THE EFFECT OF STATIC AIR PRESSURE IN THE
EXTERNAL AUDITORY MEATUS ON HEARING ACUITY

DISSERTATION

Presented in Partial Fulfillment of the Requirements
for the Degree Doctor of Philosophy in the
Graduate School of The Ohio State
University

By

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1954

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ACKNOWLEDGMENT

Acknowledgment is due Major Horace O. Parrack, Chief of the Bioacoustic Section, Aero Medical Laboratory, Wright-Patterson Air Force Base, for his cooperation and helpfulness in making available the physical facilities in which this study was conducted, and to Dr. Henning von Gierke of the same Laboratory for his suggestions and advice on experimental procedure.

The writer is grateful to Dr. John W. Black, Department of Speech, The Ohio State University, for his guidance and counsel in the design and early stages of the study.

I am especially grateful to Dr. Dorothy H. Sherman, Department of Speech, The Ohio State University, who assumed the responsibility as adviser in the latter stages of the study. Her advice on statistical analyses and the careful editing of the manuscript were invaluable.

I also wish to thank the staff members of the Aero Medical Laboratory who served as subjects.

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CHAPTER I

INTRODUCTION AND STATEMENT OF PROBLEM

Introduction

A pressure differential across the tympanic membrane is produced with changes of atmospheric pressure, most commonly associated with variations of altitude, when the Eustachian tube remains closed. The tympanic membrane is displaced inward or outward according to the increase or decrease of atmospheric pressure. These effects, however, are usually slight and transitory because the act of swallowing opens the Eustachian tube and equalizes the pressure in the middle ear cavity which permits the tympanic membrane to return to its normal position. If the Eustachian tube remains closed temporarily, as it might with a head cold or with a sudden change in altitude, a pressure differential between the middle ear cavity and the external auditory meatus is produced. The question then arises as to the extent of the effect on hearing acuity of a pressure differential across the tympanic membrane.

A review of the literature reveals two methods to apply static air pressure to the tympanic membrane experimentally: (1) through the Eustachian tube into the middle ear and (2) through the external auditory meatus.

Rasmussen¹ reviews the early work on pressure in the

¹ Helmer Rasmussen. "Studies on the Effect Upon the Hearing Through Air Conduction Brought about by Variations of the Pressure in the Auditory Meatus." Acta Oto-Laryngologica. 34 (1946), p.p. 415-25.

middle ear and he notes that Bezold in 1888 and Siebenmann in 1892, both using tuning forks for the sound stimuli and the Valsalva* procedure to introduce the pressures in the

* The Valsalva procedure consists of closing the mouth and nostrils and trying to exhale thus forcing the air through the Eustachian tube into the middle ear cavity. This procedure produces a positive pressure on the eardrum. A negative pressure is produced by making an effort to inhale. The subject must refrain from swallowing during the test in order to keep from equalizing the pressure.

middle ear, found that for high tones a "negative Valsalva" caused a loss of hearing while a "positive Valsalva" often gave a slight improvement.

Fowler² in 1920 applied pressures through a cannula

² E. P. Fowler. "Drum Tension and Middle Ear Air Pressures, Their Determination, Significance and Effect on Hearing," Annals of Otology Rhinology and Laryngology. 29, (1920), pp. 688-694.

in the Eustachian tube and reported that hearing was reduced by both air and bone conduction and was especially marked for low tones.

Loch,³ using the Valsalva procedure made audiometer

³ M. D. Loch, "Effect of Experimentally Altered Air Pressure in the Middle Ear on Hearing Acuity in Man," Annals of Otology, Rhinology and Laryngology. 51 (December, 1942), pp. 995-1006.

tests before and after each pressure condition on six normal subjects. By using one manometer in the external auditory canal and another in the nostril of the opposite side, he was able to determine that some pressures were greater than others but he could not determine by what amount. He grouped the pressure changes as "slight," between 5 and 20 mm of mercury, and "moderate" between 20 and 50 mm of mercury. He concluded that for both positive and negative pressures of moderate degree, thresholds for frequencies of 32 to 1024 cps were impaired by as much as 20-30 db and for the frequencies of 2048 and 2896 cps, by as much as 10 to 15 db. He also stated that neither positive nor negative pressures had much effect on thresholds for 4096 and 5793 cps and that thresholds for the higher frequencies were improved slightly under positive pressure and were impaired slightly under negative pressure.

Wever⁴ also summarizes the work on pressure in the

⁴ E. G. Wever and M. Lawrence, "Physiological Acoustics," Princeton New Jersey, Princeton University Press, 1954, pp. 203-8.

middle ear and he reports several animal experiments. (1) Kobrak with rabbits introduced pressure into one bulla while observing the tensor reflex on the opposite side and found moderate reductions for all tones used. (2) Thompson, Howe and Hughson in experiments on cats, using the electrical potentials of the ear as the indicator, introduced pressure either into the bulla or the Eustachian tube and obtained reductions for positive and negative pressures up to 50 mm of mercury. (3) Wever, Gray, and Lawrence made further experiments on cats using the cochlear potential method. They bored two small holes into the bulla through which pressure was introduced and the effects of positive pressures up to 50 mm of mercury were observed for tones from 100 to 10,000 cps. In general the responses were diminished on the application of pressure.

As early as 1872, Mach and Kessel⁵ investigated the

⁵ E. Mach and J. Kessel, "Die Function der Trommelhöhle und der Tuba Eustachii, Sitzungsber. Acad. Wiss. Wien, math.-nat. Cl., Abt. 3. 1872, 66 329-336 (cited in Rasmussen).

influence on hearing of overpressure in the auditory meatus. For their studies they employed a pneumatic chamber with an overpressure corresponding to a pressure of 14 cm of water in the external auditory meatus. They used themselves as subjects and found, in general, a weakening of the loudness of all tones with the most pronounced effect on hearing

for the low tones.

In 1921 Griessman,⁶ using normal subjects, found that

⁶ B. Griessmann. Beitr. z. Anat., Physiolo., Path. U. Therap. d. Ohres. 16: 47 1921 (cited in Rasmussen, page 415).

with positive pressure in the auditory meatus tones at threshold value rapidly decreased in intensity and then became inaudible. Griessman employed a so-called pneumatic telephone, with a sound proof capsule and two openings, one of which was connected airtightly with the auditory meatus. He used an audiometer for a sound source.

Pohlman and Kranz⁷ in 1925 used a similar experiment-

⁷ A. G. Pohlman and D. Kranz, "The Effect of Pressure changes in the External auditory canal on acuity of Hearing. Annals of Otology, Rhinology and Laryngology. 2 (1923) pp. 545 to 553.

al technique to demonstrate that hearing generally was best at the pressure of zero or a slight negative pressure.

In 1929 von Békésy⁸ found that the loudness of low

⁸ G. von Békésy, "Zur Theorie des Hörens; Ueber die Bestimmung des einem reinen Tonempfinden entsprechenden Erregungsgebietes der Basilar membran vermittelt Ermüdungserscheinungen, Phys. Zeits., (1929 30, 115-115).

tones up to 1000 or 1800 cps was reduced for positive and negative pressures of 10 cm of water pressure in the

auditory meatus. He found a small frequency region around 1800 cps where there was a slight increase in loudness and for higher tones slight or irregular effects. He also reported that an intense tone under pressure is reduced in loudness relatively more than a tone weak in intensity, and explained this variation as due to an exaggeration of the middle ear's nonlinearity. He used himself as a subject.

In 1938 Dishoeck⁹ used an apparatus which he called

⁹ H.A.E. van Dishoeck. Arch. f. Ohren-Nasen u. Kehlkeph. 144. 53, 1938 (cited in Rasmussen).

a "pneumophone" which consisted of an electrical buzzer in a soundproof box with a tube leading to the auditory meatus. He controlled the pressure in the meatus by means of a Politzer bag. He studied both normal and defective ears and determined the pressure values that gave optimum sensitivity. According to Dishoeck, less than one half of the normal subjects showed a pneumophone value of zero and not infrequently values from -4 to -10 cm H₂O as the pressure at which they demonstrated optimal sensitivity.

In 1943 Flodgren¹⁰ modified the Dishoeck pneumophone

¹⁰ E. Flodgren. Nordik Medicin, 20; 2239 1943 (cited in Rasmussen)

using acetylene tetrabromide (which is three times as heavy as water) for fluid in the manometer instead of water. He

demonstrated that in normal subjects the tone became weaker at an overpressure and underpressure of 2 cm.

Rasmussen¹¹ reports that most comprehensive study to

¹¹ Rasmussen, op. cit., p. 416.

date. He used a Dishoeck pneumophone with a glass syringe and like Dishoeck he used acetylene tetrabromide in the manometer to measure the pressure. The sound was produced by an audiometer connected to an amplifier with a perforated membrane within a sound proof box. He used seven frequencies between 64 and 11600 cps. Twenty-nine subjects were used in whom the examined ear was normal. For four frequencies below 1025 cps the tone was heard most distinctly for most subjects at a pressure of zero to -1 cm of acetylene tetrabromide. He states that in a few subjects the zone in which the tone was heard was distinctly wider; at the most, it extended from +12 to -4 cm of acetylene tetrabromide. He also states that the results were more divergent at the frequencies of 2050 and 4100 cps. For frequencies of 8200 and 11600 cps he states that a striking phenomenon was demonstrated. "With increasing underpressure the intensity of the tone decreased or kept unchanged; on increasing overpressure, as a rule, there was first a decrease in the intensity of the tone with a relatively low overpressure, and then the intensity increased with increasing overpressure, in most cases to such an extent that the

intensity was greater than at a pressure of zero."

Early experimental work must be evaluated in terms of the limitations of equipment and the fact that data were gathered only on a few selected frequencies. The need for a complete picture of the effect on hearing acuity as a function of frequency with varying moderate pressure differentials between the middle ear and the external auditory meatus is evident.

Such information would contribute to our knowledge of the theory of middle ear function by describing more fully the role of the tympanic membrane in the transmission of sound through the middle ear.

Information of this type would also be valuable in the evaluation of earplugs. In determining the attenuation characteristics of earplugs the testing is frequently complicated when a negative or a positive static pressure is produced upon insertion of the earplug into the ear canal. When this happens the low frequencies are attenuated more than they are when no pressure is present. This suggests that the coupling of an ear defender with static pressure to provide added protection for the lower frequencies, the region in which all ear defenders are least effective, might be feasible.

There are also a number of practical situations where man has to communicate when there is a pressure differential between the middle ear and the external auditory

meatus such as in some Air Force flying helmets and when the ear is exposed to an underpressure caused by exposure to wind. Rapid changes of altitude as in aircraft landings and take-offs also produce temporary pressure differentials across the tympanic membrane that could possibly affect vital aircraft communication.

Statement of Problem

The present study was conducted to secure data to support or refute the hypothesis that static air pressure in the external auditory meatus decreases hearing acuity. The specific purposes were to determine the effect of pressure on (1) threshold sensitivity, (2) hearing acuity at two loudness levels above threshold, and (3) speech intelligibility.

The hypothesis was tested by (1) obtaining threshold sensitivity values for 41 frequencies under each of five different pressure conditions, (2) obtaining equal loudness balance judgments at two loudness levels above threshold under five pressure conditions, (3) obtaining intelligibility scores under each of five pressure conditions, and (4) treating the resulting data by the technique of analysis of variance to determine whether it is reasonable to assume that real differences exist under the conditions of this experiment.

The particular pressures chosen for this study were

zero (ambient) -10, -20, +10 and +20 cm H₂O pressure. For the threshold sensitivity part of the experiment frequencies at 100 cps intervals from 100 cps to 4000 cps, at 6000 cps and at 8000 cps were selected. To determine the effect of pressure on hearing above threshold, reference loudness levels of 30 db and 60 db above threshold were selected for each of the following frequencies: 200, 400, 1000, 1600, 2000, 4000 cps. The Multiple-Choice Intelligibility Test, Form C, was used in evaluating the effect of pressure on listening to speech.

CHAPTER II

EQUIPMENT AND PROCEDURE

A block diagram of the equipment used to present the test stimuli for (1) threshold sensitivity, (2) equal loudness balance judgments, and (3) speech intelligibility is presented in Figure 1. The equipment is pictured in Figures 2 and 3. All listening sessions were conducted in an anechoic chamber.

Threshold Sensitivity

Instrumentation

Instrumentation for determining threshold values for each of the 41 experimental frequencies combined with each of the 4 experimental pressures included equipment to (1) present and control the sound stimuli, and (2) present and control the static air pressure in the auditory meatus.

Equipment for presenting the sound stimuli. The following equipment was used to control the signal through earphones: (1) a General-Purpose Audiometer, (2) an attenuator-set, (3) an earphone, and (4) a signal key.

The General-Purpose Audiometer¹ was developed at the

¹ Wolf W. von Wittern, H. E. von Gierke, "A General-Purpose Audiometer," WADC Technical Report 53-30, March, 1953.

Figure 1

ARRANGEMENT OF EQUIPMENT

Figure 2

EQUIPMENT OUTSIDE ANECHOIC CHAMBER

1. Air Reservoir	3. Pressure Safety Valve
2. Special Purpose Audiometer	4. Water Manometer
5. Vacuum Pump	

Figure 3

INSIDE ANECHOIC CHAMBER

1. Pressure and Signal Earpiece. 2. Water Manometer
3. Attenuators. 4. Signaling Key.

Ohio. It was used to produce and control the sound stimuli. It utilizes a Hewlett-Packard audio signal generator, model 206-A, to produce the signal. The output was controlled by a calibrated attenuator and an automatic control which switched the signal on for two seconds and off for two seconds. A special feature of this audiometer is the elimination of the objectionable click that accompanies the turning off and on of a tone. Built-in circuit elements permit the attainment of the time constants necessary for a smooth signal envelope and thus eliminate unwanted transients. The output of the attenuator in the audiometer was connected to a Hewlett-Packard, Model 350-B, attenuation-set inside the anechoic chamber.

The ANHB-1 earphone with a 250 ohm impedance matching circuit was connected to the attenuator set. The earphone was located within the pressure earpiece. The earphone was calibrated under the various pressure conditions of the study and the frequency characteristics were found to remain unchanged.

A telegraph key was connected to a sound source and was used to signal from subject to experimenter.

The anechoic chamber had an ambient noise level of 40 db as measured on a General Radio Sound Level Meter, type 1551 C scale.

Equipment for presenting static air pressure. The following equipment was used to present and control static

air pressure in the auditory meatus: (1) an air compressor, (2) a vacuum pump, (3) a safety valve, (4) two water manometers and (5) a pressure earpiece.

There were two pressure sources. The air pressure line in the laboratory was used for the positive pressure source. A manually-controlled oxygen pressure regulated the pressure in a 30 gallon air reservoir tank. Regulating the pressure in the tank prevented pressure changes in the line from being reflected in pressure changes on the eardrum and minimized the amount of adjustment of the manually controlled oxygen pressure valve. The negative pressure source was a Cenco Hyvac vacuum pump which was also connected to the 30 gallon tank. The amount of negative pressure in the reservoir tank and consequently in the auditory meatus was controlled manually by an electrical switch for turning the vacuum pump on or off. The use of positive pressure required no adjustment of the negative source as the vacuum pump provided a closed system. When negative pressures were used, however, the oxygen valve on the positive pressure line was closed.

One air line from the reservoir served for both negative and positive pressures. It was connected to a safety valve through which positive or negative pressure above 25 centimeters escaped through a waste outlet instead of reaching the auditory meatus.

The design of the safety valve is presented in Figure

4. A glass tube two inches in diameter and 36 inches long was filled with water to within four inches of the top. An airtight rubber stopper with two holes, each one-fourth inch in diameter, was placed in the open end of the tube. A six-inch long glass tube was inserted into one of the holes to protrude through the bottom of the rubber stopper. Into the other hole in the stopper a 40-inch long glass tube was inserted so that its end was 25 cm below the surface of the water. For positive pressures the pressure line to the ear was connected to the long tube by means of a "t" connection. Any pressure in excess of 25 cm, the depth to which the long tube was inserted into the water, escaped through the long tube, bubbled up through the water and out through the short waste tube. This method of controlling the amount of pressure on the tympanic membrane, by adjustment of the depth of the long tube in the water, could not be used for the experimental pressure conditions because the sound of escaping air bubbles was clearly audible through the 35 feet of air hose between the safety valve and the earpiece. For negative pressures the "t" connection on the main pressure line was changed to the short tube. This created a vacuum in the area between the rubber stopper and the water level of the safety valve and a negative pressure in excess of 25 cm drew air in through the long tube, thus protecting the eardrum from any negative pressure above 25 cm H₂O pressure.

Figure 4

PRESSURE INDICATOR AND PRESSURE SAFETY VALVE

A water manometer was connected to the pressure line by means of a "t" connection close to the safety valve. (See Figure 4.) It was constructed of two one-fourth inch in diameter 36-inch long glass tubes connected with a U-shaped rubber hose, and mounted on a wooden stand. A water level of 18 inches was marked as the zero point and a centimeter scale above and below this point marked off and labeled. A pressure of +10 cm caused a deflection of 5 cm downward on one side and 5 cm upward on the other. This manometer was used by the experimenter to monitor the amount of pressure reaching the subject. All of the above apparatus was located outside of the anechoic chamber. A similar manometer, for the subject to monitor, was connected to the pressure earpiece and located inside the chamber.

The pressure earpiece, shown diagrammatically in Figure 5, contained an ANHB-1 earphone which reproduced the signal. The earpiece was designed to fit over the ears of the subjects and produce an airtight seal. The earphone was placed in the closed end of a plastic cylinder two and one-half inches in diameter and two inches long. This cylinder was connected a doughnut shaped plastic plate on which was cemented a foam rubber doughnut three inches thick. The doughnut was dipped in liquid rubber to obtain an airtight coating. A one-half inch thick rubber form was attached around the outer edge of the doughnut to permit the external ear to fit within the earpiece thus avoiding

Figure 5
PRESSURE EARPiece

mechanical pressure on the external ear. A thin rubber flap was attached to the rubber form. Pressure forced this rubber flap to the contour of the area around the external ear providing an airtight seal. The earpiece was strapped onto the head by attached helmet liner straps which permitted adjustment forward or backward and upward or downward. The pressure line and the second water manometer were connected to the earpiece through a hole in the plastic cylinder. A microphone could be inserted through an opening to calibrate the earphone under the various amounts of pressure.

Procedure

Preliminary study to determine stimuli. In a preliminary investigation two subjects determined threshold values at 100 cps intervals from 100 cps to 4000 cps, at 6000 cps and at 8000 cps under each of the following pressure conditions: zero, +5, +10, +30, zero, -5, -10, -20 cm H₂O pressure. Thresholds determined at +5 and -5 cm H₂O pressure could not be distinguished from those made at zero pressure. A perceptible difference from zero pressure appeared under the other pressure conditions for both subjects. Also indicated were considerable differences due to frequency.

To determine whether fatigue and order of presentation of frequencies had important effects, two subjects each determined threshold values at 100 cps intervals from 100

cps to 4000 cps, at 6000 cps and at 8000 cps in five different orders. A one-hour time interval separated adjacent testing sessions, each of which required approximately 40 minutes. (See Appendix 1 for the orders of presentation of the frequencies.) Variation of the threshold values under any of the five different orders of frequency did not exceed 5 db for any frequency and there was no consistent trend attributable to different orders for either subject. The fatigue factor also appeared to have no important effect upon the results. The 15 to 20 minute rest period between each set of measurements was considered to be sufficient.

To determine whether threshold values determined under zero pressure were affected by previous pressure conditions, the two subjects determined threshold values for 41 frequencies under the following pressure conditions in the order as listed: (1) zero, (2) +10 cm H₂O, (3) +20 cm H₂O, (4) zero, and on the following day (5) zero, (6) -10 cm H₂O, (7) -20 cm H₂O, and (8) zero. The threshold value determined under zero pressure at the beginning of any one series did not vary by more than 5 db from the threshold value determined after the same series for either subject for any frequency.

Subjects. Seven male Air Force officers of the staff of the Aero Medical Laboratory, Wright-Patterson Air Force Base, between 23 and 30 years of age, served as

subjects. All were practiced in threshold determination from having served as subjects in an extensive earplug evaluation program. In a preliminary investigation 10 subjects determined thresholds for 10 different frequencies from 125 cps to 8000 cps on three different occasions. The three threshold values for each of seven of the 10 subjects did not vary more than 7 db. Ten ears from these seven subjects were used on the final study. All subjects were given a sweep check on a Maico H-1 audiometer. All subjects except one had less than a 15 db loss for any of the frequencies tested. One subject had a loss of 20 db at 4000 cps and of 25 db at 6000 cps. In the opinion of the experimenter these losses had no differential effect upon the results of the experimentation with pressure. The auditory canals and tympanic membranes of the subjects were checked by a physician for any pathology or abnormality. Results of the medical examinations were negative. The subjects were free from colds at the time of the experiment.

Stimuli. The stimuli consisted of 41 frequencies presented under each of five different pressure conditions. Frequencies at 1000 cps intervals from 100 cps to 4000 cps (with the exception of 300 cps tone which had to be omitted because of equipment failure), at 6000 cps, and at 8000 cps were presented under the pressure conditions of +10, +20, -10 and -20 cm H₂O. At least three sets of thresholds for the zero pressure condition were obtained. Each tone

automatically alternated on for two seconds and off for two seconds.

Instructions. Each subject was comfortably seated in the anechoic chamber at a table on which were placed an attenuator-set with a 10-db-step control knob and a one-db-step control knob, a water manometer with a centimeter scale, and a signaling key. The pressure earpiece was then placed over the test ear, and the subject was instructed to adjust the attached helmet liner straps until the earpiece felt comfortably tight. He was cautioned about an excessively tight adjustment which might cause pain after a period of time.

All subjects were familiar with the General-Purpose Audiometer and with finding their own thresholds, but in order to standardize the procedure each was instructed first to adjust the 10-db-step control to the setting at which the presence of the alternating signal was last detected and then to adjust the one-db-step control upward to the threshold point. This point was then checked by alternating above and below threshold. The attenuator setting for this point was recorded by the subject and the attenuator readjusted so that the signal was sufficiently loud for hearing the change to the next frequency.

Each subject was told not to clench the teeth nor to hold the breath when making a threshold judgment. He was informed of the pressure condition to be expected and was

instructed to check it on the water manometer at each reading. If the pressure was unstable, the subject was told to adjust the earpiece and the straps. Instructions to swallow frequently in order to maintain constant middle ear pressure were also given.

The subject was told to signal the experimenter by two short "dots" with the signaling key after each frequency threshold had been determined or with continuous tone if any question arose. A practice run of three threshold determinations was made under the first pressure condition to check procedure.

Presentation of stimuli. The experimenter controlled and presented the stimuli. The desired pressure condition as measured on a water manometer was applied to the tympanic membrane. Outside the anechoic chamber this involved for positive pressures the manual control of an oxygen valve and for negative pressures the manual switching on and off of the vacuum pump when indicated by reading the water manometer. Pressures were held within plus or minus one cm.

A continuous tone of the desired frequency was set on the audiometer and the output voltage adjusted to an amount constant for all frequencies. Attenuations of from 10 to 50 db were randomly employed. The continuous tone was switched to the automatically interrupted pattern. The experimenter recorded the attenuation and the frequency.

When the subject had determined his threshold he signaled by two short "dots" and the experimenter switched the interrupted tone to constant, set the desired attenuation, adjusted the frequency slowly upward to the next frequency to be tested and checked the output voltage. The pressure was then checked and the signal switched from the continuous tone to the alternating on-off pattern. The subject listened to the change in frequency and when the alternating signal came on found his threshold for that particular frequency. This procedure was followed for each of the 41 frequencies for each of five pressure conditions. Subjects were given 15 to 20 minutes rest periods between pressure conditions.

Thresholds for the positive pressure conditions were determined for all subjects before any negative pressure data were gathered. The order of presentation of the positive pressure conditions and of the negative pressure conditions was counterbalanced. A threshold value for each of the 10 ears under the zero pressure condition was obtained for each frequency both before the presentation of the positive pressure conditions and before the presentation of the negative pressure conditions. Corresponding threshold values were obtained for the 10 ears after the positive pressure conditions and for three ears after the negative pressure conditions. This step was omitted for seven ears after the negative pressure conditions. Repair work on the

audiometer had altered the reference level. Thresholds under zero pressure obtained at different times could thus not be combined.

Equal Loudness Balance Tests

Five subjects made equal loudness balance judgments for six frequencies at 30 db and at 60 db above threshold under each of five pressure conditions.

Instrumentation

The equipment used in making equal loudness balance judgments for varying frequencies and varying pressure was essentially the same as that used in determining threshold sensitivity values with minor modifications. The General-Purpose Audiometer was adjusted to present an alternating signal first in one ear and then in the other. This adjustment was accomplished (1) by strapping input channels numbers 1 and 2 and (2) by switching in a circuit which put the automatically interrupted tone alternately in output channel 1 and then in channel 2. The output of channel 1 led to the test ear while the output of channel 2 led to the nontest ear. The attenuator in the audiometer was connected to channel 1 which permitted the intensity of the signal to be changed by the experimenter for each condition. (See Figure 1 for arrangement of equipment.)

Procedure

Subjects. Five ears from five of the six subjects used in the threshold study served in making equal loudness balance judgments.

Stimuli. The stimuli in this study consisted of 200, 400, 1000, 1600, 2000, and 4000 cps tones presented 30 and 60 db above their respective thresholds in the test ear, under each of the following pressure conditions: +10, +20, -10, and -20 cm of H₂O pressure. The threshold for each frequency was first found for the test ear. The intensity was then increased 30 db in the test ear and the signal in the non-test ear matched to it. The same procedure was followed for the 60 db above threshold condition. The loudness level of the signal in the test ear was matched under each pressure condition to the reference level determined for the non-test ear.

Instructions. The subject was comfortably seated in the anechoic chamber at a table on which were placed two attenuator sets, a water manometer, and a signaling key. The pressure earpiece was placed over one ear and a standard earphone, of the same type as in the pressure earpiece, placed on the opposite ear. The earpiece was then adjusted to a comfortable tightness. As all subjects had served previously in the threshold study, this situation was familiar to them. Each attenuator controlled the intensity

of the signal in its corresponding receiver. A form for recording the necessary information under each pressure condition was placed in front of the subject. (See appendix 2.) The procedure involved several steps and was explained in detail by the experimenter as follows:

You will hear a tone first in one ear and then in the other. Your first job is to find your threshold in your test ear, the one with the pressure apparatus on. You first turn up the attenuation in your non-test ear (experimenter points to it and to the corresponding attenuator) so that no signal comes through, then find your threshold in the same manner used in the previous study. When you find your threshold, record the attenuator setting where indicated on the form and decrease the attenuator by 30 db. This increases the intensity in the test ear to 30 db above your threshold. You now must adjust the non-test ear until it sounds equally loud. You do this by first using the 10 db step control for the gross adjustment, then using the 1 db step control find the point at which the two signals sound equally loud. You will have to go below and above the point a number of times, don't hurry, be as accurate as you can. When you have found the point at which the two signals sound equally loud, then record the attenuator setting of the attenuator on the non-test ear here (points to place on form). Exactly the same procedure is followed for the 60 db above threshold condition. The figures that you have recorded for the non-test ear are to be used later under each different pressure condition. You are now ready to make the equal loudness balance tests under the various pressure conditions. The first one for each frequency is always the 0 pressure condition. You are to make three judgments with the test ear under each pressure condition: threshold, 30 db above threshold and 60 db above threshold (experimenter again showing appropriate spaces on form). You are familiar with the procedure to find your threshold. Once you have found it signal me with two "dots" and I will change

the attenuation in your test ear. For the 30 db above threshold condition, you first set the attenuator in the non-test ear to the value you recorded when you matched it with the test ear at 30 db above threshold (experimenter shows on form). You must then adjust the attenuator for the test ear until the signal sounds equally loud again following the procedure described. When you are satisfied that the signals sound equally loud in both ears record the attenuator setting and signal me with two "dots." I will again change the attenuation and you set the attenuator in the non-test ear to the figure you recorded for the 60 db above threshold condition. After you have made your equal loudness balance judgment for this condition, record the attenuator setting and signal me and I will adjust the pressure for the next pressure condition. Look at your form for the expected pressure and check the water manometer for the correct reading. If the manometer is not stable then you have a leak at the earpiece, readjust it and tighten the straps if necessary. You are now ready to repeat the three judgments under this condition of pressure. There will be a practice period in which you will determine the two standard readings for the non-test ear which will be used for all pressure conditions for one frequency, plus the necessary loudness balance judgments under the pressure condition, after which I will check for proper procedure. Signal me to ask questions at any time.

Presentation of the stimuli. The several pressure conditions were presented and controlled in the manner previously described in the section on procedure of the threshold sensitivity study. The frequency conditions, also, were presented as in the threshold sensitivity experimental procedure except for the range of attenuations, which was limited to 10 db to 30 db. An attenuation of more than 30 db for the 50 db above threshold condition for the test ear would preclude a loudness balance with the standard

signal in the non-test ear.

The six frequency conditions were presented to each subject in order from lowest to highest frequency. Order within positive pressure conditions and within negative pressure conditions was randomized for each subject. Order with respect to negative and positive pressure conditions was counterbalanced. Each series of positive pressure conditions was preceded by the zero pressure condition.

Under each frequency and pressure combination, equal loudness balance judgments were made first for threshold, second for the 30 db above threshold condition and third for the 60 db above threshold condition.

All combinations of conditions for a single frequency were presented in approximately one hour of continuous testing. Each subject was given a 15-minute rest period between frequency conditions.

The attenuation values as recorded by the subject and by the experimenter were added to give a total attenuation for each frequency under each pressure condition for each subject. Criterion measures were the deviations in db of attenuation of each frequency under each pressure condition from the corresponding judgments under the zero pressure condition.

Intelligibility

Ten subjects responded to two speech intelligibility

lists under each of five pressure conditions.

Instrumentation

The study required equipment (1) to present speech and noise signals through earphones and (2) to present and control the static air pressure in the external auditory meatus.

Equipment for presenting the speech and noise signal. The following equipment, as shown in Figure 1, was used to present and control the speech and noise signal through earphones: (1) An Ampex Tape Recorder Model 306-1, (2) a tape recording of the Multiple-Choice Inteligibility Test, Form C, (3) a white noise generator, PAL type 422, (4) a General-Purpose Audiometer, with both the signal from the tape recorder and the noise led into the mixing stage of the audiometer, and (5) an ANHB-1 receiver in the pressure earpiece.

Equipment for presenting the static air pressure. The equipment for applying and controlling pressure to the external auditory meatus, also shown in Figure 1, was the same as for the threshold sensitivity experiment and the loudness balance experiment previously reported.

Procedure

Subjects. Ten male subjects between the ages of 22 and 31 selected from the staff of the Aero Medical Laboratory, Wright-Patterson Air Force Base, Ohio served as

subjects. Each subject was given a pure-tone sweep check for audiometric frequencies from 125 to 4000 cps. No subject had more than a 15 db loss for any one frequency in the test ear. The auditory canals and tympanic membranes of each subject were checked by a physician for any pathology or abnormality. Results of the medical examinations were negative. All subjects were free from colds at the time of testing.

Stimuli. The stimuli consisted of a tape recording of the Multiple-Choice Intelligibility Test, Form C. Two recorded speaker lists were presented as word reception tests under the following pressures: zero, +10, +20, -10, and -20 cm H₂O. The speech signal had an average peak value at 80 db and was presented simultaneously with a white noise of 76 db, as measured at the pressure earpiece at zero cm pressure with a General Radio Sound Level Meter, type 1551, C scale.

Form C of the Multiple-Choice Intelligibility Test is made up of 12 lists, each list consisting of 27 items that appear as nine 3-word groupings. The recording was made as follows: Nine American male speakers of the staff of the Naval School of Aviation Medicine, Pensacola, Florida stood in an equi-acoustic distant circle around a stand mounted Altec 21 B microphone in a sound treated room. The microphone led to an Ampex Recorder, model 400,

operating at a speed of 15 inches per second. The recording was copied with a limiting of 3 db. Each speaker read the number of each series as he recorded, for example, "number one drew modern vice." A sweep-second hand-timer cued the speakers to read a 3-word group item every six seconds in a round robin style through the 12 lists.

Presentation of stimuli. The subject was seated in the anechoic chamber and the pressure earpiece adjusted. A Form C answer sheet (see appendix 3) was placed on the table in front of him. Above each pair of lists was marked the pressure condition to be expected. The subject was instructed to draw a line through the word he heard and to guess if he wasn't sure. He was then shown the illustrated example on the form. He was also informed that the noise accompanying the speech signal was for the purpose of making his task more difficult. The subject was also told to check the correct pressure on the water manometer at the beginning of each new pressure condition and to swallow frequently. For the purpose of learning the experimental task each subject responded to the first two lists under the condition of zero pressure. The subject was then given the opportunity to ask the experimenter questions with respect to procedure.

The desired pressure condition was applied to the ear as described previously. Two word-lists at each pressure level were presented by means of the tape playback with the

Ampex Recorder at an average peak level of 80 db simultaneously with the presentation of white noise at a level of 76 db. The subjects responded to each 3-word item by drawing lines on the answer sheet through the words he thought he heard.

The order of positive and negative pressure conditions was randomized independently for each subject. Pressure conditions within negative pressures and within positive pressure were also randomized. The zero pressure conditions randomly preceded all others, came between positive and negative conditions, or followed all others. In so far as possible speaker lists were randomized with respect to pressure conditions.

The criterion measure was the number of errors for each pair of speaker lists for one subject under one pressure condition.

CHAPTER III

RESULTS AND DISCUSSION

Threshold Sensitivity

Criterion measures were obtained for each of 10 ears at each of 41 frequencies at each of the four pressure conditions - a total of 1640 measures. Each criterion measure is the difference for one ear between a threshold measurement under one combination of frequency and pressure conditions and the average of the thresholds of the "before" and "after" determinations for the same frequency. The obtained criterion measures are reported in Appendix 4.

For each frequency the root mean square was calculated for the deviations between "before" and "after" determinations under the zero pressure condition. The results are presented graphically in Figure 6. The dotted line indicates the mean for all frequencies, approximately 3.5 db. The solid line connects the root mean square values for individual frequencies. The root mean square values vary from 2 to 5 db. Subjects were thus quite consistent in the "before" and "after" determinations. An error margin of 5 db is ordinarily to be expected.

Obtained mean differences were evaluated by an analysis of variance which included the following factors: (1) pressures, (2) frequencies, and (3) ears. The results of the analysis are shown in Table 1. The significant interaction

Figure 6

Table 1

Results of Analysis of Variance for Evaluating the Effects Upon Threshold Sensitivity of 4 Pressures and 41 Frequencies With 10 Ears.

Source of Variation	df	ss	ms	F
Pressures (P)	3	4,329.88	1,443.29	
Frequencies (F)	40	10,343.10	258.58	
Ears (E)	9	639.37	71.04	
PxF	120	3,342.94	27.85	3.26*
PxE	27	6,910.82	255.95	
FxE	360	9,090.29	25.26	
PxFxE	1080	9,237.62	8.85	
	1639	43,894.02		

* $F = \text{Map}_{\text{PxF}} \text{Map}_{\text{PxFxE}}$. The required F for 120/1080 df at the 1% level of confidence is less than 1.38 (the value required for 100/1000 df).

between pressures and frequencies indicate that the relative differences among pressures vary from frequency to frequency; and the relative differences among frequencies vary from one pressure level to another. Hence, there is no interest in a test of the main effect of pressures for frequencies combined or in a test of the main effect of frequencies with pressures combined. The main interest is in determining which means for the various pressure-frequency combinations are significantly different from zero. Both the mean and the medians

significantly* different from zero are indicated.

* The critical difference (c.d.) from zero necessary for significance at the five percent level was computed as follows:

$$c.d. = t_{.05} \frac{ss_w \bar{P}\bar{F}}{p \times f \times (n-1)} = 2.6 \text{ db}, df = p \times f \times (n-1) = 1476$$

Where $ss_w \bar{P}\bar{F}$ = sum of squares within pressure-frequency combinations.

p = number of pressures
f = number of frequencies
n = number of ears

To determine whether a median was significantly different from zero a non-parametric sign test was employed. The test is performed by noting for each of the obtained values whether the sign is plus or minus. If the null hypothesis is true, about an equal number of plus and minus signs would be expected. The hypothesis of no difference from zero may be rejected if there are too few of one sign. The probability of 10 plus and zero minus (or 10 minus and zero plus) values is .002. P (9 minus, 1 plus or 9 plus, 1 minus) is .022. P (8 minus, 2 plus or 8 plus, 2 minus) is .066. A division of 10 and zero or of 9 and 1 was thus considered as sufficient evidence for rejection of the null hypothesis. Zero values were considered one-half plus and one-half minus. An 8 1/2, 1 1/2 division was interpreted as significant.

Figures 7 through 10 present graphically for each of the four pressure conditions the change in threshold as a function of frequency. The middle line connects the median values obtained for the 10 experimental ears; the top line connects the next-to-the-largest* values; the bottom line connects the next-to-the-smallest* values.

* Largest and smallest in an algebraic sense.

Figure 7

Figure 8

Figure 2

Figure 10

An inspection of the graphs and the table of means and medians clearly indicates some obvious trends of the effect of pressure on threshold sensitivity as a function of frequency. Threshold sensitivity is generally decreased under all four pressure conditions for frequencies below 1500 cps, with +20 cm H₂O pressure showing the largest decrease and with -10 cm H₂O pressure having only a slight effect. Roughly between 1500 and 2300 cps the pressures of +10, -10, and -20 cm H₂O cause the ear to become more sensitive than it is without pressure and these same frequencies are the ones least affected by the +20 cm H₂O pressure condition. That the tympanic membrane is resonant in this frequency range appears to be a reasonable explanation. Threshold sensitivity for the frequencies from 2400 to 8000 cps is generally decreased under all four pressure conditions with the +20 and the -20 cm H₂O pressure condition showing the most marked effect. The data for the +10 and -10 cm H₂O pressure are in good agreement with von Békésy's data on his own ear under +10 and -10 cm H₂O pressure.

The wide range of differences between the next-to-the-highest values at each frequency and the next-to-the-lowest values at each frequency as shown in the graphs in figures 7 through 10 indicate differences among ears. This seems to indicate that the impedance of the tympanic membrane differs considerably from ear to ear. These individual

Table 2

Means and Medians in db of Threshold Sensitivity Measures for Each Pressure-Frequency Combination. Positive Numbers Indicate Increased Sensitivity and Negative Numbers a Decrease in Sensitivity.

Pressure Levels in cm of Water									
cps	+10		+20		-10		-20		
	M	Mdn.	M	Mdn.	M	Mdn.	M	Mdn.	
100	-5.4*	-5.0*	-10.9*	-7 *	-1.0	-1.0	-5.6*	-5.5*	
200	-5.2*	-5.0*	-9.4*	-8.5*	-1.0	-1.0	-5.5*	-5.0*	
400	-4.7*	-5.0*	-12.4*	-11.0*	-2.4	-1.5	-9.1*	-9.0*	
500	-5.0*	-4.5*	-11.8*	-11.0*	-2.8*	-2.0*	-9.5*	-10.0*	
600	-4.0*	-3. *	-10.5*	-8.5*	-2.5	-2.5*	-9.4*	-7.5*	
700	-5.2*	-5. *	-11.2*	-10.5*	-2.9*	-2.0	-8.9*	-8.0*	
800	-4.1*	-4.5	-9.6*	-9.0*	-1.9	-1.0	-6.6*	-5.5*	
900	-3.5*	-4.5	-9.1 *	-8.5*	-1.0	-1.0	-5.8*	-5.5*	
1000	-3.4*	-4.5	-8.2*	-11.0*	+1.0	-1.0	-5.4*	-5.5*	
1100	-3.7*	-5.0*	-9.0*	-11.5*	+ .7	-0	-3.8*	-1.5	
1200	-2.2	-3.0	-6.5*	7.0*	+1.9	+1.5	-1.0	-0.5	
1300	-1.1	- .0	-5.8*	-7.0	+2.3	+3.5	+ .5	+1.0	
1400	- .6	.0	-4.2*	-3.5	+ .6	+2.0	- .4	-0	
1500	+1.2	+2.0	-3.7*	-7.5	+1.3	+1.5	+ .6	+0.5	
1600	+1.3	+2.0	-2.0	-3.5	+2.3*	+3.5	+1.4	+3.0	
1700	+1.6	+1.0	-1.1	-1.0	+3.1*	+3.5*	+1.1	+2.0	
1800	+3.1*	+3.5*	- .3	+1.5	+2.8*	+3.5	+2.5	+3.0	
1900	+3.0*	+2.0*	-1.2	+2.0	+2.6*	+3.5*	+1.8	+2.0	
2000	+2.7*	+2.5	-1.9	+2.5	+2.4	+1.5	+ .5	+0.5	
2100	+1.9	+2.5	- .4	-1.0	+2.6*	+2.5*	+1.8	+3.0	
2200	+1.1	+1.5	-1.1	-1.5	+2.1	+2.5	+1.6	+4.0	
2300	-1.9	-1.5	-1.0	-1.0	+2.1	+2.0	- 0	+2.0	
2400	-2.1	-2.0	-2.8*	-2.5	+ .1	-0	- .7	-1.0	
2500	-1.4	-3.0	-1.3	-3.0	-1.3	-3.0	-2.3	-2.0	
2600	-1.7	-2.0	-1.6	-3.0	- .9	+1.0	-2.5	-2.5	
2700	-2.2	-1.5	-3.5*	-4.0	+ .6	+3.0	-3.5*	-4.0	
2800	-4.9*	-5.5*	-4.4*	-4.5*	+ .5	-0	-5.0*	-6.0*	
2900	-4.0*	-4.5	-4.5*	-3.5*	+ .4	+1.0	-3.8*	-4.5*	
3000	-5.6*	-6.0*	-4.2*	-4.5*	- .9	- .5	-4.7*	-4.0*	
3100	-3.3*	-3.0	-3.8*	-2.0*	-1.1	-2.0	-4.5*	-5.0*	
3200	-3.0*	-3.0*	-4.1*	-4.5*	+ .8	+2.5	-3.6*	-3.5	
3300	-1.4	-1.5	-4.2*	-3.5*	-2.0	-1.5	-5.5*	-7.0	
3400	-3.2*	-3.5*	-4.2*	-3.5*	-1.2	-0	-4.6*	-4.5*	
3500	-1.1	- 0	-3.3*	-3.5*	-1.5	-0.5	-6.4*	-6.0*	
3600	- .6	-1.0	-3.1*	-3.0	- .9	-0	-6.0*	-6.5*	
3700	- .5	-1.0	-2.0	-1.0	-1.1	-0.5	-3.4*	-2.5*	
3800	- .2	-1.0	-2.6*	-2.5	-1.6	-1.5	-3.4*	-3.5*	
3900	- .9	-0	-1.7	-1.0	-1.3	-2.0	-3.8*	-4.5	
4000	-1.2	-0	-2.3	-2.0	-1.3	-2.5	-4.4*	-4.0	
6000	-1.4	-1.0	-1.4	-2.0	-1.5	+1.0	-1.5	-0	
8000	-2.9*	-2.5	-3.5*	-1.	-1.8	-1.5	-1.5	-2.5	

* Significant at the 5% level.

differences are also illustrated graphically in Figure 11 which shows threshold sensitivity as a function of frequency for two ears for each of the four pressures.

The considerable loss of sensitivity for the lower frequencies observed under the +10, +20 and -20 cm H₂O pressure conditions has a practical implication with respect to increasing the attenuation characteristics of earplugs. The attenuation provided by the best possible earplug is limited (28 db at 100 cps) at the low frequencies by the compliance of the skin. For this reason the upper limit for protection set by bone-conduction cannot be reached. At higher frequencies a good earplug will provide 40 to 50 db attenuation. Above 40 to 50 db the sound bypasses the earplug by bone conduction. The average decrease in sensitivity for the low frequencies under the +20 and -20 cm H₂O pressure condition suggests investigation of the feasibility of using an earplug coupled with a pressure device to obtain needed protection in this range.

Sensitivity for Varying Loudness Reference Levels

Criterion measures were obtained for five subjects at the threshold and at loudness levels above threshold at six frequencies at each of the four pressure conditions. Each measure was the deviation in db of attenuation for one subject for one frequency-pressure-loudness level condition. A table of the obtained criterion measures is given in Appendix 4.

Threshold Sensitivity Test: Results for Subjects H-L and B-L

Figure 11

Figured 11 (continued)

Obtained mean differences were evaluated by an analysis of variance which included the following factors: (1) pressures, (2) loudness reference levels, (3) frequencies and (4) subjects. The results of the analysis are shown in Table 3. In agreement with the results of the investigation of threshold sensitivity the interaction between pressures and frequencies is significant, indicating that the relative differences among pressures vary from frequency to frequency and the relative differences among frequencies vary from one pressure level to another. The loudness levels of 30 and 60 db above threshold at which equal loudness balance judgments were made did not interact with frequency, with pressure, or with pressure-frequency combinations. The non-significant result of the F -test of the effect of loudness reference levels provides no evidence to support the hypothesis that loudness balance judgments vary with loudness reference level. In table 4 are shown the mean differences for the five subjects for the various pressure, frequency, and loudness reference level combinations. The means that are significantly* different from zero are

* the critical difference (c.d.) from zero necessary for significance at the 5 percent level was computed as follows:

$$c.d. = t_{.05} \frac{ss_w \bar{p}\bar{f}\bar{l}}{p \times f \times l (n-1)} = 5.82 \text{ db} \quad \begin{array}{l} df = 4 \times 6 \times 3 \times 4 \\ = 288 \end{array}$$

where $ss_w \bar{p}\bar{f}\bar{l}$ = sum of squares within pressure - freq.-loudness reference level combinations.

p = number of pressures

f = number of frequencies

l = loudness reference levels number

n = number of subjects

Table 3

Results of Analysis of Variance for Evaluating the Effects Upon Hearing Acuity at three Loudness reference Levels, Four Pressures and Six Frequencies with five Subjects.

Source of Variation	df	ss	ms	F
Frequencies (F)	5	2575.7	515.09	
Loudness-reference Levels (L)	2	129.09	64.54	1.68
Pressures (P)	3	1,328.42	442.81	
Subjects (S)	4	146.20	36.55	
FxL	10	225.26	22.53	1.16
FxP	15	269.13	17.94	2.98
LxP	6	35.71	5.95	1.36
FxS	20	290.28	14.51	
LxS	8	307.75	38.47	
PxS	12	114.66	9.56	
FxLxP	30	155.14	5.17	1.43
FxLxS	40	776.57	19.41	
FxPxS	60	361.12	6.02	
LxPxS	24	105.12	4.38	
FxLxPxS	120	435.70	3.62	
	360	4,255.85		

$1F = ms_L / ms_{LxS}$. - Not significant

$2F = ms_{F \times L} / ms_{F \times L \times S}$. Not significant

$3F = ms_{F \times P} / ms_{F \times P \times S}$. Significant beyond the 1% level
(required F at this level for 14/60
df is 2.40).

$4F = ms_{L \times P} / ms_{L \times P \times S}$. Not significant.

$5F = ms_{F \times L \times P} / ms_{F \times L \times P \times S}$. Not significant.

Table 4

Means in db of Equal Loudness Balance Measures for Each Pressure-Frequency-Loudness
Combinations with Five Subjects

Pressure Levels in cm of H ₂ O											
cps	Thres- hold	+30 db	+60 db	Thres- hold	+30 db	+60 db	Thres- hold	+30 db	+60 db	Thres- hold	+ 30 db +60db
200	-4.2	-9.2*	-9.8*	- 8.8*	-12.6*	-13.0*	-2.0	-7.0*	-4.0	- 8.2*	-10.0* - 9.2*
400	-6.2*	-6.8*	-8.4*	-10.2*	-10.8*	-11.6*	-4.4	-5.0	-5.8*	-10.0*	-11.4* -11.8*
1000	-5.4	-4.2	-6.5*	- 7.8*	- 9.8*	-11.6*	-2.4	-2.6	-3.6	- 7.0*	- 6.2* - 9.2*
1600	-2.0	-3.4	-2.2	- 3.8	-4.6	- 4.4	-0.6	+0.8	+1.2	- 2.8	- 2.4 - 1.0
2000	-0.4	+0.4	-3.6	- 2.4	- 3.2	- 5.4	-1.6	+0.8	-1.0	- 2.8	- 2.4 - 5.8*
4000	-2.0	-2.2	-2.2	- 5.0	- 2.8	- 3.4	-2.4	-0.8	-1.2	- 2.8	- 6.8* - 7.0*

* Significant at 5% level.

indicated.

Figures 12 through 14 represent graphically the mean change in hearing acuity, in db, as a function frequency. Although the three loudness reference levels are not significantly different, the data for each are presented separately. There are four lines on each graph representing the four pressure conditions. Figure 12 shows the mean deviation in db for each pressure-frequency combination from the corresponding values determined under the zero pressure condition. Figures 13 and 14 show the mean deviation in db for each pressure-frequency combination for equal loudness judgments at 30 and 60 db above threshold, respectively, from the corresponding value obtained under zero pressure for equal loudness balance judgments at 30 and 60 db above threshold.

Inspection of the graphs and the table of means indicates a marked effect of pressure on hearing acuity at three loudness levels as a function of frequency. The lower frequencies of 200, 400 and 1000 cps show a much greater decrease due to pressure than the higher frequencies of 1600, 2000, and 4000 cps.

In general, for all loudness reference levels, although pressure and frequency interact, the -10 cm H₂O pressure condition produced the least effect while the +20 and -20 cm H₂O pressure conditions produced the most marked effect with the +10 cm H₂O pressure condition falling between

Fig. 11

Figure 14
Frequency in cps

the two extremes.

Although loudness reference levels do not differ significantly, the trend appears to be for a greater decrease in hearing acuity with louder tones.

The effect of frequency on the subjects ability to make equal loudness balance judgments was evaluated. The within-cell standard deviations were computed for the different frequencies with the following results: 200 cps, 2.92 db; 400 cps, 2.68 db; 1000 cps, 2.56 db; 1600 cps, 2.81 db; 3000 cps, 2.40 db; and 4000 cps, 3.37 db. Since the measures are related, no test was available for evaluating these results. A superficial examination of the results reveals no definite trend.

Speech Intelligibility

Ten subjects listened to and scored two speaker intelligibility lists under each of the following pressure conditions: zero, +10, +20, -10, and -20 cm of H₂O. The criterion measure was the number of errors for each pair of speaker lists for one subject under one pressure condition. The obtained criterion measures are reported in Appendix 6.

The obtained mean scores were evaluated by an analysis of variance which included the following factors: (1) pressures and (2) subjects. The results of the analysis are shown in Table 5.

Table 5

Results of Analysis of Variance for Evaluation of Differences Among Five Pressure Conditions with Respect to Mean Intelligibility Scores of 10 Listeners.

Source of Variation	df	ss	ms	F
Pressures (P)	4	27.88	6.97	
Subjects (S)	9	324.48	36.05	
P x S	<u>36</u> 49	<u>427.72</u> 780.08	11.88	

The analysis indicates no evidence that the subject's ability to recognize words correctly was affected by the pressure conditions. The average number of errors made under the five pressure conditions were as follows: zero cm H₂O, 12.6; -10 cm H₂O, 12.2; -20 cm H₂O, 11.9; -10 cm H₂O, 11.6; -20 cm H₂O, 13.0.

CHAPTER IV

SUMMARY

The main purpose of the present study was to test the hypothesis that static air pressure in the auditory meatus affects hearing acuity. The specific purposes were to determine the effects of pressure on (1) threshold sensitivity (2) hearing acuity at two loudness levels above threshold, and (3) speech intelligibility.

The particular pressures chosen for each experiment were +10, +20, -10, and -20 cm H₂O. There were two sources of pressure: (1) An air compressor for the positive pressures, and (2) a vacuum pump for negative pressures. Two valves and two water manometers were used to control and measure both negative and positive pressure. An earpiece fitted airtightly over the external ear presented the pressure to the external auditory meatus.

For the threshold sensitivity experiment, frequencies at 100 cps intervals from 100 cps to 4000 cps, at 6000 and at 8000 cps were selected. Each tone automatically alternated on for two seconds and off for two seconds. The subjects found their own threshold by adjusting an attenuator set. Criterion measures were the deviations in db of each pressure-frequency combination from the corresponding frequency threshold determined under zero pressure. Criterion measures were obtained for 10 ears at each of 41 frequencies at each of four pressure conditions, 1640 measures.

The interaction between pressure and frequency was significant indicating that the relative differences among frequencies vary from pressure to pressure; and the relative differences among pressures vary from frequency to frequency. Threshold sensitivity was generally decreased from 5 to 12 db for frequencies below 1500 cps for the +10, +20, -20 cm H₂O pressure conditions. The -10 cm H₂O pressure appears to have very little effect on threshold sensitivity in the same frequency range. In the frequency range from 1500 to 2300 cps the +10, -10, -20 cm H₂O pressure conditions increase sensitivity slightly. Sensitivity for frequencies above 2300 cps was only slightly affected by pressure.

To test the effect of pressure on hearing acuity at different loudness reference levels five subjects made equal loudness balance judgments for six frequencies (200, 400, 1000, 1600, and 4000 cps) at 30 db and at 60 db above threshold under each of the four experimental pressures. Thresholds for the above frequencies were also determined. The subjects adjusted an attenuator set in making the equal loudness balance judgments. Criterion measures were the deviations in db of attenuation of each frequency under each pressure condition from the corresponding judgments under the zero pressure condition. Criterion measures were obtained for five subjects at three loudness reference levels at six frequencies at each of the four experimental pressure conditions. As in the threshold sensitivity study there was a

significant interaction between pressure and frequency. Sensitivity for the lower frequencies 200, 400, and 1000 cps was generally decreased from 5 to 10 db for all three loudness reference levels for the +10, +20 and -20 cm of H₂O pressure conditions. The -10 cm pressure condition had little effect on this frequency range. The three upper frequencies of 1600, 2000, and 4000 cps were only slightly affected by the several pressure conditions. Loudness levels did not interact with any other factor. Loudness levels were not significantly different with respect to sensitivity. A slight decrease in sensitivity however, appeared to accompany an increase in loudness.

To test the effect of pressure on listening to speech, the responses of 10 subjects to two speech intelligibility lists under each of five pressure conditions were obtained. A tape recording of the Multiple-Choice Intelligibility Test, Form C was played to each subject under the several pressure conditions. The speech signal was presented to the subject at an average peak level of 80 db simultaneously with a white noise of 76 db. The criterion measure was the number of errors for a pair of speaker lists for one subject under one pressure condition. An analysis of the data provided no evidence that the pressure conditions of this study have any effect upon listening ability as measured by the Multiple-Choice Intelligibility Test, Form C.

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APPENDIX 1

Orders of Presentation of
Frequency used in Prelim-
inary Study.

Table 6

CPS				
Order 1	Order 2	Order 3	Order 4	Order 5
100	100	8000	8000	100
200	200	6000	6000	200
300	300	4000	4000	300
		3900	3900	
		3800	3800	
4000	1000			4000
6000	8000			6000
8000	6000	100	1100	8000
	4000		100	
	3900		200	
	3800		300	
	1100			
			1000	

APPENDIX 2

Recording Form for Equal Loudness
Balance Data

Thres-	+ 30	Match	+60	Match	+10 CmH ₂ O			+20 Cm H ₂ O		
hold test	test	non-test	test	non-test	Thres-	+30*	+60**	Thres-	+30 db	+60 db
ear	ear	ear	ear	ear	hold	db	db	hold		

200
400
1000
1600
2000
4000

-10 Cm H ₂ O			-20 Cm H ₂ O		
Thres-	+30	+60	Thres-	+30 db	+60 db
hold	db	db	hold		

200
400
1000
1600
2000
4000

APPENDIX 3

Form C Intelligibility Answer Sheet

YOUR NAME DATE

CLASS & WING POSITION

WHEN YOU HEAR....

Number 1
MORTAR SHUT ASSIST

Number 2
BLIMP INJURE KNOB

Number 3
GLIDING BATTLE IGNITE

MARK YOUR PAPER LIKE THIS...

Speaker 1 is Doe, R. J.

	order	shook	enlist
1	mortar	shout	resist
	border	shut	assist
	water	shot	insist
	flip	injure	sob
2	limp	insure	knob
	blimp	picture	cog
	limb	contour	no
3	lighting	battle	
	gliding

Speaker 1 is		
1	groove drew crew grew	modern moderate modesty modest vice fight mice bite
2	say stay stayed spade	forbade pervade surveyed survey chink kink check chin
3	stung stun sun stunned	drunk grunt brunt runt intent intend content intense
4	quench went whence when	busy physics physic visit wade waves wave way
5	pass past cast task	clearly quarry query fine find sign kind
6	popular poplar hopper opera	nurse first birth burst get gap guess guest
7	immense commence emit cement	named name main knave only woman pullman omen
8	latter ladder lattice rabbit	last lash laugh glass slain flame plain
9	crash crab craft crack	gold bowl cold bold poor polo palace

Speaker 2 is		
1	ninety nineteen nightly nine	drum rung rum run harrow peril herald arrow
2	ran rank rang rag	putter tucker pocket pucker need lead lean leave
3	kick tick pick hick	see seed siege seize depot people equal decoy
4	shower scholar sour scour	earthen earthly urban bourbon bath bat bad back
5	berry carry bearing very	spring pray spray spread listless mistress restless blissful
6	mouse mouth now mount	Saturn sat second satin fog bar bog bug
7	quarter fortress portrait porter	felt belt dealt bell horrible halt orphan organ
8	heavy happen package happy	did live led lid dollar jealous zealous develop
9	hamper pamper panther pamphlet	tendon tender pendant pendulum pond on hound pawn

Speaker 3 is		
1	apply supply amply fly	gift if hit it lamp lance glance land
2	bust fuss but bus	handle anvil amble ample free freeze freed tree
3	airy hairy arid carry	fed stead spend sped laugh glad lash flash
4	throw froze prose probe	low rose loathsome lonesome rod brown brow proud
5	desk depth dead death	stance stand stamp spent science silent sound silence
6	broke growth throat wrote	code told cold coal begun begot forgot deduct
7	sister system cistern pistol	hulk halt pulp fault mild mile miles mine
8	strike spite fight spike	limp limb lend lent town townsman townsmen count
9	paid page age haze	cute cunning honey puny fell spell feiled bell

Speaker 4 is		
1	much mud month monk	uplift uproot approve group cypress cipher siphon sightless
2	twelve well dwell weld	mind mild mine line blister blissful listful wistful
3	wren went rent lent	barter barker sparkle parker found crown cloud clown
4	guide die died dive	lively widen wisely widely love lull low lag
5	stove sold stole soul	amiss omit amid emit equipped acquit equip quit
6	reverse traverse perverse pervert	sired siren fire sire simple dimple pimple temple
7	drove stroke strode strove	warrant one warm warn dog gone don darn
8	fire hire tired tire	stale jail dale gale evil easel measles needle
9	gaily fail daily five	barn bark bought spark lip lift lisp list

Speaker 5 is		
1	crash drag trash thrash	least lease niece leaf wouldn't wood wooden wooded
2	pillow pillar killer filler	peg keg egg pay loosely gruesome loosen nuisance
3	lava loud lock robber	wait which wake wig hour how howl owl
4	glad lad laugh lag	fable tablet habit cattle part art heart arch
5	puncture teacher tincture picture	sigh size side scythe bake bait fate faith
6	tempt tense tent hemp	green cream tree creed seller solemn solid sullen
7	youth you use mute	allege away allayed allay muster lusty bluster luster
8	tight pike height hike	birds bird birth burden chat cap check chap
9	devise defy divide beside	chaff shaft chap shack Ed head add ebb

Speaker 6 is		
1	feel deal steal veal	fruit true troop truth pelvis elder elbow eldest
2	tasty hasty hasten pastry	sheep shield she sheath add ask as has
3	wrist risk rip list	depth death deaf guest fortune fort important forty
4	shoe choose too chew	defense methinks repent bethinks hamper tamper hampered hamburg
5	led red ledge leg	palace palate talent pilot stow stole stowed stove
6	butter flutter flood fluttered	heat hate paint ink tick chicken ticket pickel
7	thumb from come sum	coy toy tore torque auto bottom often autumn
8	bower borrow flower power	fast fact fat that sit six sick sift
9	deceive precede concede receive	cars carve card car heard verge urge herb

1
2
3
4
5
6
7
8
9
10
11
12

Speaker 7 is

1	providence problem promise province	worse work worst worth	pledge sled sledge sleigh
2	row throw grove grow	wearing wearer wary wear	stomach staunch stark starch
3	suffer zipper supper zephyr	scram swing slam swam	grandsire grandstand transpire grandchild
4	bathe save space spade	reverse invert divert revert	anew unused amuse unuse
5	depth deck death debt	dangling sandy sandwich sanguine	bristle brittle ripple riddle
6	attend akin attempt again	bold fold bowl hole	steward sewer stool Stewart
7	break rate rape rake	spurt stirrup sterile syrup	increase entreat retreat intrigue
8	tack tax facts tact	souse south sound sack	mystery mystic mischief misty
9	anew balloon aloof allude	bake date bait fake	rhythm written ridden ribbon

Speaker 8 is

1	eighty acre aching eight	trump front truck trunk	irk hurt earth heard
2	delude remove elude renew	head edge hedge egg	gauge gaze gave gay
3	can't scant scamp scan	arm armed on odd	flatter climate planet plant
4	find bind vine fine	purse burst hurt first	fitness thickness sickness picnic
5	dumb gum dump done	bedroom reverend brother brethren	royal broil broiled boil
6	snout smelt snub snap	wide why wise ride	afford abhor accord afore
7	stead dead sped bed	price Christ fight strike	bury barely fairly fairly
8	white poison hoist voice	gown down gam gauze	error errand barren Arab
9	next nets mix neck	racket blacken blackened black	drab draft graft grab

Speaker 9 is

1	bite bike vice fight	abhor applause applaud apply	pulse fault pulp false
2	apace attain face aface	runny rubbish ready ruddy	goose noose use deuce
3	bruise brood brew cruise	by spy fire five	rather letter lever leather
4	bramble scramble gravel ramble	love mark large lark	hence tense tent hint
5	stain stink sting sing	patron patient hasten paper	train crane brain frame
6	groom prune broom room	cub tug tough tub	listen christen Christmas prison
7	handsome cancer camphor cancel	parcel hardly partly parsley	fear peer hear tear
8	suit soon soothe sue	cotton coffin coffee copy	neither meter meager leader
9	steam seen speed esteem	hump hunt pump punk	exalt result gulf exhaust

Speaker 10 is

1	artist harness harvest orchid	vesper fester pester festive	knoll known no mold
2	simple sinful summon stomach	bomb bound bond barn	Boston frosty frosting cross
3	litter little glitter liquor	wrestle rascal rapture raffle	pope hope oak post
4	main mink make mate	twelve welt wealth twelfth	march margin marching Martin
5	lengthen ointment Lincoln link	geese east meat yeast	rain wing green ring
6	bud bus bust but	rough drunk rump rum	hearing hairy carry herring
7	pleasant pheasant peasant present	widen wide wife wagon	saint safe faint sink
8	winter winner where woman	model marvel marvelous marble	log lawn blond long
9	lose loose loot blue	itself excel sell himself	mash gnash smash nag

Speaker 11 is

1	toward forge ford board	feeling dealer fever feeler	dome don't zone stone
2	destroy deprive defraud defrost	girl pearl curled curl	flicker clipper liquor quicker
3	chart short shark sharp	frightful rifle greatful rightful	sultry culprit sculpture sculptor
4	native navy naked nature	pearl crow throw grow	calf cad calves cab
5	lathe lay laid leg	candy pantry pansy handy	ink pinch inch hint
6	thus bust duck dust	legend ledger leaden lessen	hit fist this kiss
7	bulb bulge bald ball	cut carpet cotton copper	net met neck nest
8	breast friend breath bread	Capital hapless hatless happen	glass lad blast black
9	harbor harder ardor artist	soft sought salt sulk	hood could put good

Speaker 12 is

1	needle evil meal neither	large lodge lie live	haven heaven even able
2	dimple gentle devil dental	interest penguin hindrance kindred	cast past pass path
3	armload armholed armhole armful	pen ten tend tent	wooden woody wood witty
4	gem gent gin gym	glaze play blade blaze	creeping greeting greedy reading
5	flush pledge fresh flesh	size sigh scythe side	waitful wake wasteful wakeful
6	auburn often author autumn	astride ascribe prescribe describe	dial guile vial guide
7	nest mess meant met	rug love rough rub	harrow herald arrow peril
8	grain raise raid rage	bench theft fetch thatch	nuptial nocturnal nutshell neptune
9	flapper leopard leper letter	stole stone school scold	wallet swallow wall wallow

APPENDIX 4
Criterion Measures
Threshold Sensitivity

Table 7
Pressure Condition: +10 cm H₂O
Ears*

CPS	1	2	3	4	5	6	7	8	9	10
100	-2	-2	0	-6	-8	-12	-4	-1	-6	-13
200	0	-5	1	-5	-5	-11	-5	-12	-5	-5
300										
400	-2	-6	0	-1	-4	-5	-6	-9	-5	-9
500	-3	-4	-4	-4	-5	-5	-7	-10	-5	-3
600	0	-3	0	-1	-8	-3	-7	-10	-4	-4
700	-3	-6	0	-4	-10	-5	-7	-9	-3	-5
800	1	-5	4	-2	-9	-5	-9	-7	-5	-4
900	1	-6	2	-1	-5	-6	-8	-4	-5	-3
1000	4	-4	10	-6	-13	-11	-3	-6	0	-5
1100	0	-6	7	-8	-9	-9	-5	-1	-1	-5
1200	0	-6	5	1	-7	-7	-3	-3	-1	-3
1300	2	-6	3	-1	-8	-4	1	0	2	0
1400	-1	-6	1	1	-8	-2	3	-1	5	2
1500	-1	-4	5	7	-2	0	2	-2	5	2
1600	0	-4	6	5	2	-1	2	1	3	-1
1700	-1	-1	5	-2	4	1	4	1	5	0
1800	0	-1	5	3	5	4	3	5	5	2
1900	0	1	4	2	2	4	12	1	2	2
2000	7	-2	0	2	3	4	12	1	-2	2
2100	5	3	-1	0	0	5	6	5	-6	2
2200	5	1	-1	1	2	-2	4	4	-6	3
2300	9	-4	0	-6	-6	-2	-3	2	-8	-1
2400	1	-7	-1	-5	3	0	-3	1	-6	-4
2500	-6	-8	-2	-4	5	4	-4	-1	-6	8
2600	-6	0	-2	-6	-6	8	-4	0	-7	6
2700	-4	2	-4	-13	0	-8	4	6	1	-6
2800	-5	-8	-5	-12	-2	-10	-6	4	-3	-2
2900	-3	-9	-4	-15	0	-6	-3	4	-6	2
3000	-5	-7	-6	-12	-10	-8	-1	-4	-3	0
3100	-6	-2	-3	-10	-7	0	0	-4	-1	0
3200	-9	-6	-1	-3	-3	-5	-2	-3	0	2
3300	0	-6	3	-1	-3	-5	-6	-2	0	6
3400	-1	-5	2	-3	-9	-5	-5	-4	-1	-1
3500	1	-6	1	2	-1	-1	-8	-3	2	2
3600	0	-3	6	-1	0	-6	-6	-2	3	3
3700	4	1	1	5	-2	-4	-8	-3	0	1
3800	4	1	3	6	-6	-4	-6	-4	1	3
3900	-2	1	1	0	0	-2	-11	1	0	3
4000	0	1	1	0	-1	-4	-8	5	2	2
6000	2	0	-4	-6	-1	-2	-4	-1	-2	4
8000	3	-11	-6	-1	-8	-0	-4	-8	0	6

* Ears 1 and 2 from subject 1, ears 3 and 4 from subject 2
ears 5 and 6 from subject 3, ears 7,8,9,10, from subjects 7,8,9 and 10 respectively.

Table 7 (Continued)
 Pressure Condition: +20 cm H₂O
 Ears*

CPS	1	2	3	4	5	6	7	8	9	10
100	-6	-8	-17	-11	-10	-18	-6	-8	-21	-17
200	-5	-9	-6	-8	-7	-9	-7	-12	-22	-9
300										
400	-9	-11	-9	-13	-11	-7	-21	-12	-20	-11
500	-8	-10	-11	-10	-14	-11	-16	-12	-19	-7
600	-6	-9	-7	-6	-17	-8	-21	-12	-13	-6
700	-7	-11	-10	-10	-18	-10	-16	-11	-11	-8
800	-3	-8	-5	-8	-19	-8	-10	-10	-12	-12
900	-2	-12	2	-12	-20	-7	-7	-8	-12	-13
1000	-2	-13	12	-6	-15	-11	-13	-11	-9	-15
1100	-1	-14	6	-10	-13	-13	-12	-7	-11	-15
1200	-2	-14	7	0	-11	-11	-8	-5	-6	-15
1300	2	-16	-1	-1	-14	-11	0	-3	-1	-13
1400	4	-13	2	-3	-14	-10	2	-4	2	-8
1500	3	-13	1	5	-10	-9	0	-6	1	-9
1600	0	-9	3	5	-2	-5	1	-5	1	-9
1700	1	-5	5	2	-3	-5	2	-5	4	-7
1800	5	-6	2	2	-2	-2	3	1	5	-5
1900	5	-5	2	5	-8	0	12	2	4	-5
2000	6	4	3	3	-3	-6	12	1	2	-3
2100	6	-2	1	1	-5	-3	-1	5	-5	-1
2200	7	-2	-1	-1	-5	-7	-3	4	-3	0
2300	8	-1	0	-2	-8	-7	5	1	-5	-1
2400	0	-4	1	1	-5	-8	-3	-2	-6	-2
2500	-3	-4	-3	3	-6	6	-1	-4	-5	4
2600	-6	-3	1	8	-7	6	-4	-3	-7	-1
2700	-9	3	-3	-3	-7	-6	4	-1	-5	-8
2800	-6	6	-8	-3	-9	-9	-3	-2	-2	-8
2900	-6	-3	-6	-5	-11	-2	-3	-4	-3	-2
3000	-6	-3	-7	-4	-12	-5	-4	-3	-1	-5
3100	-4	-3	-6	-1	-13	-2	0	-1	-1	-7
3200	-6	2	-6	-2	-9	-5	-5	-3	-3	-4
3300	-3	-4	-2	-2	-11	-6	-2	-5	-2	-5
3400	0	-7	-1	-1	-13	-3	-1	-6	-4	-6
3500	-3	-7	-4	1	-5	-4	-3	-3	-1	-4
3600	-5	-9	-1	-2	-4	-6	1	-3	1	-3
3700	-4	-9	-4	-3	-1	-4	-1	0	1	-1
3800	-4	-5	-3	1	-10	-6	-2	-1	3	1
3900	-3	-4	-6	0	-7	-1	1	1	0	2
4000	-3	-5	-4	-1	-8	-6	-3	2	1	4
6000	-4	-2	3	4	-5	-1	-5	6	-8	-2
8000	3	-12	-8	-6	-6	-6	1	1	-2	0

* Ears 1 and 2 from subject 1, ears 3 and 4 from subject 2
 ears 5 and 6 from subject 3, ears 7,8,9,10, from subjects 7,8,9 and 10 respectively.

Table 7 (Continued)
 Pressure Condition: -10 cm H₂O
 Ears*

CPS	1	2	3	4	5	6	7	8	9	10
100	-1	2	-10	-3	3	-1	-1	-1	-1	1
200	-2	-2	-12	2	5	0	-1	-1	-2	3
300										
400	-4	0	-12	0	-1	2	2	-5	-2	-4
500	-3	-2	-9	-2	-1	-1	1	-6	-2	-3
600	-5	1	-6	-4	-3	-2	2	-8	2	-2
700	-6	2	-6	-2	-4	0	0	-9	-3	-1
800	-6	0	-3	-2	-5	-1	3	-3	-1	-1
900	-4	0	-4	-1	3	1	1	-1	-3	-2
1000	-3	4	2	3	5	1	0	1	1	-4
1100	-1	2	-4	-2	10	4	1	-1	2	-4
1200	-2	5	-1	4	7	4	1	0	2	-1
1300	-5	5	-2	3	7	8	2	4	-4	5
1400	-5	2	-4	1	2	5	3	2	-2	2
1500	-3	1	-4	2	4	1	1	4	2	5
1600	-5	6	0	3	5	4	1	1	4	4
1700	-5	7	2	3	9	4	6	0	1	4
1800	2	7	1	4	8	-4	3	1	2	4
1900	4	10	-1	1	4	-2	-3	8	3	2
2000	1	9	-3	1	6	-2	1	5	2	4
2100	0	7	-1	0	6	-3	6	6	3	2
2200	5	8	1	-3	4	-1	3	5	-3	2
2300	-1	7	0	-4	8	-1	4	4	0	4
2400	-4	-2	1	-5	10	0	3	0	0	-2
2500	-6	-1	-4	-5	10	0	4	-2	-5	-4
2600	-10	5	4	-6	7	2	2	0	-6	-7
2700	-7	1	2	-6	8	6	4	5	-1	-6
2800	-5	6	-8	-2	10	4	0	2	0	-2
2900	-7	5	-7	-1	2	4	5	3	0	0
3000	-7	2	-9	-2	-1	5	5	0	-2	0
3100	-3	6	-9	-4	2	3	9	-1	-5	-9
3200	-5	7	-8	2	6	3	6	4	-6	-1
3300	-3	2	-6	-2	4	1	-1	2	-8	-9
3400	-1	1	1	-3	-1	2	5	4	-11	-9
3500	-4	0	-1	-3	3	2	3	1	-9	-7
3600	-8	-1	1	-3	5	1	5	5	-9	-5
3700	-8	0	-5	-1	5	3	6	3	-8	-6
3800	-9	1	-7	-4	0	4	6	1	-5	-3
3900	-4	3	0	-7	0	-4	11	0	-7	-4
4000	-7	6	-3	-4	2	-2	8	1	-7	-7
6000	-9	6	-11	0	6	2	4	2	-9	-6
8000	2	-4	-4	-4	12	-3	2	0	-9	-10

* Ears 1 and 2 from subject 1, ears 3 and 4 from subject 2
 ears 5 and 6 from subject 3, ears 7,8,9,10, from subjects 7,8,9 and 10 respectively.

Table 7 (Continued)
 Pressure Condition: -20 cm H₂O
 Ears*

CPS	1	2	3	4	5	6	7	8	9	10
100	-7	0	-6	-15	-6	-2	-8	-2	-5	-5
200	-3	-4	-3	-6	-7	-7	-13	-3	-3	-6
300										
400	-11	-7	-9	-6	-12	-6	-12	-10	-9	-9
500	-10	-9	-10	-8	-10	-12	-13	-10	-6	-7
600	-7	-7	-6	-8	-11	-13	-16	-13	-1	-1
700	-7	-5	-8	-8	-1	-8	-12	-9	-7	-8
800	-6	-1	-2	-10	-14	-5	-12	-11	-1	-4
900	-6	-2	-2	-9	-14	-8	-8	-3	-5	-1
1000	-6	-1	4	-14	-12	-6	-12	0	-2	-5
1100	-4	1	-3	-11	-6	-1	-10	2	-2	-4
1200	-5	0	2	-2	-5	6	-7	1	2	-2
1300	-5	1	1	1	-2	7	-6	8	-2	2
1400	-6	2	-3	-1	-5	4	-8	9	1	3
1500	-4	0	-1	4	-1	1	-6	6	3	4
1600	-3	3	4	4	0	1	-8	5	3	5
1700	-3	4	4	1	-4	0	-1	4	3	3
1800	3	7	4	3	-3	2	-3	5	3	4
1900	1	8	7	3	-7	-4	-2	8	1	3
2000	0	4	1	2	-1	-7	-1	5	-1	3
2100	2	7	5	2	4	-10	-2	5	-2	7
2200	7	5	5	1	4	-1	-3	4	-12	6
2300	2	2	3	-1	5	-2	-8	2	-9	6
2400	-1	7	1	-2	5	-3	-9	2	-6	-1
2500	-7	5	-3	-8	9	0	-9	4	-13	-1
2600	-8	3	1	-7	6	0	-10	4	-5	-9
2700	-8	-9	-1	-8	8	-6	-9	1	-2	-1
2800	-10	-7	-9	-5	6	-2	-9	-5	-7	-2
2900	-9	-3	-6	-6	3	-1	-7	-2	-7	0
3000	-6	-1	-4	-7	-3	0	-4	-10	-8	-4
3100	-3	3	-8	-9	-1	-2	0	-9	-7	-9
3200	-1	3	-10	-3	5	-4	0	-10	-9	-7
3300	-3	2	-7	-7	2	-7	-5	-8	-11	-11
3400	-1	5	-8	-4	-1	-6	-3	-6	-14	-8
3500	-4	-8	-6	-3	-8	-8	-5	-2	-14	-6
3600	-6	-9	-7	-3	-9	-4	-3	3	-13	-9
3700	-3	-2	-3	-7	-2	-2	-1	-3	-10	-7
3800	-7	1	-8	-7	-5	-3	0	6	-7	-4
3900	-7	-1	-8	-11	-5	-4	-4	-9	-9	-6
4000	-4	-1	-10	-9	-4	-6	2	6	-9	-9
6000	2	-2	-7	2	3	2	-6	5	-5	-9
8000	-2	-8	-3	-3	8	-8	-10	10	0	-1

* Ears 1 and 2 from subject 1, ears 3 and 4 from subject 2, ears 5 and 6 from subject 3, ears 7,8,9,10, from subjects 7,8,9 and 10 respectively.

APPENDIX 5
Criterion Measures
Loudness Reference Levels

Table 8

Pressure Condition: +10 cm H₂O

Cps	Threshold Subjects					+30 db Subjects					+60 db Subjects				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
200	-3	-6	-5	-3	-4	-9	-6	-13	-10	-8	-8	-8	-13	-10	-10
400	-9	-8	-7	-4	-3	-5	-6	-6	-11	-6	-11	-6	-8	-6	-11
1000	-5	-4	-10	-2	-6	-5	-2	-6	-5	-3	-10	-6	-6	-3	-7
1600	-4	-2	-2	+1	-3	-3	-6	-6	0	-2	-2	-4	+1	-4	-2
2000	-4	-1	+2	+2	-1	+8	-4	-1	0	-1	-4	-1	-2	-8	-3
4000	-5	-4	+1	0	-2	-6	+1	+1	-2	-5	-3	+3	-4	-3	-4

Pressure Condition: +20 cm H₂O

200	-10	-10	-8	-7	-9	-20	-11	-13	-10	-9	-17	-7	-15	-12	-14
400	-13	-12	-10	-8	-8	-13	-11	-8	-10	-12	-16	-8	-11	-8	-15
1000	-10	-7	-10	-3	-9	-12	-9	-8	-8	-12	-15	-9	-13	-11	-10
1600	-4	-2	-2	-3	-8	0	-8	-4	-6	-5	-7	-6	0	-5	-4
2000	-8	-1	+1	+1	-5	+1	-3	-8	-4	-2	-9	+3	-9	-6	-6
4000	-7	-5	-4	-3	-6	-3	-2	-4	-2	-3	-5	+4	-6	-5	-5

Table 8 (Continued)

Pressure Condition: -10 cm H₂O

Cps	Threshold Subjects					+30 db Subjects					+60 db Subjects				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
200	-1	-2	-2	-1	-4	-10	-4	-8	-11	-2	-10	+2	-2	-4	-6
400	-8	-5	-3	-2	-4	-6	-8	-3	-3	-5	-8	-5	-6	-1	-9
1000	-2	-3	-2	-2	-3	-5	-4	+1	-2	-3	-5	-5	+2	-5	-5
1600	+1	+1	-1	+1	-5	+6	-3	0	+2	-1	+4	+1	+5	0	-4
2000	-5	-2	+3	-3	-1	+4	-1	+1	-1	+1	-1	-1	-1	+1	-3
4000	-4	-4	0	-3	-1	-3	-1	-2	-1	-2	-3	0	-3	+2	-2

Pressure Condition: -20 cm H₂O

200	-9	-12	-5	-6	-9	-13	-8	-11	-10	-8	-10	-5	-11	-10	-10
400	-10	-13	-7	-8	-12	-9	-15	-10	-14	-9	-15	-13	-9	-8	-14
1000	-7	-5	-10	-5	-8	-6	-5	-6	-5	-9	-14	-12	-6	-4	-10
1600	-1	-2	-1	-3	-7	+2	-4	-5	-3	-2	-1	-4	+5	-4	-1
2000	-6	-2	+1	-5	-2	+4	-7	-6	-4	+1	-9	-4	-9	-3	-4
4000	-10	-9	-3	+10	-2	-5	-7	-10	-7	-5	-7	-2	-12	-6	-8

APPENDIX 6
Criterion Measures
Intelligibility

Table 9
Pressure Conditions in cm H₂O

<u>Subject</u>	<u>0 cm</u>	<u>+10 cm</u>	<u>+20 cm</u>	<u>-10 cm</u>	<u>-20 cm</u>
1	20	30	26	21	24
2	28	19	18	21	29
3	20	24	25	21	27
4	27	26	22	28	31
5	24	24	24	26	24
6	34	28	25	30	26
7	18	18	22	21	21
8	24	23	21	23	27
9	26	29	31	23	29
10	30	24	29	28	29

AUTOBIOGRAPHY

I, Ronald G. Hansen, was born in Gisborne, New Zealand, 23 May, 1924. In 1929 I immigrated to the United States with my parents. I became a naturalized citizen in 1943. I received my secondary school education in the public schools of the Utah County, Utah. My undergraduate training was obtained at Utah State Agriculture College, from which I received the degree Bachelor of Science in 1949. From The Ohio State University, I received the degree of Master of Arts in 1950. I was a graduate assistant in the Ohio State University Speech and Hearing clinic during the year 1949-50. In 1950 I returned to active duty in the U.S. Air Force. In 1952 I returned to The Ohio State University under the Air Force Civilian Institutions Training program and continued under this program for two years while completing the requirements for the degree of Doctor of Philosophy.