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Insertion Gain Repeatability versus Loudspeaker Location: You Want Me to Put My Loudspeaker W H E R E?

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ABSTRACT

The traditional 0° (straight-ahead) location of the loudspeaker during insertion gain measurements is a poor choice, based on theoretical considerations, from the standpoint of measurement repeatability. In a series of experiments, we were able to demonstrate that a location 45° to the side, or 45° up and 45° to the side, provided a much more repeatable measurement of basically the same insertion gain response.

Probe-microphone measures of hearing aid insertion gain can be extremely helpful in obtaining an appropriate real-ear frequency response for an individual. Modifying the response of the hearing aid based on a particular insertion gain measurement is risky business, however, if the measurement itself may be at fault rather than the hearing aid.

Available data indicate the measurement itself is less likely to be at fault with objective insertion gain measurements than with subjective functional gain measurements. In the latter case the standard deviation of the difference between aided and unaided sound field threshold measurements is roughly 5 dB as routinely obtained in the clinical setting (1) and thus one time in 20 the answer will be in error by ±10 dB or more, as illustrated in the data of Hawkins and Haskell (2). As indicated in the Dillon and Murray (3) experiments, the variability of functional gain measurements can be reduced to that of probe microphone insertion gain measurements by using 1 dB step attenuators and many replications (e.g., averaging the multiple zero crossings in single-frequency Békésy threshold tracings), but the roughly order-of-magnitude increase in measurement time makes that appealing primarily for research and not routine clinical measurements.

There are several causes of probe microphone measurement variability. The variability due to probe position in the ear canal has been well discussed by Gilman & Dirks (4). As long as the probe is inserted deeply enough, however, this can be reduced to a relatively minor problem. The variability due to sound field conditions has been well discussed by Morgan et al (5) and more recently by Dillon and Walker (6).

We were interested in the variability caused by motion of the test subject's head. While the exact position of the subject's head is often of little consequence as long as he or she holds still, a different position during the unaided and aided measurements may be of substantial consequence.

There are two components to the variability introduced by head motion:

1. Nonuniformity in the sound field, especially in the vicinity of a relative minimum in pressure, where small motions can result in relatively large changes in SPL, and
2. The directional properties of the head, so that even in a uniform sound field angular motion of the head will change the SPL. This is illustrated in the extreme by the 20 dB or greater change in SPL that would occur at high frequencies (due to "head shadow") if the subject turned 180° around [(7) and others].

Woodford and Tecca (8) concluded from their experiments that it was "apparent . . . that head *angle* contributes considerably more to variability in obtained threshold than does head *position* . . .," and Ringdahl and Leijon (9) included intentional angular variations as part of their reliability study. We were particularly interested in the possibility that a loudspeaker position other than the traditional "0 degrees" (straight ahead) location might significantly reduce the variability in measured insertion gain resulting from motion of the head.

The relationship between ear canal SPL and the angular position of the head in a progressive sound field has been summarized by Shaw in curves for the horizontal plane (7) and for the vertical plane (10). Figure 1 shows the "angular sensitivity of pressure" (ASOP) extracted from Shaw's 1974 data, in dB per 10° rotation of the head, for three angles in the horizontal plane: 0°, 45°, and 90°. Note that ASOP is greatest for 0°, indicating that the traditional 0° location of the loudspeaker will produce the maximum variability for measured insertion gain. In contrast, a nearly zero ASOP obtains for the 90° location at low frequencies, but at the critical high frequencies 90° appears no better than 0°. A good compromise appears to be 45°, with an approximately 0.5 dB/10° ASOP at low frequencies and a nearly zero ASOP in the 2 to 5 kHz region.

Similarly, Figure 2 shows the vertical-plane ASOP for the same three angles, taken from Shaw's 1980 data. Here the traditional 0° incidence gives nearly zero ASOP at low frequencies, but an explosive value near the frequency of

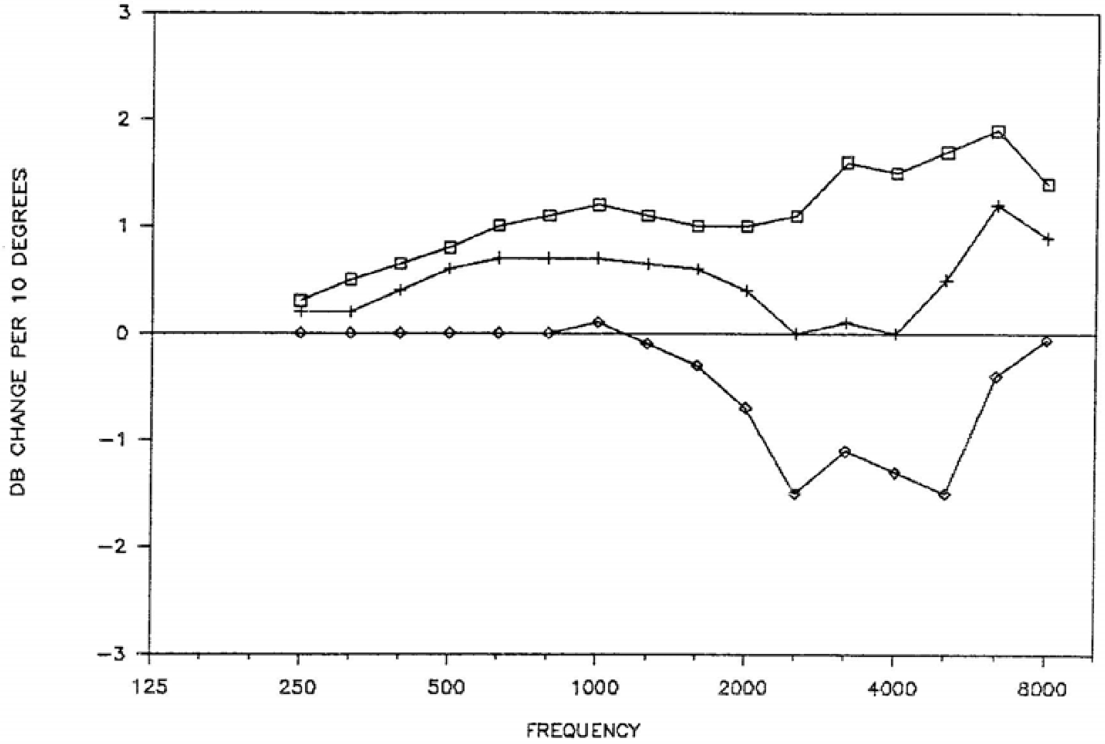

Figure 1. Sensitivity to head movement in horizontal plane, change in ear canal SPL caused by 10° change centered about: 0° (□), 45° (+), 90° (◇).

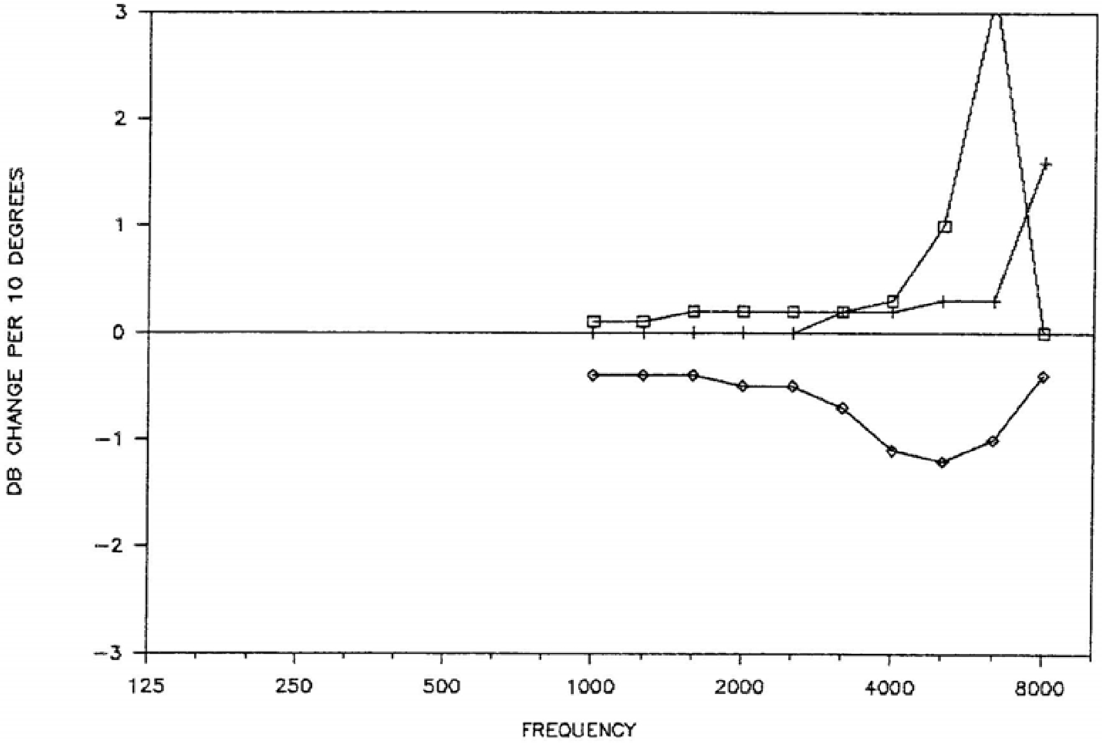

Figure 2. Sensitivity to head movement in vertical plane, change in ear canal SPL caused by 10° change centered about: 0° (□), 45° (+), 90° (◇).

the concha antiresonance [which provides an important cue for vertical localization but wrecks havoc with insertion gain measurements at 6 kHz as discussed by Killion and Monser (11)]. The 90° vertical location also provides a relatively large ASOP at high frequencies. Here again, the 45° location provides an attractively low ASOP everywhere below 8 kHz.

The data in the first two figures suggest that a loudspeaker location of 45° in the horizontal plane, or perhaps 45° up and 45° over, might provide lower variability in measured insertion gain. The later "45,45" position is an unusual suggestion that, to the authors' knowledge, has never been investigated.

But there is another issue. Lower variability would be of little interest if the insertion gain measurement itself bore no relationship to the gain experienced by the subject wearing the hearing aid in the real world. Fortunately, the measured insertion gain is not heavily dependent on loudspeaker position.

Figure 3 shows the calculated differences between a 0° incidence insertion gain measurement and a diffuse field measurement for OTE, ITE, and ITC (canal) hearing aids. Accepting the arguments of Killion and Monser (11), the diffuse field measurement is taken as the "true" measurement based on its similarity to typical real world conditions. Also shown are the calculated differences for 90° incidence versus diffuse field measurements. These differences were taken from the CORFIG curves of Killion & Monser (11) for the three sound fields and three types of hearing aids. No CORFIG data are available for the 45° or 45,45° incidence measurements.

Note that the measured insertion-gain frequency response ("insertion response") is virtually independent of where the sound is coming from for (small) canal aids, which are located deeply enough within the external ear so that the directional properties of the ear are preserved in their microphone pickups. A greater dependence is seen with ITE aids, but the differences are only a dB or so up to 5 kHz. Even with OTE aids, the measured insertion gain falls within a 3 to 4 dB range out to 5 kHz.

We thus appear to have some freedom to choose the loudspeaker location to minimize variability without jeopardizing validity. The fact that ITE and canal aids now account for the majority of hearing aid fittings (and presumably of insertion gain measurements) adds weight to this argument.

With the foregoing considerations in mind, we investigated the variability of insertion gain measurements in a more or less typical environment (IAC booth) for four loudspeaker locations:

1. 0,0° (directly in front)
2. 0,45° (in the horizontal plane, 45° off to the side)
3. 45,45° (45° up and 45° off to the side)
4. 90,0° (directly overhead).

METHOD

Four Radio Shack Minimus 3.5 loudspeakers were arranged in a double-walled IAC booth in the orientations described above, and at a distance of 18 in (0.5 m) from the tip of a plumb bob which was used to place the subject's left ear in position. (In subsequent measurement, we found the 45,45 position was closer to 40° elevation than 45°.) An adjustable high-backed stool allowed the ear canal opening to be positioned at the tip of the plumb bob in each case, after which the subject was instructed to close one eye, note the spot on the wall or floor where the tip of his nose occluded his line of vision, repeat with the other eye, and then hold that position as nearly as possible using those two visual targets.

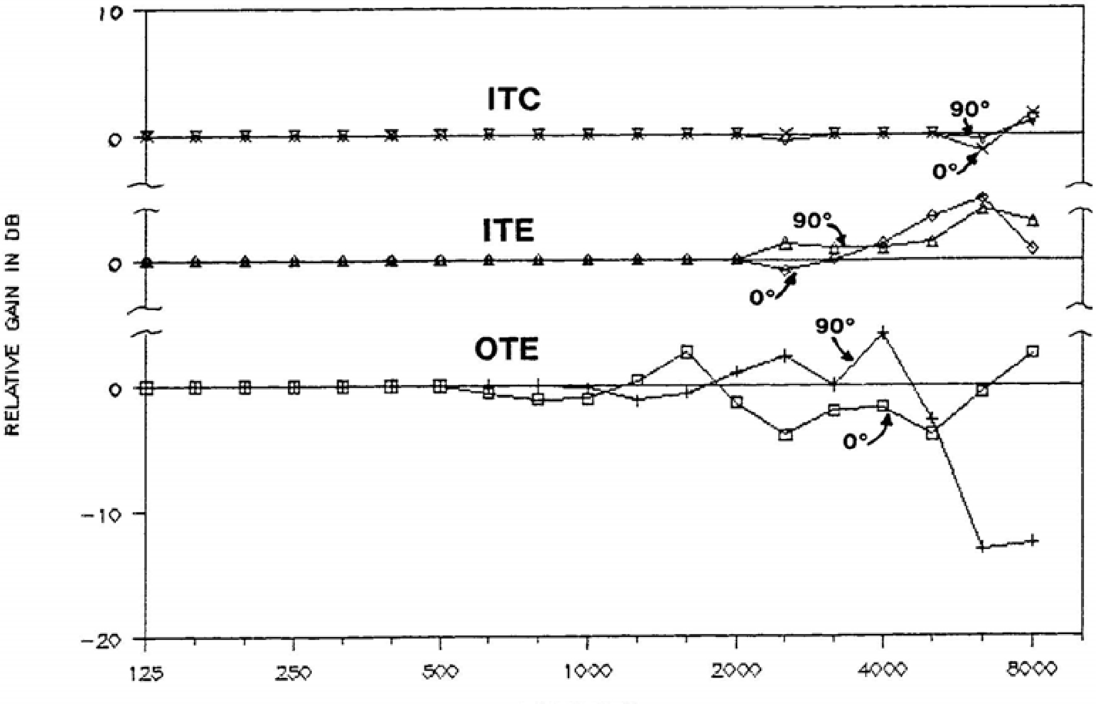

Figure 3. Expected shape of measured insertion-gain curve for 0° and 90° loudspeaker locations for three types of hearing aids, each having flat insertion gain frequency response curve when measured in a diffuse (random incidence) sound field: ITC (canal) aids, ITE (in-the-ear) aids, OTE (over-the-ear) aids.

Ten subjects participated, with five replications of each measurement obtained on each subject in order to obtain an estimate of both within-subject and across-subject variability in the insertion gain measurement. For one subject at one location, only four replications were obtained.

An Etymotic Research ER-7C probe microphone and a Frye model 6500 computerized test box were used to make sound pressure measurements in the subject's ear canal under unaided and aided conditions. A flat-spectrum tonal complex was sent to one of the four loudspeakers, with the resulting microphone output subjected to fast Fourier transform (FFT) analysis. Four FFT samples were averaged and printed out numerically by the 6500, with an apparent system resolution of 0.3 dB. Although SPL readings were printed every 100 Hz, we used only 10 frequencies in our data analysis: 200, 500, 700, 1000, 1500, 2000, 3000, 4000, 5000, and 6000 Hz.

A Beltone Suprimo wideband over-the-ear hearing aid was coupled through a section of No. 13 tubing to an adapter nipple and a disposable foam eartip both normally used with an Etymotic Research ER-3A TUBEPHONE® insert earphone. The foam eartip allowed a good seal to be quickly and reliably obtained with each subject. A 1500 ohm Knowles damper was placed at the tip of the earhook, which helped smooth the response irregularity introduced by the use of the adapter nipple (which was chosen on the basis of convenience rather than to optimize the delivered frequency response of the hearing aid). An OTE aid was chosen as a worst-case trial of the loudspeaker locations based on the data of Figure 3, indicating the OTE aid might produce the greatest variability in the insertion gain measurement, and because we were interested in the differences we might find in the insertion response measured with our nontraditional loudspeaker locations.

The 1 mm o.d. silicone-rubber probe microphone tubing was marked at 18 mm back from the tip and inserted so the mark was approximately flush with the tragus (leaving a presumed 12 mm from the typical eardrum). The hearing aid was placed on the subject, the foam eartip compressed and inserted into the ear canal while the probe tubing was held in position, and the aided ear canal SPL was recorded for each of the loudspeaker locations without removing the hearing aid. The aid was then removed (usually, but not always, the probe tubing came out with the eartip and had to be replaced in the ear canal) and unaided ear canal SPL was recorded for each of the loudspeaker positions. The subject was not removed between replications, only the hearing aid and (sometimes) the probe tubing. The order of loudspeaker presentation was randomized both within and across subjects, with all possible combinations exhausted before repeating.

RESULTS

Figure 4 shows the across-subject average insertion gain measured with each loudspeaker location. The 90,0 (overhead) location produced a significantly different insertion response curve, but the other three locations produced similar results.

The across-subject standard deviation of the insertion response was similar for each loudspeaker location (as opposed to the within-subject or "test repeatability" standard deviation discussed below), and the average value is plotted as a function of frequency in Figure 4. The across-subject standard deviations at each frequency are quite similar to those reported over a decade ago by Dalsgaard and Jensen (12) and greater by approximately the square root of two than those reported by Sachs and Burkhard (13) for the ear canal SPL developed by an insert phone.

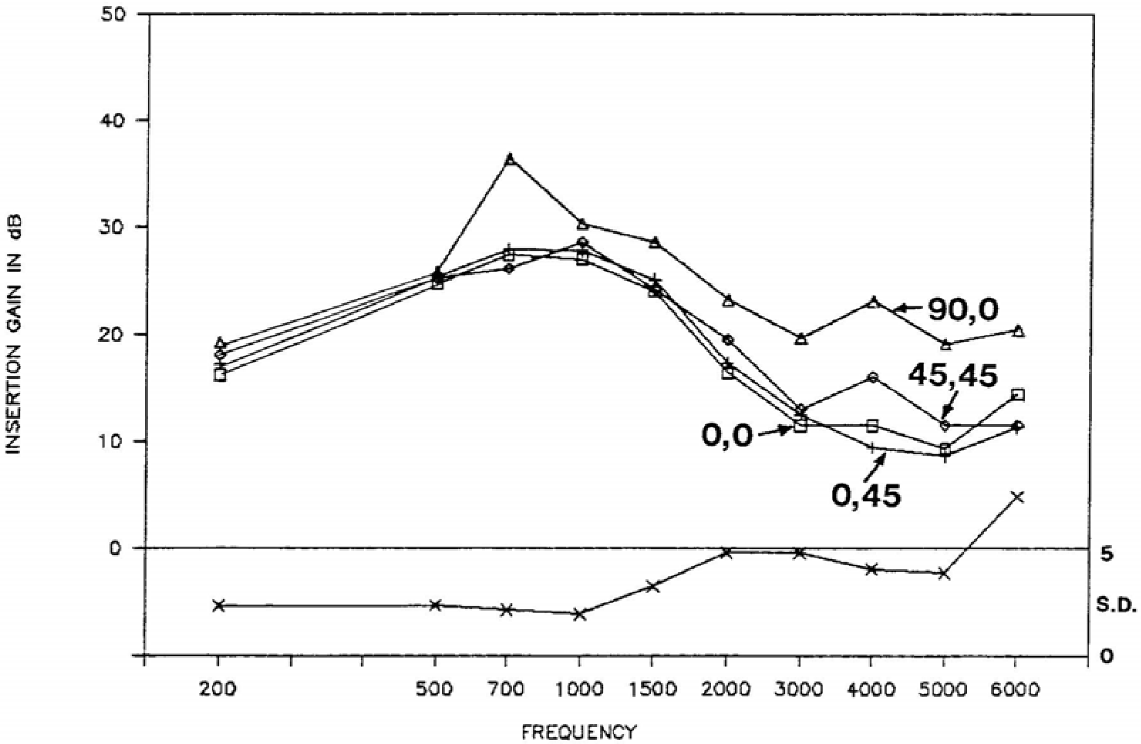

Figure 4. Insertion gain response curves measured on an OTE hearing aid in this experiment with four loudspeaker locations: 0,0°, 0,45°, 45,45°, 90,0°. Average across-subject standard deviation (×).

The latter observation indicates that about half the variance is coming from variations in closed-ear impedance and half from across-subject differences in the external ear effects.

Figure 5 shows the main result: The within-subject standard deviation is highest for the traditional 0° loudspeaker location, and lowest for the two 45° locations (0,45 and 45,45) as expected on theoretical grounds. What was not expected, at least to the senior author, was that the 90,0 (overhead) position was almost as bad (from the standpoint of measurement reliability) as the traditional 0° location. Since the overhead location also produced an unusual insertion-response curve, that location appears unattractive for anything except light bulbs.

Finally, Figure 6 compares our results with those of two other recent studies of variability in insertion gain measurement which used 0° loudspeaker locations. Our results for the 0° location are slightly better than those obtained in the other two studies, although the standard deviations reported by Dillon and Murray (3) included the variation caused because they compared their measurements to a presumed true insertion gain value rather than to themselves. We speculate that asking our subjects to monitor and control their head position using their noses as visual sights may have contributed to our unusually low test-retest variability.

In any case, our results at the 0,45 and 45,45 locations represent a reduction of nearly 3:1 over previously reported standard deviations. [Note added in proof: The variability data of Tecca et al (14) for a 0° loudspeaker location are quite close to our 0,0 results except at low frequencies. They used a headrest as a passive restraint.] Since the average measured insertion response curve for those loudspeaker locations was similar to that obtained for the more traditional 0° location, we recommend use of the 45,45 location where practical. When they are performed carefully with the right loudspeaker location and well-fitting earmolds, our data indicate a standard deviation of less than 1 dB thru 3 kHz and less than 2 dB thru 5 kHz is possible for insertion gain measurements. The latter corresponds to a 95% confidence interval of ± 4 dB, in marked contrast to the 95% confidence interval of ±10 dB for typical clinical functional-gain measurements.

A GOOF AND A RECHECK

After the experiment was completed and more or less casual rechecking was underway, we discovered that the variability in the data for the 0,0 condition might have been increased due to a software characteristic in the (early model) Frye 6500 test system we had been using: With all other loudspeaker conditions the overall SPLs were always high enough to reset the averaging circuit, so that a stable completed average was obtained in under 5 sec. The SPLs in the 0,0 condition were sometimes low enough not to reset the averager, however, so that the data had not completely settled by the time (about 5 sec after the loudspeaker was turned on) that the "print" button was pushed. A complete replication of the experiment for the 0,0 and 45,45 conditions was thus undertaken as a double check. Much to our relief, the resulting plots of within-subject standard deviations were virtually identical to the corresponding curves in Figure 5 except at 5000 and 6000

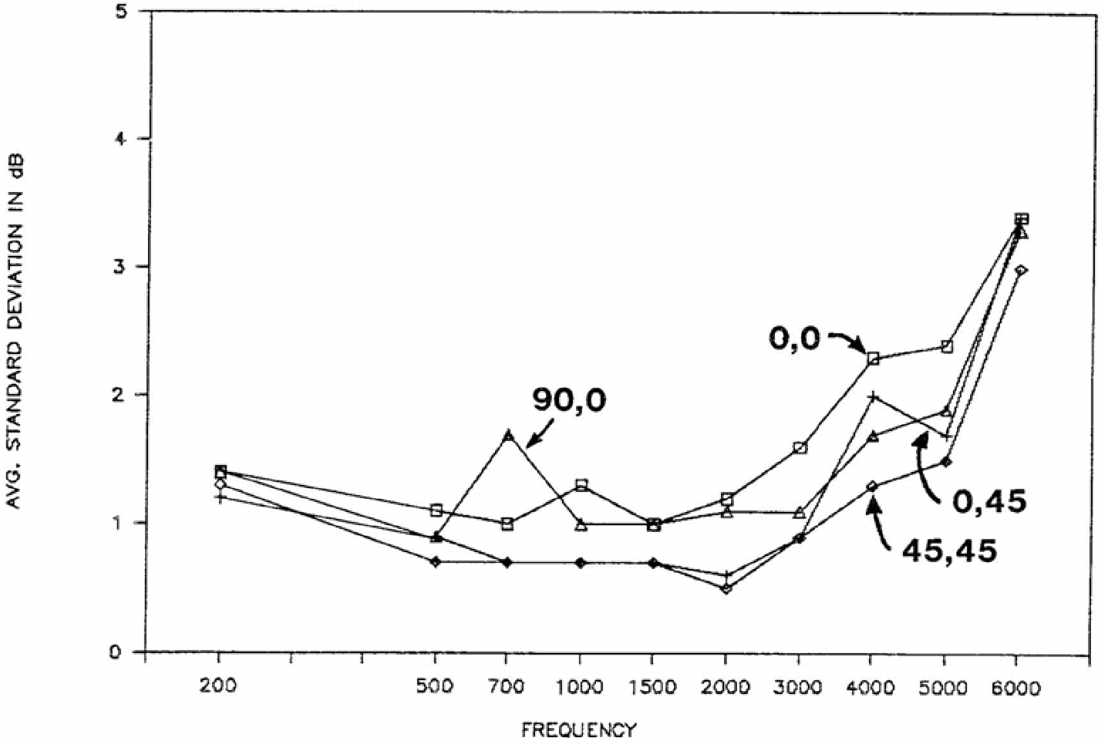

Figure 5. Test-retest variability (average within-subjects standard deviation for five replications) in insertion gain for the four loudspeaker locations of Figure 4.

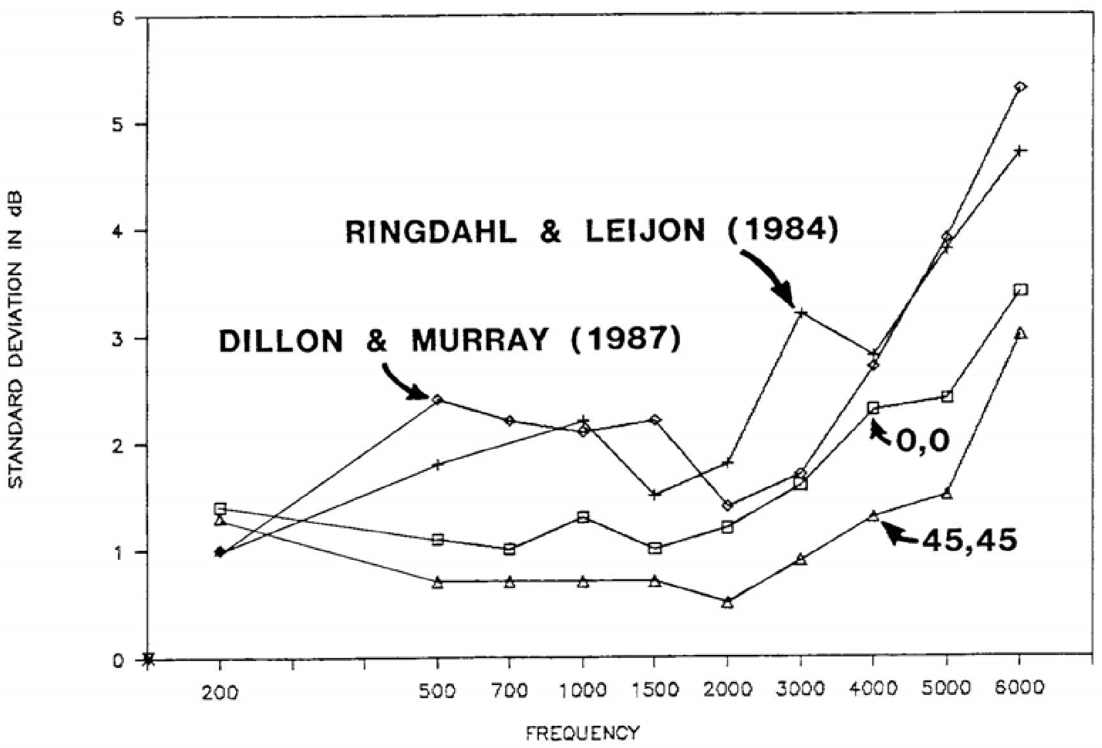

Figure 6. Comparison of present results with previous experiments concerning variability (average within-subject standard deviation of insertion-gain measurement). Improved results in present experiment may have been due to (a) instructions used, and (b) well-fitting (foam) earmolds.

Hz, where the variability in the 45,45 condition was somewhat lower than that obtained in the initial experiment.

We also used the KEMAR® manikin for a single-subject replication of our experiment. The standard deviations calculated for the 5 test-retest replications were essentially independent of frequency and loudspeaker position: The across-frequency averages were 0.42, 0.33, 0.39, and 0.43 dB, respectively for the four loudspeaker positions. It appears that the head motions of our live subjects were indeed the primary source of variability; i.e., it appears that we did measure what we set out to measure. We thus believe our 45,45 recommendation is solidly based.

A FINAL REMARK

The relatively large variability in functional gain measurements is sometimes thoughtlessly used as an argument against the sound field measurement of aided thresholds themselves, whose variability should be no greater than that of the traditional earphone measurement of unaided thresholds (1) and whose importance often far exceeds that of the traditional (unaided) earphone threshold measurement. After all, the earphone measurement only indicates the magnitude of the problem to be solved. It gives no information about how well the problem has been solved by the dispenser, and only indirect information about the real world problems the aided individual can still expect to encounter due to the remaining inaudibility of some speech sounds.

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The work reported here was performed by L. J. R. as part of his Master of Science degree at Northwestern University.

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