# The "Missing 6 dB" of Tillman, Johnson, and Olsen Was Found—30 Years Ago

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## To Tom Tillman, with Gratitude

When I arrived at Northwestern University as a new doctoral student in the fall of 1971, I was in awe of the fact that I was going to be in what most people then considered to be the center of audiology. The people I would work with were those who wrote most of the texts and research I had read. Little did I realize that I would also be in the midst of a period of transition.

The old Speech Annex was being replaced with the new Frances Searle Building to house the School of Speech. The Northwestern way of connecting pieces of equipment using coax cable with banana plugs routed at right angles along the edges of the equipment was giving way to MAC Panel plug boards and plug wires. The use of calculators to run statistical analyses was giving way to computer punch cards and the SPSS software package. The system of storing subject information on McBee keysort cards was being replaced with newly developed computer database systems. The use of transformers to match different signal sources was being replaced by a new semiconductor called an operational amplifier. A newly developed pressure pump was changing the way we understood middle-ear function.

I was caught between the tradition of the Northwestern way of doing things and the emerging technology of computers, new facilities, new electronics, and new diagnostic tools. Naturally, I was nervous. I had so much to learn but confused about the right path to follow. Tom Tillman was a source of direction and inspiration for me. He helped me to see the value in both the traditional and the modern. He taught me to embrace change without disregarding the past. Tom helped me to understand that to move into the future we must not lose sight of our past. I will always to be grateful to Tom for his insight, his ability to analyze a problem and see a solution, and the help he gave me in finding the path to my eventual graduation in the summer of 1975.

Michael G. Block, Ph.D.

## Missing Tom Tillman

I've missed Tom; really missed having him answer the phone when I had a knotty academic or research problem. And I miss the reminder that one of my idols had become one of my friends.

I had called only a few weeks before Tom died when a Ph.D. student discovered that the way she set the gain on the digital hearing aid she was using could arguably have been set a better way. She had originally checked it three ways, including the old-fashioned oscillator-voltmeter method, but its high-frequency gain for dynamic speech sounds was higher than expected (and higher than might have been optimum). Tom listened to the account, to her willingness to redo half of her data collection, and said "As you go along in every research project, you encounter ways that you could have done it better. But the time comes when you need to stop improving and complete what you started. I think that is

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Current Topics in Audiology: A Tribute to Tom Tillman; Editor in Chief, Catherine V. Palmer, Ph.D.; Guest Editor, Wayne Olsen, Ph.D. *Seminars in Hearing*, volume 25, number 1, 2004. Address for correspondence and reprint requests: Michael G. Block, Ph.D., Qualitone, 4931 West 35th Street, St. Louis Park, MN 55416. E-mail: Michael_block@qualitonehearing.com. [1]Director of Technical Services, Qualitone, St Louis Park, Minnesota; [2]Etymotic Research, Inc., Elk Grove Village, Illinois; Visiting Professor of Audiology, Rush University, Chicago, Illinois; Adjunct Professor of Audiology, City University of New York Graduate School, New York, New York; [3]deceased; former Associate Dean, School of Speech, Northwestern University, Evanston, Illinois. 333 Seventh Avenue, New York, NY 10001, USA. Tel: +1(212) 584-4662. 00734-0451,p;2004,25,01,007,016,ftx,en;sih00284x.

where you are here." You can imagine her relief (and mine). The answer was all the more welcome because of Tom's absolute integrity; he would never have given such an answer to make a student (or advisor) feel better at the expense of good research.

Tom genuinely liked and cared for students. Tom is almost the sole reason I have a Ph.D. Over 30 years ago, I called Tom about an article he had written with R.M. Johnson and Wayne Olsen on the "Missing 6 dB."[1] I thought the experimental findings were correct, but didn't think anything was "missing." Tom not only wasn't defensive, but invited me to Northwestern to discuss the article. At the end of that discussion, he enlisted a graduate student, Michael Block, to carry out the additional experiments we devised to settle the question. Some eight years later, I decided that my preconceptions about the type of people who obtain Ph.D.s couldn't be entirely correct, and—with Tom's encouragement—enrolled at Northwestern where Tom became my Ph.D. advisor.

The next time I saw Tom under pressure was when a check on the levels of the recorded stimuli used in some perceptual masking experiments indicated that the reported "8 dB of perceptual masking" was an artifact of a complicated calibration procedure (not Tom's). To explain, it turned out that the real-speech masker was ~8 dB more intense than the speech-envelope-modulated speech-spectrum noise masker. Tom had been associated with many of the early perceptual masking findings, and might have been expected to be defensive. I watched Tom during the meeting as the new findings and calibration checks were described. He listened intently and at the end said, "We should check this new finding and, if it holds up, report it so that no one else will make the same mistake." Other colleagues expressed concern for their reputations and for that of Northwestern. Tom always focused on the search for truth; I never saw him flinch in light of possible personal consequences.

After my own dissertation committee had listened to my third Ph.D. proposal and rejected it as "not interesting" and worse, I wrote a blistering three-page retort, explaining the committee's abysmal lack of insight. I sent all five copies to Tom to distribute, gave up on my Ph.D., and went back to work full time. Tom waited quietly for six months, then invited me over for a visit whereupon he confessed that he had never distributed my diatribe and wondered if finishing my research (and Ph.D.) wasn't more important than being right? Tom could be just as gentle when necessary as he could be rigid as iron when facing poor science or questionable ethics. As a scientist, a writer, a teacher, and a mentor, Tom had few peers. But mostly I will miss him as a trusted friend.

Mead C. Killion, Ph.D.

## ABSTRACT

This article describes the experiments undertaken to track down the missing 6 dB that Tillman, Johnson, and Olsen reported in 1966. In keeping with earlier findings of other authors, we found that nothing was really missing. We made probe-microphone recordings of the original stimuli and obtained the same differences reported by Tillman, Johnson, and Olsen once we took into account differences between anechoic-chamber and test-booth sound fields. Historically, these differences have been rediscovered by each new generation, with the same subtle experimental errors having to be uncovered anew.

**KEYWORDS:** Missing 6 dB, thresholds, earphone thresholds, sound-field thresholds, probe microphones

**Learning Outcomes:** After reading this article the reader should (1) be able to explain how reports of a missing 6 dB can be traced to the difference in the threshold equivalent SPLs corresponding to sound field and earphone

calibrations; and (2) explain why eardrum pressure at threshold is identical whether the sound is produced by loudspeakers or earphones, except when the physiological noise generated under earphone cushions produces masking of the thresholds at low frequencies.

The formal write-up of these experiments has been on the to do list of two of the authors (MGB and MCK) for 30 years. The problem has always been that the text of Tillman's original verbal presentation[3] was so pleasant to read that each of the other two authors always bogged down trying to make a formal written version that lived up to the original presentation. We finally decided that 30 years was long enough. Following an honorable tradition (Rudmose waited 20 years before publishing his classic "Case of the missing 6 dB"[4]), we offer the present previously unpublished 30-year-old text of Tillman's presentation with only minor revisions. To bring the reader up to date, we cover the intervening history in this prologue.

The phenomenon of the "missing 6 dB" as originally described by Sivian and White[5] was the roughly 6 dB difference they saw between earphone and sound-field loudness judgments after both measurements had been translated to eardrum pressure. This phenomenon was later confirmed by Munson and Wiener,[6] who found approximately a 6 dB difference in thresholds and loudness judgments even at 100 Hz. They concentrated on 100 Hz because that frequency has a wavelength of 11 feet. The long wavelength meant that for a distant sound source, the sound pressure measured at the eardrum and the sound pressure measured at the same side of the head are within a fraction of a decibel of each other. This explanation essentially states that both the eardrum pressure and sound-field pressure should be the same at 100 Hz.

Following the publications of Shaw and Piercy,[7] and Rudmose,[8] Villchur[9] also reported a 6 dB threshold elevation due to physiological masking noise with the TDH-39 earphones, thus providing part of the explanation.

Killion[10] undertook a determination of the eardrum pressure produced in decades of earphone and sound-field threshold studies. He was encouraged by conversations with Wayne Rudmose, who had spent a decade tracking down all the missing 6 dB artifacts, and by the Northwestern University experiments then being reported. Killion used the newer data of Shaw[11] and Zwislocki[12] on the relationship between earphone, ear-canal, and eardrum pressures. Calculations with those new data showed no difference between estimated pressures at threshold except at low frequencies. Corrections for the masking effect of physiological noise eliminated that remaining difference. Earphone and sound-field data, transformed to threshold, gave the same estimate of minimum audible pressure at the eardrum (MAPD).[2] The statement, "MAPD = 12 dB," is accurate within ±3 dB between 500 and 8000 Hz. Thus, Killion concluded, "nothing is really missing."[10]

Rudmose[4] later reported his earlier experiments on the missing 6 dB, especially those explaining the vexing differences at 100 Hz. At threshold, part of the difference was due to physiological noise masking under the TDH-39 earphone cushion. It could be measured directly with a quiet enough probe microphone, and eliminated with the use of insert earphones (in which case the difference between eardrum pressure and sound-field pressure at threshold disappeared). The most surprising finding was that sub-threshold vibrations carried through the chamber floor made some subjects auditory thresholds better. Isolating the subject's chair completely from vibration (or having the subject kneel on a cushion, as we did later in the experiment) would bring the thresholds up to normal.

Rudmose found that the artifacts in loudness-balance experiments were more subtle. Some subjects judged a distant loudspeaker to be louder—for the same probe-measured eardrum SPL—than a loudspeaker held at the side of the head. Others were sensitive to floor vibrations from the sound-field loudspeaker. The reader is invited to read Rudmose's article—a classic detective story—for more details.[4]

The following text reports our experiments essentially as Tillman[3] first read it. No attempt has been made to remove the nice things the authors say about each other. An important observation reported here is that real-ear sound-field recordings made in an anechoic chamber and in a clinic test booth may differ by several decibels when calibrated with the subject absent.

## BACKGROUND

Tillman, Johnson, and Olsen[1] reported spondee threshold sound-pressure levels measured under earphones and in an anechoic sound field using two groups of subjects. One group consisted of 12 normal-hearing individuals ranging in age from 20 to 39 years (26.9 average). A second group of 10 subjects with mild to moderate hearing loss was included to avoid the possibility of ambient-noise contamination. This group ranged in age from 45 to 79 years (63.2 average). The results indicated that the earphone thresholds averaged ~7.5 dB higher than the sound-field thresholds. The normal-hearing group averaged 8.1 dB poorer under earphones while the hearing-loss group averaged 7.0 dB. When the testing was performed with insert earphones instead of supra-aural earphones, the differences were more dramatic. The overall difference was 12.5 dB (11.9 dB for the normal-hearing group and 13.1 dB for the hearing-loss group.) Tillman, Johnson, and Olsen[1] also measured the sound pressure in the field with the subject absent. Inserting a dummy head into the field resulted in an increase of ~4 dB in sound pressure measured at the ear of the dummy head. This diffraction effect clearly accounted for more than half the difference between the sound-field and earphone thresholds. Tillman, Johnson, and Olsen[1] speculated that the remaining 3.5 dB might be the result of a closed ear effect. Wever and Lawrence[13] reported physiologic data suggesting that in the cat the impedance of the ear might be matched better to that of open air than that of a closed volume of air trapped under the earphone. Later findings obtained by Dirks, Stream and Wilson[13] have confirmed and extended these measurements with respect to the MAP-MAF threshold differential for spondees.

The explanation that the 7.5 dB difference was the result of head-diffraction effects plus an impedance mismatch between the ear and an earphone provoked some disagreement. Wiener and Ross[14] demonstrated that when a human head is inserted into a sound field, sound pressure builds up at the entrance to the ear canal. This so-called baffle effect is in the range from 350 to 850 Hz and averages ~4 dB. A second effect is ear-canal resonance. When a listener is immersed in a sound field, the ear canal acts to amplify the pressure for frequencies above ~1000 Hz, so that the sound pressure at the eardrum significantly exceeds that measured in a sound field with the observer absent. A smoothed version of a curve from Wiener and Ross is shown in Figure 1.[15] It demonstrates the effects of both diffraction and ear-canal resonance. Below ~1000 Hz this curve primarily shows the effects of diffraction

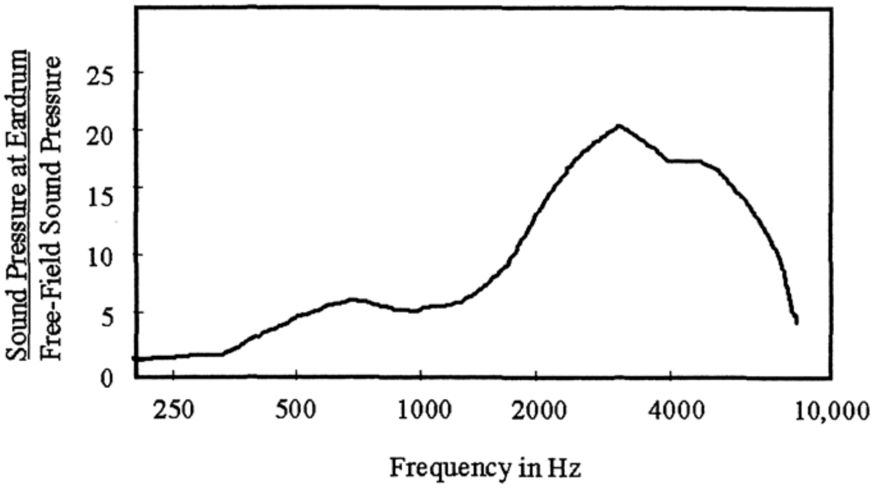

**Figure 1** Increased eardrum pressure in a sound field, after Weiner and Ross.[15]

while above 1000 Hz the diffraction and resonance effects combine.

Tillman, Johnson, and Olsen[1] were aware of these factors but felt that the spondee threshold was determined almost exclusively by the energy contained in the spectrum below 1000 Hz. They took the position that only ~4 dB of the MAP-MAF differential could be accounted for by the effects shown in Figure 1 and that the remaining 3 to 3.5 dB might be due to what Wever and Lawrence[13] had termed the closed ear effect. Tillman and his colleagues[1] accepted that argument and concluded that their findings "strongly support the contention that the 'missing 6 dB' first encountered by Sivian and White[5] is a real phenomenon produced, in part, by diffraction effects and, in part, by impedance mismatches that result when the ear canal is closed by the pressure transducer."[1]

Objections to this interpretation were lodged independently, immediately, and in a very scholarly fashion by both Wayne Rudmose[4] and Mead Killion.[10] Neither questioned the magnitude of the MAF-MAP differential we had reported, but both felt that the entire difference could be accounted for by diffraction and resonance. Rudmose suggested an experiment, which we were never able to do, that he felt would have settled the issue once and for all. Wayne Olsen and I continued to feel that the frequency range above 1000 Hz just wasn't that important in establishing the spondee threshold. Killion was persistent in his harassment, however, and we began to listen to him when results of some of our experiments in the masking of spondees suggested that the frequency region above 1000 Hz was indeed critical. Specifically, we discovered that at the same spectrum level, a thermal noise extending only to 3000 Hz produced a slightly but significantly lower masked threshold than did the same noise limited only by the response characteristics of a TDH-39 earphone.

At about this time, Industrial Research Products, where Killion [was] senior engineer, developed a microphone with a broad frequency response, but was small enough to be inserted into the entrance of the ear canal. The microphone is the Knowles BL 1685 and its frequency response is shown in Figure 2. It is a calibrated, nondirectional, ceramic microphone displacing a volume of 0.1 cc. This development seemed to present a means for settling our argument relating to the explanation of the "missing 6 dB." The experiment to be reported here was therefore designed in collaboration with Mead Killion.

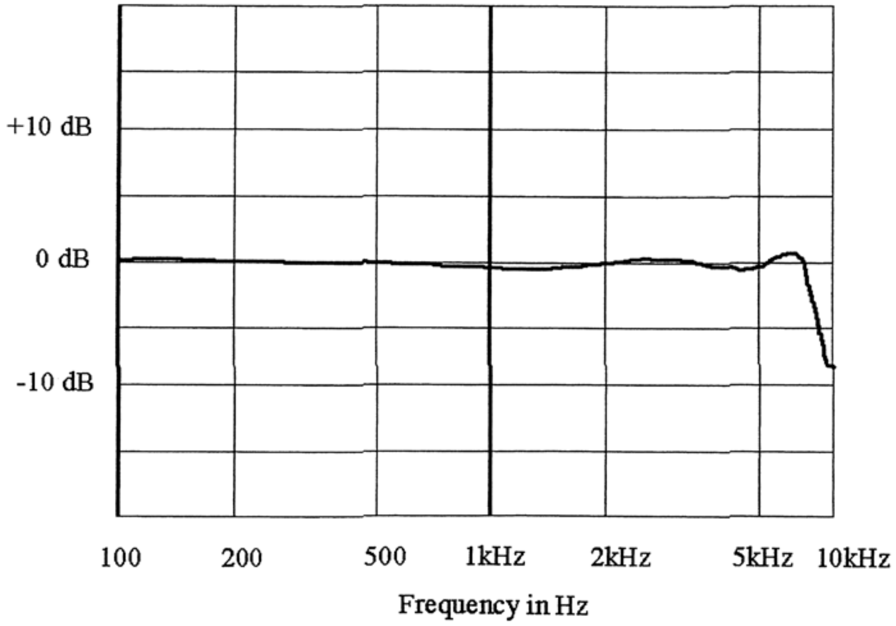

**Figure 2** Frequency response of probe microphone used in present experiments.

## PROCEDURE

The first step was to record spondaic words on magnetic tape under three different conditions. In each condition, the input to the tape recorder was the output of the miniature microphone. All recording was conducted in an IAC audiometric booth.

In one recording condition, the microphone was suspended in a sound field of 84 dB SPL at a point in space later to be occupied by the subject's head. This sound-field level was achieved by setting the intensity of a speech-spectrum noise to 84 dB SPL after the electrical amplitude of the noise signal had been adjusted to produce the same VU meter deflection as those produced by the peaks of the spondees. In this condition, the intensity of the speech signal reaching the recording microphone—and hence the input of the magnetic tape recorder—was unaffected by either diffraction or ear-canal resonance.

In a second condition, the microphone was positioned in the entrance to a subject's ear canal, and the subject sat in the same sound field as in the first condition. In this second instance, sound pressure at the microphone was increased relative to that in the first condition by head diffraction effects and ear-canal resonance effects as these latter are manifested at the entrance to the ear canal.

In a third condition, the miniature microphone remained in the entrance to the ear canal but the subject wore TDH-39 earphones in MX41/AR cushions. In this earphone condition, the intensity of the electrically equivalent speech spectrum noise was adjusted to produce a sound-pressure level of 84 dB measured in a NBS-9A coupler, and then the earphone was positioned over the subject's ear. In this condition, diffraction effects were largely eliminated and the intensity of the speech signal reaching the recording microphone was altered only by the normal difference between real-ear and coupler response of the earphone. In the last two recording conditions, three different subjects, one female and two males, served as live couplers since they acted simply as passive receptacles to house the miniature microphone during the tape recording session. The three were used to having some variety insofar as ear-canal characteristics captured on the tape were concerned.

As a result of these recording sessions, seven different conditions were captured on magnetic tape: an earphone or minimum audible pressure condition for each of the three subjects, a loudspeaker or minimum audible field condition for each subject, and a single sound-field condition where a human subject was not involved in the tape recording process. Table 1 identifies the terminology used in this article. MAP will designate the condition where the microphone was in the ear canal driven by an earphone. MAF will designate the condition where the microphone was in the ear canal, but was driven by a loudspeaker located at a 45° azimuth with respect to the subject. Sound field (SF) will describe the condition where the microphone was simply suspended in the space usually occupied by the subject's head.

Using the magnetic tapes obtained in this manner, we measured spondee thresholds for 40 normal-hearing subjects in each of the seven conditions. In all of these tests, the listeners monitored the signal presented monaurally via TDH-39 earphones. Differences between mean thresholds in various combinations of the three conditions were then compared with actual differences in signal sound pressure

**Table 1 Terminology**

MAP—Minimum Audible Pressure

A signal transduced by a microphone in an ear driven by an earphone. (Resonance effects only.)

MAF—Minimum Audible Field

A signal transduced by a microphone in an ear driven by a loudspeaker. (Both resonance and diffraction effects.)

SF—Sound Field

A signal transduced by a microphone that is suspended in an audiometric booth. (Unaffected by diffraction or resonance.)

captured in the recording process for the same conditions. This step was done in an effort to discover whether any residue of the missing 6 dB remained unexplained after the actual acoustic differences between conditions were taken into account. The actual sound-pressure differences between any two conditions were then determined. 100 Hz noise bands, 100 through 8000 Hz, at constant electrical input measured either in the field or in the coupler, were delivered to the miniature microphone in the seven conditions. The output of the microphone was measured and various comparisons revealed the changes in sound pressure produced by diffraction and resonance.

Figure 3, for example, shows the relative sound pressure impinging on the microphone in the MAF and SF conditions. These and all the following curves are smoothed curves averaged over the three subjects. Note that throughout the frequency range, the sound pressures in the MAF condition significantly exceed those in the SF condition. Thus, diffraction and ear-canal resonance acted to increase sound pressure relative to that in the SF condition where these variables were not involved. Incidentally, the solid curve in this figure essentially represents the frequency response of the loudspeaker in our audiometric booth.

Figure 4 compares MAF and MAP, the conventional comparison yielding the missing 6 dB. In general, MAF exceeds MAP and, in the region from 500 to 2000 Hz, the differences are substantial. The question then becomes, are the two sets of differences we have just examined reflected in the psychophysical responses that generated the spondee thresholds? The next two tables suggest that they are.

Table 2 shows the comparison of the MAF and SF that were examined, abstracted from the curves at 500, 1000, and 2000 Hz. The positive differences averaging 5.5 dB indicate that diffraction and resonance increased the signal level in the MAF condition relative to what we have called the SF condition. This same absolute difference emerges when one compares the spondee thresholds for the two conditions.

Table 3 compares the MAP and MAF, the traditional conditions used for comparison in studies searching for the missing 6 dB. The measured difference averaged 5.2 dB from 500 to 2000 Hz across the three subjects. The mean threshold difference is 4.4 dB, less than 1 dB

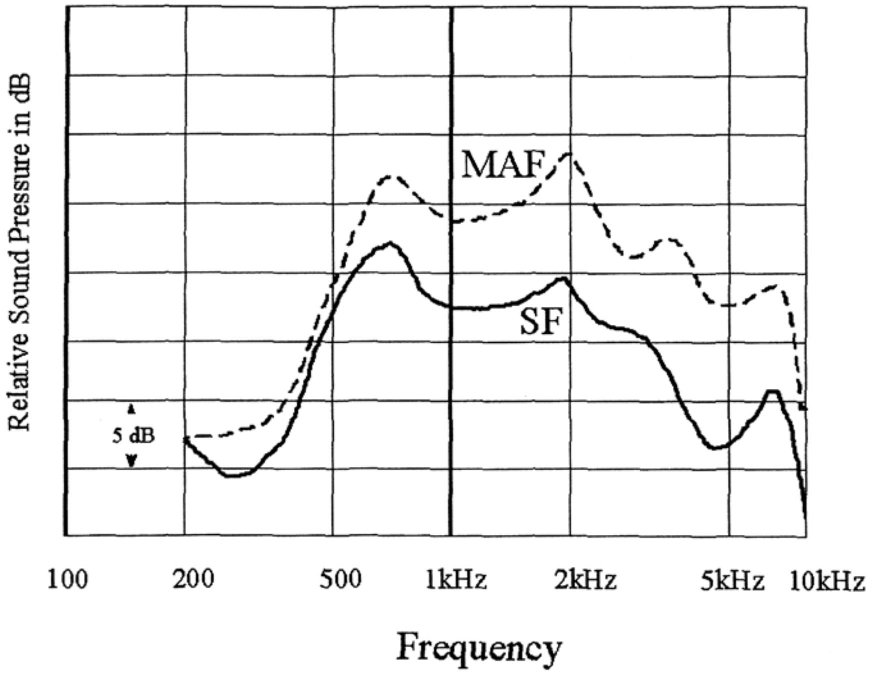

**Figure 3** Average (N = 3) sound pressure for probe in ear canal in sound field (MAF), compared with probe in sound field (SF) at the location of the subject's absent head.

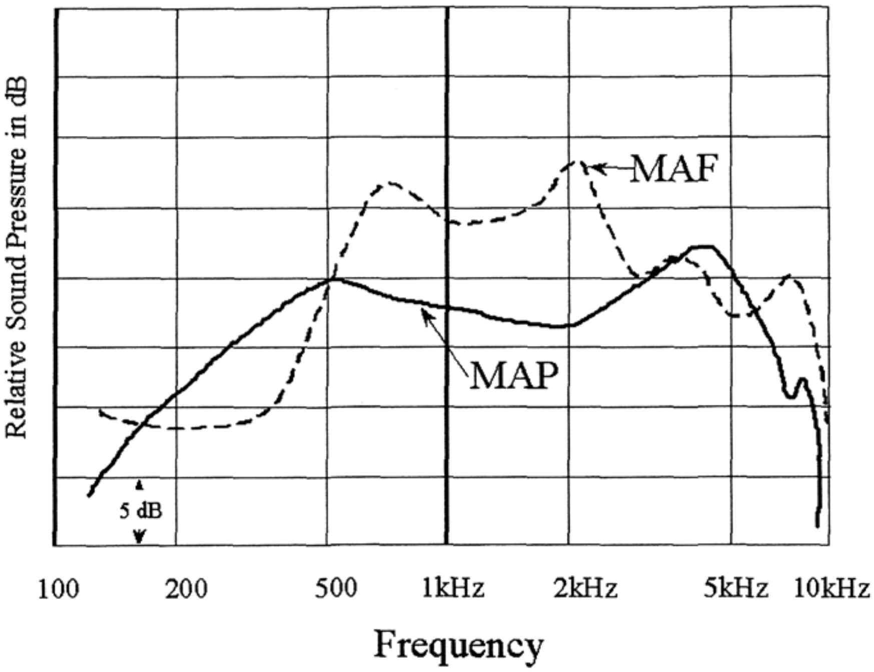

**Figure 4** Average sound pressure for probe in ear canal in sound field (MAF), compared with probe in ear canal under earphone (MAP). Note: By normal calibration methods, both sound field and earphone produced identical sound pressures.

smaller. It is worth noting at this point that the 4.4 dB difference between MAF and MAP found here in an audiometric booth is significantly smaller than the 7.5 dB difference reported by Tillman, Johnson, and Olsen,[1] and later by Dirks et al.[14] Both of these studies were conducted in anechoic chambers and therein lies the difference between 7.5 dB and 4.4 dB. Tillman and his colleagues[1] replicated their anechoic chamber experiment in an audiometric test room and found that the mean differential between MAF and MAP dropped from 7.5 to 4.6 dB. The difference is largely due to an increase in the MAF threshold in the audiometric test room. These latter data were never reported. Later, Dirks et al[14] noted similar shifts in the MAF threshold level—and hence in the MAF-MAP differential—as they moved from an anechoic chamber to an audiometric booth. They further observed that the differential in the audiometric booth could be changed significantly by altering the absorptive characteristics of the room.

Figure 5 compares the physical differences between the MAF and MAP conditions in the anechoic chamber,[1] and in the audiometric booth.[3] The curves in the upper portion of the figure were calculated using data from Shaw,[11] reporting ear canal pressure generated at the entrance to the ear canal by free field sources and various earphones. The differences between the upper two curves for the anechoic chamber are substantially larger than the differences between the two curves in the lower figure for the audiometric booth data. These physical differences easily account for the

**Table 2 Mean Intensity Differences and Spondee Threshold Differences in Decibels between MAF and SF (MAF-SF) Recordings**

| 500 HZ | 1000 HZ | 2000 HZ | MEAN | SRT |
|---|---|---|---|---|
| 2.3 | 6.1 | 8.1 | 5.5 | –5.5 |

**Table 3 Mean Intensity Differences and Spondee Threshold Differences in Decibels between MAF and MAP (MAF-MAP) Recordings**

| 500 HZ | 1000 HZ | 2000 HZ | MEAN | SRT |
|---|---|---|---|---|
| –0.6 | 5.2 | 11 | 5.2 | –4.4 |

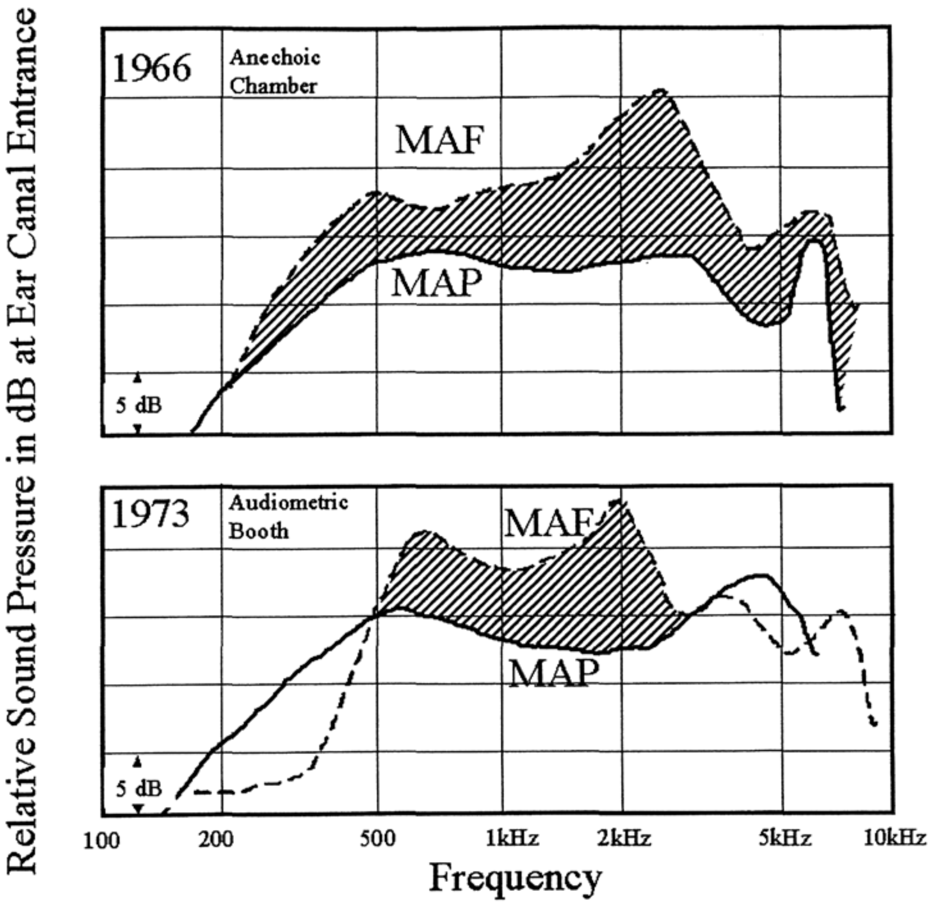

**Figure 5** The physical differences between MAP and MAF for anechoic chamber (from Tillman et al[1]) and the differences between MAP and MAF in an audiometric booth (from Tillman et al[13]).

discrepancy between the 7.5 dB MAP-MAF differential reported in Tillman, Johnson, and Olsen[1] for anechoic conditions, and the 4.4 dB difference found in the present study using an audiometric booth. As Dirks et al[14] suggest, the difference is most likely due to reverberation, and therefore we can conclude that Rudmose[4] and Killion[10] were right—nothing is really missing.

## ABBREVIATIONS

| | |
|---|---|
| MAPD | minimum audible pressure at the eardrum |
| RETSPL | reference equivalent sound pressure level |
| SF | sound field |
| SPL | sound pressure level |

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