting speech sounds because of potential distortion. Future investigation should consider the use of supporting systems which will not affect the intelligibility of the transmitted signal, or the use of air conduction microphones.

Comparisons of intelligibility of air conducted sound with intelligibility of tissue conducted sound may provide a means of determining the overall usefullness and efficiency of contact microphones.

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APPENDICES

APPENDIX A

SHELDON'S CLASSIFICATION SYSTEM

Sheldon attempted to find a first-order criterion for the classification of human physique. The Sheldon body classification system resulted from a study of the physiques of over thirteen-hundred undergraduate males. He photographed his subjects from three angles: back, front, and side. In addition to obtaining the height and weight for each subject, he made seventeen precise measurements from the photographs. Sheldon found three basic components of body constitution which could be used to classify the body structure of every subject. These were ectomorph, mesomorph, and endomorph.

In endomorphy, there is a predominance of softness and roundness with massive digestive viscera. In mesomorphy, there is a predominance of muscle and connective tissue. The mesomorphic structure is hard and rectangular. In ectomorphy, there is a predominance of linearity and fragility. The ectomorphic structure has the greatest surface area in proportion to its mass and the largest brain and central nervous system.

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[1]Sheldon, Atlas of Men; Sheldon, The Varieties of Human Physique.

Sheldon concluded that every physique had components of all three morphologies. He devised a system for classifying each physique by three numbers. The first number represented the predominance of endomorphic component; the second, mesomorphic, and the third ectomorphic. A scale of seven points was used with the number one representing a minimal degree of a component and number seven representing a maximal degree of a component. This patterning of three body components was called somatotyping. Sheldon was able to demonstrate seventy-six different somatotypes.

The pure endomorph was classified as 7 1 1; the pure mesomorph was classified as 1 7 1; and the pure ectomorph as 1 1 7. A somatotype with an average degree of all components was classified as 4 4 4.

APPENDIX B

DESCRIPTIVE DATA FOR SUBJECTS

APPENDIX B.--Descriptive data for the six subjects employed in the study.

Subject	Age (Years-Months)	Height (Inches)	Weight (Pounds)	Body Type
1	28-0	72	130	Ectomorph
2	23-0	72	145	Ectomorph
3	25-9	71	175	Mesomorph
4	27-9	71	190	Mesomorph
5	29-5	73	205	Endomorph
6	35-0	70	185	Endomorph

APPENDIX C

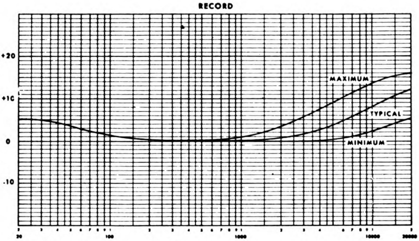
MEAN AGE, HEIGHT, WEIGHT FOR BODY CLASSIFICATIONS

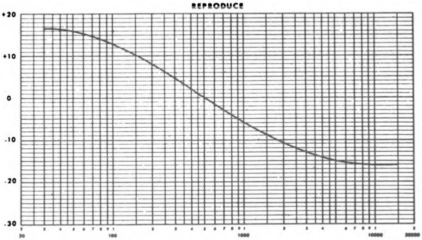
APPENDIX C.--Mean age, height, and weight for each body classification.

Body Type	Mean Age (Years-Months)	Mean Height (Inches)	Mean Weight (Pounds)
Endomorph	24-6	72	137.5
Mesomorph	26-7	71	182.5
Ectomorph	32-3	72	195.0

APPENDIX D

FREQUENCY RESPONSE CURVES OF TAPE RECORDERS



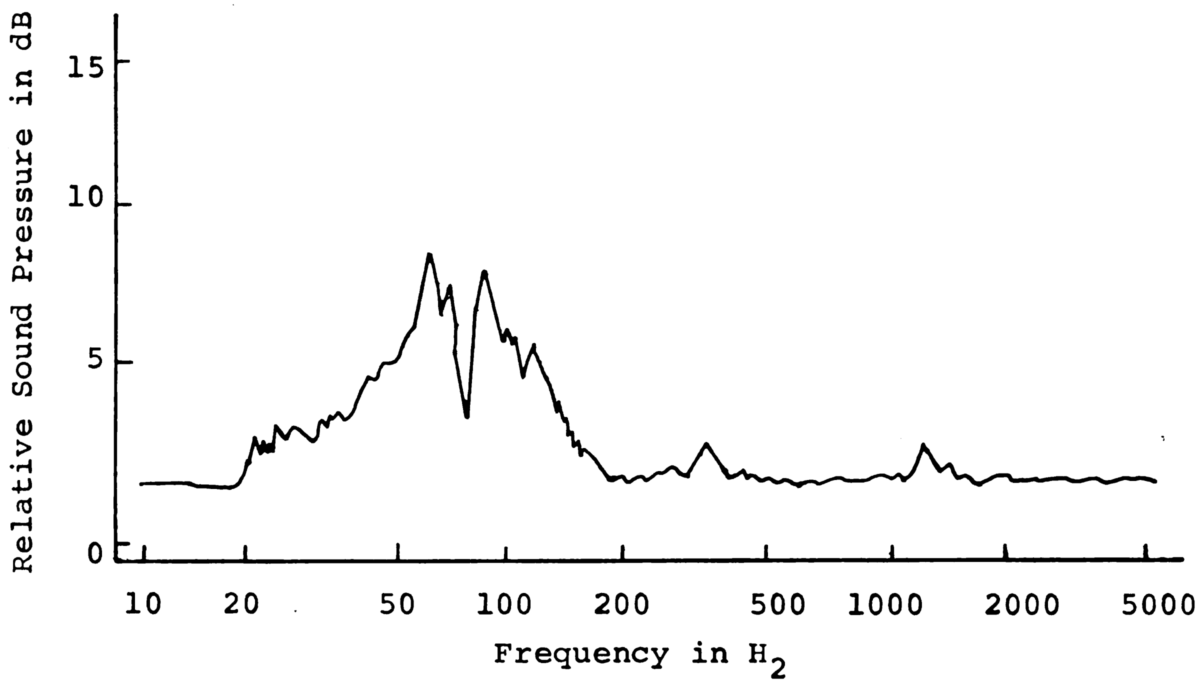


Frequency response curves of tape recorders.

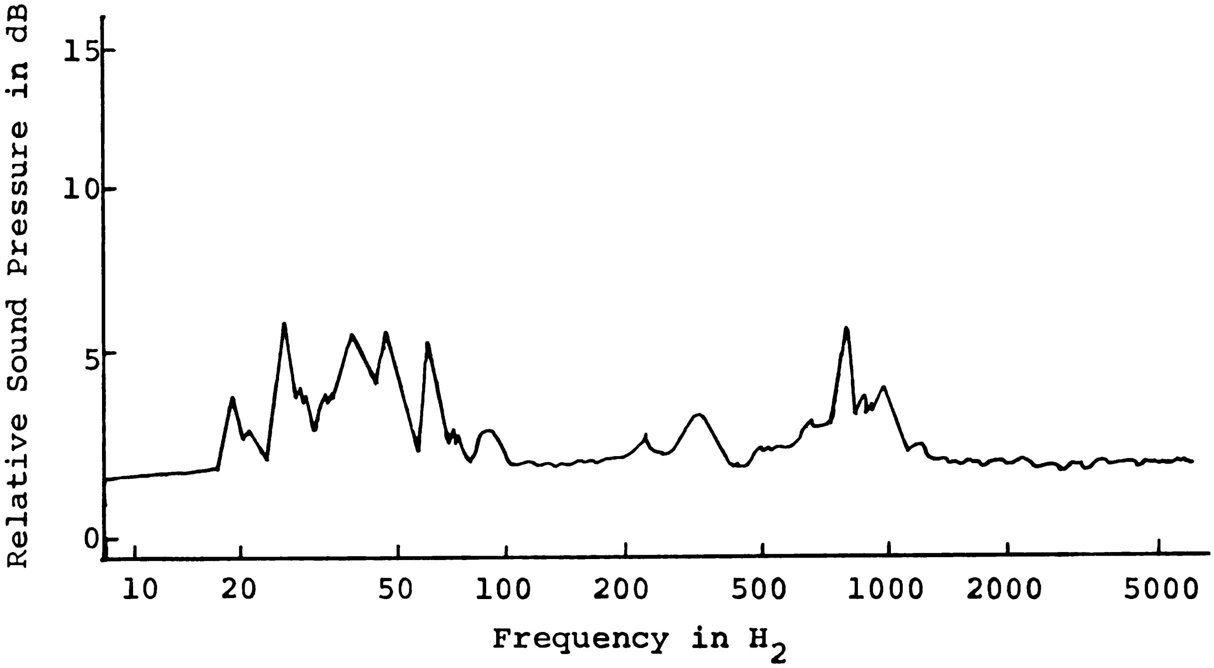
APPENDIX E

EXPERIMENTALLY DERIVED CURVES

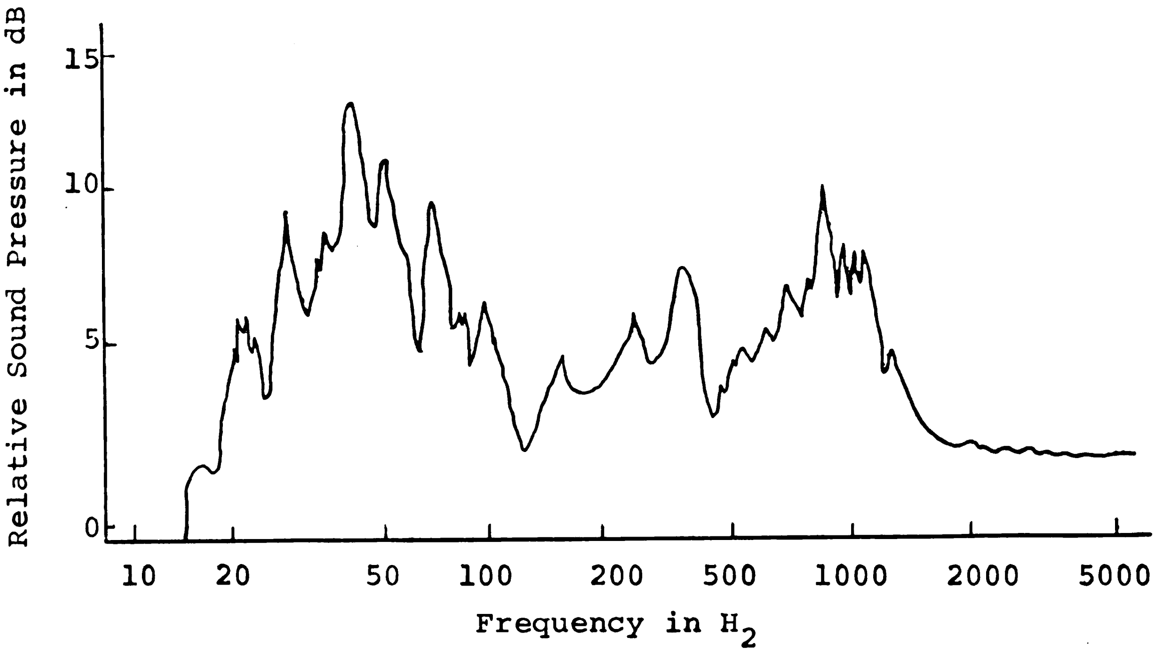
FOR ACCELEROMETERS



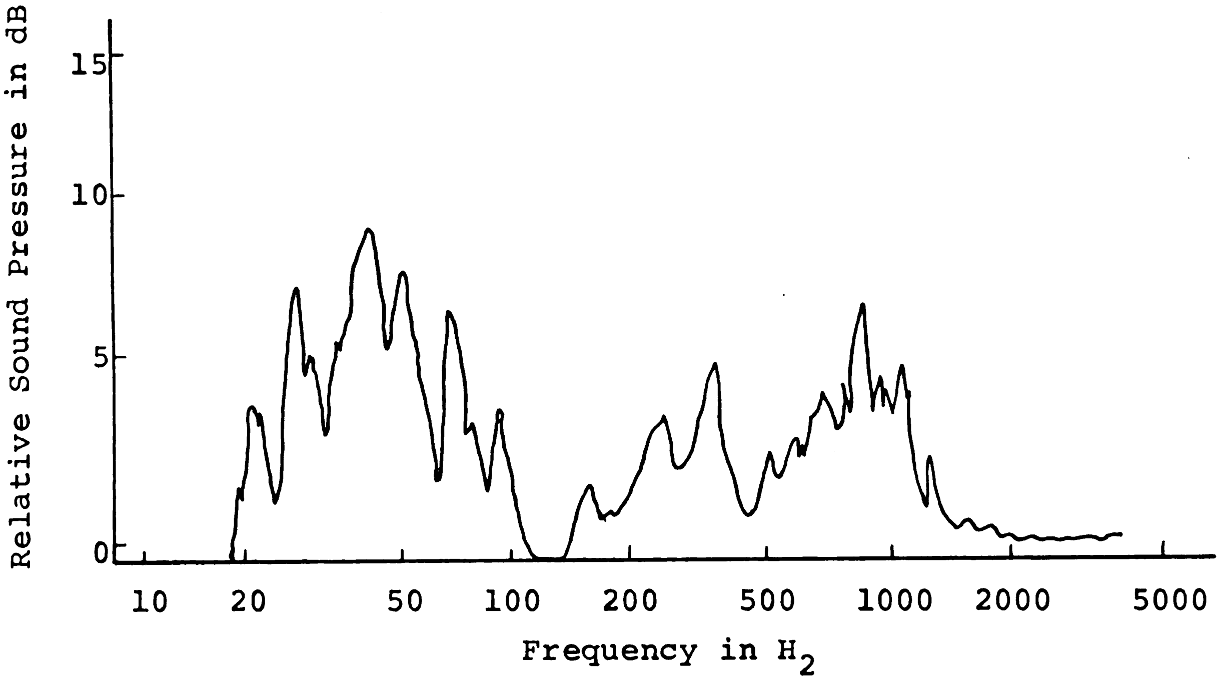
Output from accelerometer mounted in helmet:
Coronal Location
Constant Input of 0.1g



Output from accelerometer mounted in helmet:
Frontal Location
Constant Input of 0.1g



Output from accelerometer mounted in helmet:
Frontal Location
Constant Input of 0.3g



Output from accelerometer mounted in helmet:
Frontal Location
Constant Input of 0.5g

APPENDIX F

STATISTICAL METHODS EMPLOYED

Assumptions underlying statistical tests: Before selecting and proceeding with the several statistical analyses to be attempted, it was necessary to consider the extent to which the assumptions underlying the use of the statistics had been met. Analysis of variance, multiple comparison tests, and a Pearson product-moment correlation were the statistics employed.

The assumptions underlying the use of the analysis of variance were (1) normality: the samples selected were drawn from populations that are normally distributed; (2) homogenity of variance: the variances are assumed to be statistically the same from group to group, within the bounds of random variation, over the observations made; and (3) continuity and equal intervals of measure: the measures to be analyzed are continuous measures with equal intervals.[1]

Examination of the data obtained from the six subjects reveals that the distribution of scores was mildly skewed but remained as a good approximation to a normal distribution. Lindquist points out that the F-test

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[1]Fred N. Kerlinger, Foundations of Behavioral Research (New York: Holt, Rinehart and Winston, 1966), pp. 258-260.

is quite insensitive to the shape of the distribution, even when the distribution is moderately to markedly skewed. He has stated that the F-test is so insensitive

> . . . to the form of the distribution of criterion measures that it hardly seems worthwhile to apply any statistical test to the data to detect non-normality, even though such tests are available. Unless the departure from normality is so extreme that it can easily be detected by mere inspection of the data, the departure from normality will probably have no appreciable effect on the validity of the F-test. . .[1]

Since examination of the data reveals only mild skewedness, it would appear that the assumption of normality is satisfactorily met.

Regarding the second assumption of homogeneity of variance across treatment groups, Kerlinger points out that this assumption along with the assumption of normality are generally overrated. He indicates that unless there is good evidence to believe that homogeneity of variance is violated, a parametric statistic such as the F-test should be employed.[2] Hays supports the view that so long as sample sizes are equal for all conditions of the analysis, violation of the homogeneity assumptions have little effect upon the F-distribution.[3] In the present

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[1]E. F. Lindquist, Design and Analysis of Experiments in Psychology and Education (Boston: Houghton Mifflin Company, 1953), p. 87.

[2]Kerlinger, Foundations . . ., p. 259.

[3]William L. Hays, Statistics for Psychologists (New York: Holt, Rinehart and Winston, 1964), p. 408.

study, sample sizes for all conditions of the analysis were equal. The assumption of homogeneity of variance seems to be satisfied for this study.

The third assumption of continuous measures with equal intervals seems to be met also. Blalock states that an "interval scale level of measurement requires a physical unit of measurement which can be agreed upon as a common standard and which is replicable."[1] The unit of the decibel, which is the unit of measurement in this study, satisfies all of these requirements.

The three-factor analysis of variance for repeated measures on two of the three factors was selected as the most appropriate statistic to test the null hypotheses derived from the questions concerning relative intensity. The variable of body type (subject) did not have repeated measures, where-as the variables of vowel and anatomical location did. Although a sample size of two in each body group was small, the large amount of data collected for each subject allowed the use of analysis of variance technique.

Duncan's Multiple Range Test[2] was selected to determine the significant differences between the array of

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[1]Hubert M. Blalock, Jr., Social Statistics (New York: McGraw-Hill Book Company, 1960), p. 14.

[2]Agricultural Experiment Station, AES MISC Series Description 108, Michigan State University, "Duncan's Multiple Range Test", 1968.

means generated by the analysis of variance because of the large number of means which were compared and the large number of degrees of freedom associated with them. This statistic is a multiple comparison test which calculates the shortest significant range using Harter's table which is associated with degrees of freedom, number of means being compared, and the confidence level desired. Each mean is compared to every other mean to determine whether their differences exceed the shortest significant range.

The Pearson product-moment correlation coefficient was used to assess the correlation between the subjects' test-retest measurements. This correlation is based on the concomitant variation of members of sets of ordered pairs. Each member of the pair must be measured in an ordinal scale or a higher scale.[1] The present measurements were made in an interval scale which is higher than the ordinal scale required. No further assumptions need be made in the use of this statistic.

The Pearson product-moment correlation treats the paired scores as test-retest data because the same subjects were used.

The presentation of the results of the statistical treatment is organized on the basis of the two-way and three-way comparisons of the independent variables,

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[1] Blalock, Social Statistics, p. 286.

followed by test-retest correlation analysis. Because meaningful observations can be made by examination of the original data, a section discussing the descriptive analysis of the data is included. A discussion of the obtained results concludes this chapter.

The null hypotheses generated by the seven questions concerning the relative intensity measurements obtained from the subjects were tested by means of three factor analysis of variance for repeated measures. The repeated measures entered the analysis as the factors of Vowels, Positions, and Body Types.

The three factors of the analysis could be imagined to be arranged as a three dimensional table of a 12 x 16 x 3 design. Twelve columns would represent the twelve vowels, and sixteen rows would represent the sixteen anatomical positions. The third dimension could be conceptualized as three layers of the 12 x 16 matrix (Vowels x Positions). The layers would represent the three groups of subject body types--ectomorph, mesomorph, and endomorph. Relative intensity values, the dependent variable, would be entered for each of the six subjects in the appropriate cell of the 192 cell matrix associated with this body type.

APPENDIX G

ORIGINAL AND RETEST SCORES

APPENDIX G.--Original and Retest Scores: Subject 1--Ectomorph.

Positions	Vowels											
	i	*	I	*	e	*		*		*	a	*
A1	-25.1	-14.7	-24.4	-17.0	-25.0	-17.1	-25.2	-18.8	-28.5	-23.6	-27.5	-23.0
A2	-12.2	-8.1	-14.5	-12.8	-14.3	-13.1	-17.1	-14.0	-18.4	-16.2	-18.7	-16.2
A3	-7.3	2.0	-0.6	-3.0	-4.2	-4.0	-8.8	-6.1	-11.0	-10.8	-11.2	-10.3
A4	7.9	1.2	5.1	-5.0	4.0	-4.6	1.2	-5.6	-1.6	-7.8	-1.5	-7.4
B1	-7.0	-19.6	-13.6	-24.4	-17.0	-25.0	-19.5	-26.8	-23.3	-27.6	-22.9	-27.0
B2	-20.4	-13.2	-23.3	-16.0	-22.4	-16.6	-23.2	-17.1	-24.6	-17.0	-23.2	-16.1
B3	-31.5	-8.3	-13.4	-13.2	-16.9	-14.6	-19.4	-17.0	-21.5	-21.4	-18.5	-18.2
B4	-9.0	2.0	-13.4	-3.1	-13.9	-4.0	-12.6	-5.5	-11.9	-4.2	-11.0	-5.1
C1	14.2	8.5	5.4	2.0	3.0	1.5	-6.4	-2.5	-2.0	-5.0	-10.2	-6.5
C2	7.2	1.2	2.0	-7.0	-0.6	-7.5	-9.5	-12.5	-5.7	-14.0	-14.0	-16.6
C3	-10.5	-1.0	-20.1	-11.3	-21.2	-11.0	-24.0	-13.2	-23.5	-14.6	-25.1	-14.2
C4	4.1	-4.6	-3.2	-10.7	-3.7	-11.3	-6.5	-12.7	-5.0	-14.0	-8.0	-13.2
D1	8.2	-3.3	-1.3	-5.5	-4.0	-6.1	-9.0	-9.0	-13.0	-10.8	-15.3	-11.1
D2	-9.0	3.0	-13.7	-6.0	-18.5	-6.5	-19.5	-8.1	-21.5	-13.6	-11.2	-11.6
D3	-5.0	-1.2	-9.0	-6.7	-11.3	-7.6	-12.5	-10.1	-14.0	-10.7	-9.4	-9.0
D4	-6.3	-2.2	-12.4	-7.3	-15.1	-7.7	-8.5	-10.2	-18.6	-11.8	-11.0	-8.7
		*		*		*	o	*		*	u	*
A1	-23.9	-22.5	-26.0	-22.3	-23.0	-18.0	-22.5	-19.0	-22.7	-21.8	-25.0	-18.0
A2	-16.4	-15.2	-18.6	-16.7	-15.5	-12.0	-15.5	-13.5	-16.5	-14.2	-15.5	-16.7
A3	-6.5	-11.4	-10.6	-15.1	-3.9	-3.5	-3.0	-3.5	-5.2	-6.1	-3.4	-3.0
A4	2.8	-6.0	2.0	-7.5	4.5	-2.2	4.9	-3.5	3.0	-4.2	8.0	-1.0
B1	-20.9	-28.2	-22.9	-29.6	-16.9	-27.6	-17.8	-29.0	-18.8	-29.8	-11.0	-27.0
B2	-23.5	-18.6	-24.1	-17.5	-20.9	-15.0	-21.5	-15.5	-23.0	-16.4	-21.4	-16.2
B3	-18.8	-16.6	-19.4	-19.1	-17.3	-15.6	-18.5	-17.1	-20.2	-16.0	-18.7	-13.4
B4	-9.6	-2.5	-13.0	-4.8	-12.5	-2.2	-8.8	-1.8	-10.3	-1.6	-10.0	-0.3
C1	-3.6	-4.8	-6.4	-5.1	1.5	4.0	-2.0	-2.0	-1.9	-2.2	-9.5	5.6
C2	-7.8	-13.6	-11.6	-16.8	-2.8	-9.5	-4.5	-11.7	-6.2	-13.6	4.8	-5.2
C3	-23.2	-14.0	-24.3	-16.0	-21.6	-13.0	-22.5	-14.5	-22.5	-14.4	-16.6	-8.2
C4	-4.9	-14.0	-6.8	-13.0	-2.4	-8.8	-4.2	-11.5	-4.0	-10.5	2.8	-5.2
D1	-15.6	-12.6	-10.0	-12.0	-.62	-5.0	-11.0	-9.3	-12.5	-10.8	1.3	-2.5
D2	-10.0	-4.3	-15.8	-11.7	-21.0	-13.0	-18.0	-15.2	-22.0	-15.0	-3.0	-4.1
D3	-8.2	-7.1	-11.5	-8.6	-15.0	-6.0	-9.2	-7.3	-12.2	-8.0	-10.4	-6.3
D4	-10.8	-6.0	-14.2	-9.0	-15.0	-6.1	-11.4	-6.6	-13.7	-8.1	12.0	-4.0

*Indicates retest score.

APPENDIX G.--Continued. Subject 2--Ectomorph.

Positions	Vowels											
	i	*	I	*	e	*	ε	*		*	a	*
A1	1.2	-1.0	-8.6	-8.0	-15.0	-6.1	-12.2	-10.7	-15.1	-14.0	-11.2	-8.6
A2	-10.6	-11.0	-15.0	-15.7	-16.6	-20.1	-15.6	-15.6	-15.3	-13.0	-15.6	-17.1
A3	10.0	7.0	4.0	-2.8	3.1	-3.5	-3.5	-5.3	-4.6	-6.5	-3.8	-3.8
A4	1.0	0.3	-4.0	-5.1	-5.4	-6.3	-7.3	-7.1	-9.8	-11.7	-9.3	-9.7
B1	10.0	20.0	0.6	13.3	-1.6	12.2	-8.2	10.0	-7.3	6.2	-4.8	7.5
B2	-12.2	-11.0	-17.7	-15.2	-20.0	-16.0	-22.0	-15.4	-22.3	-18.3	-21.5	-16.0
B3	-10.3	-7.4	-12.0	-12.5	-15.0	-13.0	-20.1	-14.3	-20.7	-14.1	-20.0	-14.2
B4	4.5	3.1	0.4	1.0	-3.8	-2.7	-7.5	-6.4	-10.8	-11.8	-9.1	-8.1
C1	-2.3	9.0	-3.8	3.3	-4.4	1.2	-7.0	-0.5	-10.2	-0.7	-11.3	-0.7
C2	8.5	5.0	3.5	-1.0	-1.7	-5.5	-7.7	-7.2	-11.3	-8.2	-8.8	-8.3
C3	-1.4	-11.0	-2.6	-13.5	-5.1	-16.2	-4.8	-19.0	-16.6	-25.1	-15.6	-28.5
C4	7.0	-15.0	8.6	-13.6	5.6	-19.0	-1.7	-18.1	-2.8	-22.0	-3.5	-15.5
D1	-1.5	15.0	1.7	4.5	-1.2	1.8	-0.6	3.5	3.6	2.0	0.3	8.0
D2	4.0	9.3	1.8	7.5	-1.7	-7.0	0.7	-5.0	-6.0	-1.6	-2.8	-1.0
D3	10.0	-0.3	2.4	-6.4	-0.5	-10.6	0.0	-10.8	0.0	-14.7	4.5	-6.6
D4	12.0	2.0	4.2	-4.8	8.7	-7.5	9.0	-18.1	6.2	-11.1	5.5	-1.0
		*	Λ	*		*	o	*		*	u	*
A1	-10.3	-8.2	-10.8	-7.0	-6.8	-4.2	-11.0	-5.0	-10.2	-4.0	-7.8	-3.5
A2	-13.5	-14.7	-13.6	-14.7	-14.4	-16.7	-13.0	-13.0	-12.2	-13.0	-8.7	-10.1
A3	-6.2	-2.8	-5.0	-2.9	7.8	2.5	2.0	-0.5	3.2	2.3	10.2	9.3
A4	-8.8	-10.8	-9.3	-10.7	-1.2	-2.1	-6.3	-7.1	-6.6	-7.6	-3.2	-5.0
B1	-3.5	11.0	-4.5	10.5	4.8	19.4	-1.0	14.0	1.2	15.5	8.2	16.6
B2	-21.6	-13.3	-20.3	-14.6	-16.3	-10.2	-18.8	-13.2	-19.8	-13.0	-17.3	-11.0
B3	-19.2	-13.0	-20.1	-13.0	-13.2	-8.5	-16.7	-11.3	-17.0	-11.5	-11.7	-5.0
B4	-5.5	-5.7	-6.2	-6.2	-1.2	-1.4	-3.5	-3.7	-2.2	-4.1	-0.2	-7.0
C1	-12.1	-1.0	-15.5	-3.6	-6.1	5.1	-11.6	3.3	-12.2	1.2	-4.8	10.5
C2	-10.2	-6.5	-12.3	-8.2	-4.8	4.0	-9.6	-3.3	-7.5	-1.8	2.0	6.7
C3	-9.5	-15.3	-11.3	-17.2	-1.1	-14.7	-7.6	-21.3	-4.1	-17.2	-3.7	-18.0
C4	-1.1	-16.8	-1.6	-16.6	5.5	-11.6	2.0	-15.8	3.1	-14.6	5.0	-15.8
D1	-3.1	8.0	-3.6	6.5	-9.5	7.0	-9.0	7.8	-4.2	8.0	7.8	11.0
D2	-0.5	-5.8	0.8	-2.3	4.4	5.0	2.1	4.6	6.6	1.3	8.8	6.1
D3	5.4	-4.5	6.0	-6.5	7.8	-4.0	8.6	-3.5	7.0	-2.5	10.5	-1.5
D4	3.4	0.2	6.0	-2.5	8.6	-2.3	5.0	-1.5	7.8	-1.0	6.0	0.0

*Indicates retest score.

APPENDIX G.--Continued. Subject 3--Mesomorph.

Positions	i	*	I	*	e	*	ε	*		*	a	*
A1	-0.5	-19.0	-8.3	-17.7	-13.5	-20.2	-16.2	-22.7	-19.3	-25.7	-22.2	-26.4
A2	-9.0	-8.0	-10.6	-10.0	-11.3	-9.5	-15.2	-14.6	-16.6	-13.5	-21.8	-16.4
A3	0.3	3.6	-2.5	3.0	-5.2	-3.5	-9.0	-6.2	-12.2	-8.2	-15.0	-10.3
A4	7.4	6.0	11.0	10.1	3.7	2.0	-0.2	0.0	-4.8	-3.6	-6.8	-5.8
B1	1.2	0.0	1.0	-4.4	-1.5	-5.8	-4.8	-8.6	-10.8	-11.3	-12.8	-13.8
B2	-5.0	-11.5	-8.0	-13.8	-9.0	-16.4	-10.3	-19.4	-13.0	-21.2	-13.2	-20.0
B3	-13.5	-11.5	-11.4	-10.5	-16.4	-11.5	-18.5	-13.5	-20.3	-16.6	-19.3	-16.0
B4	-21.0	-17.7	-19.3	-18.6	-22.6	-19.2	-23.4	-20.0	-22.5	-22.8	-22.8	-22.8
C1	10.2	5.4	5.0	3.4	3.1	2.0	-2.3	-2.3	-9.0	-5.6	-7.0	-11.0
C2	11.7	4.6	6.0	-1.0	3.3	-2.0	-1.5	-6.0	-2.3	-8.7	-6.5	-14.0
C3	2.2	-5.0	-2.5	-9.6	-5.2	-11.5	-7.5	-14.0	-11.2	-15.8	-9.0	-18.8
C4	-27.2	-15.0	-27.9	-18.6	-27.0	-18.0	-27.0	-19.5	-27.0	-20.5	-27.0	-21.0
D1	-18.3	13.0	-25.8	2.1	-21.2	9.5	-23.0	2.0	-25.7	1.5	-25.2	-1.5
D2	-1.7	0.0	-4.0	-6.0	-4.0	-10.3	-7.5	-10.0	-11.0	-10.0	-10.0	-13.3
D3	-4.7	-4.7	-7.1	-5.1	-6.5	-8.3	-10.5	-9.0	-12.5	-9.5	-10.5	-10.7
D4	11.0	-8.3	8.7	-11.0	9.0	-15.2	4.0	-16.5	2.2	-17.0	2.7	-17.0

Positions		*		*	Λ	*	o	*		*	u	*
A1	-16.8	-25.2	-23.0	-24.5	-17.8	-22.2	-16.6	-20.5	-18.5	-21.5	-10.0	-16.5
A2	-16.4	-14.5	-20.0	-13.7	-16.8	-10.6	-15.4	-10.0	-16.7	-11.0	-9.7	-5.5
A3	-10.2	-8.2	-12.6	-9.7	-11.5	-3.2	-8.3	-1.5	-9.8	-2.7	-2.0	3.0
A4	-3.4	-1.0	-7.4	-6.0	-0.8	-0.1	-1.5	-2.0	-2.1	-1.9	2.3	5.0
B1	-10.8	-13.8	-11.2	-12.7	-9.1	-9.2	-12.3	-10.2	-10.1	-9.8	-3.5	-1.7
B2	-12.0	-18.7	-12.0	-18.8	-9.8	-17.6	-9.7	-17.0	-9.0	-17.7	-3.0	-12.5
B3	-20.3	-13.5	-19.0	-12.7	-19.4	-10.2	-19.2	-11.0	-18.6	-11.5	-14.1	-8.0
B4	-23.5	-21.8	-23.0	-21.0	-23.6	-20.0	-24.0	-20.6	-22.1	-23.0	-23.1	-16.8
C1	-5.0	-9.0	-10.7	-8.2	-0.8	-2.0	-2.0	-2.5	-2.7	-2.5	7.2	5.5
C2	-5.2	-13.0	-5.7	-12.7	-2.0	-7.0	-3.2	-7.5	-5.3	-7.0	-6.7	1.0
C3	-8.1	-18.6	-12.2	-17.3	-5.4	-13.0	-7.0	-15.0	-8.5	-15.0	-0.3	-8.6
C4	-27.0	-21.2	-27.0	-21.6	-27.0	-18.6	-27.0	-19.7	-27.0	-20.3	-27.0	-19.0
D1	-27.0	-3.5	-20.2	-3.2	-11.4	2.0	-13.7	1.2	-14.4	0.0	-3.2	6.0
D2	-6.7	-11.3	-6.4	-14.3	-6.0	-14.0	-5.2	-12.0	-6.5	-13.0	-2.0	-7.0
D3	-8.7	-7.0	-9.0	-6.6	-9.4	-5.5	-7.5	-4.6	-8.1	-6.0	-4.6	-2.0
D4	5.2	-15.0	6.0	-13.5	7.4	-13.5	8.0	-13.0	6.7	-13.0	12.0	-8.5

*Indicates retest score.

APPENDIX G.--Continued. Subject 4--Mesomorph.

Positions	Vowels											
	i	*	I	*	e	*	ε	*		*	a	*
A1	-8.8	-7.2	-16.6	-18.7	-11.7	-15.5	-19.8	-21.0	-21.4	-20.2	-20.0	-22.0
A2	-25.2	3.6	-30.0	-7.0	-26.3	4.3	-30.0	-9.3	-30.0	-10.3	-30.0	-10.0
A3	4.0	-3.5	-5.2	-10.8	-0.8	-7.5	-9.7	-10.8	-10.4	-11.0	-9.8	-10.6
A4	12.6	10.0	2.3	-0.3	6.2	1.3	-1.7	3.4	-3.0	-4.5	-4.4	-4.5
B1	-0.9	11.0	-5.8	-2.7	1.3	2.7	-10.8	5.5	-7.6	-7.0	-8.4	-5.0
B2	-21.0	-8.1	-25.1	-20.1	-23.5	-17.6	-25.4	-20.0	-25.5	-19.8	-25.7	-16.5
B3	-18.5	-8.6	-21.0	-20.5	-19.3	-19.5	-21.5	-23.0	-20.6	-23.6	-20.4	-22.7
B4	-18.9	2.1	-22.1	-8.7	-20.9	-5.7	-21.6	-11.6	-21.2	-11.8	-21.6	-10.1
C1	12.7	6.0	-2.0	-4.6	0.4	-5.0	-5.4	-9.2	-5.8	-8.3	-7.8	-11.8
C2	-2.2	6.1	-13.7	-5.5	-11.2	-5.5	-15.7	-11.3	-16.2	-11.4	-17.2	-13.5
C3	-3.0	-6.5	-14.8	-13.0	-13.4	-15.6	-18.4	-17.0	-18.3	-17.7	-18.3	-18.5
C4	-5.0	-5.0	-17.5	-11.5	-16.4	-14.3	-20.2	-15.8	-18.8	-15.8	-18.6	-16.5
D1	1.1	6.5	-11.0	0.1	-9.3	2.5	-18.2	-3.3	-10.8	-7.0	-6.3	-3.0
D2	-5.8	-0.5	-15.1	-10.2	-7.0	-5.0	-13.0	-15.0	-13.8	-16.2	-21.0	-15.3
D3	0.0	0.0	-9.0	-7.5	-5.0	-3.0	-11.3	-13.7	-10.7	-13.6	-7.2	-12.0
D4	-4.5	-2.0	-12.4	-9.5	-6.8	-7.0	-15.4	-11.3	-16.6	-13.5	-11.5	-10.2
		*	ʌ	*		*	o	*		*	u	*
A1	-18.8	-19.8	-21.0	-20.8	-15.3	-17.8	-16.2	-16.7	-17.6	-19.3	-9.0	-10.0
A2	-30.0	-10.0	-30.0	-10.0	-26.0	-4.0	-25.8	-3.3	-26.6	-5.5	-26.4	1.3
A3	-8.6	-11.3	-7.0	-10.7	-2.6	-8.6	-1.0	-5.5	-3.6	-8.1	-6.5	-4.2
A4	-3.7	-3.3	-1.8	-3.2	4.7	-2.3	4.5	4.2	0.5	1.5	10.0	9.5
B1	-6.7	-4.0	-7.0	-5.1	0.0	0.5	4.0	5.5	-1.6	0.0	5.4	5.5
B2	-24.5	-15.0	-25.1	-17.0	-22.1	-13.0	-21.2	-11.1	-23.8	-15.3	-18.6	-11.6
B3	-19.0	-21.0	-18.8	-23.7	-16.8	-18.5	-17.0	-16.7	-17.7	-20.6	-17.3	-17.5
B4	-21.0	-7.2	-20.6	-10.5	-17.7	-4.8	-18.5	-4.2	-18.3	-7.1	-18.1	-2.5
C1	-5.6	-12.3	-7.6	-13.6	0.0	-6.5	-1.0	-4.0	-4.5	-8.0	7.0	2.2
C2	-17.6	-14.3	-18.6	-15.0	-13.0	-8.4	-13.5	-6.2	-17.5	-11.3	-8.5	-1.6
C3	-16.5	-19.0	-17.5	-20.1	-11.2	-15.0	-13.3	-15.7	-14.2	-17.0	-10.3	-13.0
C4	-18.2	-16.6	-19.6	-16.9	-14.2	-14.0	-17.1	-13.5	-18.0	-15.7	-12.7	-11.3
D1	-7.0	0.0	-11.5	-2.5	1.7	4.0	0.0	3.0	-4.0	2.0	5.5	2.5
D2	-20.6	-15.0	-25.8	-21.5	-20.5	-20.6	-20.4	-25.0	-22.2	-26.7	-14.3	-21.8
D3	-6.2	-5.1	-13.7	-7.5	-8.3	-3.5	-6.0	-4.6	-11.0	-6.2	-3.5	-1.7
D4	-10.0	-9.0	-15.5	-11.0	-12.0	-7.5	-17.0	-8.5	-14.2	-9.5	-7.0	-4.6

*Indicates retest score.

APPENDIX G.--Continued. Subject 5--Endomorph.

	Vowels											
Positions	i	*	I	*	E	*		*		*	a	*
A1	-7.4	8.5	-10.5	1.0	-11.3	-1.6	-16.5	-6.1	-17.7	-6.0	-17.6	-5.3
A2	-1.0	7.0	-5.6	0.0	-9.7	-2.1	-13.5	-6.5	-14.3	-6.6	-13.2	-6.5
A3	4.5	5.0	0.4	1.0	1.5	0.6	-4.6	-5.2	-5.5	-5.1	-6.7	-5.7
A4	6.5	0.0	3.5	-6.5	2.3	-8.0	-1.0	-12.7	-2.2	-13.3	-2.2	-13.6
B1	6.8	7.6	3.2	2.5	1.2	1.3	-1.7	-3.7	-3.7	-6.5	-4.0	-5.7
B2	-11.7	-8.3	-15.2	-16.0	-17.0	-16.3	-19.1	-21.2	-19.8	-21.6	-18.7	-21.0
B3	-11.0	-2.0	-12.2	-9.3	-13.8	-9.0	-15.8	-13.0	-17.0	-13.3	-15.5	-13.5
B4	-7.7	-14.0	-11.4	-18.6	-12.5	-17.7	-13.8	-20.0	-13.7	-20.2	-12.1	-14.6
C1	1.0	11.0	-7.2	4.0	-7.2	2.5	-13.0	-3.1	-14.0	-5.3	-14.2	-5.6
C2	-9.7	10.0	-18.0	1.6	-16.3	0.6	-22.0	-5.1	-21.8	-8.5	-23.2	-8.0
C3	-8.1	-3.3	-14.4	-10.0	-16.8	-12.5	-18.0	-15.5	-19.7	-17.1	-18.6	-16.2
C4	-5.8	-10.5	-13.6	-16.8	-14.6	-18.0	-16.4	-20.2	-18.5	-22.0	-17.6	-21.0
D1	18.7	17.5	5.2	9.5	5.6	9.5	0.7	7.0	-2.5	6.5	-5.0	4.5
D2	-5.0	10.5	-14.2	9.3	-15.4	9.5	-18.0	5.0	-16.3	5.0	-14.7	4.0
D3	15.6	-2.0	10.0	-7.6	6.6	-7.0	4.8	-11.0	3.5	-11.5	5.0	-11.0
D4	3.6	6.0	3.0	-0.6	-3.2	-1.0	-7.3	-4.0	-6.0	-4.0	-5.8	-4.1
		*	ʌ	*		*	o	*		*	u	*
A1	-17.5	-4.2	-17.0	-3.0	-10.2	-1.0	-11.7	-1.3	-12.0	-2.1	-10.0	2.5
A2	-13.5	-5.1	-12.5	-4.5	-9.0	-1.6	-10.7	-3.0	-10.6	-3.1	-3.7	0.9
A3	-7.4	-5.3	-3.6	-4.7	4.0	-0.8	4.0	-3.0	1.0	-2.5	6.4	2.0
A4	-2.6	-12.7	-0.5	-12.0	4.0	-11.3	2.5	-8.0	1.6	-8.0	10.0	-2.5
B1	-4.4	-7.6	-6.4	-4.3	3.8	2.7	2.2	2.3	2.1	2.5	4.5	5.8
B2	-19.2	-22.3	-20.2	-21.0	-16.0	-16.5	-17.0	-18.6	-17.0	-19.0	-12.0	-15.0
B3	-16.4	-14.7	-15.1	-13.7	-10.8	-10.7	-13.0	-10.5	-14.0	-11.0	-10.0	-14.0
B4	-9.8	-20.8	-13.7	-20.8	-10.7	-18.0	-11.6	-16.3	-12.8	-17.5	-13.5	-20.0
C1	-13.2	-5.0	-13.4	-5.1	7.5	2.1	-10.0	-0.6	-11.2	-1.0	-8.0	6.3
C2	-23.2	-6.8	-23.0	-9.0	-20.1	-1.0	-22.0	-3.	-21.8	-3.2	-15.0	3.3
C3	-17.0	-17.0	-18.0	-16.6	-14.5	-13.0	-15.5	-14.0	-16.3	-14.5	-11.4	-10.5
C4	-16.7	-21.0	-17.1	-22.1	-14.1	-19.1	-14.7	-18.1	-16.1	-20.0	-11.0	-18.5
D1	-5.0	2.5	-6.1	4.2	-0.5	3.0	-5.4	3.5	-5.6	5.0	2.5	9.3
D2	-14.3	3.7	-15.5	3.9	-13.6	7.7	-17.1	6.0	-15.6	6.0	-10.2	11.5
D3	5.7	-9.1	4.2	-10.0	9.0	-8.0	8.0	-7.4	6.3	-7.6	6.5	-4.8
D4	-7.2	-3.7	-6.2	-4.1	-3.7	-2.4	-1.3	-1.5	-3.0	-1.5	3.0	1.0

*Indicates retest score.

APPENDIX G.--Continued. Subject 6--Endomorph.

Positions	Vowels											
	i	*	I	*	e	*		*		*	a	*
A1	6.1	-0.5	-4.2	3.0	-8.8	-0.5	-7.2	-4.6	-8.0	-7.5	-9.2	-10.5
A2	-21.1	-1.0	-26.0	-5.5	-24.5	-5.5	-26.5	-8.4	-28.2	-8.0	-27.1	-7.5
A3	9.0	2.3	3.5	1.8	2.5	-1.1	0.0	-4.6	-4.7	-7.6	-1.2	-8.1
A4	3.3	9.5	2.8	3.5	1.8	3.5	0.5	1.5	-3.3	0.8	-4.3	1.0
B1	-1.5	6.0	-0.8	2.5	-2.4	-0.2	-2.6	-3.0	-4.2	-7.1	-3.0	-5.8
B2	-2.3	-2.2	-7.7	-8.0	-15.2	-7.5	-17.0	-9.0	-19.5	-10.0	-18.8	-7.5
B3	5.0	-15.0	-1.7	-17.8	-2.0	-17.0	-5.0	-18.1	-9.4	-17.6	-7.4	-19.1
B4	-9.0	-3.1	-12.4	-8.4	-15.0	-8.0	-16.6	-9.0	-17.3	-10.0	-16.7	-10.0
C1	13.5	12.0	0.0	5.0	-2.7	4.6	-10.0	1.0	-12.7	-2.5	-17.5	-8.1
C2	6.2	9.7	-18.2	0.0	-10.7	-1.6	-18.2	-4.5	-24.4	-9.5	-23.7	-10.0
C3	-1.0	12.0	-7.5	5.0	-8.0	4.6	-11.5	4.0	-11.5	1.7	-13.0	0.0
C4	2.5	1.5	-4.2	-6.7	-3.3	-7.0	-7.5	-8.6	-11.4	-10.6	-11.5	-15.6
D1	19.5	7.0	16.5	13.0	13.9	13.1	12.7	10.1	17.0	9.3	8.6	10.0
D2	3.0	1.5	-7.5	-5.2	-11.0	-7.0	-15.0	-13.0	-15.0	-12.3	-17.9	-12.1
D3	-2.4	2.0	-10.9	-1.6	-12.0	-2.6	-15.0	-4.1	-16.9	-7.3	-13.1	-5.3
D4	-2.0	5.5	-10.2	1.1	-10.0	-0.3	-12.0	1.0	-13.8	2.5	-9.5	3.5
		*	Λ	*		*	o	*		*	u	*
A1	-7.7	-8.1	-8.0	-7.5	-2.8	-5.5	-4.2	-3.6	-4.5	4.0	-4.0	0.0
A2	-25.7	-7.0	-26.0	-5.0	-24.4	-4.0	-25.0	-4.0	-26.1	-7.0	-23.1	-3.0
A3	0.6	-5.5	-1.0	-4.6	1.2	-1.7	-1.0	-2.6	-4.0	-3.0	1.7	-1.4
A4	-4.2	3.0	-1.9	4.5	3.6	5.5	1.8	5.5	3.0	3.0	6.0	7.0
B1	-2.4	-4.6	-4.6	-4.9	-0.5	3.6	-0.6	1.5	-1.3	0.0	2.5	7.0
B2	-17.6	-6.0	-17.8	-6.0	-13.2	-2.6	-15.5	-3.0	-15.7	-5.0	-9.7	-2.4
B3	-7.0	-19.3	-4.2	-21.3	0.0	-20.1	-3.0	-18.9	-1.7	-21.0	1.0	-16.6
B4	-17.0	-8.1	-17.0	-7.5	-15.0	-4.0	-16.9	-5.0	-17.0	-7.3	-18.0	-4.0
C1	-15.7	-8.0	-13.8	-6.0	-4.5	4.7	-10.0	-1.0	-6.8	-3.0	2.5	3.6
C2	-24.4	-10.1	-22.0	-8.1	-12.7	0.5	-15.0	-4.2	-10.0	-5.3	-3.2	4.6
C3	-13.5	-0.5	-15.6	0.0	-13.2	5.7	-18.3	2.0	-15.0	1.8	-11.8	8.6
C4	-10.6	-18.1	-11.5	-16.9	-8.2	-7.0	-9.4	-15.0	-10.0	-15.0	-8.0	-6.0
D1	-1.7	11.1	13.5	10.6	17.5	8.1	13.5	12.5	12.5	11.6	14.3	16.0
D2	-13.0	-6.4	-14.0	0.0	-15.4	-4.4	-14.2	-1.7	-14.7	-1.0	-5.6	6.0
D3	-13.7	-2.7	-8.8	-3.4	-10.0	-1.0	-7.0	-1.3	-7.5	-4.0	-4.7	1.0
D4	-8.6	3.1	-11.5	2.3	-11.2	3.4	-3.7	4.5	-6.0	1.7	-4.6	5.5

*Indicates retest score.

APPENDIX H

MEAN RELATIVE SOUND PRESSURE SCORES

FOR EACH BODY TYPE

APPENDIX H.--Mean relative sound pressure scores for ectomorphs.

	Vowels											
Positions	i	I	e	ε		a		Λ		o		u
A1	-11.9	-16.5	-20.0	-18.7	-21.8	-18.3	-17.1	-18.4	-14.9	-16.7	-16.9	-16.4
A2	-11.5	-14.7	-15.4	-16.3	-16.8	-17.1	-14.9	-16.6	-14.9	-14.2	-14.3	-12.2
A3	-8.6	1.7	-0.5	-6.1	-7.8	-7.5	-6.3	-7.8	1.9	-0.5	-1.0	3.4
A4	4.4	0.5	-0.7	3.0	-5.2	-5.4	-3.0	-4.6	1.4	-0.7	-1.8	2.9
B1	1.5	-6.5	-9.3	-18.8	-15.3	-13.8	-12.2	-13.7	-6.7	-9.4	-8.8	-1.4
B2	-16.3	-20.5	-21.2	-22.6	-23.4	-23.2	-22.5	-22.2	-18.6	-15.1	-21.4	-19.3
B3	-17.0	-12.7	-15.9	-19.7	-21.1	-19.7	-19.0	-19.8	-15.2	-12.6	-18.6	-15.2
B4	-2.2	-6.5	-8.8	-10.1	-11.3	-10.1	-7.5	-9.6	-6.8	-6.1	-6.2	-5.1
C1	5.9	0.8	-0.7	-6.7	-6.1	-10.7	-7.8	-10.9	-2.3	-6.8	-7.1	-2.3
C2	8.0	-0.7	-1.1	-8.1	-8.5	-11.4	-9.0	-11.9	-3.8	-7.1	-6.8	3.4
C3	-5.9	-11.3	-13.1	-16.4	-20.4	-20.3	-16.3	-17.8	-11.3	-15.1	-13.3	-10.1
C4	5.5	-3.2	2.7	-4.1	-3.9	-5.7	-3.0	-3.7	1.5	-1.1	-4.0	3.9
D1	3.3	-1.3	-2.6	-4.8	-4.9	-7.5	-9.3	-6.9	-8.7	-10.0	-8.3	4.5
D2	-2.5	-5.8	-10.1	-10.1	-13.7	-7.0	-5.2	-7.5	-8.3	-7.9	-7.7	2.5
D3	2.5	-3.3	-5.9	-6.2	-7.0	-2.4	-1.4	-2.7	-3.6	-0.8	-4.6	0.1
D4	2.2	-4.1	-1.8	0.7	-6.2	-2.7	-6.7	-4.1	-3.2	-3.2	-2.9	-3.0

APPENDIX H.--Continued. Mesomorphs.

Positions	Vowels											
	i	I	e	ε		a		Λ		o		u
A1	-4.6	-12.3	-12.6	-18.0	-20.3	-21.1	-17.4	-23.0	-16.6	-16.4	-17.5	-9.5
A2	-17.1	-20.3	-18.8	-22.6	-23.3	-25.9	-23.2	-25.0	-21.4	-20.6	-21.6	-18.5
A3	2.1	-3.8	-3.0	-9.3	-11.3	-12.4	-9.4	-9.8	-17.1	-4.6	-6.7	2.2
A4	10.0	6.6	4.9	-0.9	-3.9	-5.6	-3.5	-4.6	1.9	1.5	-0.8	6.1
B1	0.1	-2.4	-0.1	-7.8	-9.2	-10.5	-8.7	-9.1	-4.5	-12.3	-5.8	0.9
B2	-13.0	-16.5	-16.2	-17.8	-19.7	-19.4	-18.2	-18.5	-15.6	-15.4	-16.4	-10.8
B3	-16.0	-16.2	-17.8	-20.0	-20.4	-19.8	-19.6	-18.9	-18.6	-18.1	-18.1	-15.7
B4	-19.9	-20.7	-21.7	-22.5	-21.8	-22.2	-22.2	-21.8	-20.6	-21.2	-20.2	-20.6
C1	11.4	1.5	1.7	-3.8	-7.4	-7.4	-5.3	-9.6	-0.4	-1.5	-3.6	7.1
C2	4.7	-3.8	-4.2	-8.6	-9.2	-11.4	-11.1	-12.6	-2.0	-8.3	-11.4	-0.9
C3	-0.6	-8.6	-9.3	-12.9	-14.7	-18.6	-12.3	-14.8	-8.3	-10.1	-11.3	-5.3
C4	-16.1	-22.2	-21.7	-23.7	-22.9	-22.8	-22.6	-23.0	-20.0	-22.1	-22.5	-14.8
D1	-8.6	-18.4	-15.2	-20.6	-18.2	-16.0	-17.0	-15.7	-6.5	-6.7	-9.2	1.2
D2	-3.7	-9.5	-5.5	-10.2	-12.4	-15.5	-13.6	-16.1	-13.2	-12.8	-14.3	-8.1
D3	-2.3	-8.1	-5.7	-10.9	-11.6	-8.8	-7.4	-11.3	-8.8	-6.7	-9.5	-4.1
D4	3.7	-1.8	1.1	-5.7	-7.2	-4.4	-2.4	-4.7	-9.7	-12.5	-3.7	2.5

APPENDIX H.--Continued. Endomorphs.

	Vowels											
Positions	i	I	e	ε		a		ʌ		o		u
A1	-0.7	-7.3	-10.1	-11.8	-12.8	-14.4	-12.6	-12.5	-6.5	-7.8	-8.2	-3.0
A2	-11.1	-15.8	-17.1	-20.0	-21.2	-20.1	-19.6	-14.2	-16.7	-17.8	-18.3	-13.4
A3	6.6	2.9	2.0	-2.3	-5.1	-3.9	-4.0	-2.3	2.6	1.5	-1.5	4.1
A4	4.9	3.1	2.1	-0.2	-2.7	-3.2	-3.4	-1.2	3.8	2.1	2.3	8.0
B1	2.6	1.2	-0.6	-2.1	-3.9	-3.5	-3.4	-5.5	1.6	0.8	0.4	3.5
B2	-7.0	-11.3	-16.1	-18.5	-19.6	-18.7	-18.9	-18.5	-14.6	-16.2	-16.3	-10.8
B3	-3.0	-13.2	-7.9	-10.4	-13.2	-11.5	-11.7	-9.6	-5.4	-8.0	-7.8	-4.5
B4	-8.3	-11.9	-13.7	-15.2	-15.0	-14.4	-13.4	-15.3	-12.8	-14.2	-14.6	-15.7
C1	1.0	7.2	-7.2	-3.6	-7.2	-15.8	-14.4	-13.6	-6.0	-10.0	-8.6	-2.7
C2	-1.7	-18.1	-13.5	-20.1	-23.1	-23.4	-23.8	-22.5	-16.4	-18.5	-15.9	-9.1
C3	-4.3	-10.9	-12.3	-14.7	-15.6	-15.8	-15.2	-16.6	-13.8	-16.6	-15.6	-11.6
C4	-1.6	-8.9	-8.9	-11.8	-14.9	-14.5	-13.6	-14.3	-11.1	-12.1	-13.1	-9.5
D1	19.1	10.8	9.7	6.7	7.2	1.8	-3.3	3.7	8.5	4.1	3.4	8.4
D2	-1.5	-10.8	-13.2	-16.5	-15.6	-16.3	-13.6	-9.7	-14.5	-15.6	-15.1	-10.2
D3	6.6	-0.4	-2.7	-5.1	-6.7	-4.1	-4.0	-2.3	-0.5	0.5	-0.6	0.9
D4	0.8	-6.6	-6.6	-9.6	-9.9	-7.6	-7.9	-2.6	-7.4	-2.5	-4.5	-3.8

APPENDIX I

MEAN RELATIVE SOUND PRESSURE SCORES

FOR ALL SUBJECTS

APPENDIX I.--Mean relative sound pressure scores for all subjects.

	Vowels											
Positions	i	I	e	ε		a		Λ		o		u
A1	-5.7	-12.1	-14.3	-16.1	-18.3	-17.9	-15.8	-17.6	-13.0	-13.7	-14.4	-9.6
A2	-13.2	-16.9	-17.1	-19.7	-20.5	-21.1	-19.2	-20.0	-17.6	-15.4	-18.1	-14.1
A3	3.3	-0.1	-0.5	-5.9	-8.1	-7.8	-6.3	-6.6	-0.8	-1.2	-1.6	3.3
A4	4.7	3.4	2.1	-1.3	-4.1	-4.5	-3.3	-3.1	2.4	0.9	-0.1	5.5
B1	3.7	-2.5	-3.3	-7.9	-9.4	-9.3	-8.1	-9.4	-2.9	-4.2	-4.7	1.2
B2	-12.1	-16.1	-17.8	-19.5	-20.7	-20.1	-19.7	-19.9	-16.3	-17.2	-8.0	-13.6
B3	-8.5	-11.9	-13.9	-16.7	-18.2	-16.8	-16.7	-16.1	-12.9	-14.5	-14.8	-11.8
B4	-10.1	-13.3	-14.7	-15.9	-16.2	-15.5	-14.2	-15.5	-13.4	-13.8	-13.7	-13.8
C1	8.2	-0.4	0.1	-7.2	-8.9	-11.3	-11.1	-11.8	-2.9	-6.0	-6.4	2.1
C2	3.6	-7.5	-6.1	-12.4	-13.6	-15.5	-14.6	-15.5	-9.2	-11.3	-11.3	-2.2
C3	-3.1	-9.8	-11.6	-14.6	-16.6	-16.5	-14.6	-16.6	-11.1	-12.0	-13.4	-9.0
C4	-4.0	-9.4	-9.9	-13.2	-13.9	-11.5	-13.0	-13.6	-10.0	-11.7	-12.0	-10.2
D1	4.6	-2.4	-1.1	-3.2	-3.9	-7.2	-9.0	-6.2	-7.2	-4.1	-4.7	4.6
D2	-2.4	-7.1	-9.6	-11.7	-13.9	-12.9	-10.6	-12.7	-12.0	-12.1	-12.4	-4.5
D3	2.2	-3.9	-0.7	-7.4	-8.4	-5.1	-4.2	-5.4	-4.3	-2.1	-0.5	-1.0
D4	2.3	-4.1	-2.9	-5.0	-7.7	-4.9	-4.6	-5.8	-7.1	-3.4	-3.7	-1.4