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thesis entitled

Comparison of the Model-51 and MX41/AR Earphone Cushions Regarding Occlusion Effects and Coupler Calibration.

presented by

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has been accepted towards fulfillment of the requirements for

Master of Arts degree in Audiology

Major professor

Date 12/17/82

O-7639

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COMPARISON OF THE MODEL-51 AND MX41/AR EARPHONE CUSHIONS REGARDING OCCLUSION EFFECTS AND COUPLER CALIBRATION

By

Joseph John Holmes, Jr.

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF ARTS

Department of Audiology and Speech Sciences

1982

ABSTRACT

COMPARISON OF THE MODEL-51 AND MX41/AR EARPHONE CUSHIONS REGARDING OCCLUSION EFFECTS AND COUPLER CALIBRATION

By

Joseph John Holmes, Jr.

The new Model-51 one-piece earphone cushion was compared to the standard MX41/AR two-piece earphone cushion in terms of (1) interactions with acoustic couplers and (2) occlusions effects on bone-conducted pure tones. Frequency response curves were generated from a single TDH-39 earphone capsule in combination with six cushions of each type, two acoustic couplers (NBS-9A and Zwislocki-type ear simulator), and six coupling forces (100, 200, 300, 400, 500, and 1000 grams). Occlusion effects in the frequency range of 250-4000 Hz were measured on 12 normal-hearing subjects for three different headset conditions: (1) MX41/AR, (2) Model-51, and (3) MSH-87, a circumaural system expected to yield greater occlusion.

The Model-51 cushion was found to yield slightly higher coupler Sound Pressure Levels from 50-1000 Hz and from 6000-8000 Hz in the NBS-9A coupler, and a smaller mass-effect (although no mass-effect exceeded 1 dB). Occlusion effects for the Model-51 and MX41/AR cushions were not statistically different. The MSH-87 headset,

however, produced greater occlusion effects at all test frequencies. Occlusion effects ranged from 20 dB at 250 Hz to -8 dB at 4000 Hz for the Model-51 and MX41/AR cushions, and from 26 dB at 250 Hz to -6 dB at 4000 Hz for the MSH-87 headset.

To Paula

ACKNOWLEDGEMENTS

To my friends:

(1) Members of my committee - Dr. Paul A. Cooke, Dr. Linda L. Smith, for their time, patience, and hospitality.

(2) Subjects, who graciously endured.

(3) Thesis advisor - Dr. Michael Chial. He encouraged, trusted, pulled no punches, and fine-tuned.

(4) Michael Pawluk - who provided an expeditious opportunity, and humor.

(5) Tom Simpson, who provided afternoons of laughter.

(6) My wife, Paula, who often did not understand my madness.

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CHAPTER I

INTRODUCTION AND REVIEW OF THE LITERATURE

BACKGROUND

Headsets are used in audiometry for three reasons. First, headsets enable the examiner to present auditory signals to each ear individually, and thus obtain ear-specific information regarding auditory sensitivity. Isolation of the ears also allows the examiner to employ dichotic listening techniques to evaluate an individual's ability to integrate auditory information. Second, headsets enable examinmers to evaluate auditory sensitivity in sub-optimal ambient conditions by reducing the amount of noise that reaches the ear (Coles, 1967). Ambient noise capable of masking auditory thresholds may lead to inaccurate determinations of auditory sensitivity (Waugh, 1970, ANSI S3.1, 1977). Finally, headsets avoid some of the difficulty encountered in calibration of the sound field. Dillon and Walker (1982) discussed several issues related to this problem: because of differences in room size, loudspeaker type, orientation of loudspeaker, room furniture and subject placement, comparison of audiometric measures among clinics is next to impossible. Use of the sound field for determining auditory sensitivity is also limited by restrictions placed on signal parameters which may interact with the sound field (e.g., standing waves produced by pure tone stimuli).

One factor associated with headphone use is the acoustical environment of the test site. Criteria for permissible ambient noise levels become less stringent as the attenuation capabilities of headsets increase (Michael and Bienvenue, 1981; Roeser, Seidel, and Glorig, 1975; Copeland and Mowry, 1971). Characteristics of headsets that may affect attenuation are the acoustical seal provided by the cushion, coupling force of the earphone against the ear and physical characteristics of the materials used in the manufacture of the earphone capsules and cushions (Michael and Bienvenue, 1976; Villchur, 1970; Zwislocki, 1955).

No pure tone test is complete without both air conduction and bone conduction results. Because there is essentially no interaural attenuation of bone conducted sounds, masking must be employed to eliminate the non-test ear from threshold estimations (Studebaker, 1979; Dirks, 1978). Masking is delivered to the non-test ear through an earphone, while the test ear is left unoccluded. By occluding the non-test ear with an earphone the level of the bone conducted signal is enhanced for that ear. This seemingly increased sensitivity to bone conducted sound by occlusion is termed the occlusion effect. During masked bone-conduction testing, this effect must be included in determining minimum masking levels of the masking signal. The occlusion effect varies as a function of the enclosed volume under the occluding device, the acoustical seal provided by the occluding device, the force of its application to the head, and the test frequency (Dirks and Swindeman, 1967).

Audiometric headsets used in the United States consist of four basic components: a pair of earphone capsules (e.g., Telephonics TDH-39, TDH-49, or TDH-50), a pair of supra-aural earphone cushions (e.g., Telephonics MX41/AR), a headband (e.g., Telephonics TC-89E), and cables to carry electrical signals to the earphone capsules. The current audiometer standard, ANSI S3.6, 1969, specifies the physical dimensions of only one of these components: the earphone cushion. Also specified by the standard are the physical dimensions of the acoustic coupler to be used for level calibration, in part to match the dimensions of cushions.

Calibration of earphones to standardized reference levels is carried out through the use of the NBS-9A coupler. Although circumaural earphones would be beneficial in terms of increasing the attenuation of ambient noise and reducing the oclusion effect (Dirks and Swindeman, 1967; Elpern and Naunton, 1963; Michael and Bienvenue, 1976), coupler calibratrion of such earphone-cushion combinations has not proven reliable.

Although standardized supra-aural earphone cushions (MX41/AR) are used in routine clinical audiometry, and although calibration methods, reference levels, and physical dimensions have been standardized, significant variations still exist among samples of the MX41/AR earphone cushion manufactured by Telephonics (Michael and Bienvenue, 1980; Richards, Frank, and Prout, 1979). These differences include sound hole diameter, manufacturing process, quality of the bond between the two pieces and aging characteristics. These differences have been shown to cause significant variability in threshold determinations and acoustical measurements, thus affecting the calibration of an audiometer (Michael and Bienvenue, 1980; Richards, Frank, and Prout, 1979; Villchur, 1970).

Telephonics Corporation, the major domestic supplier of audiometric headsets, discontinued production of the MX41/AR cushion in 1980, replacing it with a new model designated "PN510C017". The new model (here referred to as Model-51) differs in several ways from the MX41/AR earphone cushion standardized in ANSI S3.6, 1969. The most striking differences are the flange angle of the earphone cushion on the surface that fits the ear, the texture of the material with which the earphone cushion is manufactured, and the process followed in the manufacturing of the earphone cushion. The Model-51 earphone cushion has a greater flange angle than the MX41/AR earphone cushion, and the material is more pliable. The manufacturing process of the Model-51 earphone cushion is a single-piece injection molding while the MX41/AR earphone cushion is manufactured as two separate pieces that are later joined. Figures 1 and 2 illustrate other physical variations including differences in density and thickness of walls (possibly

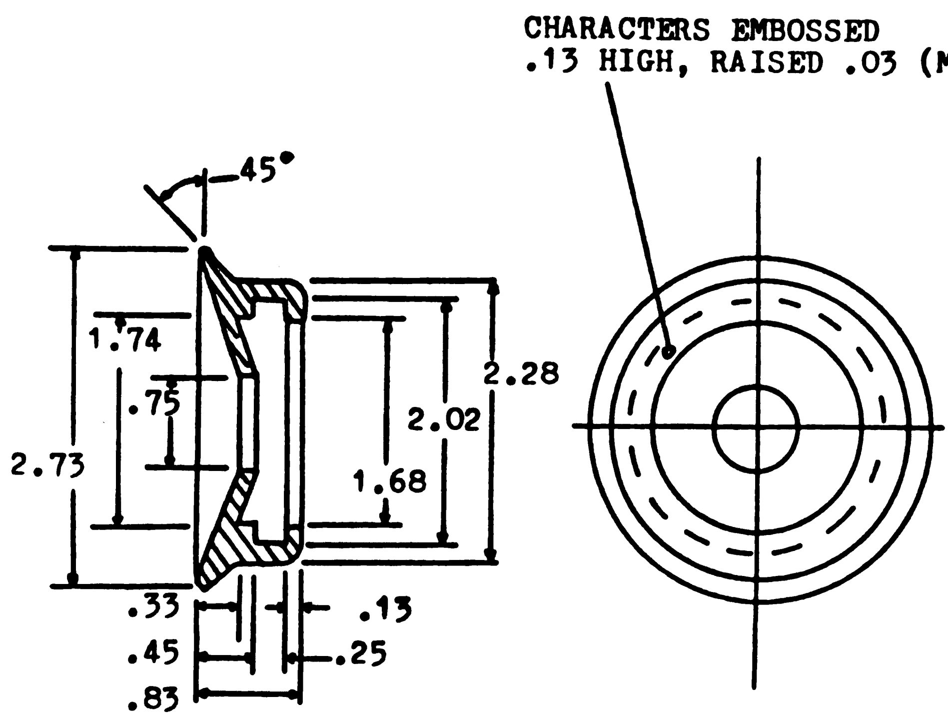

Figure 1. Specifications for the Model-51 earphone cushion.

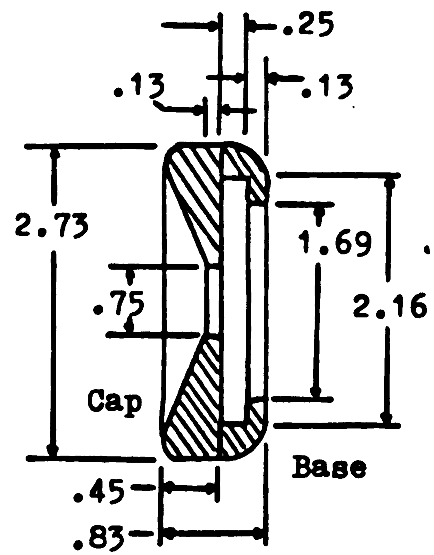

Figure 2. Specifications for the MX41/AR earphone cushion.

NOTES:

(1) Material for Model-51 is synthetic rubber compound, MIL-R-3065; Durometer (Shore A): 30 ± 5.

(2) Material for Base of MX41/AR is Buna-S rubber; Durometer (Shore A): 40 ± 5.

(3) Material for Cap of MX41/AR is sponge neoprene; Durometer (Shore A): 20 ± 5.

(4) All dimensions are in inches; tolerance is .01 inch.

affecting mass). Michael and Bienvenue (1980) noted variations in aging characteristics of the sponge material used in the manufacture of the MX41/AR cushion. Because the MX41/AR and the Model-51 earphone cushions employ different compounds, they may also differ in aging characteristics and susceptibility to body exudates.

It is suggested that these physical differences may produce differences in the acoustical performance of the earphone cushion when they are used with a TDH-39 earphone. Specifically, physical variations between earphone cushions may result in differences in measured occlusion effects and differences in interactions with acoustic couplers.

GOALS

The goal of the present study was to evaluate headsets using the MX41/AR and Model-51 earphone cushions regarding occlusion effects and interactions with acoustic couplers. The Madsen MSH-87 circumaural headset, currently used clinically in evoked response audiometry, was also evaluated. The Madsen headset was included for comparative purposes: as a circumaural system, it was expected to yield occlusion effect results different from those obtained with supra-aural systems, thereby indexing the sensitivity of experimental methods. Further, the MSH-87 employs a new housing for which no occlusion effect data are available.

This study replicates previous studies on the c

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acoustical effects of the Model-51 earphone cushion during coupler calibration of earphones and provides new information on the occlusion effect when using the Model-51 earphone cushion with a TDH-39 earphone capsule. Similarly, the study provides new information about the occlusion effects of the Madsen MSH-87 headset system.

REVIEW OF THE LITERATURE

A review of the literature to date follows regarding the attenuation characteristics, coupler interactions, and occlusion effects as they relate to the current standard audiometric earphone cushion (MX41/AR) and the new earphone cushion manufactured by Telephonics (Model-51). Literature regarding the attenuation characteristics of the MX41/AR and Model-51 earphone cushions is discussed only to review the issue and relative data.

ATTENUATION

Definition

Attenuation of headsets, for the purposes of this study, is defined as the "real-ear protection at threshold" given in ANSI S3.19, 1974:

The mean value (in decibels) of the occluded threshold (hearing protector in place) of audibility minus the open threshold of audibility (ears open and uncovered) for all listeners on all trials under othewise identical test conditions.

Methodological Issues

The standard method for measuring hearing protector attenuation (ANSI S3.19, 1974) is also to be used in the determination of the attenuation characteristics of audiometric earphones (Michael and Bienvenue, 1981). The method employed for determining occluded and unoccluded thresholds has traditionally been a Bekesy recording audiometer technique (method of adjustment) (Copeland and Mowry, 1971; Frank, 1980; Michael and Bienvenue, 1981). Ambient noise conditions of the environment are to be controlled because an increase in background noise will reduce the attenuation measured (Waugh, 1970). The test environment should conform to table II, one-third octave band levels, ears not covered in ANSI S3.1, 1978 "Criteria for Permissible Ambient Noise during Audiometric Testing". Test signal parameters are specified in ANSI S3.19, 1974. Test signals have been recorded on audio tape (Michael and Bienvenue, 1981) to avoid random variations due to the nature of the test signal, and to provide consistent quality.

Experimental Results

Michael and Bienvenue (1981) evaluated the attenuation characteristics of the Model-51 and MX41/AR earphone cushions following ANSI S3.19, 1974, and found no significant difference between the two. Small differences do exist between the two models of earphone cushions, with the Model-51 providing slightly more attenuation at all but one frequency (a difference of .7 dB at 4000 Hz). Generally attenuation increases with frequency to 4000 Hz, then declines slightly. Attenuation figures range from approximately 8 dB at and below 500 Hz to a maximum of approximately 29 dB at and above 3000 Hz. Transition from relatively low attenuation values in the low frequencies to higher attenuation values in the higher frequencies occurs at 1000 and 2000 Hz. Attenuation values measured for the MX41/AR earphone cushion on TDH-39 capsules using the working draft ANSI Z24.22, 1957 "Measurement of the Real- Ear Attenuation of Ear Protectors at Threshold" are provided by Copeland and Mowry (1971) and others. These values are not directly comparable to those measured with ANSI S3.19, 1974 because the procedures and test signals specified in the two standards are fundamentally different. While ANSI Z24.22 specifies attenuation measurements taken for pure tones in a free field, ANSI S3.19 specifies the use of 1/3 octave bands in a diffuse field.

Sources of Variability in Results

Even though the measurement of hearing protector attenuaton has been standardized in ANSI S3.19, 1974, measurements of hearing protector attenuation by different laboratories using the same standardized procedures and the same hearing protectors differ. Berger and Kerivan (1982) described an inter-laboratory comparison which was organized and funded by the Environmental Protection Agency. They found significant differences between laboratories in the mean and standard deviation of the attenuation measured for several types of hearing protectors. They attribute the variance to differences between laboratories in hearing protector fit, subject selection, training, and motivation procedures. Other sources of variance may be psychophysical method, the physiological status of subjects, and the coupling force of the hearing protector or headset (Dirks and Swindeman, 1967; Villchur, 1970). Compressibility of subjects' pinnas and external auditory meati may alter cushion fit and application force of the hearing protector.

Relevance to Clinical Procedures

Any of the hearing protectors labeled with values obtained by one particular laboratory (Laboratory 8--evidently the Michael and Bienvenue facility) would have failed a compliance audit test by any of the other seven laboratories (Berger and Kerivan, 1982). Thus, attenuation provided by hearing protectors and audiometric headsets should be independently verified by different laboratories. For the sake of replicability, attenuation values reflecting a typical use condition should be preferred over those which are simply the highest measurable values. Clinicians routinely using audiometric headsets could be confident that attenuation provided during use approximates that upon which ambient noise criteria for ears covered is based. Estimations of auditory threshold could then assuredly be free of ambient noise influences, given that the test environment, testing apparatus, and procedures conform to clinical standards.

COUPLER EFFECTS

Methodological Issues

The method for measuring the coupler response of earphones has been standardized in ANSI S3.7, 1973. Although use of the NBS-9A acoustic coupler is standardized for the calibration of audiometric earphones, the coupler does not provide an accurate representation of the earphone's response in the real ear (Lippmann, 1981).

Zwislocki (1970) reports the conclusions of Working

Group 48 of the Committee on Hearing, Bioacoustics and Biomechanics of the National Research Council, National Academy of Sciences (1967). The group summarized the inadequacies of the then current standard couplers for earphone calibration as follows:

1.1 inadequate specification of sound pressure in the outer ear.
1.2 inappropriate load for earphones, which leads to large sound pressure differences between the real ear and the couplers, especially at low and high frequencies.
1.3 ambiguity of pressure calibration at high frequencies which is particularly disturbing since it coincides with the range where the noise induced hearing loss occurs most frequently.
1.4 necessity of time consuming and inherently inaccurate loudness balance determinations for transfer of calibraation from one earphone to another.
1.5 lack of fundamental acoustical information necessary for meaningful interpretation of measurements.
1.6 aggravation of the problems listed above when circumaural earphone cushions are used.

Zwislocki (1970) went on to describe an acoustic coupler (ear simulator) designed to circumvent the problems listed above. He offered validating data and concluded that "the coupler matches the acoustic characteristics of the outer ear sufficiently well for the purpose of earphone calibration." The Zwislocki coupler is described in numerous sources (Zwislocki, 1971; Burkhard, 1977; Burkhard, 1978), and is standardized by ANSI S3.25, 1979: "American National Standard for an Occluded Ear Simulator". Use of the ear simulator for earphone calibration, however, has not yet been standardized.

ANSI S3.7, 1973 specifies that a 400-500 gram coupling force be applied to the cap of the earphone being calibrated, regardless of the material with which the earphone cushion is manufactured. Presumably, this force is specified to minimize the effects of leaks between the coupler and cushion. No studies have been found that report the effects of coupling force on the response of earphones of different material when calibrated using acoustic couplers.

Experimental Results

Richards, Frank, and Prout (1979) found differences in acoustical performance when a single earphone capsule (TDH-39) was mated to different units of a single-model earphone cushion (MX41/AR). An NBS-9A coupler was used as an acoustic load. They noted differences in the physical dimensions of the earphone cushions (diameter of the soundhole), and observed that acoustical and threshold estimation variations occurred mainly in the high frequencies. Michael and Bienvenue (1980), evaluated the acoustical performance of TDH-39 earphone capsules when used with MX41/AR and Model-51 earphone cushions and found no significant differences between the two when using an NBS-9A coupler. They indicated that the Model-51 earphone cushion provided more consistent coupler measurements (possibly due to better consistency in the manufacture of the cushions). They measured output of the earphone for drive signals at nominal audiometric frequencies and at the 3 percent limits both above and below the nominal value. For both models of earphone cushions they found "considerable differences between mean signal levels with the on-frequency and the 3 percent frequency limits for test frequencies at and above 4000 Hz." This suggests a possible interaction between coupler resonance and earphone response, or perhaps an artifact related to repeated placement of the earphone on the coupler.

Sources of Variability in Results

As indicated above, differences in physical dimensions of earphone cushions are partially responsible for variation in coupler measurements of earphones. Another source of variation is the repeatability with which coupling force can be applied to the earphone being measured. Kruger, Kaplan, Karp, and Joscelyn (1982) state that:

> The use of weights increases the variability of earphone responses on acoustic couplers since they are more susceptible to low frequency room vibration and poor signal-to-noise ratios, to say nothing of the physical problem of balancing the weights on non-flat earcup surfaces.

An optimum earphone/coupler coupling procedure should be sought.

Relevance to Clinical Procedures

The need for consistent and accurate calibration of headsets has already been discussed. The simple, primary goal of earphone calibration is to insure accurate estimations of signal levels presented to real ears. The inadequacies of the coupler presently used for this purpose are indicated above. Accurate earphone calibration (preferrably with the point of reference at the eardrum) is essential for repeatable and valid clinical estimations of auditory thresholds and for test-retest comparisons and rehabilitative decisions (e.g., hearing aid applications).

OCCLUSION EFFECT

Definition

As mentioned previously, the occlusion effect is an apparent increase in sensitivity of the occluded ear to bone-conducted stimuli in individuals with normal middle ears. The effect varies as a function of test signal frequency, total enclosed volume, integrity of the acoustical seal, and force of application. The occlusion effect is greatest in the low frequencies and is virtually absent above 1000 Hz. Several authors have noted these frequency and magnitude effects (Pohlman and Kranz, 1926; Huizing, 1960; Elpern and Naunton, 1963; Chandler, 1964; Goldstein and Hayes, 1965; Dirks and Swindeman, 1967; Liebman and Arasim, 1971; Berrett, 1973). Particular occlusion effect values obtained by various researchers differ because of variations among devices and subjects; however, the general trend has been the same.

Methodological Issues

Measured occlusion effects vary for methodological reasons. One aspect of method affecting the occlusion effect is the volume enclosed under the occluding device. Tillman (1962), as reported in Hodgson and Tillman (1966), found differences in occlusion effect when using different occluding devices. He used TDH-39 earphones in an MX41/AR cushion and Sharpe circumaural earphones. He found mean occlusion effect values of 17, 17, and 12 dB at 250, 500 and 1000 Hz respectively for the TDH-39--MX41/AR headset and 11, 2 and 0 dB at the same frequencies for the Sharpe headset. These effects were attributed to differences in volume between the two occluding devices. Elpern and Naunton (1963) also attributed differences in occlusion effect measured with two types of occluding devices to differences in enclosed volume. Liebman and Arasim (1971) studied volume effects by occluding the ear with an aluminum tube fitted with a plastic piston, the volume of which could be manipulated. The tube was mounted in an MX41/AR cushion, and was adjusted to duplicate three volumes: the volume enclosed when an MX41/AR cushion was used, MX41/AR plus 6cc, and MX41/AR plus 12cc. They found no significant differences in occlusion effect among the three cavity volumes, but did report a trend toward reduced occlusion effect with increases in volume. A probable explanation for the different conclusions drawn is that occluding cavity size interacts with the seal provided by the occluding device in affecting the magnitude of the occlusion effect. Goldstein and Hayes (1965) observed that different occluding devices come in contact with different locations and areas of the head, changing the amount of occlusion. Hodgson and Tillman (1966) found that changes in the coupling force of earphones (affecting the acoustical seal provided) from test to retest may produce large differences in the magnitude of the occlusion effect. Dirks and Swindeman (1967) suggested that variability in the occlusion effect may be reduced by employing a cushion which fits more effectively over the entire external ear than the MX41/AR. Because of the increased pliability of the Model-51 earphone cushion relative to the MX41/AR earphone cushion, and the difference in flange angle, the Model-51 earphone cushion may provide a better acoustical seal, thus providing a different occlusion effect than the MX41/AR earphone cushion. As can be seen in Hodgson and Tillman's data (1966), a reduction in coupling force from test to retest caused a reduction in the measured occlusion effect. This finding is related to volume effects in that an acoustic leak couples the enclosed volume under the occluding device to the infinite volume of air in the test environment.

Another difference in method is the mechanism used to place the occluding device on the subject's head. Liebman and Arasim (1971) indicated that the removal of hardware from the skull causes a decrease in the occlusion effect regardless of the occluding volume. They attributed the change to the manner in which the skull vibrates with various coupling mechanisms.

The occlusion effect also varies as a function of the placement of the bone vibrator (forehead vs. mastoid). Goldstein and Hayes (1965) studied the occlusion effect using both placements, and their results indicate an interaction with frequency: at 250 Hz the occlusion effect is greater for the mastoid placement than the forehead placement. Still, the mean mastoid occlusion effect nearly falls into the range of one standard deviation from the forehead mean. The occlusion effect at 500 through 2000 Hz is essentially independent of placement (a difference on the order of approximately 1 dB). Dirks and Swindeman (1967) and Barrett (1973) used a forehead placement, but

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corrected values for threshold in determining the occlusion effect (correction values were provided by the manufacturer of the bone vibrator). The use of such correction data constitute an additional source of variation among studies. Elpern and Naunton (1963) used a forehead placement, but do not indicate whether corrections were applied. Their data agree relatively well with the corrected data of Dirks and Swindeman (1967) and Berrett (1973).

Threshold measurement method also appears to systematically influence estimates of the occlusion effect. Elpern and Naunton (1963), Dirks and Swindeman (1967), and Berrett (1973) used a Bekesey recording audiometer technique, and their results agree relatively well. Goldstein and Hayes (1965) used the Carhart-Jerger ascending method for threshold estimation. As can be seen in Table 1, Goldstein and Hayes (1965) reported a smaller occlusion effect than did Elpern and Naunton (1963), Dirks and Swindeman (1967), and Berrett (1973). Hodgson and Tillman (1966) compared occlusion effects when the two methods of threshold estimation were used and found that the Bekesey technique produced occlusion effects approximately 6 dB greater at 250 Hz than the Carhart-Jerger ascending method. The mean unoccluded threshold at 250 Hz using the Bekesey technique was approximately 6 dB poorer than the mean unoccluded threshold using the Carhart-Jerger method. They indicated that despite careful checks of the equipment, no explanation for this result could be found. This discrepancy

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agrees with the discrepancy between Goldstein and Hayes' (1965) results and results obtained by Elpern and Naunton (1963), Dirks and Swindeman (1967), and Berrett (1973). The difference between Goldstein and Hayes' (1965) forehead data and results of other studies is greater than 6 dB in the lower frequencies. The difference in threshold estimation methodology would appear to account for the majority of the differences in occlusion effect magnitude between Goldstein and Hayes (1965) and other studies mentioned.

Relevant Experimental Results

Occlusion effect values for headsets using TDH-39 earphone capsules and MX41/AR cushions have been reported by several authors (Elpern and Naunton, 1963; Goldstein and Hayes, 1965; Dirks and Swindeman, 1967; Berrett, 1973). Their results are summarized in Table 1. No such data have been reported in the literature for the Model-51 earphone cushion when used with any type of earphone capsule. Similarly, no data are available for the MSH-87 headset.

Sources of Variability in Results

Several instrumental and methodological sources of variability in measured occlusion effects are noted above

TABLE 1. Summary of mean and standard deviation occlusion effect values in decibels for M141/AR earphone cushions used with TDH-39 earphone capsules taken from Elpern and Naunton (1963), Goldstein and Hayes (1965), Dirks and Swindeman (1967), and Berrett (1973).

		FREQUENCY IN HZ				
		250	500	1000	2000	4000
Elpern and Naunton						
1963	MEAN	28	20	9	0	0
	S.D.	6.5	4.0	4.5	4.5	3.0
Goldstein and Hayes						
1965 (mastoid)	MEAN	19	13	6	1	-4
	S.D.	8.1	9.7	7.1	3.8	9.7
(forehead)	MEAN	12	13	5	0	0
	S.D.	6.5	6.6	3.5	3.0	4.0
Dirks and Swindeman						
1967	MEAN	24	19	8	-1	X
	S.D.	4.1	3.7	4.0	2.7	X
Berrett						
1973	MEAN	19	18	9	1	X
	S.D.	6.1	5.4	8.4	4.8	X

NOTE: Mean values are rounded off to the nearest decibel; standard deviation values are rounded to the nearest tenth of a decibel; "X" indicates no data given.

(i.e., volume, coupling force, threshold estimation procedures, vibrator placement). It should be noted, however, that inter-subject differences are largely responsible for the large spreads in occlusion effect data. Hodgson and Tillman (1966) reported "while the average effect for groups of subjects tends to be a stable figure for a particular frequency or occluding agent, there appears to be considerable variability from subject to subject." Similarly, Berrett (1973) notes that:

> standard deviations computed for the occlusion effect across....studies...are relatively small. A great deal more variability across subjects within a given study is usually reported.

This variability is possibly related to physical differences among subjects in terms of pinna and ear canal size and compressibility.

Many authors attribute variations in mean occlusion effect to subject differences (Pohlman and Kranz, 1926; Elpern and Naunton, 1963; Dirks and Swindeman, 1967). It has also been observed that the wide range of occlusion effect magnitudes in normals agrees well with other aspects of normal auditory behavior, such as air conduction thresholds (Elpern and Naunton, 1963). Further, the occlusion effect appears relatively stable from test-to-retest (Elpern and Naunton, 1963; Dirks, 1964; Hodgson and Tillman, 1966; Dirks and Swindeman, 1967). Indeed, retest values can be predicted with as much accuracy as that associated with pure tone air conduction testing (Elpern and Naunton, 1963). Berrett (1973) noted statistical differences across studies and concluded that:

> Even though the occlusion effect for a given individual may vary significantly from the average, the means derived from the literature for each frequency probably are representative of the occlusion effect for a population of subjects with normal hearing.

Relevance to Clinical Procedures

It is important to know what the specific occlusion effect values are for a specific type of headset being used for masking purposes in bone conduction testing in order to determine appropriate levels of masking to introduce to the non-test ear (Studebaker, 1962, 1979). As Studebaker (1964) points out:

> The occlusion effect increases the level of the test tone in the masked ear, increasing the noise level necessary to mask the tone....//The noise level required to return the threshold of the masked ear to the unoccluded value (minimum masking for bone conducted stimuli) equals the minimum masking level for an air conducted stimulus of the same frequency plus the occlusion effect in decibels.

It is assumed that bone conduction thresholds are sought with the test ear unoccluded.

The occlusion effect also influences interaural attenuation. Berrett (1973) points out that "20 to 25 dB of interaural attenuation can be gained in the low frequencies if the opposite ear is unoccluded, and if that ear exhibits a normal occlusion effect." This has obvious relevance to clinical application of masking techniques: the frequency of masking dilemmas and indeed, the very need to mask is reduced as interaural attenuation is increased. Thus it is desirable in clinical audiometry to use a headset with a negligible occlusion effect; however, an acceptable substitution meeting this criteria has not yet been introduced for routine clinical use. Until such a headset gains popularity, audiologists can only acknowledge the existence of the effect and specify values for the effects caused by various headsets.

SUMMARY

Because headsets are necessary in routine clinical audiometry, much of an audiologist's behavior centers around the goal of proper calibration of earphones and of the testing environment. Calibration of earphones is essential to the accurate estimation of hearing threshold level. Proper calibration of earphones requires the use of an acoustic coupler, the properties of which are well known and stable. The dimensions of acoustic couplers must be consistent with those of laboratory microphones and other equipment that is not a part of the coupler itself, including any earphone cushions designed for use with a particular coupler. Differences in the nominal shapes or dimensions of couplers and cushions, or variations in the consistency of dimensions across cushions, bode ill for consistent and accurate coupler calibration.

Other characteristics of headsets, such as occlusion effect and attenuation of external sounds, are important concerns of audiologists. The occlusion effect caused by an audiometric headset is an important factor in masking decisions for bone-conduction testing. Attenuation characteristics of audiometric headsets must be determined to specify permissible ambient noise criteria of the test site. Thus, when any component of an audiometric headset is altered, the interaction with acoustic couplers, occlusion effect, and attenuation characteristics must be specified. Data regarding use of the MX41/AR and Model-51 earphone cushions with the NBS-9A coupler are available. However, there have been no published reports regarding the use of the Model-51 earphone cushion with the Zwislocki ear-simulator. Similarly, occlusion effect data are available for the MX41/AR earphone cushion, but not the Model-51 earphone cushion. Available attenuation data indicate no significant differences between these cushions.

PURPOSE

Because of differences between the MX41/AR and Model-51 earphone cushions in material, physical dimensions, and manufacturing processes, their interactions with acoustic couplers and their impact on occlusion effects may differ. No significant differences between the two models of cushions have been reported in the literature to date. However, indications of inter-laboratory differences and the lack of occlusion effect values for the Model-51 earphone cushion with a TDH-39 earphone capsule warrant further investigation of the acoustical performance of the Model-51 earphone cushion.

Statement of Questions

1. Do variations in coupling force affect the measured sensitivity or frequency response of an earphone in the NBS-9A acoustic coupler and the Zwislocki ear-simulator when the earphone is mounted in the MX41/AR versus the Model-51 earphone cushion?

2. Do the Model-51 and MX41/AR earphone cushions (used together with a TDH-39 earphone capsule) and the Madsen MSH-87 circumaural headset differ in the occlusion effects they produce for bone conducted stimuli in normal ears?

CHAPTER II

METHOD

INTRODUCTION

Two studies were proposed to evaluate the Model-51 earphone cushion regarding use with acoustic couplers and occlusion effects:

1) an evaluation of coupler responses of a TDH-39 earphone when fit with the Model-51 vs the MX41/AR earphone cushion using both the NBS-9A coupler and the Zwislocki-type ear simulator while systematically varying the coupling force

2) a comparison of the occlusion effects produced by three headsets: TDH-39--Model-51, TDH-39--MX41/AR, Madsen MSH-87 circumaural.

PARADIGM

The general experimental paradigm of the two studies were as follows:

1) Coupler Study: frequency response curves were generated for six samples of each cushion type (Model-51, MX41/AR) on a single TDH-39 earphone capsule using a series of coupling forces (100, 200, 300, 400, 500, and 1000

grams) on both the NBS-9A coupler and the Zwislocki-type ear simulator. Curves were then evaluated for differences.

2) Occlusion Effect Study: bone-conduction thresholds for pure tones at 250, 500, 1000, 2000, and 4000 Hz were determined for normal subjects in both open and occluded conditions using a Bekesey recording audiometer technique with a traditional button pressing response. TDH-39--Model-51, TDH-39--MX41/AR, and Madsen MSH-87 headsets were used as occluding devices. All subjects underwent binaural occlusion with these devices. A forehead placement was used for the bone vibrator in all conditions.

COUPLER STUDY

The purpose of this study was to compare frequency response curves of a single TDH-39 earphone fitted with MX41/AR and Model-51 earphone cushions. Six new cushions of each type (Model-51, MX41/AR) were randomly selected. The signal was a swept pure tone from 20-10,000 Hz, held constant at an arbitrary 30.5 millivolts (± 1 mv).

Apparatus

The signal was produced by a sine-random generator (B&K 1024), verified by a volt meter/frequency counter/

oscilloscope (Tektronix TM 504) and delivered to a TDH-39 earphone. The signal was measured by a half-inch pressure microphone (B&K 4134) installed in the Zwislocki-type ear simulator (Industrial Research Products DB-100). Measurements were also taken using a one-inch pressure microphone (B&K 4144) installed in an NBS-9A coupler (B&K 4152). The output from the microphone was pre-amplified (B&K 2619), amplified (B&K 2607), and recorded by a graphic level recorder (B&K 2305). The system was calibrated for level and checked for frequency response and amplitude linearity with a sound level calibrator (General Radio 1986). When the NBS-9A coupler was in use, the level calibration procedure was as follows: with the level calibrator set to a SPL of 94 dB at 1000 Hz and placed over the one-inch microphone without the protective grill in place, the sensitivity of the measuring amplifier was adjusted to read a coupler SPL of 94 dB. The graphic level recorder was then adjusted to produce an equivalent 94 dB pen deflection. The initial calibration of the half-inch microphone used with the Zwislocki-type ear simulator was the same as that just noted except that the driving level of the calibrator was set to a coupler SPL of 104 dB instead of 94 dB due to differences in microphone sensitivities. The microphone output voltage was measured for a calibrator input of 104 dB at 1 KHz. This was used as a calibration criterion to verify other components in the system (measuring amplifier and graphic level recorder). A block diagram of the apparatus is included in Appendix A.

Experimental Procedures

A dimensional analysis was performed on ten earphone cushions of each type. Measurements included mass, outside diameter, diameter of the soundhole (inside diameter), and wall thickness at the soundhole. Face angle of the cushions was calculated by:

1) placing the cushion face-down on a flat surface and measuring from the back of the soundhole to the flat surface.
2) subtracting the thickness of the wall at the soundhole from result of (1)
3) measuring the length of the face surface from the edge of the soundhole to the perimeter of the cushion
4) face angle was calculated by the formula:

$$\sin(\text{face angle}) = \frac{\text{result of (2)}}{\text{result of (3)}}$$

Frequency response curves were obtained for three placements of six each of the MX41/AR and Model-51 earphone cushions mounted on a single TDH-39 earphone capsule. A curve was generated for each of a series of coupling forces (100, 200, 300, 400, 500, and 1000 grams) on each cushion using both the NBS-9A coupler and the Zwislocki-type ear simulator. Thus a total of 432 curves were generated (6 cushions, 2 models, 6 coupling forces, 2 couplers, 3 placements). For each placement of each earphone, a series of six curves was generated (one for each coupling force).

For the purpose of verifying the consistency of the measuring system, a reference curve was generated for a 30.5 mv input to the earphone capsule used with no cushion attached. This was accomplished by using the NBS-9A coupler as a type-1 earphone coupler by inverting the coupler, sealing the earphone capsule to the coupler with a light film of vaseline, and placing a 500-gram mass over the earphone capsule. Earphone drive voltage was checked at 1 KHz prior to the initiation of each series of coupling forces for each cushion. The system was re-calibrated if the measured level varied more than 1 dB from the original calibration.

Data Reduction and Analysis

Response curves were reviewed in order of acquisition. Coupler sound pressure levels (SPLs) were tabulated at the following ten frequencies for each curve: 50, 100, 200, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz. Mean coupler SPLs were computed across placements within individual cushions for each combination of coupling force and frequency. These data were subject to an analysis of variance (3-way with repeated measures on two factors, Bruning and Kintz, 1977) to evaluate mean differences in coupler SPLs as a function of the main effects of cushion type, coupling force and frequency, as well as interactions among these factors.

OCCLUSION EFFECT STUDY

The purpose of this study was to obtain forehead bone-conducted thresholds for four conditions: 1) unoccluded, 2) occluded with TDH-39 earphones mounted with Model-51 earphone cushions, 3) occluded with TDH-39 earphones mounted with MX41/AR cushions, and 4) occluded with a Madsen MSH-87 headset.

Subjects

Subjects were 12 trained adult listeners with normal hearing. Subjects had clinically normal external and middle ears with no history of otologic pathology. All subjects underwent audiometric, otoscopic, and tympanometric screening. Audiometric screening step size was 2 dB. Pure tone hearing threshold levels (HTLs) were no poorer than 10 dB at 250, 500, 1000, 2000, and 4000 Hz. Air-bone gaps were 5 dB or less. There was no evidence of external otitis or scarring. Tympanograms were of normal shape (type A), amplitude (.39-1.3 cc), and contour (Jerger, 1970, 1972). The majority of subjects underwent the experimental session the same day as screening. The longest time lapse between subject screening and data collection was 1 day. The subjects were then re-screened with tympanometry before data collection.

Stimuli and Apparatus

Pure tones of 250, 500, 1000, 2000, and 4000 Hz were used for the study. An automatic recording audiometer (Grason Stadler E-800) was used to generate and deliver pulsed (200 msec with a 50% duty cycle) pure tones through a bone oscillator (Radio Ear B-71). Temporal characteristics of the tonal stimuli were verified by an oscilloscope (Tektronix SC 502). The linearity of the recording attenuator (Grason Stadler E-800) was checked prior to and following collection of experimental data. All behavioral testing was conducted in a double-wall, double-room sound chamber conforming to ANSI S3.1, 1977 "Criteria for Permissible Ambient Noise During Audiometric Testing", table II, row 2: octave band levels, ears not covered.

Experimental Procedures

All subjects underwent audiometric, otoscopic, and tympanometric screening. Subjects who passed the screening were given a statement regarding the purpose of the study and were asked to sign an informed consent release form. These forms are included in Appendix B.

Instructions were read to the subject who was then permitted to ask questions. A training session consisting of three one-minute bone-conduction threshold tracings was then conducted at each test frequency (250, 500, 1000, 2000, and 4000 Hz). Any subject producing a mean excursion width greater than 15 dB during the middle 30 seconds of the training procedure was dismissed.

One-minute bone-conduction threshold tracings were then obtained for the following conditions which were counterbalanced during the study:

1) unoccluded
2) occluded with a TDH-39--Model-51 assembly
3) occluded with a TDH-39--MX41/AR assembly
4) occluded with a Madsen MSH-87 assembly

The bone vibrator was held in place at the center of the forehead approximately one inch above the eyebrows by an adjustable rubber strap. A new headband (Telephonics TC-89E) was used to couple the TDH type earphone assemblies to the subjects' heads (pre-test axial force = 567.06 grams, post-test axial force = 559.79 grams). Subjects were given a one-minute rest between each headset condition. Subjects underwent three trials at each frequency for each condition, and were given a 5-minute rest between trials.

Headset order was counterbalanced, with the exception that the unoccluded condition always occurred first. Three subjects were tested with each of four different sequences of headsets. Subjects were randomly assigned to headset orders.

Data Reduction and Analysis

Raw data were in the form of one-minute fixed frequency Bekesey tracings. Thresholds were defined as the mean of the midpoints of the last ten excursions. Differences were computed (occlusion effects) by subtracting the mean threshold for each occluded condition from the mean threshold for the unoccluded condition for each trial within each subject. Mean and standard deviation occlusion effects were computed accross subjects for each occlusion condition and for each frequency. An analysis of variance (2-way within-subjects model, Linton and Gallo, 1975) was performed to evaluate the significance of any differences observed between mean occlusion effects of each occluding condition.

CHAPTER III

RESULTS AND DISCUSSION

INTRODUCTION

The goal of this study was to compare the effects of the MX41/AR and Model-51 earphone cushions upon coupler calibrations of headphone systems and upon occlusion phenomena. A Madsen MSH-87 headset was included in the occlusion effect study to assess the sensitivity of experimental methods and to provide initial data on this headset.

COUPLER STUDY

Dimensional Data

Table 2 summarizes the dimensional analysis performed on ten randomly selected cushions of each cushion type (Model-51 and MX41/AR). Confidence intervals (.95) were computed for each mean using the small-sample approximation (Hays, 1973, p. 399) and t-tests were conducted to compare dependent variables as a function of cushion type (Bruning and Kintz, 1977, p. 10). All measurements (mass, face angle, outside diameter, diameter of soundhole, and

Table 2: Summary of dimensional measurements taken on ten MX41/AR and ten Model-51 earphone cushions

CUSHION	MASS (grams)	FACE ANGLE (degrees)	OUTSIDE DIAMETER (cm)	INSIDE DIAMETER (cm)	WALL THICK. (cm)
MX41/AR Mean	45.4	15.6	7.1	1.9	.28
Confidence Interval(.05)	42.4-48.4	14.7-16.5	7.06-7.14	1.86-1.94	.27-.29
SD	4.23	1.2	.05	.06	.014
Model-51 Mean	33.5	20.5	6.9	2	.32
Confidence Interval(.05)	33.3-33.7	19.9-21.1	6.89-6.91	1.99-2	.3-.34
SD	.27	.9	.02	.01	.03
T-STATISTIC	8.89	10.17	13.08	5.48	3.84

NOTE: all T's are significant at the .05 level of confidence thickness of cushion wall at the soundhole) differed significantly across earphone cushions. Presumably, outside diameter of an earphone cushion has little effect on coupler SPLs; however, the physical characteristics of soundhole diameter, face-angle, mass, and wall thickness at the soundhole could have a potential effect. Richards, Frank, and Prout (1979) found differences in measured coupler SPLs as a function of soundhole diameter among samples of the MX41/AR earphone cushion, but reported no other dimensional characteristics of the cushions they used. Their results indicate that differences in soundhole diameter as small as 1/16-inch affect coupler SPLs above 3000 Hz. Richards, Frank, and Prout (1979) did not provide details of the magnitude of this effect. Soundhole diameters of the MX41/AR and Model-51 cushions reported in Table 2, when converted to inches, differed by approximately 1/25-inch. Mean values of the MX41/AR cushion dimensions met ANSI S3.6, 1969 specifications regarding face angle, soundhole diameter, outside diameter, and wall thickness. The standard deviations associated with these measurements, however, were higher than specification tolerances, suggesting that the present sample was within specifications but on different extremes of tolerance limits. Mean values for soundhole diameter and wall thickness for the Model-51 cushions did not meet specifications given in Chapter I (Figure 1). Soundhole diameter should be equal for the MX41/AR and Model-51 earphone cushions. Standard deviations in Table 2 indicate that physical dimensions were more consistent with the Model-51 than the MX41/AR cushions, but the difference between empirical data and specifications for the Model-51 cushion suggests manufacturing error (the samples measured were randomly selected). Although the two cushion types differ in physical dimensions, contributions of various dimensional characteristics cannot be separated for the present study because no control was exerted on any of these variables.

NBS-9A Coupler Data

Frequency response curves were obtained for a single TDH-39 earphone capsule using six samples of both the MX41/AR and Model-51 earphone cushions on the NBS-9A coupler and on a Zwislocki-type ear simulator. Response curves were obtained for six coupling forces (100, 200, 300, 400, 500, and 1000 grams). Three placements were executed for each coupling force on each individual cushion of both cushion types. Thus a total of 432 curves was generated (6 cushions, 2 models, 2 couplers, 6 coupling forces, and 3 placements). The signal was a swept pure tone (20-10,000 Hz) held at a constant drive level of 30.5 millivolts (± 1 mv). A reference curve was generated for this signal for the TDH-39 earphone capsule without a cushion on the NBS-9A coupler by inverting the coupler, sealing the earphone on the coupler with a light film of vaseline and placing a 500-gram mass on the earphone. It was not possible to obtain a reference curve for the TDH-39 earphone capsule without a cushion on the Zwislocki-type ear simulator because of coupler design.

Coupler SPLs were read from each of the 432 curves at each of the following frequencies: 50, 100, 200, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz. Mean SPLs were obtained across placements for each cushion, cushion type, mass condition, and coupler. Matrices of mean coupler SPLs for cushion type, individual cushion and mass conditions were constructed for each coupler. A third matrix related information derived by subtracting the reference condition (TDH-39 without a cushion on an NBS-9A coupler) SPLs at each test frequency from corresponding means in the matrix for the NBS-9A coupler. Raw data are included in Appendix C.

Each of the three matrices contained 120 cells (2 X 10 X 6), each with six entries (one for each cushion). Three smaller (2 X 10 X 3) matrices were constructed to facilitate evaluation of extreme values of coupling mass (100, 500 and 1000 gram conditions). Each matrix was subject to a three-way ANOVA with repeated measures on two factors (mass and frequency) using the model outlined by Bruning and Kintz (1977, p. 73). Means and standard deviations were obtained for each cell in each matrix to assess consistency of coupler measurement as a function of coupling mass and interactions with cushion type and frequency.

Figure 3 indicates standard deviations of coupler SPLs as a function of selected frequencies and mass-loading conditions for NBS-9A data. Figure 4 presents standard deviations for the reference data. For all mass-loading conditions (100, 500, and 1000 grams), standard deviations are less than 1 dB at all test frequencies for both earphone cushion types. Generally, coupling mass did not influence repeatability of measurement for the Model-51 cushion. However, the MX41/AR SPLs were more variable in the low frequencies at low-mass conditions. Increases in coupling mass improved repeatability of SPL measurements for the MX41/AR cushion.

Figure 5 indicates standard deviations of coupler SPLs as a function of selected frequencies and mass-loading conditions for the Zwislocki-type ear simulator data. The general trend for all mass-loading conditions follows the same pattern: very low (less than 1 dB) variability in coupler measurements at low- and mid-frequencies with increasing variability in the higher frequencies of 6000 and 8000 Hz. Variability at 6000 Hz for all mass-loading conditions is near 1 dB, while at 8000 Hz standard deviations range from approximately 1.5 to 3.6 dB with no consistent pattern of differences in variability between earphone cushion types. The lack of a consistent pattern

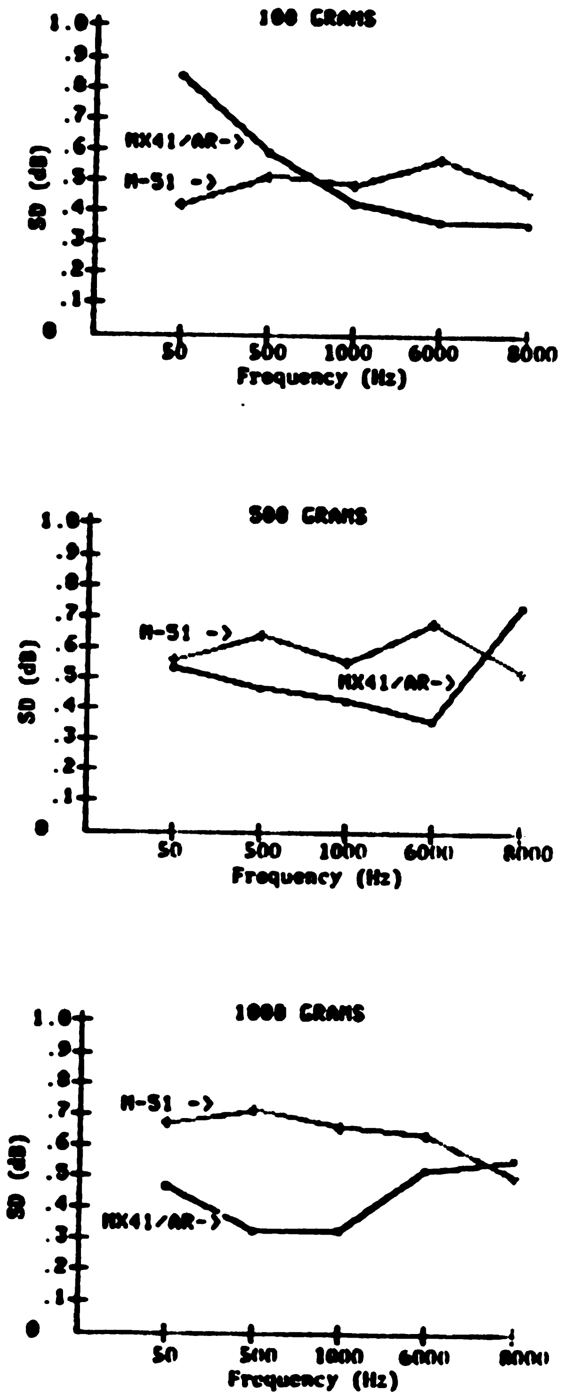


FIGURE 3: Standard deviation of NBS-9A coupler SPLs at selected frequencies for the 100-, 500-, and 1000-gram mass loading conditions on the MX41/AR and Model-51 earphone cushions on a single TDH-39 earphone capsule. Each datum represents six cushions.

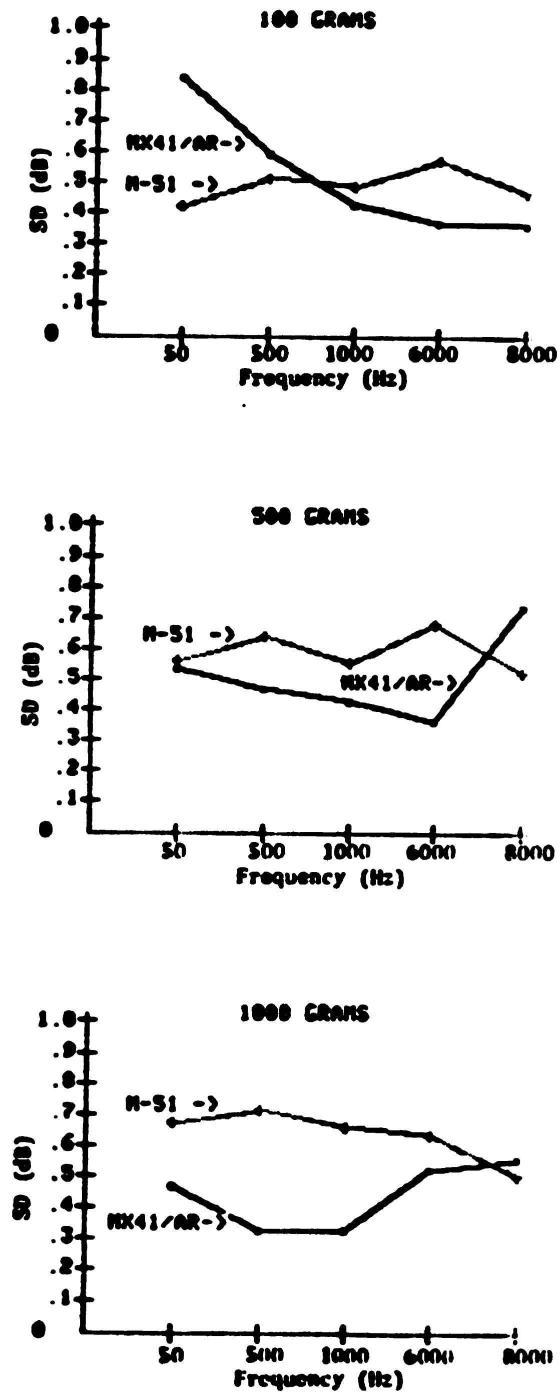
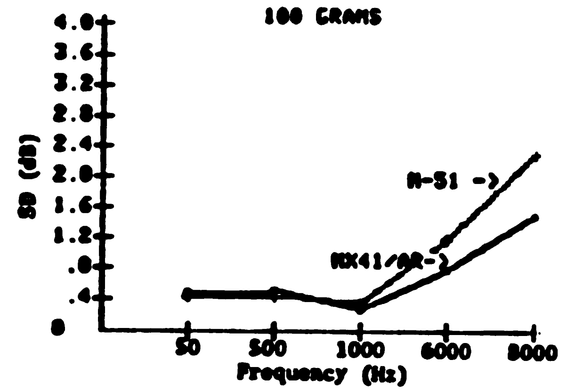
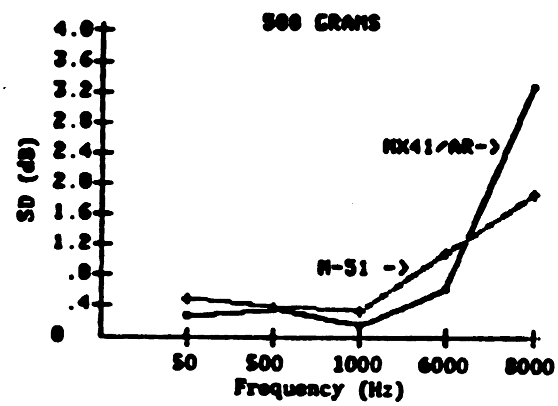


FIGURE 4: Standard deviation of cushion effects as a function of selected frequencies for the 100-, 500-, and 1000-gram mass loading condition on the MX41/AR and Model-51 earphone cushions on a single TDH-39 earphone capsule. Each datum represents six cushions.





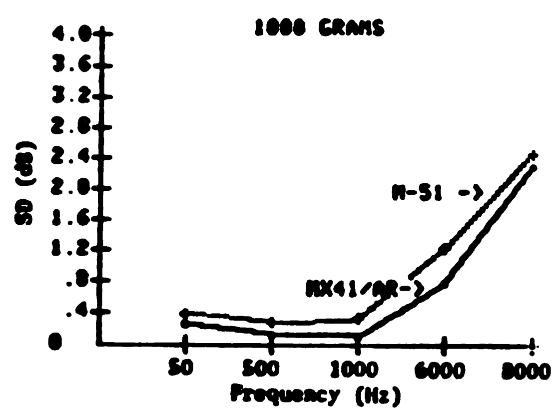


FIGURE 5: Standard deviation of Zwislocki-type ear simulator response at selected frequencies for the 100-, 500-, and 1000-gram mass loading condition on the MX41/AR and Model-51 earphone cushions on a single TDH-39 earphone capsule. Each datum represents six cushions.

suggests that this variability is likely to be a function of earphone placement on the coupler and not the earphone cushion. Also, differences in variability caused by the cushion would most likely be evident on both couplers; the standard deviations for coupler SPLs for the NBS-9A coupler are less than 1 dB for all test frequencies and mass-loading conditions for both cushion types. Generally, the Zwislocki-type ear simulator data are more variable than the NBS-9A data at frequencies above 1000 Hz. Variances on the order of 1 dB are at the limit of measurement system accuracy.

Table 3 summarizes the three-way ANOVA performed on the data from the NBS-9A coupler. F ratios were significant at the .05 level for all main effects and interactions except for the cushion-by-mass interaction. Figure 6 illustrates these effects. There is very little difference in measured SPL from 50-1000 Hz; beyond 1000 Hz coupler SPL increases slightly achieving a maximum value at 3000 Hz, then decreases dramatically with increasing frequency through 8000 Hz.

Although the analysis of variance produced several signifcant main effects and interactions, the strength-of--association indices suggest that the proportion of variance in the sample attributable to the main effect of frequency overwhelms all other effects. Eta-squared values (Linton and Gallo, 1975, p. 334) assign nearly 99 percent of variance in coupler SPLs to the frequency effect. This

Table 3: Summary table for 3-way ANOVA of NBS-9A data

SOURCE	DF	SS	MS	F	ETA^2
Between subjects	11	115.7			
Between cushions	1	54.8	54.8	9 *	.0037
Error (B)	10	61	6.1		
Within subjects	348	14816.2			
Frequency	9	14756.7	1639.6	12610.3 *	.988
Mass	2	2.1	1	7.3 *	.00014
Cushion X Freq	9	31.5	3.5	27 *	.0021
Cushion X Mass	2	.2	.1	.7	
Freq X Mass	18	4.7	.3	9.7 *	.00031
Cush X Freq X Mass	18	1.5	.1	3.1 *	.0001
Error (1)	90	11.7	.1		
Error (2)	20	2.9	.1		
Error (3)	180	4.8	0		
Total	359	14931.9			

note: "*" indicates significance at the .05 level of confidence

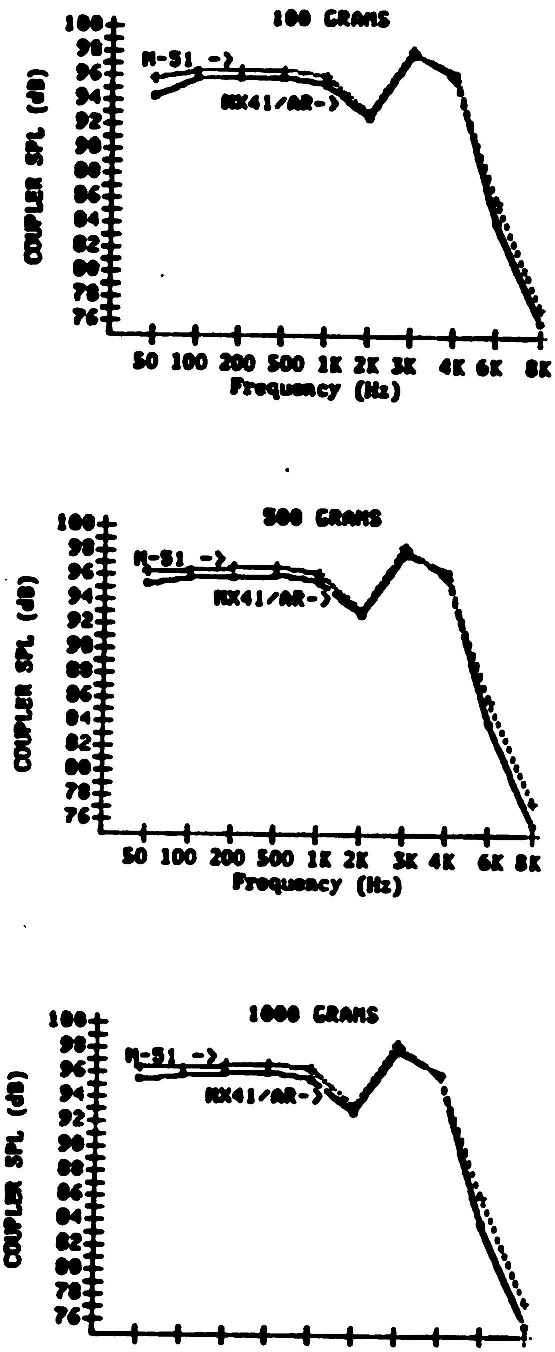


FIGURE 6: Mean frequency response curves taken on an NBS-9A coupler using a single TDH-39 earphone fit with MX41/AR and Model-51 earphone cushions under the 100-, 500-, and 1000-gram mass loading conditions. Each datum represents six cushions.

outcome is not surprising because the frequency responses of the TDH-39 earphone capsule and the NBS-9A coupler combine to cause considerable, well-documented differences in level as a function of frequency. Thus, the proportion of variance in the sample caused by other independent variables is negligible. Indeed, Figure 6 indicates that the effects of cushion type and mass-loading influence coupler SPL only to a negligible degree.

Figure 7 illustrates the cushion-by-mass-by-frequency interaction. Two effects are evident in these data. First, regardless of the mass condition, the Model-51 cushion yields higher coupler SPLs than the MX41/AR cushion from 50-1000 and 6000-8000 Hz. Although this cushion effect is consistent, it is small in magnitude, ranging from 2 dB at 6000 Hz for 1000 gram mass-loading to 1 dB at 50 Hz for 1000 grams. Second, the MX41/AR cushion shows variation in coupler SPL as a function of mass at 50 Hz and 8000 Hz (but not 6000 Hz), while the Model-51 shows a small mass-loading effect only at 50 Hz. Again, the size of the effect is small, never exceeding 1 dB.

This pattern is undoubtedly the source of the significant three-way interaction noted in Table 3, and is probably related to (1) greater soundhole diameter for the Model-51 cushion and (2) greater mechanical compliance (compressibility) of the MX41/AR cushion face. It appears that for the lowest mass condition, the MX41/AR may allow small air leaks, perhaps to the air volume in the area of

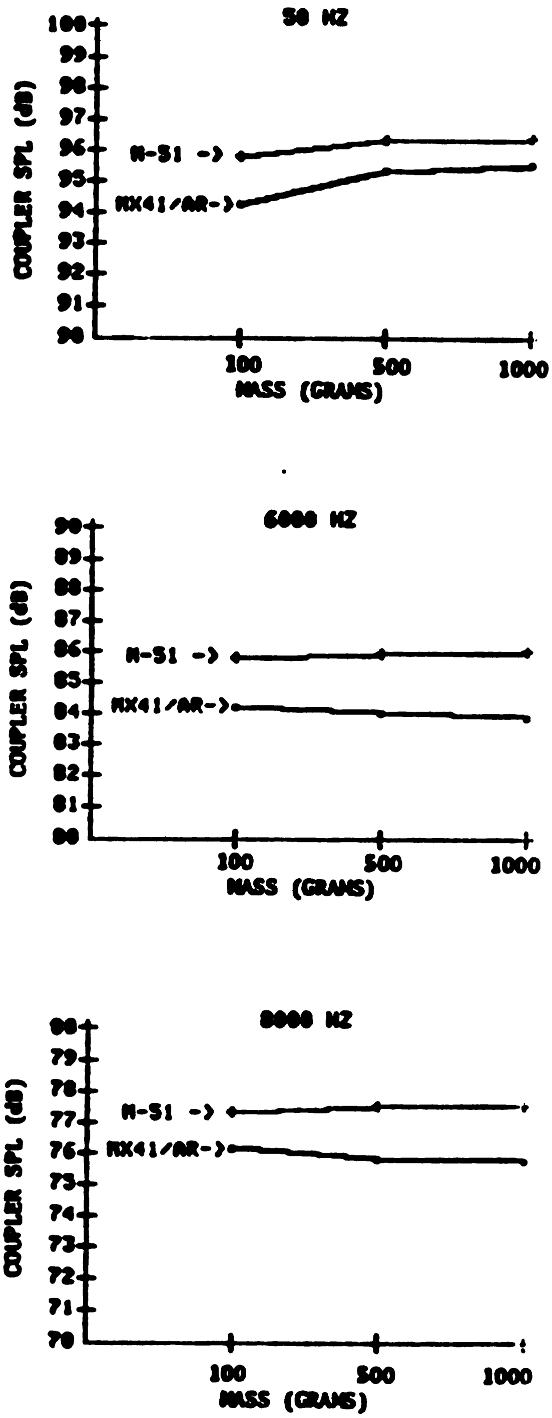


FIGURE 7: The effect of mass-loading condition on NBS-9A coupler SPL at 50, 6000, and 8000 Hz for the MX41/AR and Model-51 earphone cushions on a single TDH-39 earphone capsule. Each datum represents six cushions.

contact between the earphone capsule and cushion. This could account for the reduced coupler SPL for this cushion at 50 Hz. The highest mass-condition effect at 8000 Hz for the MX41/AR may be due to a slight reduction in total captive air volume for this condition, or to an interaction between a change in air volume (or inter-diaphragm distance) and the resonant properties of the coupler.

Reference Data

Reference data, derived by subtracting coupler SPLs of a TDH-39 earphone without a cushion at a constant drive voltage from coupler SPLs of a TDH-39 earphone with an earphone cushion in essentially the same coupler, had the effect of nullifying the effects of the frequency response of the earphone and the coupler. Results from these calculations may be considered primarily as cushion effects.

Table 4 summarizes the three-way ANOVA performed on the NBS-9A data after conversion relative to the reference curve. All main effects and interactions are significant at the .05 level of confidence except the cushion-by-mass interaction. These outcomes are identical to those of the previous analysis. Figure 8 illustrates these cushion effects. This figure shows very little cushion effect on measured couper SPLs as a function of frequency up to 3000 Hz. Above 3000 Hz, however, there is a considerable

Table 4: Summary table for 3-way ANOVA of NBS-9A reference data

SOURCE	DF	SS	MS	F		ETA^2
Between subjects	11	115.7				
Between cushions	1	54.8	54.8	9	*	.016
Error (B)	10	61	6.1			
Within subjects	348	3233				
Frequency	9	3174.2	352.7	2711.7	*	.948
Mass	2	2.1	1	7.2	*	.00063
Cushion X Freq	9	31.5	3.5	26.9	*	.0094
Cushion X Mass	2	.2	.1	.7		
Frequency X Mass	18	4.7	.3	9.7	*	.0014
Cush X Freq X Mass	18	1.5	.1	3.1	*	.00045
Error (1)	90	11.7	.1			
Error (2)	20	2.9	.1			
Error (3)	180	4.8	0			
Total	359	3349.4				

note: "*" indicates significance at the .05 level of confidence

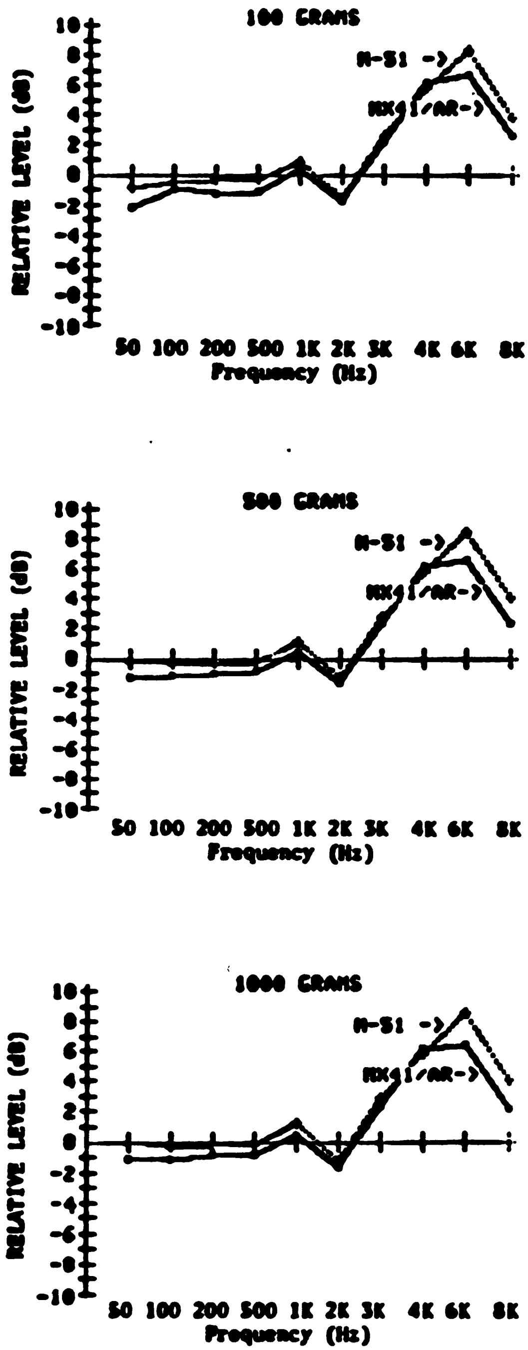


FIGURE 8: Mean cushion-effect curves for MX41/AR and Model-51 earphone cushions for the 100-, 500-, and 1000-gram mass conditions. Data were derived by subtracting a single frequency response curve (taken without a cushion on an inverted NBS-9A coupler) from frequency response curves for a single TDH-39 earphone fitted with the MX41/AR and Model-51 earphone cushions on an NBS-9A coupler. Each datum represents six cushions.

cushion effect: an increase in measured coupler SPLs. The nature of the effect is the same for both cushion types; there is an increase in cushion effect with an increase in frequency between 3000 and 6000 Hz, with the cushion effect becoming smaller by 8000 Hz. The cushion effect between the frequencies of 3000 and 8000 ranges between approximately 2 dB (at 3000 Hz) to 8.5 dB for the Model-51 cushion (at 6000 Hz) and 6.5 dB for the MX41/AR cushion (at 6000 Hz). Figures 9, 10 and 11 illustrate these cushion effects more closely. Differences in mass-loading have very little effect on cushion effects; the greatest effect appears at 50 Hz for the MX41/AR cushion and is approximately 1 dB. This may be seen graphically in Figure 9. Figures 8 through 10 also illustrate that differences in cushion effect from 50-4000 Hz between the MX41/AR and Model-51 cushions are 1 dB or less. Figure 11 suggests there is a greater difference between earphone cushion type in measured cushion effect at the frequencies of 6000 and 8000 Hz: approximately 2 dB at both frequencies with the Model-51 earphone cushion producing the larger effect.

As with the absolute NBS-9A coupler data, the strength-of-association measures indicate that the proportion of variance in the sample attributable to the main effect of frequency overwhelms all other effects. Eta-squared values assign approximately 95 percent of the variance in the sample to the main effect of frequency. Other main effects and interactions were very weak

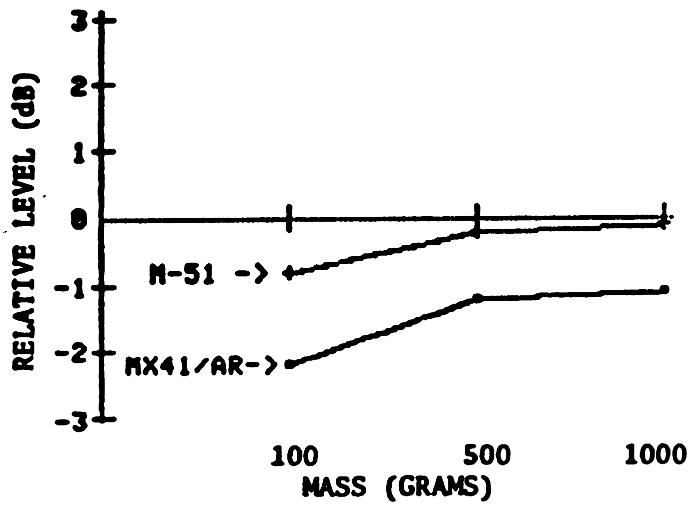


FIGURE 9: The effect of mass-loading condition on measured cushion effects at 50 Hz for the MX41/AR and Model-51 earphone cushions on a single TDH-39 earphone capsule. Each datum represents six cushions.

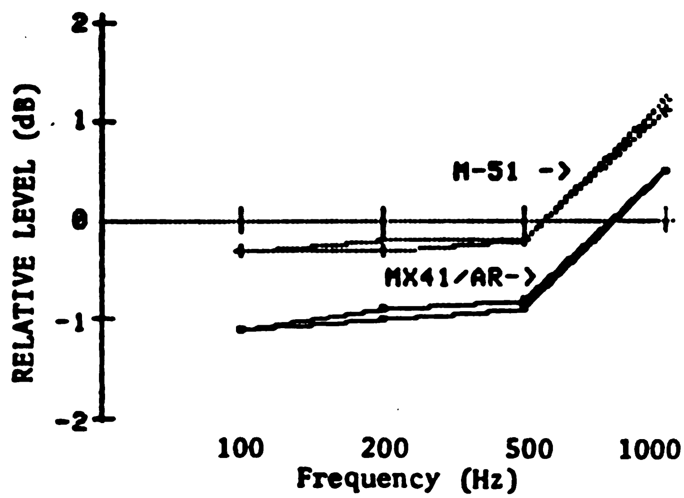


FIGURE 10: Two superimposed mean cushion-effect-by-frequency (100-1000 Hz) curves derived by subtracting a single reference frequency response curve (taken without a cushion on an inverted NBS-9A coupler) from frequency response curves taken on an NBS-9A coupler using a single TDH-39 earphone when fit with MX41/AR and Model-51 earphone cushions under two mass loading conditions (500, and 1000 grams). Each datum represents six cushions.

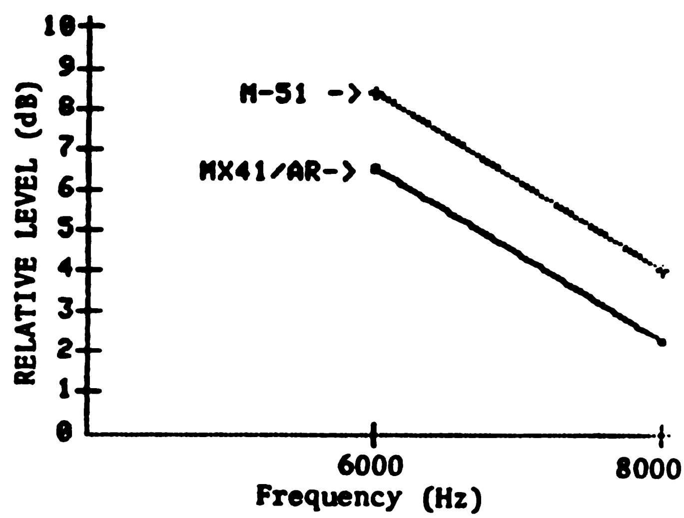


FIGURE 11: Cushion effect (derived by subtracting a single reference frequency response curve taken without a cushion on an inverted NBS-9A coupler from frequency response curves taken on an NBS-9A coupler using a single TDH-39 earphone when fit with MX41/AR and Model-51 earphone cushions) at 6000 and 8000 Hz for a 500 gram mass loading condition.

(accounting for variances in the sample on the order of 1 percent). The three-way interaction noted in Table 4 undoubtedly stems from the same pattern of differences noted for the absolute data: (1) the Model-51 cushion produced slightly higher coupler SPLs from 50-1000 Hz and 6000-8000 Hz (with a greater difference at 6000 and 8000 Hz), and (2) variation in coupler SPLs as a function of mass existed only at 50 Hz for the Model-51 cushion and at 50 and 8000 Hz for the MX41/AR cushion. The reference data substantiate the findings of the absolute data in that differences in coupler SPLs between the two cushions are in fact cushion related, probably to differences in physical dimensions (especially soundhole diameter), and compressibility of the cushions.

Zwislocki-type Ear Simulator Data

Table 5 summarizes the three-way ANOVA performed on the data from the Zwislocki-type ear simulator. The main effects of frequency and mass, and the interactions of cushion-by-frequency, frequency-by-mass, and cushion-by-frequency-by-mass are all significant beyond the .05 level of confidence. Figures 12 and 13 illustrate these effects. The well-documented frequency response of an earphone on a Zwislocki-type ear simulator is characterized by the prominent peak at 3000 Hz simulating the concha and ear canal resonances in the human ear. The Model-51 cushion

Table 5: Summary table for 3-way ANOVA of Zwislocki data

SOURCE	DF	SS	MS	F		ETA^2
Between subjects	11	81				
Between cushions	1	6	6	.8		
Error (B)	10	75	7.5			
Within subjects	348	13214.8				
Frequency	9	13002.2	1444.7	930.8	*	.9779
Mass	2	2.2	1.1	8.6	*	.00017
Cushion X Freq	9	41.8	4.6	3	*	.0031
Cushion X Mass	2	.3	.1	1.2		
Freq X Mass	18	4.5	.3	2.6	*	.00034
Cush X Freq X Mass	18	4.3	.2	2.5	*	.00032
Error (1)	90	139.7	1.6			
Error (2)	20	2.5	.1			
Error (3)	180	17.3	.1			
Total	359	13295.8				

note: "*" indicates significance at the .05 level of confidence

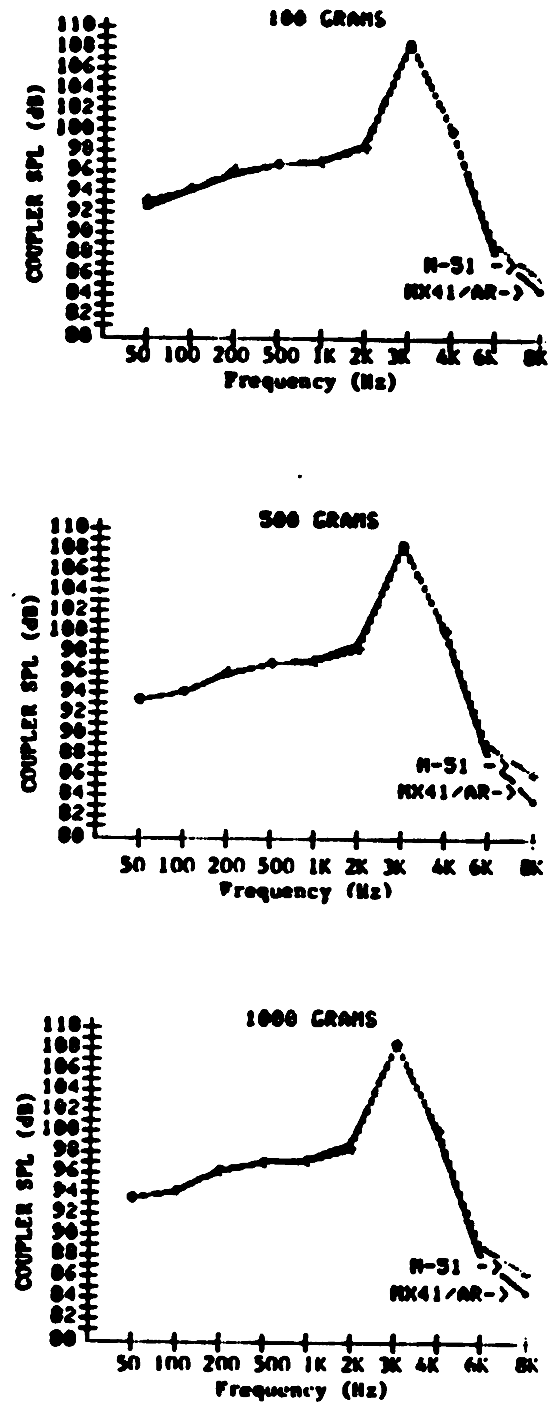
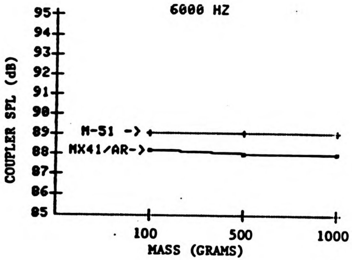


FIGURE 12: Mean frequency response curves taken on a Zwislocki-type ear simulator using a single TDH-39 earphone fit with MX41/AR and Model-51 earphone cushions under the 100-, 500-, and 1000-gram mass loading conditions. Each datum represents six cushions.



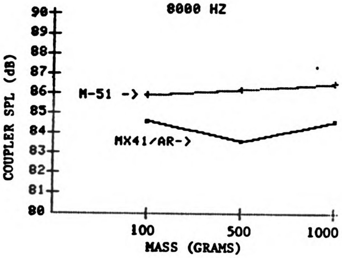


FIGURE 13: The effect of mass-loading condition on Zwislocki-type ear simulator SPL at 6000 and 8000 Hz for the MX41/AR and Model-51 earphone cushions on a single TDH-39 earphone capsule. Each datum represents six cushions.

produced higher coupler SPLs than the MX41/AR cushion at 6000 and 8000 Hz for all mass-loading conditions, but was not found to be statistically significant, probably because of the relatively high variability of measurement at these frequencies. The greatest effect was found at 8000 Hz for the 500-gram mass-loading condition (approximately 2 dB). Patterns of differences in cushion effects on frequency response between couplers in frequencies below 6000 Hz probably stem from the Zwislocki-type ear simulator's closer approximation to an optimum acoustic-impedance load.

As with the NBS-9A data, the MX41/AR cushion was more susceptible to changes in coupling mass than the Model-51 cushion, although the pattern differed. Essentially no mass-loading effect occurred at 50 Hz, while the mass-loading effect occurred at 8000 Hz with a non-linear pattern with increasing coupling force. Figure 13 illustrates this effect. The non-linearity of the pattern probably stems from an interaction of total captured air volume and coupler resonances.

Relation of Experimental Outcomes to Prior Research

As indicated, the overwhelming main effect of frequency has been well-documented (Michael and Bienvenue, 1980; Richards, Frank, and Prout, 1979; Burkhard and Corliss, 1954; and many others) and was certainly expected.

The present results agree with those of Michael and Bienvenue (1980) in that there are no marked coupler SPL differences as a function of cushion type alone. Michael and Bienvenue (1980) also observed a slightly greater coupler SPL (1.76 dB) at 6000 Hz when using the Model-51 cushion, but did not find the similar effect at 8000 Hz observed here. The results of the present study indicate slightly higher coupler SPLs (2 dB) at 6000 and 8000 Hz when using the Model-51 earphone cushion instead of the MX41/AR cushion.

Michael and Bienvenue (1980), in a study designed to evaluate differences between the Model-51 and MX41/AR earphone cushions regarding measured thresholds and NBS-9A coupler SPLs, report (regarding coupler SPLs) that "...there is a strong indication that the one-piece cushions will afford much more consistent results between units than do the conventional two-piece cushions." Incidental observations regarding consistency of measured coupler SPLs between the Model-51 and MX41/AR earphone cushions do not agree with previous observations. Figure 3 of the present study indicates essentially no difference in the consistency with which coupler measurements can be made using the two cushion types. Both cushion types yielded very consistent results (a standard deviation of less than 1 dB for all test frequencies). The Model-51 showed less change in coupler SPL with mass loading, suggesting that it may be less influenced by variations in coupling force to the head in clinical situations. This was observed only for very low frequencies, so low in fact that clinical relevance is moot.

Changes in earphone cushion characteristics appear to have effects in similar frequency ranges. Richards, Frank, and Prout (1979) reported differences in coupler SPLs between the frequency range of 3000-8000 Hz as a function of differences in soundhole diameter, with the largest difference occurring at 6000 Hz. The present study revealed cushion effects (increased coupler SPLs due to the cushion) over the frequency range of 3000-8000 Hz, with little or no effect below this range. The cushion effect undoubtedly arises from the difference in total captive air volume in the coupler for the reference condition, and the difference in the acoustic-impedance load presented to the diaphragm of the earphone driver. It is not clear, however, which characteristic of the earphone cushion causes this effect as it is present for both types of cushions. Cushions differ only slightly at the frequencies of 6000 and 8000 Hz (see Figures 8 and 11). The difference in cushion effect between cushions at 6000 and 8000 Hz probably stems from differences in soundhole diameter, but also may be related to the inter-diaphragm difference.

The frequency effects (frequency response characteristics) of the data on the Zwislocki-type ear simulator generally agree with other published results (Kruger, Kaplan, Karp and Joscelyn, 1982, and others). No other data are available comparing effects of cushion type or mass-loading on the ear simulator. The fact that small differences in coupler SPLs between cushions at low frequencies existed for NBS-9A measurements, but not for the ear-simulator measurements, exemplifies the contentions of Working Group 48 of the Committee on Hearing, Bioacoustics and Biomechanics of the National Research Council, National Academy of Sciences (1967), as reported by Zwislocki (1970), that the then current standard couplers for earphone calibration represented, in part, an:

> inappropriate load for earphones, which leads to large sound pressure differences between the real ear and the couplers, especially at low and high frequencies.

This suggests that, although slight differences between cushions exist in NBS-9A coupler measurements, these differences are not present in the real ear, and are thus artifacts of the NBS-9A coupler.

SUMMARY OF COUPLER STUDY RESULTS

Findings

All t-statistics from the dimensional analyses were significant at the .05 level of confidence. The Model-51 cushions had lower mass, a steeper face angle, smaller outside diameter, larger inside diameter, and thicker walls at the soundhole than the MX41/AR cushions. There is a need to perform a study to evaluate effects of extreme variations of the Model-51 cushion dimensions on coupler calibration and threshold estimations, such as Richards, Frank, and Prout's (1979) study of various MX41/AR cushions.

While the majority of F ratios from all analyses of coupler data was significant at the .05 level of confidence, strength-of-association measures revealed that the overriding effect was that of frequency, accounting for well over 90 percent of the variance in all three sets of sample data. The main effect of frequency for both the NBS-9A coupler and Zwislocki-type ear simulator reflects the well-known difference in coupler SPLs as the frequency responses of the earphone and the couplers combine to form responses that vary with frequency.

Other statistically significant effects were (1) a difference in NBS-9A coupler SPLs between the Model-51 and MX41/AR cushions when used on the same earphone capsule, and (2) a difference in coupler SPLs for the MX41/AR cushion as a function of mass-loading. Further research is needed to identify which earphone cushion dimensions influence earphone-coupler response on the standard NBS-9A coupler and to what extent variances in cushion dimensions influence an earphone's response on a near-optimum acoustic-impedance load. The Model-51 cushion consistently produced 1-2 dB higher coupler SPLs than the MX41/AR cushion from 50-1000 and 6000-8000 Hz on the NBS-9A coupler. Although the Model-51 produced up to 2 dB higher SPLs in the Zwislocki-type ear simulator at 8000 Hz, this effect was not statistically significant, partly because of the high variance associated with measurements taken on this coupler at high frequencies. An issue in deciding to use the Zwislocki-type ear simulator for coupler calibration is the high degree of variance of coupler SPLs at high frequencies for both the MX41/AR and Model-51 cushions. Variances at 8000 Hz are large enough to cause error in audiometer calibration, especially if calibration is based solely on one measurement. Knowing the actual signal levels presented to real ears at this frequency has always been a problem because of differences between the physical dimensions of subjects; however, if the calibration of the earphone on a coupler is not stable at this frequency it tends to compound the problem. An ear simulator may be inadequate for earphone calibration if it also simulates the variability of actual earphone response on real ears. A calibration reference is preferably both stable and valid; a choice between stability and validity seems to be a matter of opinion (when that choice is necessary) and certainly depends upon application. It is likely that the coupler itself does not produce these variances; rather, they are a result of (1) placement effects and (2) human measurement error, as there are many peaks and valleys in the response in this frequency region. Reading a dB value from a steeply sloping curve is not as certain as reading a value from a relatively flat area on the curve. Further research is needed to identify and control sources of variability in SPLs at high frequencies on the Zwislocki coupler, or to otherwise incorporate that variability into the measurement scheme.

Mass-loading had very little influence on coupler SPLs when using the Model-51 cushion (greatest effect on the order of .5 dB at 50 Hz for the NBS-9A coupler). Changes in mass-loading on the MX41/AR cushion, however, produced small differences in coupler SPLs at 50 and 8000 Hz on the NBS-9A coupler and at 8000 Hz on the Zwislocki-type ear simulator. The mass-loading effects never exceeded 1 dB, and are of no clinical significance. Mass-loading effects have not been previously reported in the literature. Results of the present study, as well as those of Michael and Bienvenue (1980), imply that while some differences do exist between the two cushion types studied regarding NBS-9A coupler SPLs, they are not of sufficient magnitude to be of clinical significance.

Conclusions

The differences between the Model-51 and MX41/AR cushions regarding coupler effects are not great enough to reject the Model-51 cushion for use in clinical audiology. Mass-loading effects have virtually no influence on calibration corrections based on coupler measurements of audiometric headsets.

OCCLUSION EFFECT STUDY

Summary of Methods

Occlusion effect data were obtained from twelve trained, normal-hearing subjects under three binaurally occluding conditions: 1) occluded with TDH-39 earphones fitted with MX41/AR cushions, 2) occluded with TDH-39 earphones fitted with Model-51 cushions, and 3) occluded with an MSH-87 headset assembly. Occlusion effect was determined by subtracting the occluded threshold from the unoccluded threshold. Forehead bone-conduction thresholds were determined by one-minute fixed-frequency Bekesey tracings for the frequencies of 250, 500, 1000, 2000, and 4000 Hz using the method of adjustment. Each subject underwent three successive trials in a single experimental session. Each trial consisted of five one-minute forehead bone-conduction threshold tracings (one for each frequency, 250-4000 Hz) for each of four randomized conditions (unoccluded, plus each of the occluding conditions noted). It was anticipated that the amount of occlusion effect would diminish with increasing frequency, and that the MSH-87 circumaural headset would produce a larger occlusion effect than either of the two supra-aural configurations (MX41/AR and Model-51).

Data Management Procedures

For each subject, minimum and maximum sound pressure levels were recorded for the last ten excursions of each one-minute tracing. Midpoints for each excursion were calculated by dividing the difference between each minimum and maximum by two and adding the result to the minimum. Midpoints for each excursion were tabulated and a trial mean was computed. Occlusion effects were computed for each condition and frequency in each trial for each subject. A mean occlusion effect was computed across trials for each subject resulting in a 180 cell matix (12 subjects X 5 frequencies X 3 conditions). Raw data are included in Appendix D. A two-way within-subjects ANOVA (Linton and Gallo, 1975, p. 175) was performed to evaluate the effects of frequency and headset type. Correlation coefficients (Pearson's r) were calculated for each headset type and frequency condition for trials 1-2, 1-3, and 2-3. Average correlation coefficients were computed for each headset type through r to z conversions as outlined in (Hays, 1973).

Experimental Outcomes

Examination of the standard deviations of occlusion effects (see Table 6) indicates that occlusion effects are fairly consistent across subjects for all test frequencies and headset types. Correlation coefficients across trials are given for each test frequency and headset type in Figure 14. Average correlation coefficients were calculated to be .704 for the MSH-87 headset, .7 for the MX41/AR--TDH-39 headset, and .64 for the Model-51--TDH-39 headset. All average correlation coefficients are significant at the .05 level. Each headset produced fairly consistent test-retest data. Although the Model-51 cushion produced somewhat less consistent data, there is essentially no difference between headset types in consistency of measurements.

Mean and standard deviation occlusion effects are given in Table 6. Occlusion effects were approximately 20 dB at 250 and 500 Hz for the MX41/AR and Model-51 cushions, decreasing with increasing frequency becoming negative beyond 2000 Hz. The MSH-87 headset produced larger occlusion effects at 250 and 500 Hz (26 and 29 dB respectively) with a similar pattern of decreasing occlusion effect with increases in frequency.

Table 7 summarizes the two-way ANOVA performed on the occlusion effect data. All F ratios are significant at the

Table 6: Occlusion effects of various headsets on forehead bone-conducted pure tones. Each datum is based upon 12 normal-hearing listeners.

FREQ:	250	500	1000	2000	4000
MX41/AR					
Mean	20.4	23.4	8.9	-2	-8.1
S.D.	5.1	6.4	5.9	2.7	4.4
Model-51					
Mean	20.3	20.9	7.4	-1.5	-8.4
S.D.	5.6	6.2	6.5	3.2	3.9
MSH-87					
Mean	26.1	29.2	10.9	4.9	-6.4
S.D	5.4	7.9	8	5.7	5.2

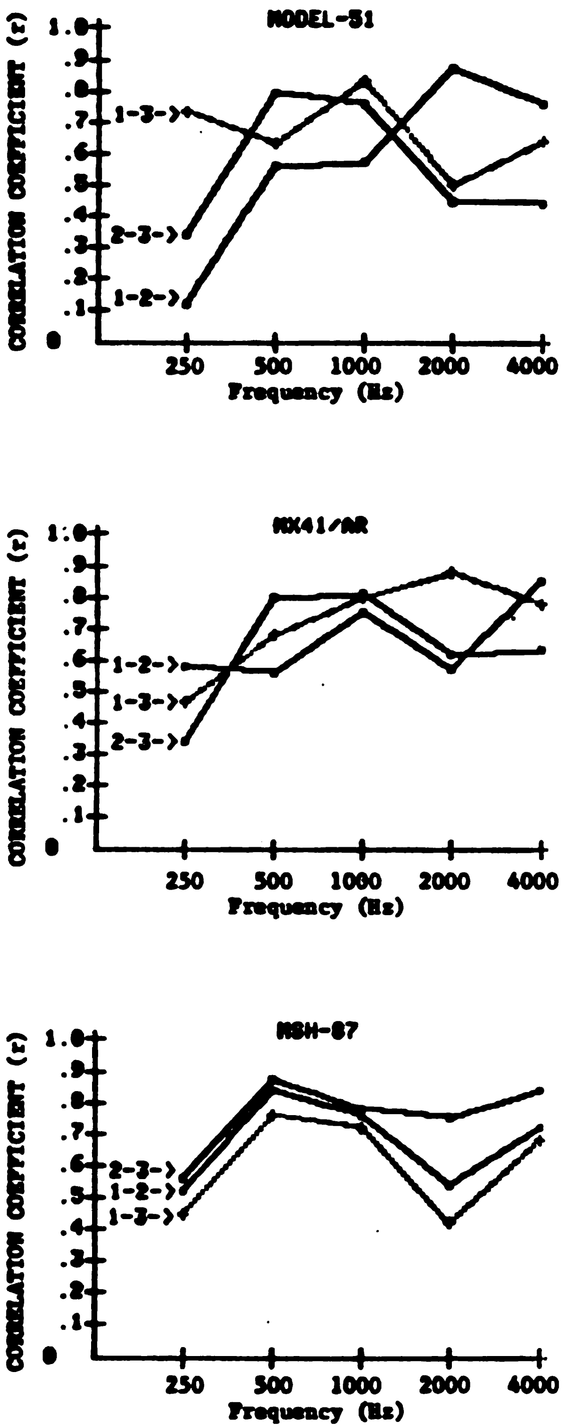


FIGURE 14: Correlation coefficients between trials 1-2, 1-3, and 2-3 for mean occlusion effects of the MX41/AR and Model-51 earphone cushions on a TDH-39 earphone capsule and the MSH-87 headset from 250-4000 Hz. Each datum represents 12 subjects.

Table 7: Summary of 2-way ANOVA of occlusion effects of three headsets and five frequencies

SOURCE	DF	SS	MS	F	ETA^2
Headset type (A)	2	945.37	472.69	37.78	.028
Frequency (B)	4	27446.36	6861.59	142.39	.811
Subjects (S)	11	1977.04	179.73		
Headset X Freq (A x B)	8	212.48	26.56	2.66	.0063
Headset X Subject (A x S)	22	275.26	12.51		
Frequency X Sub (B x S)	44	2120.19	48.14		
(A x B x S)	88	879.66	10		
Total	179	33856.36			

note: all F's are significant at the .05 level

.05 level. The nature of the effects may be seen graphically in Figures 15 and 16. Strength-of-association measures reported in Table 7 reveal that the frequency effect was the largest, accounting for approximately 81 percent of the variance in the sample. The main effect of headset type and the headset-by-frequency interaction accounted for approximately 3 percent and 1 percent of sample variation respectively. A Newman-Keuls test was performed (Linton and Gallo, 1975, p. 324) to evaluate differences between means within the headset-by-frequency interaction effect. The MX41/AR and Model-51 cushions produced essentially similar occlusion effects at all frequencies tested. The MSH-87 headset produced significantly larger occlusion effects (by 6, 9, and 7 dB) at the frequencies of 250, 500, and 2000 Hz respectively. The three headsets produced essentially similar occlusion effects at 1000 and 4000 Hz (9, and -8 dB respectively). These effects are best illustrated in Figure 15. The significant main effect of headset type stems from the difference between the MSH-87 headset and the other two types of cushions used on the TDH-39 earphones. The size of the effect is not large because only one headset type differed significantly from the other two and only at three frequencies. The significant main effect of frequency stems from the decrease in occlusion effect with an increase in frequency for all headset types. The headset-by-frequency interaction stems from the expected

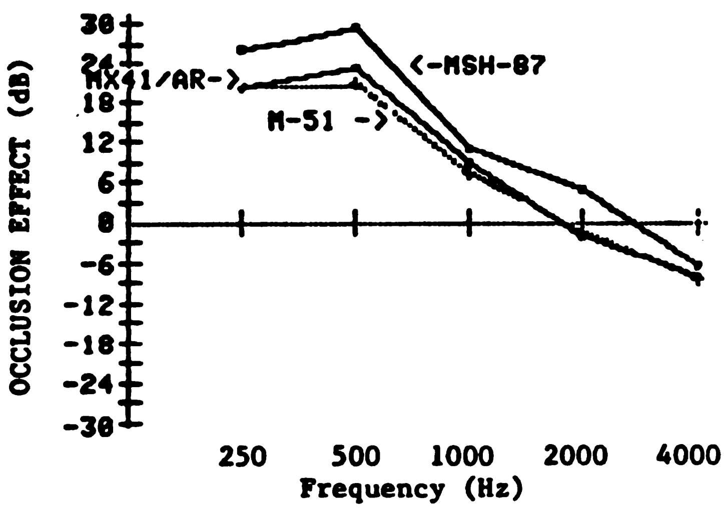


FIGURE 15: Mean occlusion effects for three headsets (TDH-39 earphone with MX41/AR and Model-51 earphone cushions and the MSH-87 headset) from 250-4000 Hz. Each datum represents 12 subjects.

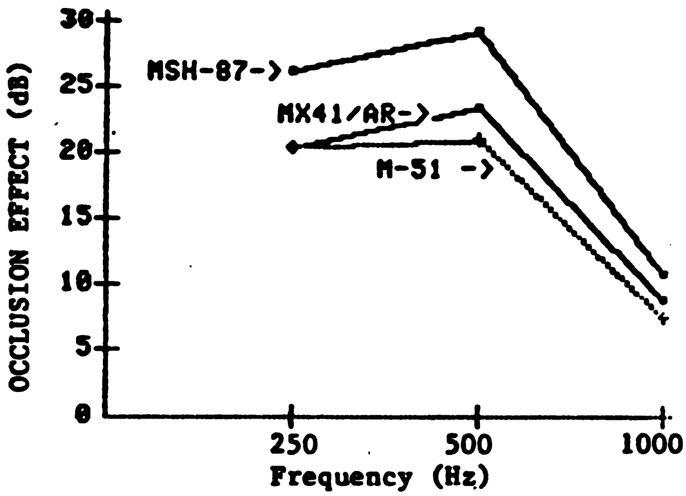


FIGURE 16: Mean occlusion effects for three headsets (TDH-39 earphone with MX41/AR and Model-51 earphone cushions and the MSH-87 headset) from 250-1000 Hz. Each datum represents 12 subjects.

convergence in occlusion effects in the higher frequencies.

Relation of Experimental Outcomes to Prior Research

The magnitudes of the occlusion effects measured in the present study agree fairly well with those reported in previous studies employing similar methods. Table 8 summarizes occlusion effects measured when using TDH-39 earphones fitted with MX41/AR cushions and a forehead placement of the bone conduction oscillator. As noted in Chapter I, the discrepancy between the magnitude of the occlusion effect at 250 Hz measured by Goldstein and Hayes (1965) and other researchers is largely the result of methodological differences.

One major difference occurs between results of the present study and others reported in Table 8: occlusion effects measured at 4000 Hz are negative for the present study and non-existent in all of the studies which report occlusion effects for TDH-39--MX41/AR headsets at this frequency (with forehead placement). Goldstein and Hayes (1965) found negative occlusion effects at 4000 Hz for mastoid data, with an associated decrease in SPL in the auditory canal for this frequency. No explanation for this phenomenon is readily available from this study's data.

No data are available in the literature for the MSH-87 headset for comparative purposes; however, a comparison of occlusion effects measured for the MSH-87 headset to

Table 8: Summary of mean and standard deviation occlusion effect values in decibels for M141/AR earphone cushions used with TDH-39 earphone capsules taken from Elpern and Naunton (1963), Goldstein and Hayes (1965), Dirks and Swindeman (1967), and Berrett (1973). Values for various headsets from the present study are included for comparison.

FREQUENCY IN HZ		250	500	1000	2000	4000
Elpern and Naunton						
1963(forehead)	MEAN	28	20	9	0	0
	S.D.	6.5	4.0	4.5	4.5	3.0
Goldstein and Hayes						
1965 (mastoid)	MEAN	19	13	6	1	-4
	S.D.	8.1	9.7	7.1	3.8	9.7
(forehead)	MEAN	12	13	5	0	0
	S.D.	6.5	6.6	3.5	3.0	4.0
Dirks and Swindeman						
1967(forehead)	MEAN	24	19	8	-1	X
	S.D.	4.1	3.7	4.0	2.7	X
Berrett						
1973(forehead)	MEAN	19	18	9	1	X
	S.D.	6.1	5.4	8.4	4.8	X
Present Study						
MX41/AR						
(forehead)	MEAN	20	23	9	-2	-8
	S.D.	5.1	6.4	5.9	2.7	4.4
MODEL 51						
	MEAN	20	21	7	-2	-8
	S.D.	5.6	6.2	6.5	3.2	3.9
MSH-87						
	MEAN	26	29	11	5	-6
	S.D	5.4	7.9	8	5.7	5.2

NOTE: Mean values are rounded off to the nearest decibel; standard deviation values are rounded to the nearest tenth of a decibel; "X" indicates no data given.

occlusion effects measured for other circumaural systems is possible. Circumaural systems potentially differ from supra-aural systems in four areas: volume, seal, coupling force, and amount of hardware. Briefly, the effects of these factors are as follows: significant increases in volume decrease the occlusion effect; increases in the integrity of the acoustical seal increase the occlusion effect; increases in coupling force increase occlusion effect; and reduction of the amount of hardware placed on the head reduces the occlusion effect.

Although the MSH-87 headset is a circumaural system, it yields consistently greater occlusion effects than the supra-aural systems evaluated in the study. Tillman (1962) (as reported in Hodgson and Tillman, 1966) measured occlusion effects of a circumaural system that were less than those measured when using supra-aural systems as occluding devices. Tillman attributed this to differences in volume between circumaural and supra-aural systems. The discrepancy between occlusion effects measured while using the MSH-87 headset as an occluding device and other circumaural systems may also be related to enclosed volume differences. Because the MSH-87 headset assembly is basically an earphone (unidentified) fit with an MX41/AR cushion encased in a large shield which uses a circumaural cushion to couple the assembly to the head, the volume enclosed is similar to that enclosed by supra-aural systems. Thus the factors of acoustic seal and hardware considerations may be the underlying causes of increased occlusion effects measured for this system. The MSH-87 headset provides a better acoustical seal and more hardware on the head than the supra-aural systems studied.

The stability of the occlusion effect for the MX41/AR cushion in the present study is in keeping with that reported in the literature. Standard deviations of measured occlusion effects are similar among studies at corresponding frequencies (see Table 8). Correlation coefficients between trials in the present study are strikingly similar to those of Dirks and Swindeman (1967), who reported test-retest r's ranging from approximately .3 to .8 for the MX41/AR cushion compared to test-retest coefficients ranging from .34 to .88 in the present study. The Model-51 cushion revealed a somewhat wider spread in test-retest correlation coefficients (.12-.87), while the MSH-87 headset revealed a somewhat smaller spread (.42-.87). No data have been reported in the literature regarding magnitude, consistency, or dispersion of occlusion effects for the Model-51 cushion or the MSH-87 headset.

The test-retest pattern between the headsets suggests that occlusion effect consistency from test-to-retest may be related to the consistency with which headsets can be fit over the ears. While correlation coefficients are very similar across headsets, slight differences present a pattern possibly related to cushion/headset dimensions.

The difference in face angle of the Model-51 cushion may interact with subject pinna size and shape to produce less reliable re-fitting; the circumaural MSH-87 enables more consistent re-fitting. Hodgson and Tillman (1966), however, report very poor test-retest correlations with a circumaural headset. The circumaural system they used was undoubtedly very different from the MSH-87 headset since it enclosed a larger volume of air than the MX41/AR when coupled to the ear. The MSH-87, on the other hand, encloses a volume of air similar to that of the MX41/AR.

A "ceiling effect" reported by Hodgson and Tillman (1966) was also reported by Dirks and Swindeman (1967): a reduction in variability of the occlusion effect at higher frequencies was caused by the reduction in size of the effect. Results of the present study would indicate that, although the variability of the occlusion effect is less for the high frequencies than for the low frequencies, this is not necessarily related to the size of the effect. Examination of mean occlusion effects and corresponding standard deviations in Table 8 shows that for the present study, variability of the occlusion effect at 4000 Hz for the MX41/AR and Model-51 conditions is greater than the variability at 2000 Hz for the same conditions, even though the occlusion effect is substantially smaller. One possible explanation would include the "ceiling effect" with an added condition: variability in measured occlusion effect is reduced as the effect nears zero from any direction. In other words, as the absolute value of the occlusion effect decreases, so does the associated variability (to the point of approximating that associated with test-retest variability for unoccluded bone-conduction tests).

SUMMARY

Findings

The study indicates that 1) there is essentially no difference in measured occlusion effects between the MX41/AR and Model-51 earphone cushions at corresponding frequencies when used with a TDH-39 earphone capsule and a model TC-89E headband, and that 2) the MSH-87 headset produces consistently greater occlusion effects at 250, 500, and 2000 Hz than either the MX41/AR or the Model-51 earphone cushion when used with a TDH-39 earphone capsule.

The results of the study suggest no need to change clinical references for the occlusion effect under masking for bone conduction when Model-51 cushions are used in place of MX41/AR cushions. Results also indicate that masking rules at 2000 and 4000 Hz for either cushion may be slightly more conservative than previously realized. However, the study offers no information about masking for air-conducted signals, when inter-aural attenuation is of interest. It has been shown that inter-aural attenuation varies with headset type and is related to the occlusion effect (Berrett, 1973; Studebaker, 1962; and others). Research is needed to compare the inter-aural attenuation effects of the MX41/AR and Model-51. Although occlusion effect data suggest no difference between the two cushions in terms of inter-aural attenuation for bone-conducted sounds, they may produce different effects on inter-aural attenuation of sounds produced by an earphone.

Results of studies regarding attenuation characteristics and threshold comparisons with the Model-51 cushion have followed trends similar to those reported here: the new cushion produces slightly different results, often more consistent, but not enough so to warrant clinical significance (Michael and Bienvenue, 1980, 1981).

The MSH-87 headset is used primarily in evoked response audiometry. This study offers no suggestions for use when this headset functions as a primary signal transducer. However, when it is used to mask bone-conducted stimuli, the magnitude of the occlusion effect for pure tones becomes troublesome. Evoked response audiometry generally makes use of high-frequency stimuli where the occlusion effect becomes negligible. If low frequency signals are to be used, it may be prudent to use a transducer other than the MSH-87 assembly to present masking signals for bone-conducted sounds. Further research is needed to evaluate the occlusion effects of the MSH-87 headset for click stimuli, the type most often used in evoked response audiometry. If other headsets (such as the TDH-39--Model-51 combination) are used to deliver masking signals in evoked response audiometry, they, too, should be evaluated for click-stimuli occlusion effects.

There are no archival data regarding Model-51 cushion or MSH-87 headset susceptibility to body exudates, bacterial cross-contamination, or changes in physical properties (primarily flexibiity/pliability) as a function of humidity, temperature or time. Such studies are not feasible until these products have been on the market for a longer period of time.

Conclusions

There is essentially no difference in occlusion effects between the MX41/AR and Model-51 earphone cushion when used with a TDH-39 earphone capsule. The MSH-87 headset yeilds greater occlusion effects, probably because of increased mass (amount of hardware), and an improved acoustical seal. The occlusion effect is a stable phenomenon from test to retest regardless of occluding device; the largest source of variability in measured occlusion effect arises from inter-subject differences.

CHAPTER IV

SUMMARY AND CONCLUSIONS

INTRODUCTION

In 1980, Telephonics corporation (the major supplier of audiometric headsets in the United States) discontinued production of the current standard cushion (MX41/AR) used in audiometry, replacing it with a one-piece earphone cushion (Model-51) of different material and slightly different physical dimensions. Although published comparisons of the two cushions report no differences in threshold measurements or coupler measurements, no data were found comparing the two cushions in terms of (1) occlusion effects, or (2) the effects of coupling force upon coupler responses. The occlusion effect produced by an audiometric headset is an important consideration in determinations of minimum masking levels for bone-conduction audiometry. Coupling force for coupler calibration of earphones (currently standardized at 400-500 grams) has not been evaluated as an independent variable, but might be expected to interact with earphone cushion material and construction.

The goals of the present study were to (1) evaluate the Model-51 earphone cushion regarding consistency of coupler measurements as a function of coupling force (mass-loading), (2) compare the Model-51 cushion to the MX41/AR cushion regarding consistency of measurement and measured SPLs in a coupler, (3) evaluate differences between the two cushion types regarding occlusion effects on boneconducted pure tones, and (4) provide new occlusion effect data for the MSH-87 circumaural headset, a system sufficiently different from those noted above to provide a check of the sensitivity of experimental methods.

COUPLER STUDY

A dimensional analysis was performed on ten MX41/AR and ten Model-51 cushions to compare mass, face angle, outside diameter, inside diameter, and wall thickness at the soundhole. Frequency response curves (20-10,000 Hz) were obtained for six cushions of each type (MX41/AR and Model-51) for a series of six mass-loading conditions (100, 200, 300, 400, 500, and 1000 grams). A single TDH-39 earphone capsule was driven at a constant 30.5 volts. Two couplers were used: the NBS-9A 6cc coupler and a Zwislocki-type ear simulator manufactured by Industrial Research Products. Three placements were executed for each combination of cushion, mass, and coupler.

Ten coupler SPLs were read from each frequency response curve (one for each frequency of 50, 100, 200, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz). SPLs were collapsed across placements for each earphone cushion, mass-loading condition, and coupler. A set of reference data was constructed by subtracting the frequency response of the TDH-39 earphone capsule without a cushion on the inverted NBS-9A coupler from each frequency response curve generated on the NBS-9A coupler for the same earphone capsule using the experimental cushions. Coupler SPLs and cushion effects were evaluated for differences as a function of cushion type, mass-loading condition, and frequency.

Findings

Differences in physical dimensions between the two cushion types were small, but statistically significant. Of the cushions studied, the Model-51 was smaller in mass, had a steeper face angle, smaller outside diameter, larger inside diameter, and thicker walls at the soundhole than the MX41/AR cushion.

Measured coupler SPLs differed across frequency reflecting the well-known frequency response of the TDH-39 earphone in acoustic couplers. Slight differences (1 to 2 dB) were noted between coupler SPLs when using the Model-51 earphone substituted for the MX41/AR earphone cushion from 50-1000 and 6000-8000 Hz on the NBS-9A coupler, and from 6000-8000 Hz on the Zwislocki-type ear simulator. Various mass-loading of earphones on couplers had a slight effect (less than 1 dB) on the NBS-9A coupler SPLs at 50 and 8000 Hz for the MX41/AR and at 50 Hz for the Model-51 cusion. Mass loading effects on the Zwislocki-type ear simulator were evident for the MX41/AR cushion at 8000 Hz. Cushion effects were present in the high frequencies (3000-8000 Hz). Cushion effects increased with increasing frequency from 3000-6000 Hz reaching a maximum at 6000 Hz (9 dB for the Model-51 cushion, and 7 dB for the MX41/AR cushion) becoming reduced by 8000 Hz. A difference of approximately 2 dB was observed between the cushion types at the frequencies of 6000 and 8000 Hz. Standard deviations of coupler SPLs were less than 1 dB for all frequencies for both cushion types on the NBS-9A coupler. For the Zwislocki-type ear simulator, variability of measurement increased with increasing frequency above 1000 Hz for both cushion types. Generally, ear simulator data were more variable than the NBS-9A data at frequencies above 1000 Hz.

Although nearly all F ratios for the coupler data were significant at the .05 level, strength-of-association measures revealed that the main effect of frequency accounted for over 90 percent of the variance in the sample, overwhelming other effects and interactions. This effect was expected as a result of the responses of the earphone capsule and the acoustic couplers.

Conclusions

The Model-51 earphone cushion may be directly substituted for the MX41/AR cushion when calibrating earphones on acoustic couplers; repeatable and comparable coupler measurements may be made using either the Model-51 or MX41/AR earphone cushions. Variations of mass-loading of earphones on couplers in the range 100 to 1000 grams has little effect on coupler SPL; thus, the effects of variations of in situ axial force are unlikely to differ between the cushions. Because differences in cushion dimensions may affect coupler response in the region of 3000-8000 Hz, care should be exercised in verifying the standard dimensions of cushion samples. Further research is needed to develop calibration strategies for use of the Zwislocki-type ear simulator as an acoustic load for the purpose of earphone calibration.

OCCLUSION EFFECT STUDY

Subjects were twelve trained normal-hearing young adults with a normal otologic history. Forehead bone-conduction thresholds were obtained via traditional one-minute fixed-frequency Bekesey tracings for 250, 500, 1000, 2000, and 4000 Hz for four conditions:

1) unoccluded

2) binaurally occluded with TDH-39 earphones fit with Model-51 earphone cushions

3) binaurally occluded with TDH-39 earphones fit with MX41/AR earphone cushions

4) binaurally occluded with a Madsen MSH-87 headset.

Each subject underwent three successive trials consisting of five one-minute threshold tracings (one for each test frequency) for each of the four experimental conditions. Threshold was defined as the mean of the midpoints of the last ten excursions of each tracing. Occlusion effect values were derived by subtracting occluded thresholds from unoccluded thresholds at each test frequency for each headset, trial, and subject. Occlusion effects were collapsed across trials for each subject.

Findings

Occlusion effects were greatest in the low frequencies of 250 and 500 Hz, varying inversely with frequency and becoming negligible beyond 1000 Hz for all headset types. For both the MX41/AR and Model-51 earphone cushions, occlusion effects were approximately 20 dB at 250 and 500 Hz, decreasing to approximately 10 dB at 1000 Hz, and becoming negative beyond 1000 Hz. Occlusion effects for the MX41/AR and Model-51 cushions did not significantly differ at any test frequency. Occlusion effects for the

MSH-87 were significantly greater than occlusion effects for the MX41/AR or Model-51 cushions at 250, 500, and 2000 Hz. The occlusion effect was relatively stable from test to retest.

Conclusions

The Model-51 earphone cushion may be substituted for the MX41/AR earphone cushion on standard audiometric earphones and headbands used for masking purposes in routine bone-conduction audiometry without altering protocols for determining minimum masking levels. The MSH-87 headset produces occlusion effects large enough to preclude its use as a transducer for masking signals during bone-conduction audiometry using pure tones. More research is needed to determine the occlusion effects of this headset for signals more typical of evoked response audiometry. The greater occlusion effect found with the MSH-87 headset is probably the result of an improved acoustical seal around the pinna, an increase in the bulk of the apparatus, and greater coupling force to the head.

APPENDICES

APPENDIX A: Experimental instrumentation block diagrams:

Figure A1. Block diagram for Coupler Study

Figure A2. Block diagram for Occlusion Effect Study

Table A1. Air conduction threshold measured with Tracoustics Program III through a 10-300 ohm impedance matching pad to Madsen MSH-87 earphone (right). Threshold was measured on both ears of 5 subjects (the same phone was used; the headset was reversed on the head). Values are Hearing Threshold Level in decibels.

Table A2. Pre-test audiometer calibration data for Grason-Stadler E-800 using a Tracor RA-310 audiometer calibrator

Table A3. Pre-test attenuator linearity; values are attenuator error

Table A4. Post-test audiometer calibration data for Grason-Stadler E-800 using a Tracor RA-310 audiometer calibrator

Table A5. Post-test attenuator linearity; values are attenuator error

Table A6. Ambient noise measurements for room 4, Communication Arts and Sciences building, Michigan State University. Tabled values are octave band sound pressure levels in decibels.

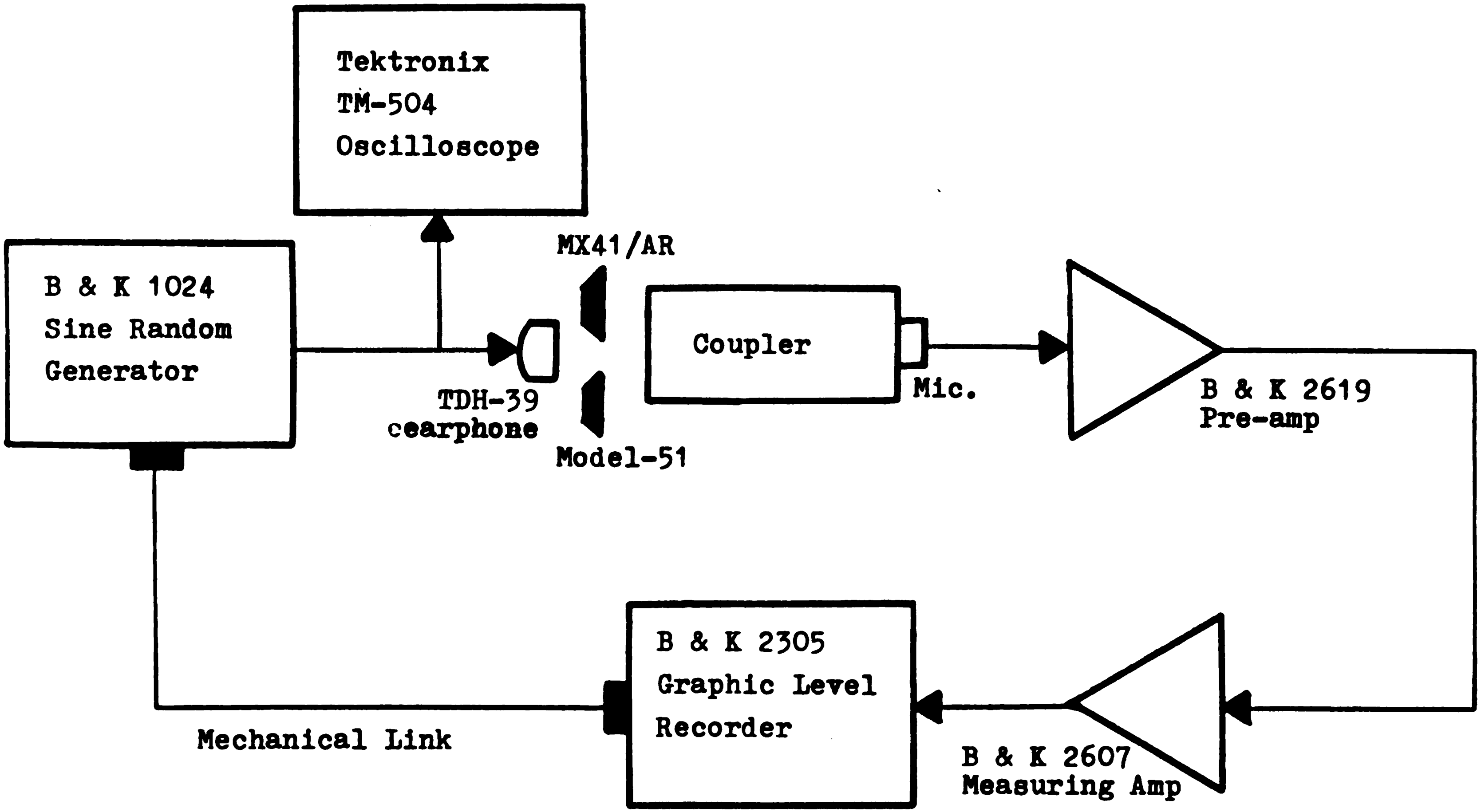


Figure A1. Block diagram for coupler study apparatus.
Coupler configuration: 1) NBS-9A (B & K 4152), used with a 1-inch pressure condensor microphone (B & K 4144)

2) Zwislocki-type ear simulator, with concha and flat plate, used with a ½-inch pressure condensor microphone (B & K 4134)

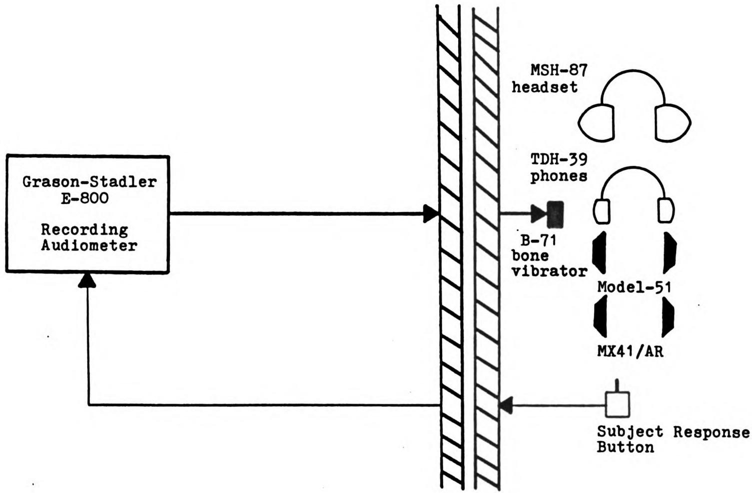


Figure A2. Block diagram for occlusion effect study.

Table A1. Air conduction threshold measured with Tracoustics Program III through a 10-300 ohm impedance matching pad to Madsen MSH-87 earphone (right). Threshold was measured on both ears of 5 subjects (the same phone was used; the headset was reversed on the head). Values are Hearing Threshold Levels in decibels.

SUB.	EAR	FREQUENCY (Hz) 125	250	500	1000	2000	4000	6000	8000
4	R	15	20	-10	-10	40	45	50	40
	L	15	25	-10	-10	45	40	60	55
5	R	15	-10	-10	-10	35	45	60	45
	L	20	- 5	-10	- 5	35	45	60	45
6	R	20	-10	-10	-10	35	55	50	40
	L	25	30	-10	-10	30	50	45	45
7	R	20	10	-10	-10	30	40	60	30
	L	25	5	- 5	-10	35	50	60	45
8	R	20	-10	25	-10	35	45	55	40
	L	25	10	35	-10	40	60	55	35

Table A2. Pre-test audiometer calibration data for Grason-Stadler E-800 using a Tracor RA-310 audiometer calibrator

FREQ.	ACTUAL FREQ (Hz)	RISE TIME PULSED (msec)	FALL TIME PULSED (msec)	OVER-SHOOT
250	242	25	25	NO
500	492	22	25	NO
1000	983	23	25	NO
2000	1973	23	25	NO
4000	3991	23	25	NO

Table A3. Pre-test attenuator linearity; values are attenuator error

FREQ. (Hz)	dB -> 100-90	90-80	80-70	70-60	60-50	50-40	40-30	30-20
250	0	0	+.1	+.5	0	+3	+5	--
500	+ .4	+.3	0	+.4	+.7	+3	+5	--
1000	+ .4	+.9	-.5	+.1	+.7	+2.7	+5	--
2000	+4	+.3	+.5	+.1	0	+1.6	+3.3	--
4000	- .2	-.1	+.2	0	+.9	+1.7	+4.3	--

Table A4. Post-test audiometer calibration data for Grason-Stadler E-800 using a Tracor RA-310 audiometer calibrator

FREQ. (Hz)	ACTUAL FREQ (Hz)	RISE TIME PULSED (msec)	FALL TIME PULSED (msec)	OVER-SHOOT
250	248	25	25	NO
500	493	23	25	NO
1000	982	23	25	NO
2000	1978	23	25	NO
4000	3967	23	25	NO

Table A5. Post-test attenuator linearity; values are attenuator error

FREQ. (Hz)	dB -> 100-90	90-80	80-70	70-60	60-50	50-40	40-30	30-20
250	- .2	0	+ .3	0	+1	+2	+5	--
500	- .1	0	0	0	+ .5	+1.9	+3.3	--
1000	0	0	0	0	+ .5	+2	+4.5	--
2000	+3.1	0	0	0	+ .6	+1.5	+4	--
4000	- .2	+ .1	- .1	+ .1	+ .3	+2	+4.2	--

Table A6. Ambient noise measurements for room 4, Communication Arts and Sciences building, Michigan State University. Tabled values are octave band sound pressure levels in decibels.

	FREQUENCY (Hz)					
	125	250	500	1000	2000	4000
NOISE FLOOR MEASURING SYSTEM	3	3	3	3	4	4
NOISE	12	5	3	3	4	4

NOTES: Measuremnets were taken in the subject side of a double-walled audiometric booth. Ambient conditions were as follows:

1 Tracoustics Program III clinical audiometer on in the tester side of the suite

2 Grason-Stadler E-800 Bekesy Audiometer on with motor running in the tester side of the suite

3 Grason-Stadler 1723 Impedance Bridge on in subject side of suite.

4 Temperature = 19 degrees C

5 Relative humidity = 70 %

APPENDIX B: Records

Figure B1. Informed consent release form.

INFORMED CONSENT RELEASE

1. I,..............................., FREELY AND VOLUNTARILY CONSENT TO SERVE AS A SUBJECT IN A SCIENTIFIC STUDY OF OCCLUSION EFFECTS CONDUCTED BY JOSEPH J. HOLMES WORKING UNDER THE SUPERVISION OF DR. MICHAEL CHIAL.

2. I UNDERSTAND THAT THE PURPOSE OF THE STUDY IS TO DETERMINE THE OCCLUSION EFFECTS OF VARIOUS AUDIOMETRIC HEADSETS.

3. I UNDERSTAND THAT I WILL NOT BE EXPOSED TO EXPERIMENTAL CONDITIONS WHICH CONSTITUTE A THREAT TO HEARING, NOR TO PHYSICAL OR PSYCHOLOGICAL WELLBEING.

4. I UNDERSTAND THAT THE DATA GATHERED FOR THIS STUDY ARE CONFIDENTIAL, THAT NO INFORMATION UNIQUELY IDENTIFIED WITH ME WILL BE MADE AVAILABLE TO OTHER PERSONS OR AGENCIES, AND THAT ANY PUBLICATION OF THE RESULTS OF THIS STUDY WILL MAINTAIN ANONYMITY.

5. I ENGAGE IN THIS STUDY FREELY, WITHOUT PAYMENT TO ME OR FROM ME, AND WITHOUT IMPLICATION OF PERSONAL BENEFIT. I UNDERSTAND THAT I MAY CEASE PARTICIPATION IN THE STUDY AT ANY TIME.

6. I HAVE HAD THE OPPORTUNITY TO ASK QUESTIONS ABOUT THE NATURE AND PURPOSE OF THE STUDY, AND I HAVE BEEN PROVIDED WITH A COPY OF THIS WRITTEN INFORMED CONSENT FORM. I UNDERSTAND THAT UPON COMPLETION OF THE STUDY, AND AT MY REQUEST, I CAN OBTAIN ADDITIONAL EXLPLANATION ABOUT THE STUDY.

DATE.................SIGNED.............................

Figure B2. Screening protocol.

SCREENING PROTOCOL

SUBJECT........................SCREENING DATE..........

AGE.......TELEPHONE.....................SEX............

EXAMINER.....................AUDIOMETER...............

AIR AND BONE CONDUCTION THRESHOLDS: dB HTL:

		250	500	1000	2000	4000
AC	R	...	...	....	....	....
	L	...	...	....	....	....
BC		...	...	....	....	....

OTOSCOPIC EVAL..

TYMPANOMETRIC RESULTS: SEE ATTACHED TYMPANOGRAM

BRIDGE..

BACKGROUND INFORMATION:

CURRENTLY ACTIVE URI?........FAMILIAL HEARING LOSS.........

NOISE EXPOSURE..............TINNITUS.......................

VERTIGO......................EAR SURGERY...................

EAR DISEASE...

INFORMED CONSENT RELEASE FORM SIGNED........................

Figure B3. Subject instructions

SUBJECT INSTRUCTIONS: OCCLUSION EFFECT STUDY

YOU WILL HEAR A PULSED TONE. IT WILL BE VERY FAINT. AS SOON AS YOU HEAR THE TONE PRESS THE BUTTON. AS SOON AS THE TONE GOES AWAY RELEASE THE BUTTON. IT IS IMPORTANT THAT YOU LISTEN VERY CAREFULLY. DO YOU HAVE ANY QUESTIONS?

Figure B4. Occlusion effect study experimental protocol

PROTOCOL: OCCLUSION EFFECT STUDY

SUBJECT...

TESTING DATE..................SCREENING DATE..............

PURPOSE OF STUDY GIVEN....................................

INSTRUCTIONS GIVEN..

SUBJECT ACCLAMATED TO TEST ENVIRONMENT....................

EQUIPMENT ON FOR AT LEAST TEN MINUTES.....................

ORDER OF OCCLUDING CONDITIONS.........MODEL 51

.........MX41/AR

.........MSH-87

TRAINING TRIALS ADMINISTERED..............................

EXCURSION WIDTH ON TRAINING...............................

HEADBAND TENSION................GRAMS(TYPICAL, 14.35 CM)

RECORD TRIAL 1 (250, 500, 1000, 2000, 4000 HZ)

RECORD TRIAL 2

RECORD TRIAL 3

REPEAT FOR EACH CONDITION IN ASSIGNED ORDER

DATA FILED IN SUBJECT'S FOLDER...........................

APPENDIX C: Raw data for coupler study.

Table C1. TDH-39 earphone fit with Model-51 cushions on an NBS-9A coupler. Data are mean Sound Pressure Levels in decibels (collapsed across 3 placements).

Table C2. TDH-39 earphone fit with MX41/AR cushions on an NBS-9A coupler. Data are mean Sound Pressure Levels in decibels (collapsed across 3 placements).

Table C3. TDH-39 earphone fit with Model-51 cushions on a Zwislocki-type ear simulator. Data are mean Sound Pressure Levels in decibels (collapsed across 3 placements).

Table C4. TDH-39 earphone fit with MX41/AR cushions on a Zwislocki-type ear simulator. Data are mean Sound Pressure Levels in decibels (collapsed across 3 placements).

Table C5: Mean coupler Sound Pressure Levels from a single TDH-39 earphone fit with MX41/AR and Model-51 earphone cushions measured on an NBS-9A coupler

Table C6: Mean coupler Sound Pressure Levels from a single TDH-39 earphone capsule fitted with MX41/AR and Model-51 earphone cushions measured on a Zwislocki-type ear simulator

Table C7: Mean difference in relative decibels (re: reference curve on 1-A coupler) for a single TDH-39 earphone capsule fitted with MX41/AR and Model-51 earphone cushions measured on an NBS-9A coupler

Table C1: TDH-39 earphone fit with Model-51 cushions on NBS-9A coupler. Data are mean dB SPL (collapsed across 3 placements).

EC #	MASS (grams)	FREQUENCY (Hz) 50	100	200	500	1000	2000	3000	4000	6000	8000
1	100	95.5	96	96	96	95.5	92.8	97.9	95.3	85.6	77
	200	95.5	96	96	96	95.5	92.9	97.7	95.2	85.3	76.8
	300	95.6	96	96	96	95.7	92.8	97.3	95.9	85.7	77.1
	400	95.8	96	96	96	95.5	93	97.8	95.7	85.6	77
	500	95.8	96	96	96	95.6	92.8	97.7	95.7	85.5	77.1
	1000	95.8	96	96	96	95.6	92.9	97.9	95.3	85.6	77.2
2	100	95.5	96.1	96.1	96.1	95.6	92.8	97.8	95.3	85.5	76.9
	200	95.5	96	96	96	95.7	92.8	97.8	95.5	85.2	77.1
	300	95.6	96	96	96	95.6	92.8	97.8	95.3	85.4	77
	400	95.6	96.1	96.1	96.1	95.6	92.8	97.7	95.4	85.2	77.2
	500	95.8	96	96	96.1	95.8	92.8	97.9	95.4	85.2	77.2
	1000	95.9	95.9	96.1	96.1	95.9	92.9	97.7	95.5	85.6	77.4
3	100	95.4	95.8	96	96.1	95.6	92.6	97.7	95.3	85	77
	200	95.5	96	96.1	96	95.6	92.7	97.8	95.2	85.2	76.8
	300	95.8	96.1	96.1	96.1	95.6	92.7	97.8	95.2	85.2	76.7
	400	95.8	96.2	96.2	96.2	95.6	92.7	97.9	95.2	85.5	76.9
	500	95.8	96	96	96	95.5	92.6	97.6	95.5	85.2	76.8
	1000	95.7	95.7	95.9	95.9	95.6	92.7	97.8	95.2	85.1	76.8
4	100	96.5	97.2	97.2	97.2	96.7	93.7	98.6	96.1	86.4	77.8
	200	96.7	97.3	97.3	97.3	97.1	94	98.9	96.3	86.7	78.2
	300	97.1	97.6	97.6	97.6	97.1	94.1	99	96	86.7	77.8
	400	96.9	97.4	97.4	97.4	97	93.8	98.7	96.7	86.7	78.3
	500	97.1	97.3	97.4	97.5	96.9	93.8	98.8	96.3	86.7	78.1
	1000	97.3	97.5	97.6	97.6	97.3	94.1	99	96.7	86.8	78.2
5	100	96	96.3	96.5	96.5	95.7	92.7	98	95.6	85.7	76.9
	200	95.9	96.4	96.4	96.4	95.7	92.8	97.8	95.7	85.7	77.2
	300	96.5	97	97	97	96.4	93.4	98.7	96.1	86.2	77.5
	400	96.5	97.1	97.1	97.1	96.5	93.5	98.6	96.1	86.2	77.7
	500	96.5	97	97	97	96.5	93.5	98.6	96.3	86.3	77.8
	1000	96.8	96.9	97.1	97.1	96.5	93.6	98.8	95.9	86.3	77.3
6	100	95.6	97	97	97	96.3	93.3	98.5	96.5	86.5	77.9
	200	96.4	96.9	97	97	96.2	93.3	98.7	96.2	86.6	77.9
	300	96.5	97	97	97	96.3	93.4	98.4	96.4	86.5	77.9
	400	96.6	97.1	97.1	97.1	96.1	93.5	98.6	95.7	86.6	77.8
	500	96.7	96.9	96.9	96.9	96.3	93.5	98.7	95.7	86.5	77.9
	1000	96.8	96.9	96.9	97	96.4	93.5	98.7	95.7	86.4	77.9

Table C2: TDH-39 earphone fit with MX41/AR cushions on NBS-9A coupler. Data are mean dB SPL (collapsed across 3 placements).

		FREQUENCY (Hz)									
EC #	MASS (grams)	50	100	200	500	1000	2000	3000	4000	6000	8000
7	100	93.9	95.6	95.3	95.4	95.2	92.7	97.8	96	83.7	75.5
	200	94.7	95.5	95.5	95.8	95.1	92.8	97.9	96	83.5	75.3
	300	94.9	95.6	95.6	95.9	95.4	92.8	97.9	96.1	83.9	75.4
	400	94.8	95.8	95.8	95.9	95.3	92.8	98	95.8	84	75.3
	500	95.2	95.7	95.8	96	95.2	92.8	98	95.7	83.8	74.9
	1000	95.5	96	96	96	95.3	93	98	95.5	83	75
8	100	95.3	96	96.2	96.2	95.5	92.9	97.9	96.1	84.1	75.7
	200	95.7	96.1	96.2	96.2	95.5	92.9	98	95.9	84	75.2
	300	95.5	96.2	96.2	96.2	95.5	92.9	98	96	84.1	75.6
	400	95.9	96.4	96.4	96.4	95.5	93	98	95.9	84	75.2
	500	95.9	96.2	96.2	96.2	95.6	93	98	96.1	84.1	75.3
	1000	96	96.2	96.3	96.3	95.6	93.1	98.1	96	84.1	75.3
9	100	94.7	96.1	96	96	95.6	92.9	98	96.3	84.5	76.2
	200	95	95.9	96	96.1	95.9	92.9	97.9	96.8	84.4	76.5
	300	95.1	96	96	96.1	95.6	92.9	98.1	96.3	84.5	76.2
	400	95.3	96.2	96.2	96.2	95.8	93	97.8	96.7	84.4	76.3
	500	95.4	96.1	96.1	96.2	95.9	93	97.9	96.8	84.4	76.7
	1000	95.7	96	96.1	96.2	95.9	93	97.8	96.7	84.4	76.5
10	100	95.1	95.6	96.1	96.2	95.9	93.1	98.1	96.5	84.7	76.4
	200	95.2	96	96.1	96.3	95.9	93.1	98.2	96.6	84.5	76.6
	300	95.4	96.1	96.1	96.4	95.9	93.1	98.1	96.7	84.7	76.4
	400	95.5	96.2	96.2	96.4	95.9	93.1	98.2	96.5	84.6	76.3
	500	95.7	96.1	96.2	96.5	96	93.2	98.1	96.7	84.5	76.6
	1000	95.7	95.9	96.2	96.3	95.7	93	97.9	96.3	84.3	76.2
11	100	93.1	95.5	94.8	94.7	94.8	92.5	97.3	96.4	83.9	76.3
	200	93.9	94.9	94.8	94.9	94.9	92.5	97.4	96.2	83.7	76
	300	94.1	94.9	94.9	94.9	95	92.5	97.5	96.2	83.9	75.7
	400	94.2	95	95.1	95.2	95.1	92.5	97.3	96.3	83.8	75.8
	500	94.4	94.9	94.9	95.2	95.1	92.5	97.5	96	83.6	75.4
	1000	94.7	94.9	95.2	95.6	95.1	92.5	97.6	96.1	83.6	75.7
12	100	93.9	96	95.5	95.5	94.9	92.1	97	95.9	84.2	76.2
	200	94.6	95.5	95.6	95.6	94.9	92.1	97.2	95.7	84.1	76.3
	300	94.9	95.8	95.7	95.7	95.1	92.4	97.1	96	83.9	76.1
	400	95	95.8	95.8	95.8	95.1	92.3	97.2	95.6	84	76
	500	95.1	95.4	95.5	95.6	95	92.2	97.1	95.7	83.8	75.8
	1000	95.1	95.3	95.6	95.6	95.1	92.3	97.1	95.6	83.9	75.7

Table C3: TDH-39 earphone fit with Model-51 cushions on the Zwislocki-type ear simulator. Data are mean dB SPL (collapsed across 3 placements).

EC #	MASS (grams)	FREQUENCY (Hz) 50	100	200	500	1000	2000	3000	4000	6000	8000
1	100	92.9	94	95.8	96.5	96.6	97.9	108	99.9	87.9	85.3
	200	93	93.8	95.7	96.5	96.8	97.1	107.3	100.8	88.2	84
	300	93.1	94	95.5	96.5	96.8	98.1	108.1	99.3	88.1	84
	400	93.1	94	95.7	96.5	96.8	97.6	107.8	100.3	87.7	85.3
	500	93.1	93.9	95.6	96.6	96.8	97.7	107.7	100.3	88	84.8
	1000	93.3	94	95.8	96.6	96.9	98	108	99.9	87.7	85.3
2	100	92.8	94	95.6	96.2	96.5	97.9	107.9	99.8	88.4	84.6
	200	92.9	93.9	95.7	96.4	96.7	97.8	107.9	99.8	88.4	84.9
	300	93	93.9	95.5	96.5	96.8	98	108	99.5	88.8	85.6
	400	93.1	94	95.7	96.5	96.8	98	107.9	99.7	88.7	85.2
	500	93.1	93.9	95.7	96.5	96.8	97.7	107.8	100.2	88.3	84.9
	1000	93.2	94	95.8	96.8	96.8	97.9	107.9	100.3	88.6	84.7
3	100	92.9	93.9	95.7	96.4	96.6	97.8	107.9	99.7	87.9	82.3
	200	92.9	93.8	95.7	96.5	96.7	97.7	107.9	99.7	87.7	83.2
	300	93	93.9	95.5	96.5	96.8	97.6	107.9	99.9	87.8	83.2
	400	93	93.9	95.6	96.5	96.8	97.3	107.5	100.6	87.4	83.2
	500	93.1	93.9	95.7	96.5	96.8	97.7	107.7	99.7	88.1	84
	1000	93.2	94	95.8	96.6	96.8	97.7	108	99.9	87.8	83.3
4	100	93.5	94.6	96.3	97.1	97.3	98.7	108.8	100.6	89.5	87
	200	93.6	94.5	96.3	97.2	97.5	98.6	108.8	101.1	89.4	88
	300	93.8	94.8	96.2	97.2	97.6	99.3	108.9	99.6	89.7	86
	400	93.9	94.7	96.4	97.2	97.5	98.7	108.8	100.7	89.6	87.3
	500	93.9	94.6	96.5	97.3	97.6	99.1	108.9	100.2	89.7	87.4
	1000	94	94.6	96.5	97.2	97.5	98.9	108.9	100.5	89.7	88.1
5	100	93.8	94.8	96.5	97.2	97.2	98.8	108.9	100.2	90.2	87.3
	200	93.8	94.8	96.5	97.2	97.2	98.7	108.9	100.3	89.9	87.4
	300	93.9	94.8	96.2	97.2	97.3	99.1	109	100.1	90	87.7
	400	93.9	94.8	96.4	97.1	97.2	99.2	109	99.6	89.7	85.2
	500	94	94.8	96.4	97.2	97.3	98.7	108.9	100.9	89.7	88
	1000	93.6	94.5	96.3	97.1	97.4	98.9	109	100.3	90.2	87.7
6	100	93.7	94.8	96.5	97.2	97.2	99.2	109	99.7	90.6	83.7
	200	93.8	94.8	96.4	97.2	97.2	98.8	108.9	100.7	90.3	90.1
	300	93.9	94.8	96.3	97.2	97.2	99.1	109	100.3	90.4	89.3
	400	93.9	94.8	96.4	97.2	97.2	98.7	108.9	100.8	90.3	89.4
	500	94	94.8	96.5	97.2	97.2	99.3	109.1	99.8	90.7	88.3
	1000	94	94.7	96.4	97.2	97.4	99	109.1	100.4	90.6	89.8

Table C4: TDH-39 earphone fit with MX41/AR cushions on the Zwislocki-type ear simulator. Data are mean dB SPL (collapsed across 3 placements).

EC #	MASS (grams)	FREQUENCY (Hz) 50	100	200	500	1000	2000	3000	4000	6000	8000
7	100	92.4	94	95.3	96.5	97	98.8	108.4	99.3	88.2	84.1
	200	92.7	93.9	95.5	96.8	97.1	99.1	108.5	98.9	87.7	83.2
	300	93	93.9	95.7	96.9	97.1	98.8	108.5	99.7	88.3	84.3
	400	93	94	95.8	97	97.1	98.9	108.4	99.2	88	82
	500	93.1	94	95.7	97.1	97.3	98.9	108.5	99.3	88	84.3
	1000	93.4	94.4	96.2	97.2	97.3	99	108.6	99.4	88.1	84.7
8	100	93.2	94.6	96.4	97	97.1	99	108.4	99.7	88	83.7
	200	93.5	94.5	96.4	97.1	97.1	99.1	108.4	99.6	87.8	82.3
	300	93.5	94.6	96.3	97.2	97.3	99.2	108.6	99.3	87.7	84
	400	93.7	94.6	96.3	97.1	97.1	98.9	108.4	99.7	88	82.3
	500	93.7	94.7	96.4	97.1	97.3	99.3	108.3	99	87.4	79.3
	1000	93.9	94.7	96.4	97.1	97.4	99.3	108.5	99.2	87.6	81.3
9	100	92.7	94.2	95.7	96.9	97.3	98.9	108.5	99.6	87	82.7
	200	93	94.2	96	97	97.1	98.9	108.5	99.3	87.2	83.2
	300	93.2	94.3	96	97.1	97.3	98.7	108.4	99.7	87.2	81.8
	400	93.5	94.5	96.2	97.1	97.5	98.7	108.4	100.1	87.2	82.2
	500	93.5	94.3	96.2	97.1	97.4	98.4	108.4	100.3	87.2	80.3
	1000	93.7	94.8	96.4	97.1	97.5	98.6	108.3	99.7	86.8	83
10	100	93.2	94.4	96.2	97.2	97.5	99.1	108.7	100.3	88.7	84.2
	200	93.2	94.4	96.2	97.1	97.5	99.1	108.6	100.1	88.7	83
	300	93.5	94.5	96.4	97.2	97.5	99.3	108.8	100.3	88.6	83.5
	400	93.5	94.6	96.4	97.2	97.5	99	108.6	100.2	88.4	82.7
	500	93.5	94.6	96.5	97.3	97.5	99.2	108.9	100	88.7	83.5
	1000	93.7	94.7	96.5	97.4	97.5	99.1	108.8	100.3	88.5	84.3
11	100	91.9	94	94.8	95.8	96.7	98.3	108.5	101.1	88.1	86.7
	200	92.2	93.9	95	96	96.7	98.8	108.5	100.1	88	86.5
	300	92.6	93.9	95	96	97	98.9	108.6	100.6	88.2	87.6
	400	93	94	95.3	96.1	97.2	98.8	108.4	100.3	87.8	86.7
	500	93	94	95.2	96.3	97.2	99.1	108.4	100.3	87.9	87.2
	1000	93.2	94.1	95.8	97.1	97.5	98.8	108.4	100.3	87.7	87.5
12	100	92.5	94.7	96.2	97	97	98.7	108.3	100.1	89.3	86
	200	93.2	94.5	96.2	97	97.1	98.5	108.2	100.3	89	85.9
	300	93.5	94.6	96	97.1	97.2	98.3	108.2	100.5	88.8	86.6
	400	93.5	94.5	96.1	97	97.1	98.2	108.3	100.1	89.1	86.3
	500	93.5	94.4	96.1	97	97.1	98.2	108.2	100.5	88.7	86.8
	1000	93.7	94.5	96.3	97.2	97.3	98.6	108.4	100	89	86.7

Table C5: Mean coupler Sound Pressure Levels from a single TDH-39 earphone fit with MX41/AR and Model-51 earphone cushions measured on an NBS-9A coupler

MASS (grams)	100	500	1000
MX41/AR			
50 HZ	94.3	95.3	95.5
100 HZ	95.8	95.7	95.7
200 HZ	95.7	95.8	95.9
500 HZ	95.7	96	96
1000 HZ	95.3	95.5	95.5
2000 HZ	92.7	92.8	92.8
3000 HZ	97.7	97.8	97.8
4000 HZ	96.2	96.2	96
6000 HZ	84.2	84	83.9
8000 HZ	76.1	75.8	75.7
Model-51			
50 HZ	95.8	96.3	96.4
100 HZ	96.4	96.5	96.5
200 HZ	96.5	96.6	96.6
500 HZ	96.5	96.6	96.6
1000 HZ	96	96.1	96.2
2000 HZ	93	93.2	93.3
3000 HZ	98.1	98.2	98.3
4000 HZ	95.7	95.8	95.7
6000 HZ	85.8	85.9	86
8000 HZ	77.3	77.5	77.5

Table C6: Mean coupler Sound Pressure Levels from a single TDH-39 earphone capsule fitted with MX41/AR and Model-51 earphone cushions measured on a Zwislocki-type ear simulator

MASS (grams)	100	500	1000
MX41/AR			
50 HZ	92.7	93.4	93.6
100 HZ	94.3	94.3	94.5
200 HZ	95.8	96	96.3
500 HZ	96.7	97	97.2
1000 HZ	97.1	97.3	97.4
2000 HZ	98.8	98.9	98.9
3000 HZ	108.5	108.5	108.5
4000 HZ	100	99.9	99.8
6000 HZ	88.2	88	88
8000 HZ	84.6	83.6	84.6
Model-51			
50 HZ	93.3	93.5	93.6
100 HZ	94.4	94.3	94.3
200 HZ	96.1	96.1	96.1
500 HZ	96.8	96.9	96.9
1000 HZ	96.9	97.1	97.1
2000 HZ	98.4	98.4	98.4
3000 HZ	108.4	108.4	108.5
4000 HZ	100	100.2	100.2
6000 HZ	89.1	89.1	89.1
8000 HZ	85.9	86.2	86.5

Table C7: Mean difference in relative decibels (re: reference curve on 1-A coupler) for a single TDH-39 earphone capsule fitted with MX41/AR and Model-51 earphone cushions measured on an NBS-9A coupler

MASS (grams)	100	500	1000
MX41/AR			
50 HZ	-2.2	-1.2	-1.1
100 HZ	-1	-1.1	-1.1
200 HZ	-1.2	-1	-.9
500 HZ	-1.1	-.9	-.8
1000 HZ	.3	.5	.5
2000 HZ	-1.8	-1.7	-1.7
3000 HZ	2.2	2.3	2.3
4000 HZ	6.2	6.2	6.1
6000 HZ	6.7	6.5	6.4
8000 HZ	2.6	2.3	2.2
Model-51			
50 HZ	-.8	-.2	-.1
100 HZ	-.4	-.3	-.3
200 HZ	-.3	-.3	-.2
500 HZ	-.3	-.2	-.2
1000 HZ	.9	1.1	1.2
2000 HZ	-1.5	-1.3	-1.2
3000 HZ	2.6	2.7	2.8
4000 HZ	5.7	5.8	5.7
6000 HZ	8.3	8.4	8.5
8000 HZ	3.8	4	4

note: values were derived by subtracting the reference condition from NBS-9A data and obtaining means

APPENDIX D: Raw data for the occlusion effect study. Values are means of the midpoints of ten excursions on forehead bone-conducted, one-minute fixed-frequency Bekesy threshold tracings.

Table D1. Sound Pressure Level threshold estimates in decibels for 12 subjects tested three times at each of five frequencies. Each datum is a mean of midpoints of the last ten excursions obtained during fixed-frequency Bekesy tracking in the unoccluded condition.

Table D2. Sound Pressure Level threshold estimates in decibels for 12 subjects tested three times at each of five frequencies. Each datum is a mean of midpoints of the last ten excursions obtained during fixed-frequency Bekesy tracking in the MSH-87-occluded condition.

Table D3. Sound Pressure Level threshold estimates in decibels for 12 subjects tested three times at each of five frequencies. Each datum is a mean of midpoints of the last ten excursions obtained during fixed-frequency Bekesy tracking in the MX41/AR-occluded condition.

Table D4. Sound Pressure Level threshold estimates in decibels for 12 subjects tested three times at each of five frequencies. Each datum is a mean of midpoints of the last ten excursions obtained during fixed-frequency Bekesy tracking in the Model-51-occluded condition.

Table D5. Correlation coefficients between trials in the occlusion effect study.

Table D1. Sound Pressure Level threshold estimates in decibels for 12 subjects tested three times at each of five frequencies. Each datum is a mean of midpoints of the last ten excursions obtained during fixed-frequency Bekesy tracking in the unoccluded condition.

		Frequency (Hz)				
Sub.	trial	250	500	1000	2000	4000
1	1	62.7	23.9	24.7	28.6	32.8
	2	60.3	21.9	25	28.6	32.3
	3	62.2	24.3	25.4	30.4	33
2	1	71.7	43.3	26	35.6	30
	2	67.9	47	28.3	36.1	33.8
	3	77.8	48.2	29.1	35.9	30.6
3	1	64.7	53.5	35.7	30.9	27.6
	2	66.4	51.1	38.1	28.1	26.9
	3	63	53	37.9	31.3	31.5
4	1	65.7	52.4	41.2	46.5	25.1
	2	68	53.1	45.2	45.8	28.5
	3	66.1	54.5	43.7	49.6	29.7
5	1	69.2	48.1	34	32.4	30.4
	2	68.5	48	35.2	33.3	34.1
	3	70	49.6	35	32.2	32.6
6	1	59.8	42.8	21	34.2	24.8
	2	60.9	43.8	22.4	34.9	24.9
	3	59.3	43.4	26.6	34.5	26.2
7	1	75	57.8	28.1	36.2	27.4
	2	70.5	55.2	30.9	37.9	32
	3	70.5	55.2	27	37.5	24.2
8	1	71.5	53.7	24.7	31.8	39.2
	2	72.5	51.6	27.8	32.1	36.6
	3	72.4	49.4	27.1	26.8	37.3

Table D1 (cont'd)

9	1	64	41.4	31	27.3	28.7
	2	65.4	40.9	31.2	30.8	33.9
	3	74.3	39.8	31.4	30	33.5
10	1	65.2	53.1	31.8	44.2	34.5
	2	64.7	50.3	31.5	40.6	33.7
	3	65.8	49	33.3	42.9	34.5
11	1	61.7	54.6	28	29.4	23.6
	2	62	48.2	23.5	35.7	25.1
	3	65.2	49.9	21.7	30.4	28.6
12	1	64.8	43.4	27.6	26.8	26.5
	2	69.3	49.1	33.5	28.7	25.5
	3	70.5	53.7	33.3	28.9	29.7

Table D2. Sound Pressure Level threshold estimates in decibels for 12 subjects tested three times at each of five frequencies. Each datum is a mean of midpoints of the last ten excursions obtained during fixed-frequency Bekesy tracking in the MSH-87-occluded condition.

		Frequency (Hz)				
Sub.	trial	250	500	1000	2000	4000
1	1	45.7	8.7	26.6	21.2	43
	2	43.8	8.7	27.7	21.1	43.4
	3	46.9	9.7	27.6	17.1	42.1
2	1	48.8	16.4	6	32.4	36.5
	2	47.1	22.7	11.5	27.1	37.5
	3	49	17.4	11.3	26.8	33.7
3	1	36.9	24.8	22.3	31.6	42.9
	2	33.1	15.3	16.1	29.6	44.1
	3	35.2	14.3	11.9	25.9	37.1
4	1	43.8	18.5	20.9	38	38.8
	2	36.1	17.2	17.7	39.6	34.2
	3	38.8	13.9	18.2	34.6	33.5
5	1	37.4	18.8	34.1	37.5	37.8
	2	38.8	22.1	35.4	38	43.1
	3	39.1	19.9	28.8	39.4	41.2
6	1	39.5	19	11.6	34.3	38.4
	2	38.6	13.1	16.4	27.6	33.5
	3	40.9	13.9	11.1	22.1	35.7
7	1	41.4	16.8	17.1	27.1	23.7
	2	44	18.9	8.8	23.6	27.2
	3	33.9	15	15.6	23.5	22.2
8	1	41.6	14.5	18.9	28.3	40
	2	51.4	17.4	16.9	27.4	44.7
	3	47.2	12.6	8.9	27.5	41.6

Table D2 (cont'd)

9	1	41.4	3.7	21.5	23.9	38
	2	40.9	4.6	17.1	18.8	36.6
	3	41	6.4	26.5	25.3	35.7
10	1	28.1	30.8	15.3	35.7	33.2
	2	31.8	22.2	20.3	27.2	33.5
	3	38.6	27.1	20.2	33.2	32.8
11	1	41	24.3	18.7	19.2	34.2
	2	27.8	21.9	22.9	37.6	27.1
	3	30.8	22.8	19.1	38.5	29.9
12	1	50.6	35.1	27.4	28.6	40.9
	2	51.9	31.1	26.2	28.5	40.5
	3	46.2	28.3	28.8	34	41.7

Table D3. Sound Pressure Level threshold estimates in decibels for 12 subjects tested three times at each of five frequencies. Each datum is a mean of midpoints of the last ten excursions obtained during fixed-frequency Bekesy tracking in the MX41/AR-occluded condition.

		Frequency (Hz)				
Sub.	trial	250	500	1000	2000	4000
1	1	45.3	10.7	28.4	26.7	46.1
	2	40.6	10.6	28.1	29	46.3
	3	41.4	12.7	27.3	27.7	43.2
2	1	41.9	14.7	16.1	38.5	37.1
	2	53.5	15.7	16.6	37	37.4
	3	50.3	19.2	16.5	39.3	37.1
3	1	39.3	27.9	26.6	35.6	37.5
	2	33.7	26.5	32	30.5	38.1
	3	37	33.6	19	33.3	37.3
4	1	47.2	19	26.6	42.3	39.4
	2	48	22.4	21.9	48.1	38.1
	3	49	24.3	19.7	46.8	37
5	1	48.5	20.7	32.7	34.8	38.2
	2	47.5	20.4	31.1	34.5	39
	3	54.6	22	33.9	35.8	38.8
6	1	46.8	29.4	13.1	33.3	36.7
	2	50.9	26.6	11.2	34.9	33.7
	3	48.8	25.9	13.6	34.4	34.7
7	1	44.4	27.8	20.9	42.1	32.2
	2	41.9	25.5	19.4	41.6	26.5
	3	50.4	28.5	21.6	46.1	29.5
8	1	60.8	30.2	15	29.3	53.5
	2	56	31.7	18.2	30.7	48.4
	3	51	25.3	14.3	26.8	53.3

Table D3 (cont'd)

9	1	47.1	17.6	20.6	28.4	32.6
	2	49	15.1	22.1	32.5	32.3
	3	44.6	12.5	21.2	32.8	37
10	1	42.5	25	19.9	48.5	39.5
	2	36.9	33.4	23.4	48.5	36.7
	3	41	37.9	22.7	49.3	40.8
11	1	39.2	14.6	13.3	33.3	30.4
	2	42.8	29.4	14.9	38.4	34.4
	3	41.3	20.4	10.7	35	31.3
12	1	53.4	25.2	21.8	28.2	40.3
	2	53.9	34.4	32.6	31.4	42.5
	3	55.2	38.2	30.3	34	43.1

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Table D4. Sound Pressure Level threshold estimates in decibels for 12 subjects tested three times at each of five frequencies. Each datum is a mean of midpoints of the last ten excursions obtained during fixed-frequency Bekesy tracking in the Model-51-occluded condition.

		Frequency (Hz)				
Sub.	trial	250	500	1000	2000	4000
1	1	40.6	13	33.2	28.2	45.4
	2	45.9	14.3	33.5	27.8	45.7
	3	45.4	13.2	32.3	27.5	45
2	1	43.4	19.1	31.2	37.5	36.3
	2	58.2	22.6	21.9	35.9	39.2
	3	42	24.7	23.2	33.9	37.4
3	1	40	42.6	22.4	34.2	38.8
	2	32.4	29.4	28.5	33.1	40.6
	3	30.3	32	24.3	34.3	36.1
4	1	48.5	24	24.8	43.8	37.2
	2	47.7	21.6	31.3	47.2	40.5
	3	43.7	28.8	28.5	46.5	32.6
5	1	51	21.9	30.8	33.9	37.1
	2	53.7	24.2	30.3	35.9	39.8
	3	53	23.2	33	38.2	39.4
6	1	47.8	31.2	11.9	34.5	35.9
	2	40.3	36.3	10.2	35.3	34.1
	3	46.8	28.8	16.6	32	35.5
7	1	49.1	27.9	20.1	41.7	29.2
	2	41.7	30.9	17.3	42.4	31
	3	42.2	28.3	18.1	36.4	26.5
8	1	51.7	25.8	18	29.3	57.2
	2	58.6	27.6	17.9	27.9	50.9
	3	63.1	26.3	16.1	25.9	47.7

Table D4 (cont'd)

9	1	50.2	27.6	17.5	26.6	40.4
	2	51.6	20.3	19.3	32.8	36.9
	3	53.7	21	17.9	29.5	40.2
10	1	45	28.1	22.2	55.5	39.3
	2	36.7	29.6	28.2	51.2	41.4
	3	41	34.6	22.9	47.9	36.2
11	1	34.5	16.9	8.2	31.8	30.8
	2	46.8	30.2	18.2	36.5	34.3
	3	41.1	26.3	12.8	38.1	31.7
12	1	50.1	30.6	29.5	29.5	39.6
	2	52.9	31.1	24.7	30.8	37.7
	3	60	32	34.1	28.1	45.5

Table D5: Correlation coefficients between trials in the occlusion effect study

FREQ:	250	500	1000	2000	4000
MX41/AR					
1-2	.58	.56	.75	.57	.85
1-3	.47	.68	.8	.88	.78
2-3	.34	.8	.81	.62	.63
Model-51					
1-2	.12	.56	.57	.87	.76
1-3	.73	.63	.83	.5	.64
2-3	.34	.79	.76	.45	.44
MSH-87					
1-2	.52	.84	.76	.54	.72
1-3	.45	.76	.72	.42	.68
2-3	.56	.87	.78	.75	.84

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