Magnetic Performance Requirements for Wireless Device/Hearing Aid Telecoil Mode Compatibility

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0. PROLOGUE

This study was initially undertaken at the behest of and in support of the ANSI C63.19 working group by Stephen Julstrom (Etymotic Research), Linda Kozma-Spytek (RERC Telecom Access), and Scott Isabelle (Motorola) to better substantiate the telecoil mode signal level and signal-to-noise needs of hearing aid users for acceptable cellphone communication.

1. INTRODUCTION

While digital wireless communications devices such as cellphones (which communicate with remote cell towers) and cordless phones (which communicate with a nearby base station) have become ubiquitous, the experiences of hearing aid wearers with many of the products have been less than satisfactory. Sometimes, the speech signal level is insufficient, especially when attempting telecoil coupling. More often, there is annoying interference. This can come from several sources. A hearing aid (HA), in either its microphone or its telecoil (magnetic coupling) mode of operation, may respond to the radio frequency (RF) emissions of the wireless device (WD). In its telecoil mode, the HA, of necessity, picks up any undesired audio frequency magnetic fields that a WD may generate in addition to the desired magnetic speech signal. These undesired magnetic fields arise from electrical currents flowing in the WD, primarily those related to the RF output signal generation (typically heard as buzzing sounds) and the display (typically heard as whining sounds).

In recent years, considerable effort has been devoted to defining, and to some extent, resolving these issues. In particular, modern hearing aids have generally shown great improvement in their immunity to RF interference, particularly in microphone mode. A standard addressing hearing aid compatibility is now in place for cellphones and related devices (ANSI C63.19 Rd 3.12) and will soon be for cordless phones (TIA-1083). The cellphone standard addresses both RF compatibility and audio frequency magnetic compatibility (telecoil mode). The cordless phone standard addresses only telecoil compatibility, since the cordless phones operate at much lower RF power than do cellphones. An overview of the technical problems of cellphone/hearing aid compatibility, the development of C63.19, and the present regulatory environment for cellphone compatibility is found in [1].

Many of the final 2006 revisions to ANSI C63.19 dealt with telecoil compatibility issues. Assuming adequately low RF interference, achieved through a combination of a limitation on the maximum near-field RF output of the WD and good RF immunity on the part of the hearing aid, then the telecoil performance of the WD as a magnetic source depends on 1) the strength of the magnetic signal in an orientation and location conveniently useable by the hearing aid, 2) the frequency response through the telephone voice band of the WD's magnetic signal, and 3) the magnetic signal-to-noise (S/N) ratio at that orientation and location.

Of these three aspects, the source frequency response was already well established by reference to the landline phone specification, as defined in FCC part 68.316, which in turn was derived from EIA RS-504. Part 68 also defines minimum magnetic levels to be produced by landline phones, but it was unclear to the standards working groups how these numbers should inform their work, as the minimums were arguably low, even for landline use. These earlier landline phone specifications had no need to include S/N specifications, so there was no prior direct reference for this important specification. Studies had been conducted earlier in the development of ANSI C63.19 to determine the required S/N ratios needed by hearing aid users for various levels of usability [2, 3, 4]. Strong implications could be drawn from these studies concerning the required telecoil mode S/N ratios, however, four primary aspects limited their direct applicability: 1) The studies addressed radio frequency interference, which invades the hearing aid in a different manner and with a different audio band frequency response than does the audio frequency magnetic interference, even if the source of the interference in both cases may be the RF waveform envelope; 2) ANSI C63.19 and TIA-1083 specify that the magnetic noise be measured with A-weighting, which was not employed in the studies; 3) The studies addressed only interference from those RF modulation protocols in use at the time, and did not attempt to address the question of expansion to future protocols or to other non-modulation related noises; and 4) The studies employed acceptability measures that did not correspond directly to the adopted performance category descriptors of C63.19.

The motivation for the present study came from a need to more specifically address the questions of the magnetic signal level and S/N ratio that cellphones and related devices falling under C63.19's purview should be required to meet to ensure compatibility with hearing aid telecoil operation. Not surprisingly, the S/N question arose in relation to cordless phone compatibility, also, so the study was expanded to include noise sources specific to cordless phone operation.

During the first round of the study, it became apparent that there were significant differences in the telecoil sensitivity, in relation to the microphone sensitivity, of the various hearing aids tested. These variations obviously could affect an implied signal level requirement, and so needed to be characterized. Thus the four areas of focus for the study became 1) measuring the orientation of primary magnetic field pickup for the hearing aids, 2) measuring the in situ matching of the magnetic and acoustic speech sensitivity of the test subjects' hearing aids, by subjective and objective assessment; 3) measuring each test subject's preferred magnetic "most comfortable level" (MCL) for speech and range of acceptable levels, and 4) measuring each test subject's telecoil mode minimum S/N requirements for several rating levels of usability, along with their S/N threshold of audibility, for various WD-related noise sources in the presence of speech. All testing was performed using test subjects wearing their own hearing aids, as programmed by their dispensers.

2. TEST SIGNALS, EQUIPMENT, AND SETUP

Test Signals

Three types of calibrated test signals were employed: 1) full-band speech, 2) telephone voice-band speech, and 3) wide-band noise. All were pre-processed and stored as readily recallable .wav files. In more detail:

1) *Full-band speech* was played back through a loudspeaker approximately 1m in front of the test subject at an average speech level of 65 dB-SPL at the subject's location. The signal was calibrated in the test environment using a 200 Hz - 5 kHz pink noise reference signal at the same average level as the average speech level. More precise and consistent calibration could be accomplished with this steady signal than by direct measurement of the speech signal.

The average speech level was determined according to Method B of ITU-T Recommendation P.56 "Objective Measurement of Active Speech Level", which specifies taking the power average of the rectified signal after filtering by dual, first-order 30 msec time constant low-pass filters and leaving out speech gaps of more than 0.2 seconds that are lower in average rectified level than a threshold 15.9 dB below the calculated speech level. This definition does imply retrospective, not real-time processing. Informal measurements have shown this method to result in speech level measurements about 3 to 4 dB lower than those obtained from a traditional approach of observing the level of frequent peaks on a VU meter [5].

The voice recording employed during the testing for both acoustic and magnetic playback was the same as employed by Nabelek [6, 7] (see discussion in section 3 below of the Acceptable Noise Level test procedure). It consists of a reading of a descriptive travelogue of the Arizona area by one male talker. It is available on CD-ROM from Robert McClocklin at email (rmcclock@shaw.ca or info@cosmosdistributinginc.com) or online at http://www.cosmosdistributinginc.com/. The recording was digitally extracted to a file (.wav format, 16-bit, 44.1-kHz sampling rate) for subsequent processing.

2) *Telephone voice-band speech* was played back magnetically to a test subject's hearing aid telecoil at average magnetic levels adjustable from -52 to +3.75 dB(A/m). Several steps were needed to obtain the final voice files. The original speech sample was first down-sampled to 8 kHz in MATLAB using its "resample" function with a 256-point interpolation filter. In accordance with generally accepted procedures for subjective evaluation in telephony, the signal was then band-limited using the Modified Intermediate Reference Standard (modified IRS) sending characteristic as given in Annex D of ITU-T P.830 "Subjective Performance Assessment of Telephone-band and Wideband Digital Codecs". This response shaping is shown in figure 1, normalized to 0 dB at 1 kHz. (The high frequencies were already limited to <4 kHz by the prior down-sampling.)

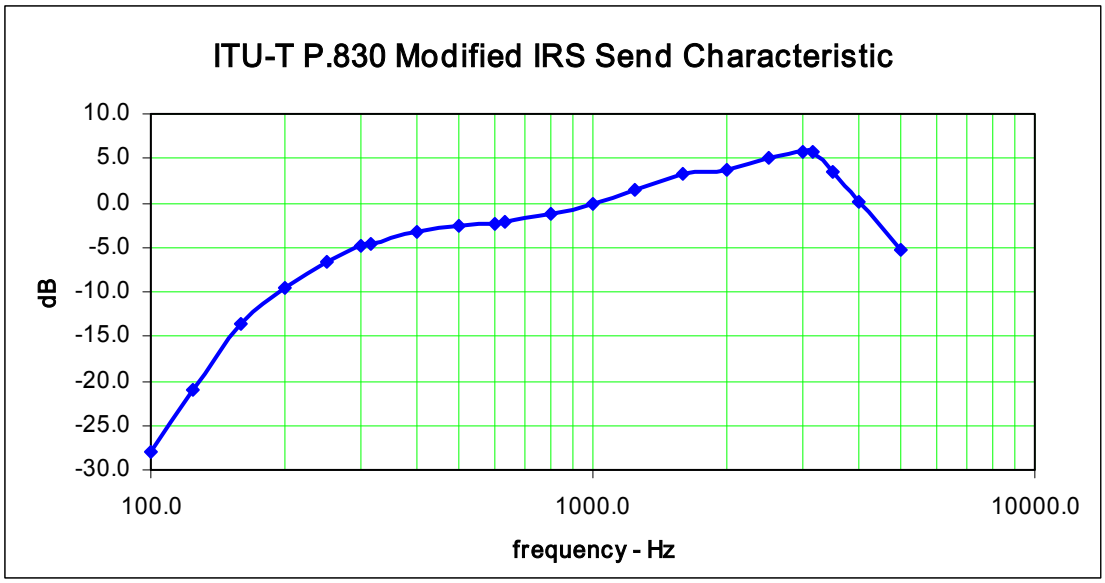


Figure 1

This shaping was then followed by bit-exact software emulation (both encoding and decoding) of various WD codec (coder-decoder) types as listed in table 1, with the ITU-T P.56 Active Speech Levels set at the appropriate codec reference modulation levels (-16 dBm0 for GSM, UMTS, FHSS, and DSSS or -18 dBm0 for CDMA and iDEN codecs). For each coding, executable programs were compiled from fixed-point C language reference source code. Implementation of the P.56 active speech level function, the P.830 modified IRS Send characteristic, and the G.726 32kbps ADPCM cordless phone codec were all taken from ITU-T G.191 "Software tools for speech and audio coding standardization." The reference source code for the Adaptive Multi-Rate (AMR) codec was obtained from 3GPP (www.3gpp.org); the Enhanced Variable Rate Codec (EVRC) from TIA; and the AMBE++ codec under license from Digital Voice Systems, Inc. (www.dvsinc.com).

TEST STIMULI

Speech Sources	Noise Sources	Number of Test Subjects
AMR MR12.2 codec	100 Hz, 20% DC (Training)	57
AMR MR12.2 codec	GSM (J-STD-007) - cellphone	57
AMR MR12.2 codec	UMTS (T1/T1P1/3GPP) - cellphone	57
EVRC codec	CDMA (TIA/EIA/IS 2000) - cellphone	57
AMBE++ codec	iDEN - cellphone	57
AMR MR12.2 codec	Cellphone Display	31
VSELP codec	TDMA (TIA/EIA-136) - cellphone	30
ADPCM codec (32kb/s)	FHSS - cordless phone	26
ADPCM codec (32kb/s)	DSSS - cordless phone	26

Note: Time intermittency effects of the interference were not considered. All noise types were presented as continuous interfering signals.

Table 1

The signals were then filtered by the typical magnetic source frequency response function of Fig. 18 of the Appendix. The resulting transcoded speech was up-sampled to 44.1kHz, again using the MATLAB 'resample' function with a 256-point interpolation filter. For each air interface type, a stereo file was created to enable simultaneous speech and noise playback, using the transcoded speech as one channel

and the appropriate interference signal as the other. A companion 1 kHz tone at the reference codec modulation level (the average speech level) was used to calibrate the magnetic link.

3) *Wide-band noise* was played back magnetically to a test subject's hearing aid telecoil (always mixed with the voice-band speech) at levels normalized to their A-weighted (according to ANSI S1.4-1983, R 2005), telecoil response (as described in the Appendix and shown in figure 19), average magnetic levels (1 kHz equivalent), adjustable from -72 dB(A/m) to +3.75 dB(A/m), and off. A-weighting (figure 2) represents a very reasonable starting point for subjective spectrum weighting according to the criteria of the study. Also, A-weighting and telecoil response are specified by C63.19 and TIA-1083 for measurement of magnetic noise. "1 kHz equivalent" means the same level that would be measured with a 1 kHz tone through the same frequency shaping. (Both the A-weighting curve and the telecoil response curve have 0 dB gain at 1 kHz.)

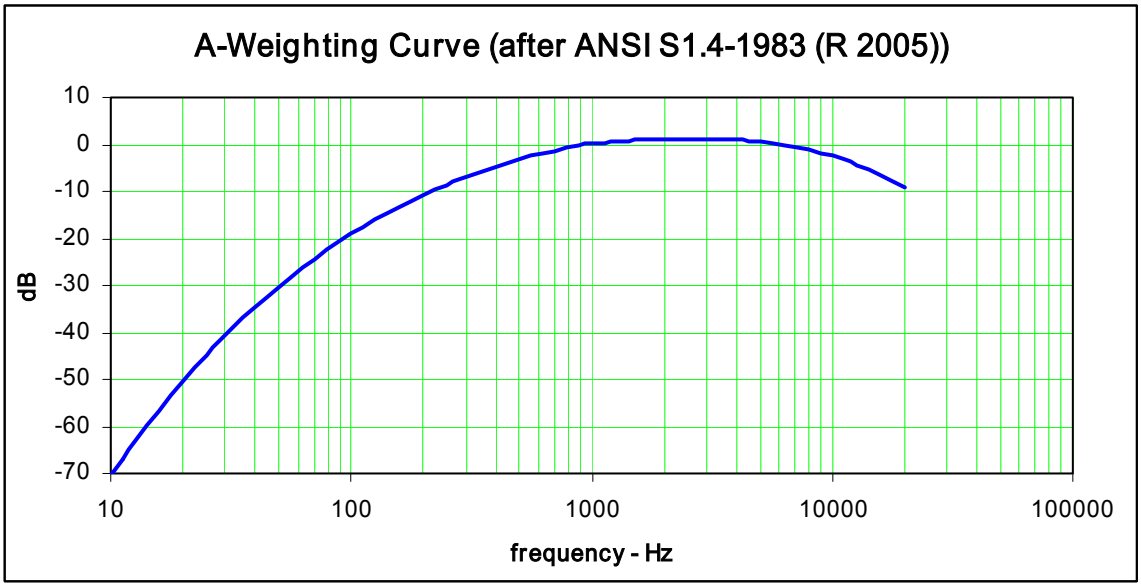


Figure 2

Table 1also lists the noise types tested, along with the total number of subjects tested for each noise type. Audio frequency magnetic noise in the vicinity of the receiver of a WD generally is most often related to the amplitude modulation envelope of the transmitted RF signal, but can also accompany the display backlight or scanning. The noise types listed were chosen to be representative of a variety of modulation protocols, along with a sample of display noise. It is unknown how representative of other display technologies this single sample might be. Its inclusion was felt necessary to give some insight into the applicability of the S/N testing to non-modulation-related noise sources. In general, such display-related noises tend to consist of higher frequency buzz sounds, in contrast to the RF modulation-related noise types, which tend to have much stronger mid and lower frequency content. The TDMA modulation protocol is no longer in wide use, but was included for historical comparison. The training noise type was of a similar nature to the modulation noises, but distinct from them.

The speech coding types were chosen to match the noise types, according to each protocol's specification. However, for the unimpaired emulations employed, there were little if any audible differences among them. The "display" noise type was from an actual recording of magnetic pickup near a lighted cellphone display, while all the modulation-related signals were generated by software simulation of the RF signal envelope. In actual WD use, these RF modulations are choppy, not continuous. Such time intermittency effects were not considered for this study. All noise types were presented as continuous interfering signals. Some of the protocols further vary their modulation envelopes (while transmitting) under different operating conditions. A single representative condition was selected for each protocol.

The tested noise types, except for the display noise, arise from currents in the WD that power the RF transmitting output circuitry and therefore follow the RF signal envelope. The noise recordings should therefore be derivable from simulations of the RF envelope. For the cellphone noise types these were obtained from the work of Louis Vannatta of Motorola, Inc. For the two cordless phone types, these were obtained from simple pulse waveform simulations. The adequacy of this approach was verified experimentally by comparison to measurements of the magnetic interference from two GSM protocol cellphones, a DSSS (direct sequence spread spectrum) protocol cordless phone, and an FHSS (frequency hopping spread spectrum) cordless phone. Spectrum matches were very close, although one of the GSM phones needed an additional small high frequency rolloff above 5 kHz for the best match, while both cordless phones needed such rolloffs above 3 kHz. These spectral rolloff effects presumably are due to high frequency supply filtering in the WD. A compromise high frequency rolloff above 10 kHz was added to the emulated cellphone noise signal envelopes while a rolloff at 3 kHz was added to both cordless phone noise types, although these frequencies are mainly above the presumed range of interest. A rolloff in the high frequency region was also introduced by the magnetic source loops used (to be described).

Telecoil Orientation Test Jig

So that a known and controlled magnetic coupling may be achieved between the magnetic source and the hearing aid telecoil, it is necessary to know the orientation of the telecoil. A simple wire loop, driven by an electrical current, produces a predictable and non-position-sensitive field orientation in its central region, perpendicular to the plane of the coil. To find the orientations with more or less magnetic sensitivity, a hearing aid switched to telecoil can be placed in the center of the loop and rotated in various orientations while listening to the output. Finding two perpendicular null orientations or equivalently a null rotation axis can imply the direction of maximum sensitivity and therefore the orientation of the telecoil. (The nulls are much more sharply defined than the maximum.)

Initially, a “free-hand” approach was used, but this proved difficult with some ITE (in-the-ear) hearing aids having telecoils at oblique angles to the faceplate. Figure 3 shows a special-built fixture that aided in rotating a hearing aid around any of three orthogonal axes, after experimentally positioning the aid with adhesive putty. Finding null orientations and, by inference, the telecoil orientation for maximum sensitivity was then relatively straightforward.

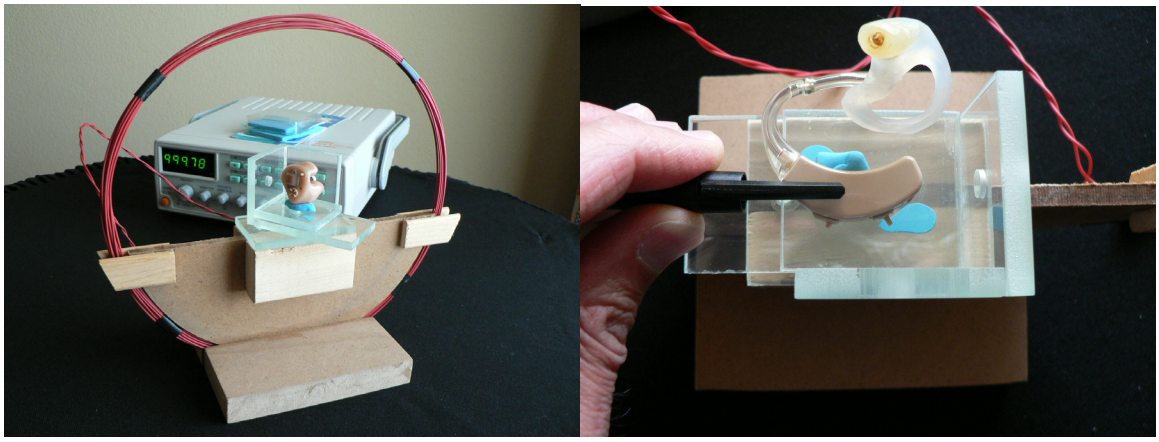


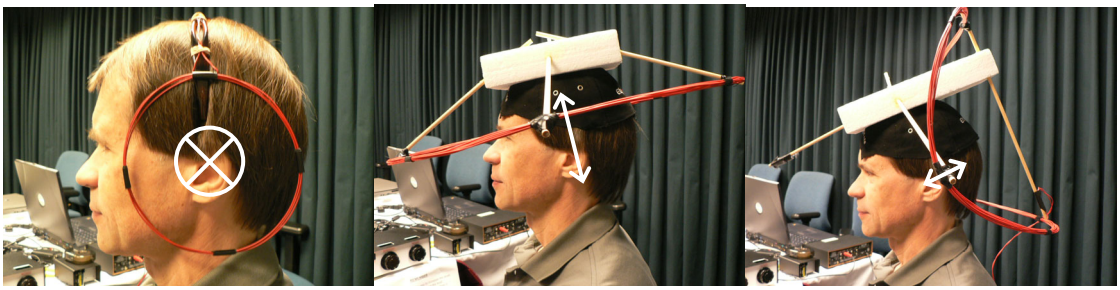
Figure 3

Magnetic Source Coils

In order to ensure the best practical coupling to the test subjects’ hearing aid telecoils, regardless of their orientations, and to stably maintain that coupling throughout the testing, three wearable magnetic source coils, or “hats” were constructed. Each applied a calibrated, precisely oriented magnetic field over a region near its center in each of the three standards-defined orientations of perpendicular (axial),

transverse (radial 1), and longitudinal (radial 2). These orientations were established in relation to a normally positioned handset, presumably angled 25 degrees from the horizontal.

The hats, illustrated in figure 4, were designed so that the coil could be centered on either ear, although they were constructed sufficiently large as to make exact positioning non-critical. They are shown positioned over the left ear, but they could be rotated to center on the right ear, depending on which hearing aid the test subject normally used for telephone conversation. The longitudinal hat's coil needed to be distorted backwards to prevent interference by the subject's back or, when turned around to the right ear, the subject's front. The field orientation was still correct at the hearing aid location.



Perpendicular (Axial) Transverse (Radial 1) Longitudinal (Radial 2)

Figure 4

The perpendicular coil had three turns of wire, 15 cm in diameter; the transverse coil 10 turns, 50 cm in diameter, and the longitudinal coil, 14 turns, 50 cm in diameter. The coils were matched in voltage sensitivity with series resistors, to enable straightforward interchange. The larger coils still exhibited some higher frequency rolloff under the voltage drive condition due their greater inductance, so capacitors paralleling the series resistors were added to flatten their responses above 3 kHz. The small transverse coil maintained flat response, down 1 dB, to 19 kHz, the transverse coil with a capacitor to 8 kHz, and the longitudinal coil with a capacitor to 6 kHz.

Complete Test Setup

Figure 5 is a photo of the complete test setup, as established in the second round test location (Gallaudet University). The laptop was the source of all the test signals. The control box in the center of the picture routed the signals to the appropriate locations for each test and provided for calibrated control of the noise and speech levels by the subject or the tester, as appropriate. The openings in the top of the control box were positioned so as to allow the tester to read the selected settings, while preventing their observation by the subject. The "Speech" and "Noise" knobs precisely controlled the signal levels in steps of 1.25 dB. There were no visual or tactile cues for the test subject that would indicate the knob settings, other than stops at the minimum (off) and maximum settings.

Figure 5

A small power amplifier drove the magnetic hats, while a powered loudspeaker (Acoustic Research Powered Partner 570/Advent AV570) provided the acoustic speech. (In the first round of testing, the acoustic source was an audiology booth loudspeaker.) Also visible in the figure is a lavaliere microphone and preamplifier to enable communication by the tester to the subject when in the telecoil listening mode. The control box provided a spring-return switch to enable this communication function and an output for monitoring and balancing the level of the tester's speech to the test recording speech. A sound level meter was used for acoustic level calibration and a magnetometer for magnetic calibration.

Test Environments

The testing was performed in three locations between February and July of 2006. The preferable acoustic environment was determined to be a medium-sized room, not unlike a typical living room, with similar acoustics. This was not felt to be critical, though, since the acoustic signal was to be taken from a loudspeaker approximately one meter away from the subject and used only as a speech level reference. The only magnetic environmental requirement was a low residual background magnetic noise. This was somewhat difficult to achieve in non-residential environments.

The initial 12 subjects were tested at Etymotic Research, Elk Grove Village, Illinois. The magnetically quietest practical location there turned out to be an audiological testing booth. Its acoustic environment was potentially smaller and more absorbent than desired, but with the door left open, the acoustic feel was reasonable. The A-weighted, telecoil response 1 kHz equivalent level of the background magnetic noise at the subject's head location was generally below about -50 dB(A/m), depending on the exact positioning and orientation of the subject's telecoil. The remaining two test locations were similar magnetically. Only in the final location did the background magnetic noise present an evident problem for one subject with an especially sensitive telecoil. Before testing, the subject was moved until a relative null in the background hum was located. It should be noted that the character of any background magnetic noise present was very different from the purposely-introduced WD-type magnetic noises. The next 19 subjects were tested at Gallaudet University, Washington, D.C., in a medium-sized hotel conference room. The final 26 subjects were tested at the Hearing Loss Association of America convention in a hotel room suite at the Disney Coronado Resort, Orlando, Florida.

3. EXPERIMENTAL PROCEDURE

Pre-test Calibration

1) With the acoustic source placed about one meter from the test subject's head location (subject not present), the speech level was adjusted to 65 dB-SPL, as read on an SLM with its microphone at the head location, using the loudspeaker power amplifier gain control. The acoustic calibration signal was 200 Hz - 5 kHz pink noise at the same recorded average level as the speech level of the wide-band speech sample. 65 dB-SPL is taken to be the most typical conversational speech level, measured in this manner.
2) The magnetometer was used to measure the field strength at the coil center of the magnetic hat to be used (or the corresponding point, in the case of the longitudinal hat). With the control box "Speech" level control at a predetermined reference setting, the magnetic level was adjusted to the calibration level of -25 dB(A/m) (56 mA/m), using the magnetic hat drive amplifier gain control. The calibration signal was a 1 kHz tone at the same recorded level as the codec reference modulation level, as described above. This adjustment also ensured calibration of the A-weighted, telecoil response noise levels.

Step-by-Step Test Procedure – Preliminaries and Telecoil Orientation Test

3) *Questionnaire:* The test subject filled out a guided intake questionnaire, yielding information about telecoil and telephone usage, demographic information, and self-reported hearing abilities.
4) *Telecoil orientation:* Using the test jig described above, the telecoil orientation was determined for the subject's preferred telephone-use aid. This was photographically recorded, as was the positioning of the aid on the subject's ear. From this information, the in-use orientation of the telecoil was determined and an appropriate magnetic hat selected.

Step-by-Step Test Procedure –Speech Level Tests

In addition to verbal test instructions, the instructions and rating scales were printed out for ready reference by the subjects for each step.

5) *Hearing aid gain setting confirmation:* The subject, seated in the test chair, listened to the acoustic reference speech using their aid or aids normally, and was given the instruction:

   "Listen to the recorded speech playing over the loudspeaker and imagine that you are having a face-to-face conversation with a friend. Adjust your hearing aid volume control to what you consider to be a comfortable listening level for normal use."

   Once this was set, the subject was instructed:

   "Be careful not to change this setting for the duration of the testing."

   If the aids did not have level controls, the subject rated the loudness of the speech (see Fig. 6 below for the rating scale used).
6) *Magnetic-acoustic level match:* The appropriate magnetic hat was placed on the subject's head. The tester pre-set the magnetic speech level to an initial setting of -25 dB (A/m), and instructed the subject:

   "Use the Speech Level knob in front of you to adjust the level of the speech that you hear through your telecoil to the same loudness as the speech that you just heard coming from the loudspeaker. The experimenter can help you with this as you switch between the microphone and telecoil modes of your hearing aid. As with the tests to follow, it may be helpful to purposely adjust the level a bit too high and then a bit too low to help you center in on the best match."

   The selected magnetic level was recorded as the "magnetic matching level". The remainder of the test was conducted only in the telecoil mode.
7) *Most comfortable level (MCL):* The subject was then directed:

   "Now imagine that you are having a telephone conversation with a friend. Is this speech level the level at which you would prefer to listen to the telephone? If not, please use the Speech Level knob in front of you to readjust the level of the speech to what you consider to be a comfortable listening level for telephone use."

   To aid them in this judgment, the rating scale of Figure 6 was presented. If a new level was chosen, that was recorded as the "MCL". Otherwise, the matching level was recorded as the MCL. The subject was given two more opportunities to change or confirm the MCL during the next step. The final judgment was the accepted answer.

How would you rate the loudness of the speech?

1	2	3	4	5	6	7
Inaudible	Very Soft	Soft	Comfortably Loud	Loud	Very Loud	Too Loud

Figure 6

8) *Minimum and maximum acceptable magnetic levels:* The subject was directed to adjust the Speech knob to the lowest and highest levels they would find acceptable for extended use with the first instruction:

   "Again using the Speech Level knob, re-adjust the speech level to the quietest setting you would consider useable for an extended telephone call. You may want to adjust the knob back and forth to help you find your minimum acceptable level. Remember; do not change your hearing aid volume setting."

   A similar instruction was given for the loudest useable setting. After returning to their previously established MCL and confirming or changing it, the lowest and highest judgments were repeated in the opposite order. Then the MCL was confirmed or changed for the last time and left at that speech level setting for the following signal-to-noise tests. The order of lowest and highest judgment was counterbalanced among subjects. The averages of the two "lowest acceptable" and the two "highest acceptable" judgments were taken as the final answers.

Step-by-Step Test Procedure – Signal-to-Noise Test Background

The Acceptable Noise Level (ANL) procedure developed by Nabelek and colleagues [6, 7] has been used in assessment of HA use, outcome, and benefit and was selected as a basis for obtaining the subjective S/N data. It proved to be relatively economical of time, requiring about 2 minutes for each judgment. Having been developed to assess the acceptability of background noise with respect to speech received by users with hearing aids, it appeared to be well suited to the measurement of acceptability of WD interferences. In this test, the noise or interference signal is presented mixed with the speech at the subject's predetermined MCL, and the subject adjusts the level of the interference until their Background Noise acceptance Level (BNL) is reached. The Acceptable Noise Level (ANL) is determined from the relation: ANL = MCL – BNL (all quantities in dB SPL). For the purposes of this study, ANL becomes the signal-to-noise ratio (S/N) and the quantities are expressed in dB(A/m) of magnetic signal or noise (1 kHz equivalent average values).

A test subject's judgment of acceptable noise level will be influenced by the instructions given. The ANL procedure as described by Nabelek directs the subject to:

> *"Now turn the level of the background noise back up to the MOST noise that you would be willing to put-up-with and still follow the story for a long period of time without becoming tense or tired."*

It should be noted that the test is not designed to directly elicit information concerning intelligibility of the speech, only its annoyance factor or general acceptability. It was evident in testing that the unnatural-sounding WD noise interferences generally become unacceptable while their level was still too low to significantly degrade intelligibility.

The subject instructions for this study were modified from the Nabelek instructions in order to elicit subject ratings most closely associated with the category ratings of ANSI C63.19, as set forth in its Sections 7 and 7.2:

> Excellent Performance; little perception of interference
> Normal Use; acceptable for normal operation
> Useable, but not acceptable for regular use

Likely Not Useable; likely not useable by most hearing aid wearers

The specific category descriptions for each S/N judgment were given verbally and printed in large type and taped below the loudspeaker, for easy reference:

Excellent Performance - You would find a phone with this level of noise to be highly usable. You would have no complaints about this amount of noise for extended phone calls.

Acceptable for Normal Use – You would find this level of noise to be acceptable for normal, regular use of a phone. You would accept this amount of noise for an extended phone call without becoming tense or tired.

Usable for a Brief Call - With this level of noise you could successfully complete a brief phone call. However, you would not accept this amount of noise for normal, regular phone use.

The instructions directed the subject to find the highest noise level that would meet each criterion, in order to seek out the category boundary.

Step-by-Step Test Procedure – Signal to Noise Tests

9) *Training noise S/N judgments:* With the speech setting at the final selected MCL, the subject was directed to adjust the training signal noise (not a specific WD protocol-related noise, but of a similar general character: 100 Hz, 10% duty cycle pulse waveform) to each of the three noise ratings in turn. Before each series of tests for each noise type, the tester pre-set the noise to either a high level (16.5 dB below the MCL speech) or a very low level (off). This initial setting (high or very low) was randomized among test subjects. The three category judgments were made in one order first (e.g., excellent performance, normal use, usable) and then repeated in the opposite order. This ordering was also randomized among subjects. Following each noise judgment, the subject rated the noise and the usability according the scales of figure 7. The data for the training noise was recorded, but not used for further data analysis.

How would you rate the interference, if any, that you hear?

0	1	2	3	4	5
No Interference I do not detect any interference	Not Annoying I detect interference, but it is not at all annoying	Mildly Annoying The interference is slightly annoying, but I can ignore it	Annoying The interference is annoying, but not uncomfortable	Very Annoying The interference is very annoying, making it hard to concentrate	Unbearable The interference is uncomfortable and intolerable, even for a short time

How would you rate the usability of a phone with this amount of noise?

1	2	3	4
Highly Usable I would use this phone for almost any voice call	Minor Limitations on Use I would use this phone for most voice calls, but it is not ideal	Major Limitations on Use I would use this phone for a few voice calls, “in a pinch”	Not Usable I would not use this phone for any voice calls

Figure 7

10) *WD noise S/N judgments:* S/N judgments for the three category ratings for each of six WD noise types were then obtained, along with subjective noise and usability ratings for each judgment. The order of the noises presented, whether they were presented first at a high or a low (off) level, and the order of the requested category judgments were all randomized among the test subjects. Testing was for a total of six noise types, which was considered, in addition to all the other aspects of the test, to be the endurance limit for the subjects.
11) *Objective noise threshold:* For each noise type, the audibility threshold in the presence of speech was determined. The tester, instead of the subject, adjusted the control box Noise knob up and down while the subject indicated audibility or non-audibility by hand movements. The test was repeated sufficient times (typically about 4 reversals) to obtain a reasonable consistency in judgment. The threshold was taken as the average of the upwards-moving and downwards-moving thresholds.

Step-by-Step Test Procedure – In-ear Recordings

12) *In-ear level match recordings:* Except for the initial twelve subjects, an Etymotic Research ER-7C probe microphone was used to obtain three recordings comparing speech spectral levels of 1) in-canal hearing aid reproduction of the acoustic reference speech and 2) in-canal hearing aid reproduction of magnetically coupled speech at the previously determined magnetic matching level, and 3) acoustic pickup near the hearing aid microphone. For this last test, the hearing aid was left in the telecoil position (or turned off) so as to avoid acoustic leakage from the output of a powerful hearing aid.

4. TEST RESULTS

Subject Data – Review of Intake Questionnaires

These results will need to await more detailed review of the intake questionnaires. For now, it can be said that the test population was skewed towards those with severe or profound hearing loss. These people are more actively engaged in the hard-of-hearing community and are more readily recruitable. They do represent many of those who could most use effective telecoil coupling.

A total of 57 subjects completed the testing. By also testing the hearing aids of additional subjects who did not undergo the complete testing and the spare or opposite-ear aids of those who did, telecoil orientation data was obtained on a total of 69 hearing aids. Of this total, 66 were BTE (behind-the-ear) and only 3 were ITE (in-the-ear). This emphasis on the larger and generally stronger BTE aids rather than ITE was reflective of the needs of the subject population.

Telecoil Orientation

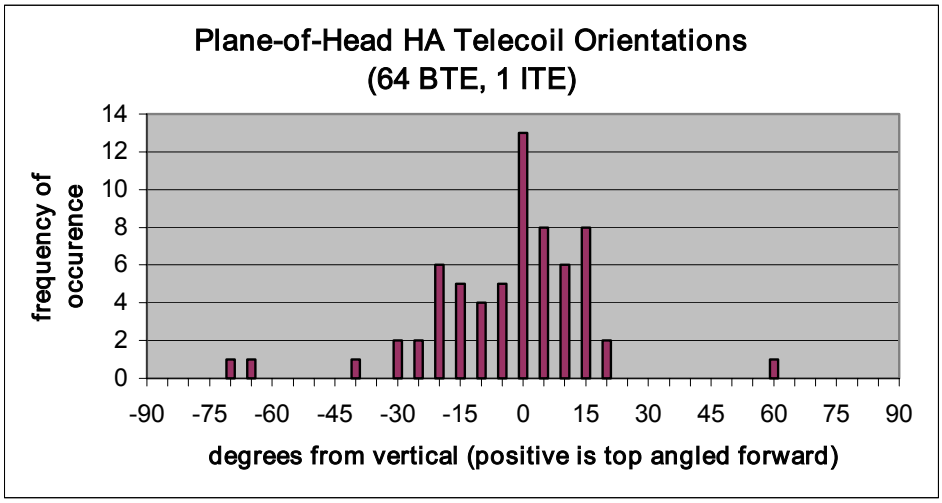
Of the 57 subjects tested, the best-choice magnetic hats for their aids were:

- The transverse hat (radial 1; field 25° forward from vertical): 53 aids
- The perpendicular hat (axial; field in and out of the side of the head): 3 aids
- The longitudinal hat (radial 2; field 25° down from horizontal): 1 aid

The perpendicular hat use was for two of the ITE aids and one of the BTE aids, although the alignment was not exact for either of the ITE aids. The longitudinal hat was used for one of the BTE aids, although, again, alignment was not exact. The transverse hat use included the remaining ITE aid (with inexact alignment) and all the BTE aids except the two mentioned. While the BTE aids showed an almost uniform compatibility with the transverse field orientation, it was not possible to draw any general conclusions about the orientation of ITE telecoils, due to the small number of ITE aids available for testing.

Of the total of 69 aids measured, 65 had orientations in the plane of the side of the head at some angle from the vertical; that is, in a radial, not axial orientation relative to a telephone handset per figure 3. The upper graph of figure 8 shows a histogram of these radial angles measured with reference to a vertical orientation, in 5° increments. The lower graph shows the approximate telecoil sensitivity relative to perfect alignment with a transverse or longitudinal source field. It is clear that the vast majority of these telecoils are covered well by a transverse source field. Only a couple of aids respond primarily to a longitudinal field. As an additional consideration, it should be kept in mind that the greatest compatibility

with room loop systems is obtained with vertically oriented telecoils. The vast majority of these aids satisfy that preference. In practice, of course, all magnetic sources produce all orientations of field somewhere in surrounding positions, albeit with differing relative strengths.



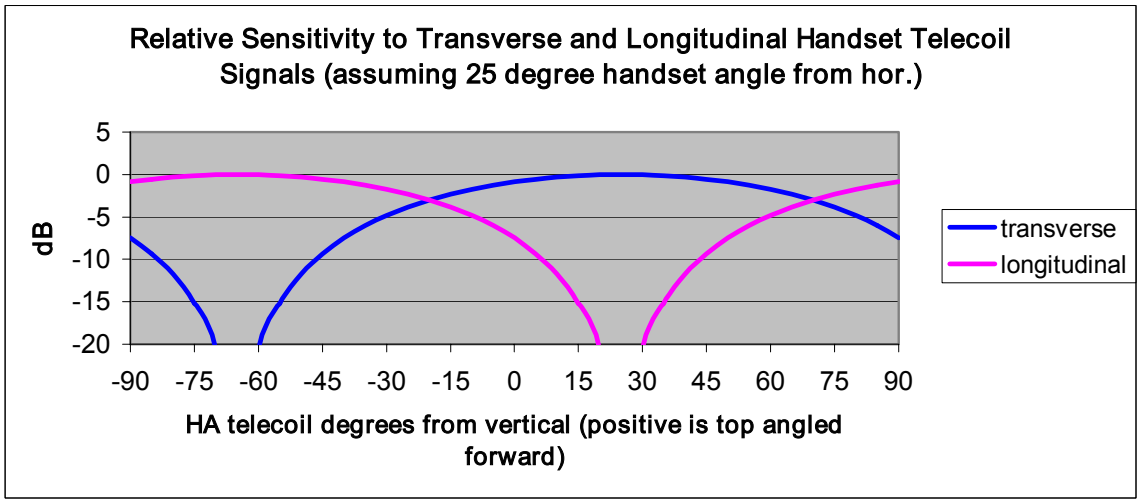


Figure 8

Magnetic Levels

After first finding the level of magnetic speech signal that matched a 65 dB-SPL acoustic speech signal for their hearing aid, the subjects selected their preferred magnetic most comfortable level (MCL). First looking at the relationship of the MCL to the 65 dB-SPL matching level, the histogram of figure 9 (1.25 dB step increments) clearly shows that the subjects' MCL preferences did not stray far from their 65 dB-SPL matching levels. Many stayed with their matching level, even by the third opportunity to reconsider. In other words, the subjects generally preferred to listen through their telecoil at the same speech level they would hear from a 65 dB-SPL acoustic speech source through their hearing aid microphone.

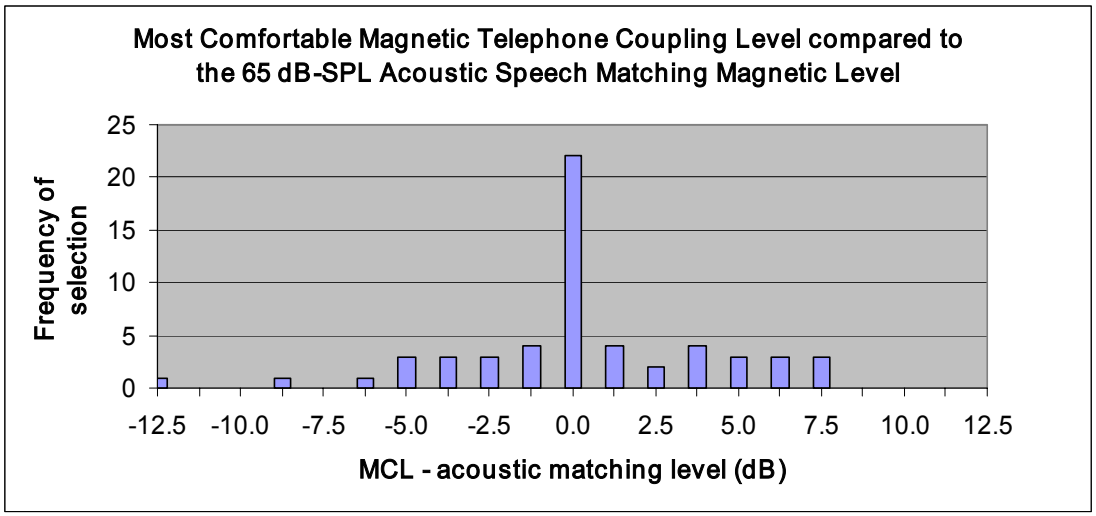


Figure 9

The most notable outlier, at -12.5 dB, came from the test subject who required the second strongest magnetic signal to match 65 dB-SPL, a level that might well have resulted in magnetic input overload of their hearing aid. Reducing the magnetic signal well below that level apparently resulted in a more "comfortable" level (perhaps less distorted). The high magnetic matching level for that subject's aid was, surprisingly, not unique.

That there would be a very wide range of 65 dB-SPL matching level results became evident during the first round of testing. This was not expected, since, as discussed, national and international standards do suggest or require an equivalency between 65 dB-SPL and -25 dB(A/m) at specified mid-band frequencies. Figure 10 shows the speech level test results for all 57 test subjects presented in order of increasing matching level. For each subject, the graph shows how far the MCL is above (white bars) or below (black bars) the matching level and the range (minimum to maximum) of acceptable magnetic levels.

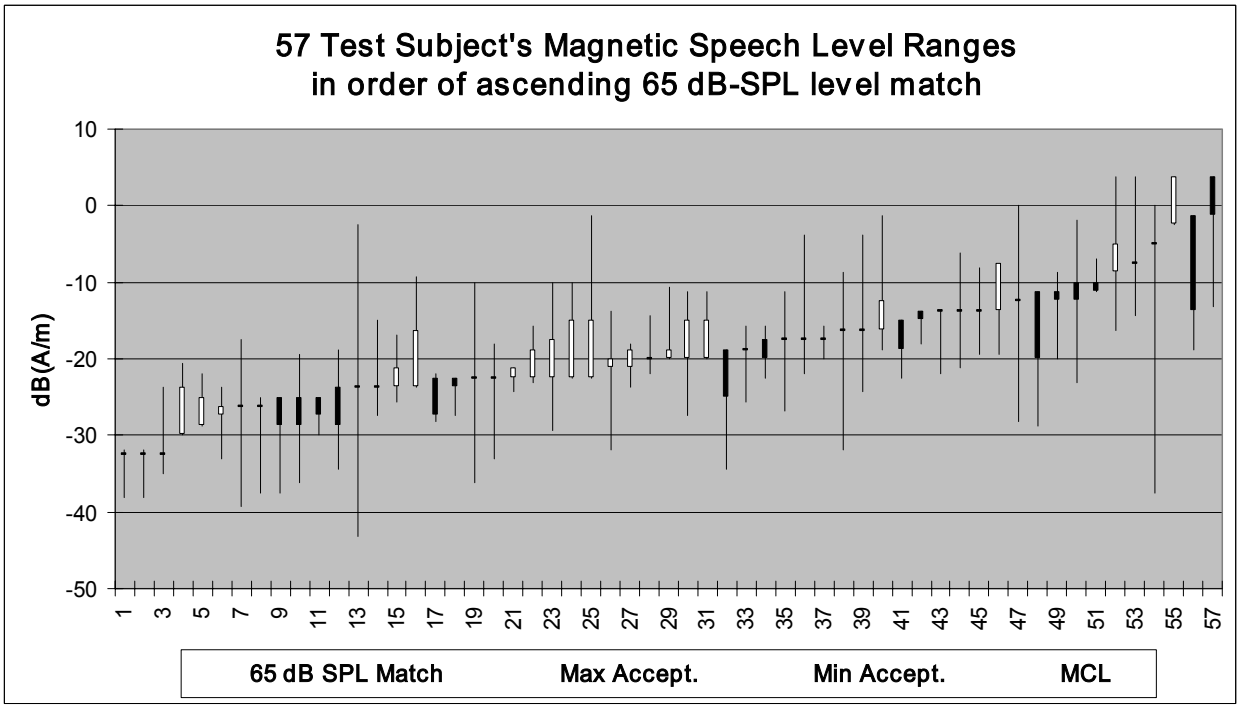


Figure 10

As noted, the subjects' MCL preferences hover near their matching levels. There also appears to be considerable differences among the tolerances of individuals to deviation from the matching level or MCL, as represented by their minimum and maximum acceptable levels. These results are not so surprising, but the wide range of matching level and resultant MCL would appear to indicate the potential for significant user problems in the field. Only about one-half of the subjects reported a matching level within +/-5 dB of the preferred -25 dB(A/m) and only about one-third of them reported an MCL within that range. 60% preferred a level over -20 dB(A/m), while 11% preferred more than -10 dB(A/m). The higher level needs among these are considerably above the field strengths commonly available from many sources, such as landline telephones and room loops. The highest of these levels could likely overload the magnetic input circuitry of many hearing aids, keeping in mind that these are average speech levels, with peaks 10-15 dB higher. The highest reported levels of +3.75 dB(A/m) were, in fact, the highest available from the test setup. It was felt prior to testing that such field strength would exceed any conceivable testing need.

Sufficient volume control adjustment range may enable many of the magnetically insensitive aids to be useable in practice. However, the evident imbalance between magnetic and acoustic sensitivity could be expected to represent, at the least, a nuisance to the user. In many cases, it could be expected to preclude usability.

A few of the odd level results may be explainable by the contrast of the monaural telecoil response to the combined effects of the subjects' two aids (which included in one instance a bone conduction aid) in responding to the 65 dB-SPL acoustic reference. Early telecoil input limiting or clipping by the hearing aids may have contributed to some of the very high matching level judgments. It appears doubtful that these possibilities could result in a full explanation, though. A further analysis of the in-ear recordings and a cross-comparison to the intake questionnaire information will hopefully provide more insight. The general question of in-the-field telecoil performance is worthy of a complete study unto itself.

In any case, it is not reasonable to use the apparent extremely high magnetic field needs of some hearing aids as a basis for requiring comparably high field strengths from wireless communication devices. The more relevant result from this study to the WD standards process is that users prefer magnetically coupled speech at essentially the same level as typical 65 dB-SPL acoustically coupled speech. Extant standards already place that level at -25 dB(A/m) at mid-band frequencies for individual hearing aids. Requiring this sort of level, with some additional margin for weak signals and perhaps monaural vs. binaural listening, seems to be a logical conclusion.

Signal-to-Noise Ratings

The S/N ratio for a category judgment was calculated as the ratio of a subject's MCL (the level at which they were hearing the speech) to their selected noise level (the maximum that they considered acceptable for that category rating). Considerable subject-to-subject variation in these boundary judgments was apparent. Displaying the results as a cumulative distribution visually smoothes this variability. Figures 11a, b, and c show the results plotted this way for the "excellent performance, "normal use", and "useable" categories, respectively. (It should be noted that results for individual subjects are not vertically aligned on the graphs. The cumulative distribution of each noise type for each category rating is calculated independently.)

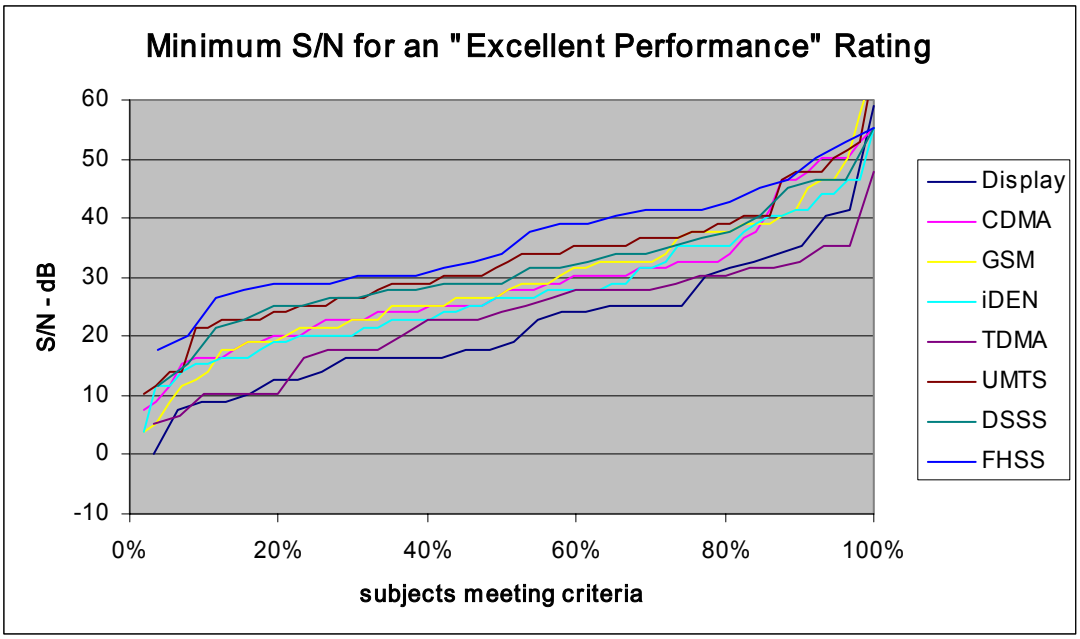


Figure 11a

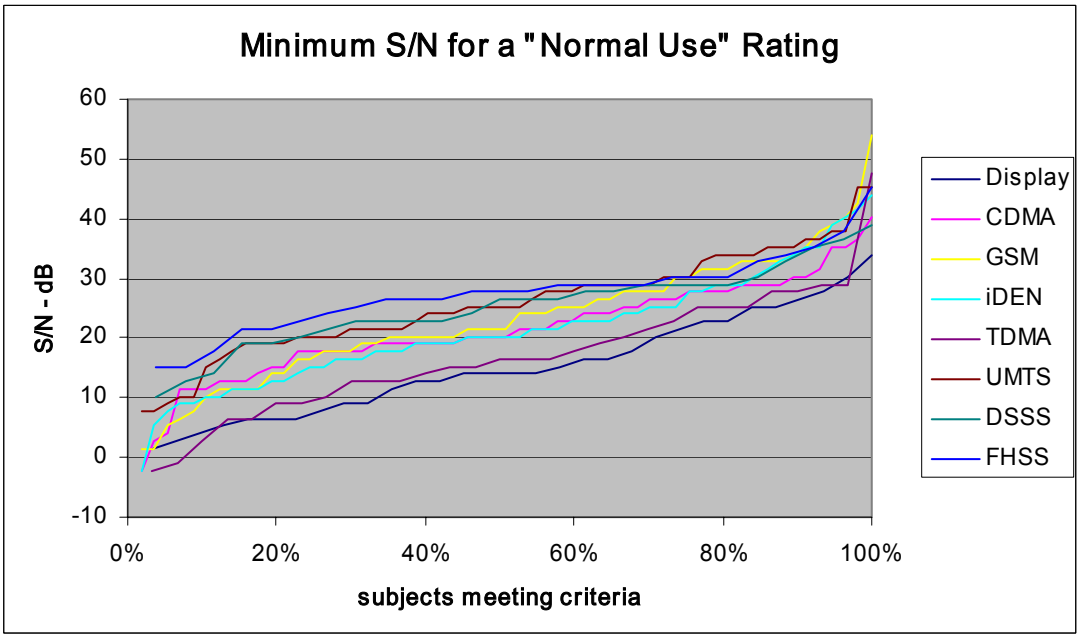


Figure 11b

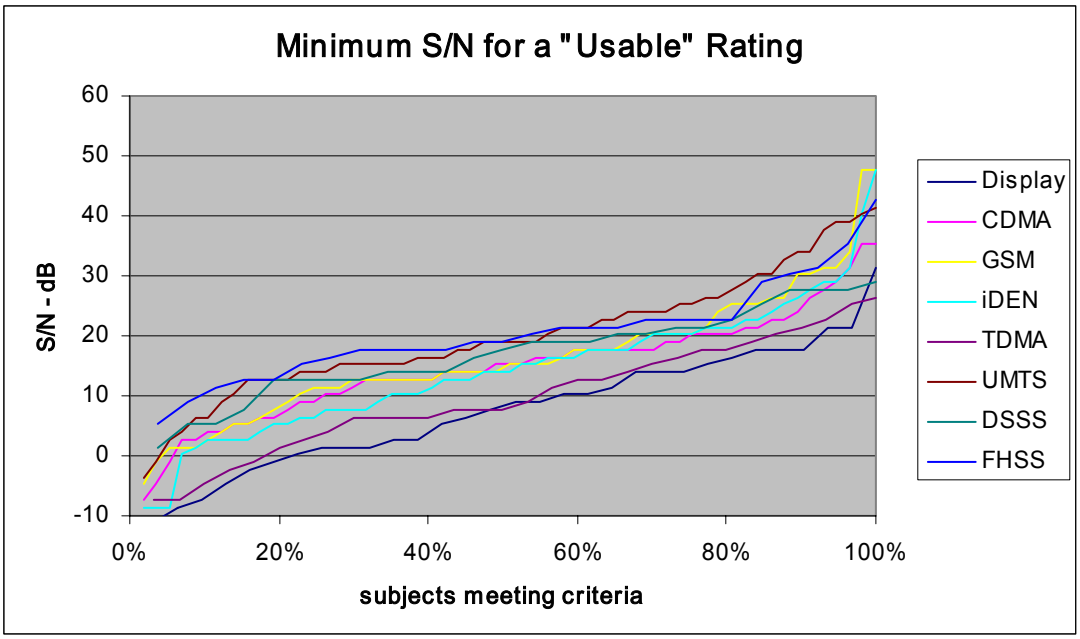


Figure 11c

It is immediately evident that the subjects showed a wide variation in their noise tolerance, apparently ranging from some “excellent performance” S/N ratios of over 60 dB all the way down to some negative “useable” S/N ratios. The further information of figure 12 can explain most of this variation.

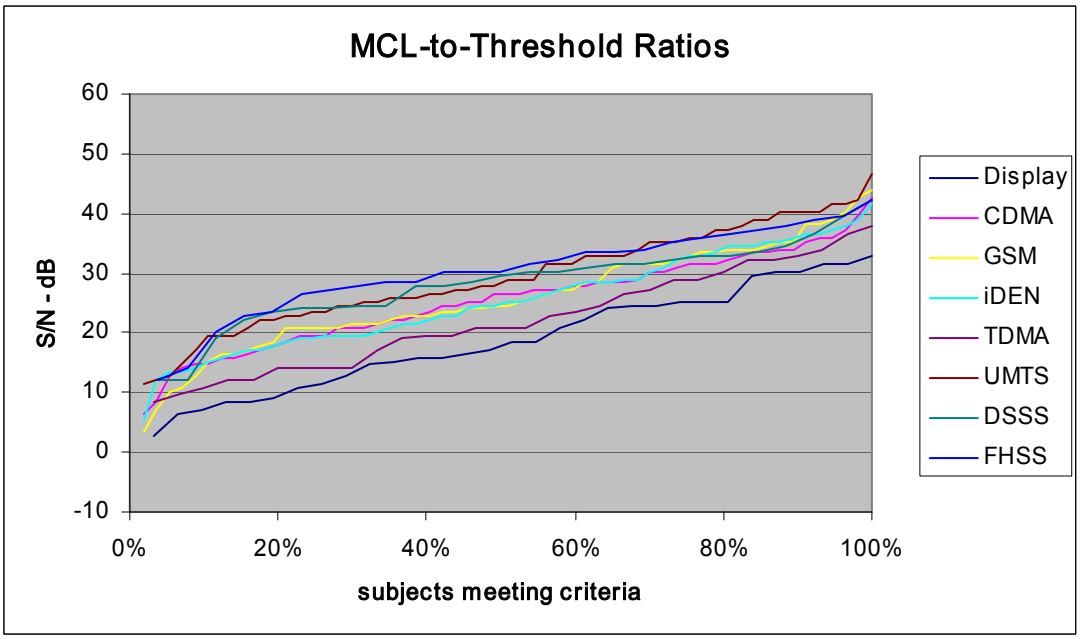


Figure 12

Shown here are the ratios of the subjects’ MCL’s to their objectively determined noise audibility thresholds, i.e., the highest S/N ratios that they can detect. A comparison to particularly the “excellent performance” curves of figure 11a shows that some of the subjects indicated that they “required” S/N ratios greatly in excess of their objective noise threshold S/N ratios. For whatever reason, they felt they needed to turn the “noise” knob down far below their objective threshold. The relevance of those judgments needs to be discounted in the analysis, although it is evident that to justify an “excellent

performance" rating, most subjects did not want to hear any noise. On average for the noise types, a measured S/N ratio of about 14 dB was needed for 50% of the subjects to give a "useable" rating. For 50% of the subjects to give a "normal use" rating, about 20 dB S/N was needed. Taking the "excellent performance" rating from the noise threshold S/N curves in order to discount the extreme outliers, about 24 dB S/N was needed to reach the 50th percentile. For 80% of the subjects to approve, all these ratios needed to raise about 9 dB. These numbers are in good general agreement with prior studies [2, 3, 4].

While the trends for the various noise types are similar to each other, both in the shape of the distribution curves and the relative S/N differences between category ratings, significant differences in absolute S/N ratio among the noise types are apparent. (This difference is best judged by comparing the results around the 80th-90th percentile ratings, where more test subjects are included than at lower percentiles, but the outliers mainly above the 90th percentile are not.) It would be wrong, though, to conclude from this that some noise types are inherently "worse" or more annoying than others. The fact that the various noise types do not all show the same measured S/N needs indicates that the present noise measurement method, consisting of taking the average A-weighted noise level picked up by the telecoil, does not yield a complete picture of noise acceptability. For example, the noise measurement relatively underestimates the annoyance of the FHSS cordless type and the UMTS cellphone type, making it appear that higher S/N is needed for those noises, and overestimates that of TDMA and display noise, making it appear that those noises are more tolerable. While A-weighting may be a good first step towards the proper subjective level modifier, it does not appear to be the final answer. If the ideal noise measurement parameters could be found that accurately modeled noise annoyance and audibility, all the noise types, including future ones, could be expected to exhibit identical S/N requirements. Finding such a noise measurement method is an area of ongoing investigation.

Relationship of Noise Tolerance to Noise Audibility Threshold

It is evident, though, that the subjects showed a wide variation in their tolerance to each noise type. This can be largely explained through comparison to their objective noise-in-speech thresholds for the noise types. Further analysis of the results shows that the noise judgments for the various category ratings for a given noise type are directly related to the subjects' noise audibility thresholds for that noise type, but importantly, not to any other evident characteristic of the noise type or, surprisingly, to the subjects' hearing dynamic ranges to any significant degree (as represented by their MCL-to-threshold ratios). In relation to the objective noise thresholds, there is no significant difference among the noise types, no matter how their levels are measured.

This can be clearly seen by re-visiting the "normal use" cumulative distribution graph for example, but now plotting in terms of the ratio of the rated category noise level to the objective noise threshold for each noise type for each subject. This is done in Figure 13, again plotted as individual noise type cumulative distributions. (The responses of a few subjects who placed their "requirements" well below their objective noise threshold are in evidence at the far left end of the plotted curves.) As can be seen, any differences among the noise types are quite small, especially in comparison to the overall range of values. Similar results can be plotted for the other category ratings.

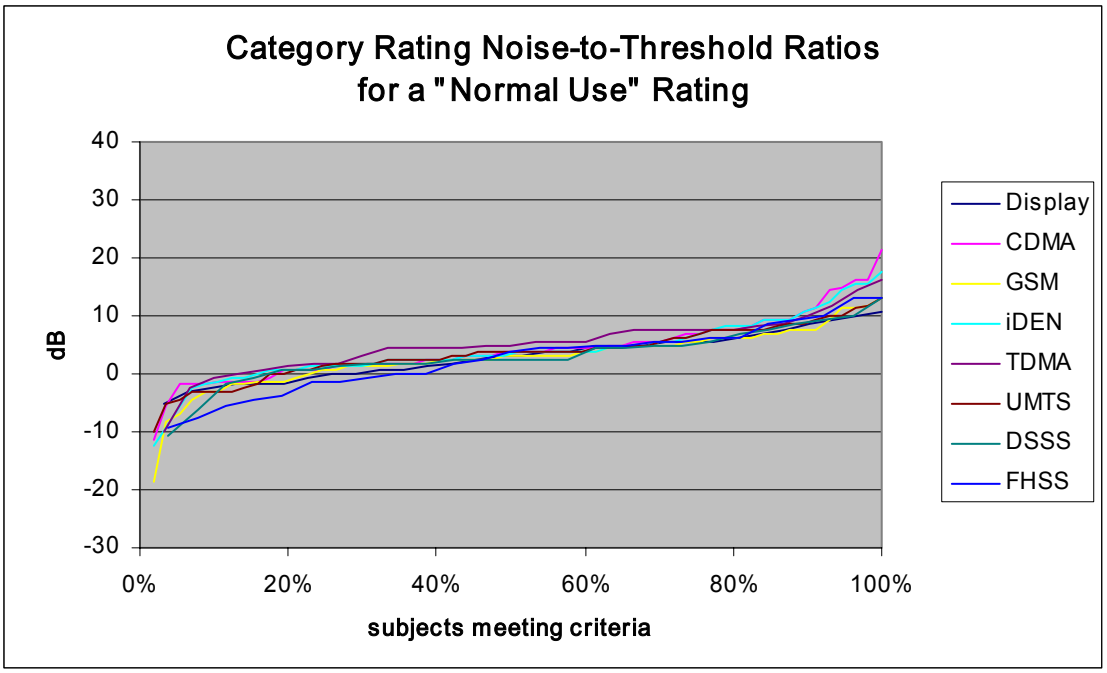


Figure 13

That the ratios of a category rating noise levels-to-objective noise threshold for each noise type shows little, if any relationship to the subject's hearing dynamic range can be seen by plotting these individual ratios ordered by their dynamic range (MCL-to-threshold ratio). This is shown in Figure 14 for the CDMA noise type. (The responses of subjects who placed their "requirements" well below their objective noise threshold are again clearly evident in this graph, especially for the "excellent performance" category.) The noise judgment ratios show no relationship to the left-to-right increase in hearing dynamic range. The slopes of the linear trend lines for the noise ratios are near zero, suggesting little if any relationship to the sloping MCL trend. The corresponding graphs for the other noise types are similar.

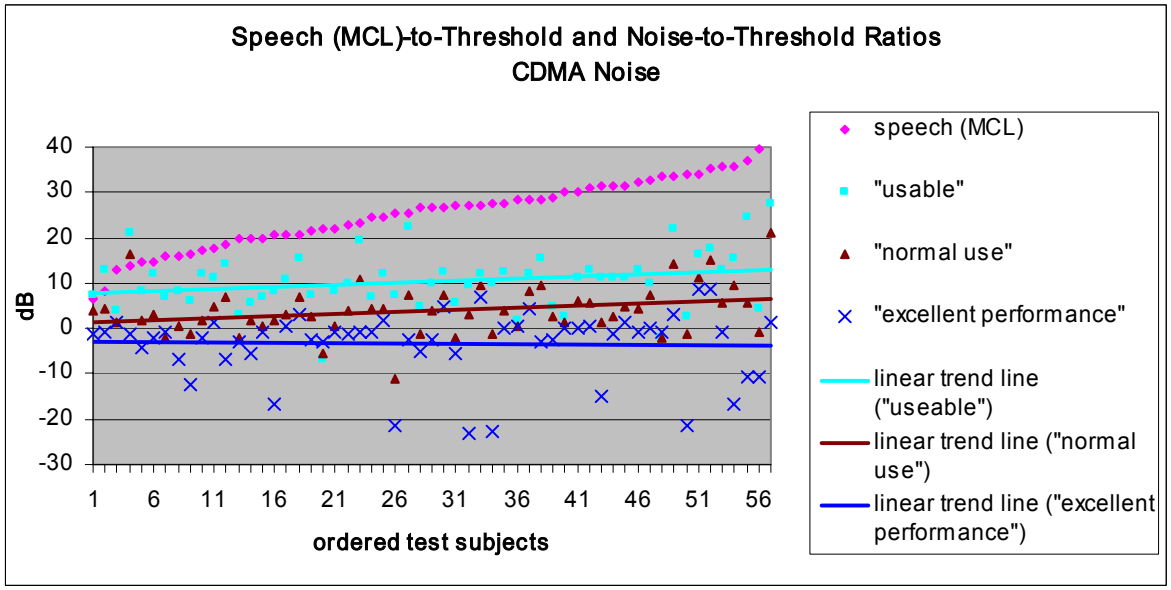


Figure 14

To illustrate the independence of the category rating noise-to-threshold ratios from noise type, Figures 15a and 15b present histograms of these ratios, along with the MCL-to-threshold ratios, for two representative noise types. Allowing for the relatively small numbers of data points, the results are very similar for the two distinctly different noise types, even in the midst of significant subject variability. The corresponding graphs for the other noise types are also very similar.

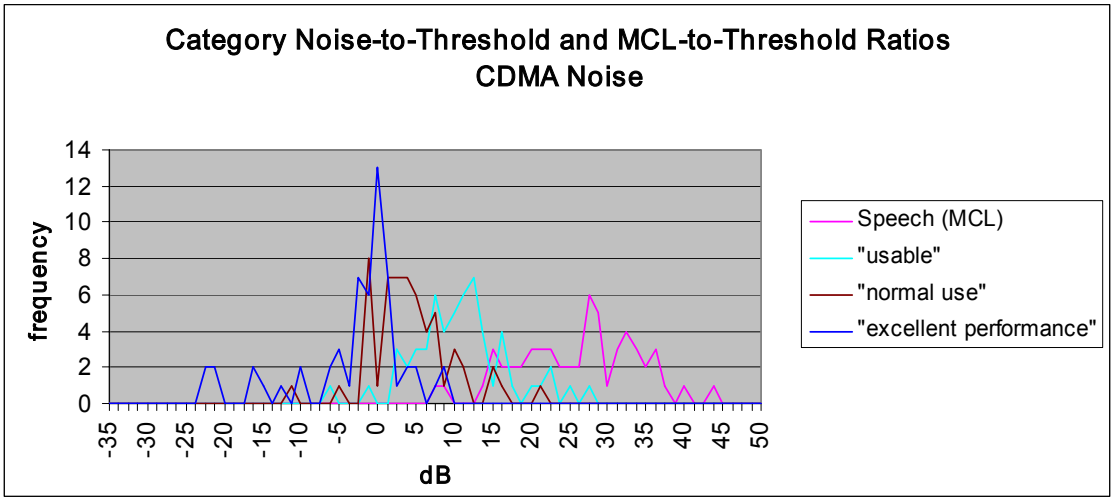


Figure 15a

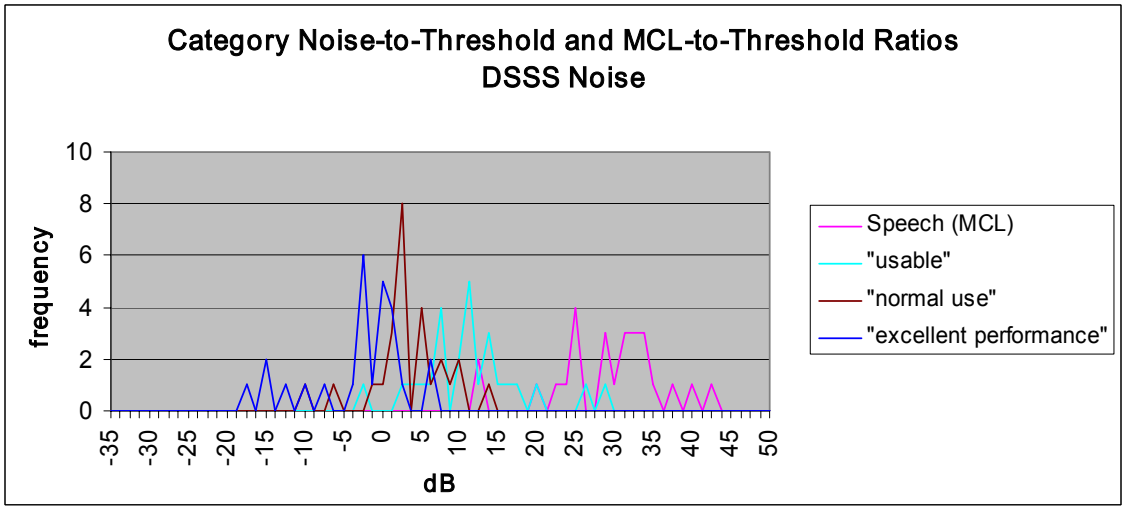


Figure 15b

The similarity among noise types is further emphasized when the ratios for all eight noise types are combined, as shown in Figure 16. In comparison to the individual noise type histograms, the data does not become more dispersed, but simply becomes smoother and more “bell-like” in place, further illustrating the uniformity among noise types. The histogram curves are matched in the graphs with best-fit normal distribution curves. These latter curves discount the influence of the extreme negative outlier data points that are far below objective threshold.

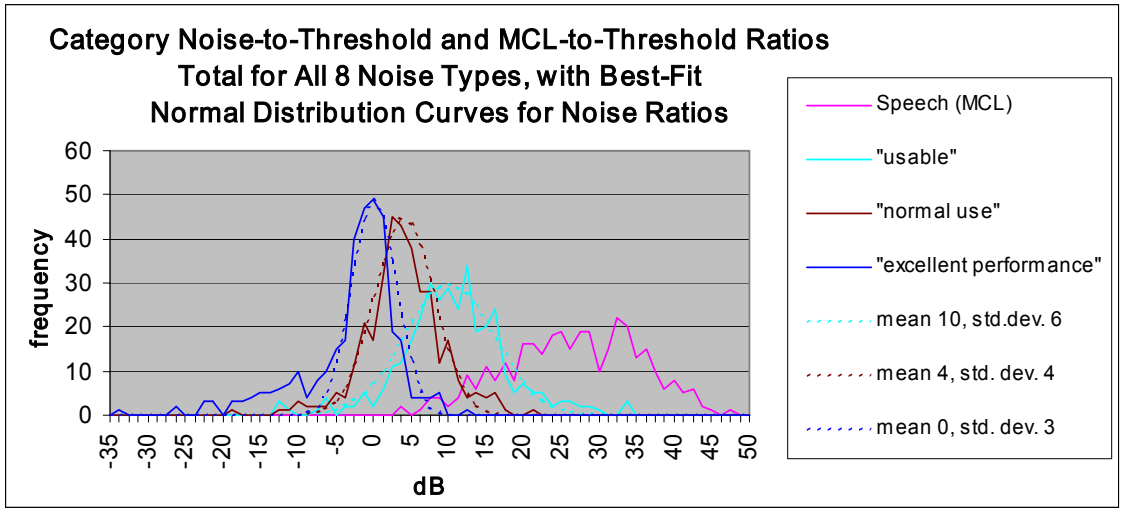


Figure 16

The best-fit curves show that for “excellent performance”, the mean judgment was at the subjects’ noise thresholds (ratio of 0 dB), with a standard deviation of 3 dB. A reasonable interpretation of this result is that for this category judgment, the subjects do not want to hear any noise. The width of the distribution curve is reasonably attributable to the repeatability and consistency of the individual noise category and noise threshold judgments. The mean ratio of the best-fit normal curve for the “normal use” category was +4 dB, with a standard deviation of 4 dB. The average subject would accept noise 4 dB above their noise threshold for this rating. For the “useable” category, the mean was 10 dB above threshold with a standard deviation of 6 dB.

Figure 17 is another illustration of the consistency among noise types of the means and standard deviations of the noise category boundary ratings relative to noise threshold. There is significant variation among the MCL to threshold ratios, reflecting the incompleteness of the A-weighted noise measurement to fully characterize the audibility of the noise. The category rating noise-to-threshold ratio averages reveal little significant differences among the noise types, especially considering the limited number of test subjects represented. The final “best fit” column is based on the best-fit normal distribution curves of the previous figure and shows the effect of discounting the outliers. The conclusion to be drawn from this analysis is that the acceptability of the WD noise types in the presence of speech is related to their audibility, rather than some other characteristic of the noise that may make it more or less objectionable, or to the subjects’ hearing dynamic range.

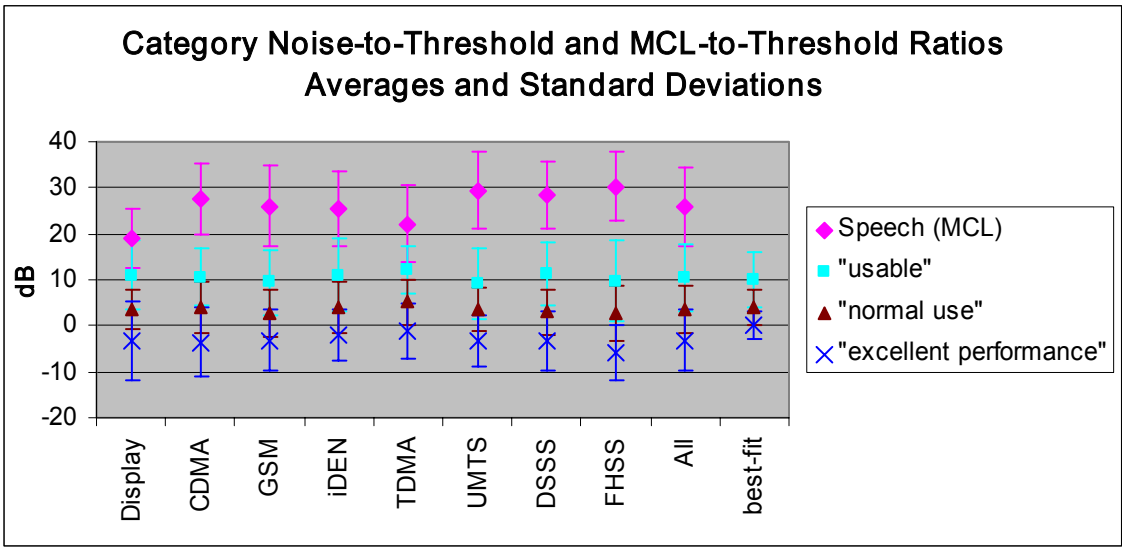


Figure 17

5. CONCLUSIONS

In-the-Field Hearing Aid Telecoil Sensitivity

The initial goals of this study were to characterize the telecoil mode magnetic signal strength and orientation requirements of hearing aids and subjective S/N requirements of the users. While these goals were largely met, inevitably additional questions arose. Perhaps most significantly, on the basis of these subjective tests, it was found that in-the-field adjustment of hearing aid telecoil sensitivity in relation to acoustic sensitivity appears to vary over a 30 dB range. Some possible contributors to this apparent variability were discussed. Better understanding of these results may come with further analysis of the in-ear recordings and intake questionnaire information. The evident initial implication, though, is that there is a field problem that needs to be addressed.

Preferred Magnetic Listening Level

In contrast, the preferred Most Comfortable Level for telecoil mode speech showed a perhaps surprising degree of consistency in relation to the hearing aid acoustic sensitivity. The subjects preferred to listen to telecoil mode WD speech at the same level that they judged equivalent to typical 65 dB-SPL acoustic speech. The variation from this preference was small. Based on this information, the best guideline for required magnetic source signal strength, then, is the implied or required standards of ANSI S3.22-1996 and IEC 60118-1, which equate a 65 dB-SPL microphone input to -25 dB(A/m). A magnetic source should be able to provide at least this average speech level, with some additional margin for weak signals and perhaps loss of subjective level due to monaural rather than binaural listening. These considerations justified the selection of -18 dB(A/m) as the minimum speech level requirement of C63.19. Such a level should prove adequate for the majority of hearing aids, but not for some aids with very low telecoil sensitivity.

Telecoil Orientation

This study must be regarded as incomplete in its survey of hearing aid telecoil orientations. Due to the nature of the subject population, only 3 of the 69 hearing aids tested for telecoil orientation were ITE. Of the BTE aids, the overwhelming majority exhibited an approximately vertical orientation when positioned on the ear. This orientation responds to a radial component of the field from a typical WD receiver, most closely aligning with the “transverse” orientation, relative to the handset (parallel to the top of the handset). The importance of adequate field strength in directions other than the axial is evident, especially if the user is not to be required to hold the handset at odd angles around their ear. From the hearing aid’s perspective, there is not a justification for different level requirements for axial and radial source orientations.

Acceptable Signal-to-Noise Ratios
The results for acceptable S/N ratio are in general agreement with previous studies. For this study, the speech level was the average level measured per ITU-T P.56 and the noise level was the A-weighted, telecoil response level. On average, about 20 dB S/N ratio was needed to provide 50% of the subjects with a "normal use" experience, a rating that did allow for some audible noise. 30 dB S/N ratio provided about 85% of the subjects with this level of satisfaction. About 4 dB higher S/N ratio was needed for the same percentile results for the "excellent performance" rating, or about 6 dB lower for the "useable" rating.

There was a spread in these required S/N ratios of about 8-10 dB among the various noise types, though. This is an indication that calculating the noise level through simple A-weighting does not yield a complete picture of noise acceptability for the subject population. An accurate predictor function would give the same results for all noise types. Continuing investigation may find such a predictor.

Noise Tolerance vs. Noise Audibility Threshold
Further analysis of the data did show that noise acceptability was consistently related to noise audibility threshold. This result was independent of both noise type and, surprisingly, the hearing dynamic range of the subject. (It was also independent of noise measurement method, since it was a noise-to-noise comparison.) On average, the subjects required the noise to be at their noise audibility threshold (measured in the presence of speech) for a rating of "excellent performance", 4 dB above that threshold for a rating of "normal use" and 10 dB above it for a rating of "useable". In other words, the acceptability of WD noises in the presence of speech is dependent on the audibility of the noise, rather than, for example, a more subjective judgment of its objectionability. Recognition of this should simplify the search for an improved acceptability predictor, since the sole parameter of concern is audibility.

Extension to Non-Magnetically Coupled Interference
While this research has been directed towards magnetically coupled audio frequency interference from WD's, there is nothing in the methodology that prevents the applicability of the results to radio frequency interference (RFI). While the display noise type is not relevant to RFI, all the RF envelope-related interferences are. When such interferences are picked up magnetically from audio frequency currents generated in the WD RF output stage, the response from the telecoil exhibits typically a 6 dB/octave rolloff below about 1 kHz compared to the RF envelope spectrum and some high frequency rolloff due presumably to local RF output stage supply filtering. These rolloffs are not present with RFI, except somewhat for the low frequency rolloff if the RF pickup is in the telecoil circuitry. Therefore, the particular results for a given noise type might vary somewhat between audio frequency magnetic pickup and RFI-induced pickup, but an accurate predictor function will be equally applicable to any such noises and will take into account any response differences.

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7. ACKNOWLEDGEMENTS

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8. APPENDIX: TELECOIL MODE THEORY OF OPERATION

An overview of telecoil operation is helpful for understanding the test procedure and interpreting the results. Ross [8] reviews the development of telecoils dating from the description by Sam Lyberger in 1947 of how the leakage magnetic field from telephone receivers then extant could be put to use to improve hearing aid telephone performance. Ross also describes the development of American standards in the area and the important extension beyond telephone use to such applications as room loops. The motivation for magnetic coupling through a telecoil is two fold: 1) to provide a strong, clear audio input while reducing the competing ambient noise and reverberation, and 2) to eliminate acoustic feedback that occurs when sound leaking from around the earmold or hearing aid case is trapped by the handset and couples back to the hearing aid microphone, creating an acoustic feedback loop resulting in a high pitched whistle. Each of these problems can reduce the utility of the hearing aid microphone for telephone listening.

Source Frequency Response

The requirement for landline phone magnetic frequency response is defined in EIA RS-504 and FCC Part 68.316 by the mask re-plotted in Fig. 1. This mask logically modeled the performance of telephone receivers in use at the time of the EIA standard's development, specifically the Western Electric U-series receiver. Viewed from an electrical perspective, the mask is most typically met by a signal voltage source driving a magnetic source inductor with some equivalent series resistance. A typical example of the response from such a source is also shown in Fig. 18, where the inductive reactance of the magnetic source is made equal to the equivalent series resistance at a crossover frequency of 1,370 Hz. This source frequency response was applied to the magnetic speech signal sources employed in this study.

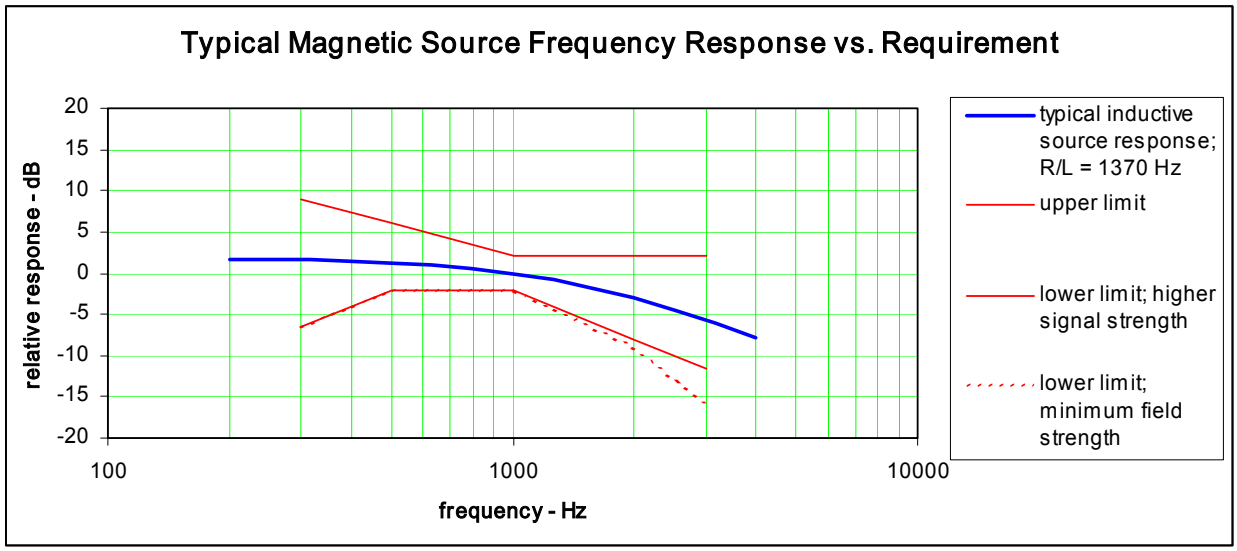

Figure 18

Fig. 18 shows two slightly different high frequency response allowances, depending on the measured 1 kHz magnetic field strength. Except for the specific field strengths specified in Part 68, the Fig. 18 mask is carried over to ANSI C63.19 and TIA-1083. It should be noted that the response graphs don't appear the same in all the documents, even though they are equivalent. ANSI C63.19 plots the field strength as in figure 1 above, directly in dB relative to 1 A/m (0 dB(A/m)), where A/m (Amps/meter) is a measurement of the magnetic field intensity. The earlier landline documents and TIA-1083 plot the magnetic field strength by reference to the output of an unloaded probe coil. Such a coil produces an output voltage that is proportional to the rate of change of the magnetic field intensity, not the field intensity itself. Relative to a direct field intensity measurement, this results in a 6 dB/octave rising response throughout the frequency range.

Telecoil Frequency Response

The relevant hearing aid standards (ANSI 3.22-1996 and IEC 60118-1) do not directly address frequency response in the telecoil mode of operation. However, it is possible to infer a consensus from known hearing aid and telecoil design directions, the published frequency responses of hearing aid components known as amplified telecoils, and the response that works well in complementing the prescribed source response. This inferred telecoil response is not that of the unloaded probe coil, but rather of a typical telecoil component operating into a current-sensing virtual ground amplifier input. A typical such response is shown in Fig. 19, where the crossover from a rate-of-change response at the low frequencies to a field magnitude-proportional response at the high frequencies occurs at 1 kHz. This typical telecoil response is codified in ANSI C63.19 and TIA-1083 for broadband magnetic noise measurement through the application of a "half-band integrator" to the output of an unloaded probe coil. In actual hearing aid use, a telecoil response such as this would be further modified by processing specific to an individual's hearing loss.

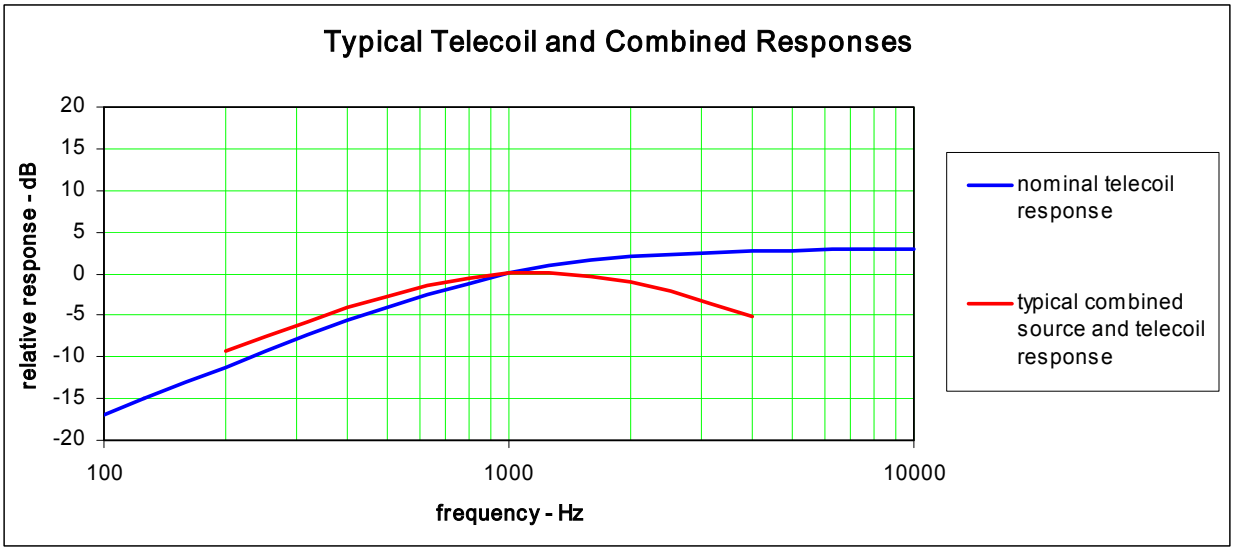

Figure 19

Net Telecoil Mode Frequency Response

The net response that results when a source with the typical frequency response of Fig. 18 is combined with the standard typical telecoil frequency response of Fig. 19 is also shown in the latter figure. This clearly illustrates that the combination of two apparently non-flat responses results in a net response that is reasonably flat throughout the telephone voice-band.

Field Orientation

The magnetic field is a vector quantity, which means that not only is the distance from the source to the telecoil important in determining the transmission effectiveness, but also the orientation of the telecoil

relative to the source field. EIA RS-504 and FCC Part 68.316 specify an array of positions and orientations at which the magnetic source must be measured. Fig. 20, taken from those standards, indicates a central "axial" position located over the center of the telephone receiver (the presumed source of the magnetic field), oriented in a direction perpendicular to the plane of the handset, and four "radial" positions on a 3.2 cm diameter circle surrounding the axial location, oriented parallel to the plane of the handset. As in the case of the standards' frequency response mask, this pattern was defined in a way that described the field produced by landline handset receivers of that time.

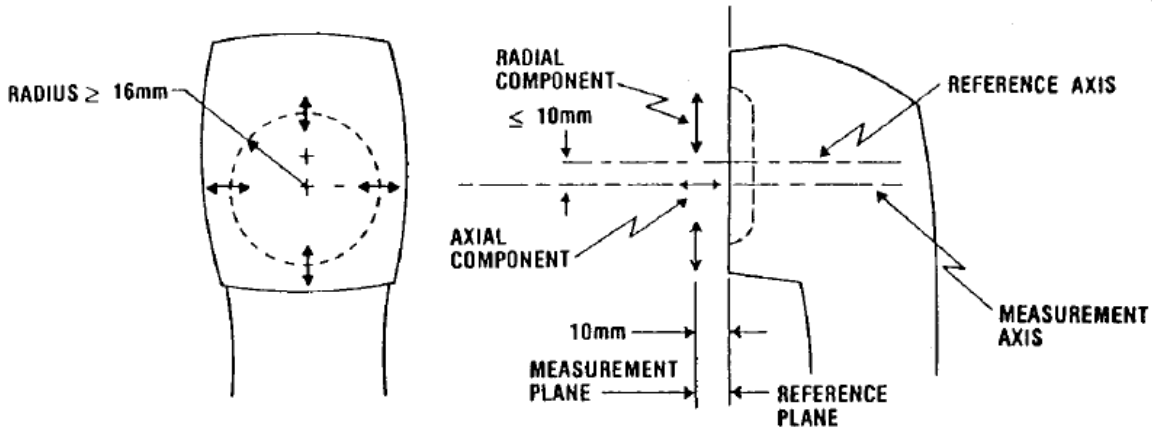

FIG 1 REFERENCE AND MEASUREMENT PLANES AND AXES

Figure 20 (from FCC Part 68.316)

The field strength produced by a handset at the various orientations is important because hearing aids are produced with differing orientations for their telecoils. The degree of magnetic coupling achieved depends on how closely the orientation of a telecoil aligns with the lines of the incident magnetic field. The coupling is proportional to the cosine of the angle of misalignment. When the alignment is perfect, the linkage is at a maximum. A 45 degree misalignment results in only a 3 dB loss compared to the maximum coupling, so the alignment does not need to be perfect, but the coupling rapidly deteriorates with larger misalignment. There is a 6 dB loss at 60 degree misalignment. At 90 degrees, the coupling is lost. As is shown by this study, the vast majority of behind-the-ear (BTE) hearing aids have telecoils positioned such that the maximum pickup orientation is vertical in use, which is optimum for room loop systems. In-the-ear hearing aids, however, appear to show much greater variation in their telecoil orientation. It is evidently not always practical to control or document this parameter in the semi-custom production of ITE aids.

ANSI C63.19 and TIA-1083 depart from the earlier standards' axial-radial source array requirement in part because the smaller receivers that may be used cannot produce sufficient field strength at the widely separated radial locations. Recognizing that the more important aspect is the various orientations, not necessarily the specific designated locations, ANSI C63.19 requires field strength and S/N minimums to be met at each of three mutually perpendicular orientations ("axial" and two "radial"), but allows the locations for each of these orientations to be specified independently. For the purposes of this study, these orientations are referred to as 1) "perpendicular" to the face of the WD, 2) "transverse", parallel to the top edge of the WD, and 3) "longitudinal", parallel to the long dimension of the WD. TIA-1083 has requirements only for the perpendicular and transverse orientations.

Magnetic Field Strength

EIA RS-504 and FCC Part 68.316 specify minimum 1 kHz field strengths of -22 dB(A/m) and -27 dB(A/m) for the axial and radial orientations, respectively, for a specific test signal level that is approximately 15 dB above typical average speech levels that a landline phone would receive in the field. Referred to average speech levels then, the implied minimums are roughly -37 dB(A/m) and -42 dB(A/m). A differentiation in the level requirement was made between axial and radial orientations, presumably in deference to typical

receiver behavior, not because of any relation to telecoil needs. ANSI C63.19 does not differentiate between the orientations in specifying minimum field strength or S/N; nor does TIA-1083 in its S/N specification, except for the inclusion of a phase-in period before the transverse specification becomes a requirement.

Any requirement for signal field strength should be considered in relation to the range of ambient magnetic noises likely to be encountered, in addition to any magnetic noise that a WD may generate. An informal survey conducted by one of the authors [9] showed a range of A-weighted, telecoil response (as defined above) environmental magnetic noise levels from lows in the range of -60 dB(A/m) in a magnetically quiet domestic environment to roughly -45 dB(A/m) in various commercial and light industrial environments, and also at typical use distances from computer monitors. (These levels are 1 kHz equivalent levels, as described in section 2.) These ambient noise numbers suggest the advisability of providing higher magnetic signal strength than the minimum allowed by the landline standards. ANSI S3.22-1996 and IEC 60118-1 both suggest an equivalency in hearing aid sensitivity adjustment between a midband magnetic input of -25 dB(A/m) and an acoustic input of 65 dB-SPL, albeit stated at different levels. By this relationship, magnetic speech input near the landline phone requirement minimums correspond to acoustic levels of only about 50 dB-SPL, roughly 15 dB below normal expected speech levels. The Part 68 minimums were not directly carried over to ANSI C63.19.