Reflections on Amplification: Validation of Performance

David B. Hawkins
Walter Reed Army Medical Center
Washington, DC

The problems encountered in hearing aid selection and evaluation procedures are outlined with an emphasis on reliability and validity. The limitations of word recognition testing, aided sound-field thresholds, and quality judgments in a sound booth are discussed. Some suggestions for new directions are discussed which involve assessment under more realistic listening conditions, including noise, reverberation, visual cues, and continuous discourse. A proposal is suggested to include (a) LDL measurements that allow direct comparison to SSPL90 specifications, (b) quality and intelligibility judgments in a rapid paired-comparison technique using an acoustic valve, and (c) subjective user comments on communication needs and hearing aid benefit.

There are many unresolved issues in amplification for the hearing impaired. Perhaps the most glaring deficiency is in research to validate performance with hearing aids. Many studies have investigated such variables as frequency response and harmonic distortion, but few studies have gone the final step to assess their effects on real-world performance and user preferences.

Most investigators have collected their data in nonreverberant environments using a traditional word recognition paradigm. Although such research has value, such findings may not be relevant to real-world communication that includes visual cues, continuous discourse, noise, and reverberation. Consideration of these issues should affect the hearing aid selection, evaluation, and follow-up process. The purpose of this article is to present some thoughts and opinions concerning the problems of hearing aid fittings and some alternatives in the search for valid procedures. The focus will be upon procedures that are most applicable to the mildly, moderately, or severely hearing-impaired adult who is capable of making loudness, intelligibility, and quality judgments.

David B. Hawkins, Ph.D., is a Research Audiologist at the Army Audiology and Speech Center, Walter Reed Army Medical Center, in Washington, DC.

PRESENT HEARING AID SELECTION AND EVALUATION METHODS

Hearing aid frequency response is one important variable in hearing aid selection. There has been a renewed interest in the past 10 years in prescriptive methods for determining appropriate frequency response. Some of the methods mentioned most often are those described by Berger, Hagberg, and Rane (1977); Byrne and Tonisson (1976); Collins and Levitt (1980); Cox (1983); McCandless and Lyregaard (1983); and Skinner, Pascoe, Miller, and Popelka (1982). A comparison of these procedures to identify which one results in best speech intelligibility has not been done, and would be difficult to do, because of the lack of an accepted measure of real-world performance and success. As a first step, Schum, Hawkins, and Collins (1984) determined if different prescriptive methods yielded different gain and frequency response curves. Figure 1 shows the prescribed frequency response for the same hearing-impaired subject using seven different selection schemes. There is clearly a large amount of variability in what is predicted to produce optimal performance. Comparisons in terms of speech intelligibility have yet to be performed.

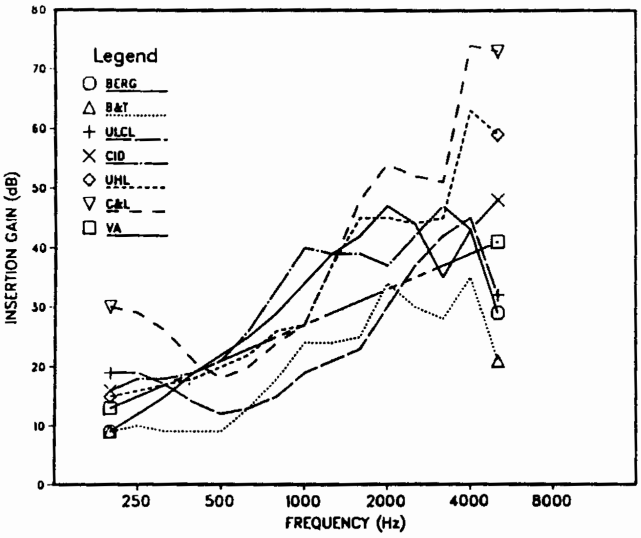

Figure 1. Frequency response/gain curves recommended by seven different selection strategies for one hearing-impaired adult. BERG = Berger, B&T = Byrne and Tonisson, ULCL = Upper Limit of Comfortable Loudness (Cox), CID = Central Institute for the Deaf (Skinner et al.), UHL = Uniform Hearing Level (Pascoe), C&L = Collins and Levitt, VA = Veterans Administration. (From Schum, Hawkins, & Collins, 1984).

Another important selection decision involves SSPL90. A common procedure is to measure loudness discomfort levels (LDLs) in dB HL under earphones, convert the values to dB SPL, and select a hearing aid whose SSPL90 on the hearing aid specification sheet is equal to or slightly below the LDLs. This procedure seems to lack validity for a number of reasons: (a) Earphones are calibrated in a 6-cm^3 coupler, while hearing aid SSPL90 is determined in a 2-cm^3 coupler. These reference values are not comparable. (b) An earmold can significantly modify hearing aid response, but its effects are not incorporated into presently popular procedures. (c) When a hearing aid is worn, there are head and body diffraction effects, as well as a unique impedance matching between the hearing aid receiver and the individual's middle ear.

Following hearing aid selection on the basis of frequency response and SSPL90, audiologists commonly use one of two evaluation techniques. The most popular procedure for evaluating hearing aid performance is the traditional comparison of word recognition scores obtained in a sound booth. A recent study by Walden, Schwartz, Williams, Holum-Hardegen, and Crowley (1983) produced data that failed to support the underlying assumptions of the comparative approach using word recognition scores. Three hearing aids having similar electroacoustic characteristics were compared using NU-6 word lists in noise. There were no significant differences among the aids at the .05 level of confidence. Further, relative aided performance over time was not stable, as evidenced in a repetition of the entire hearing aid evaluation. A rank ordering of the three hearing aids on the basis of percent of words correct was different in the first compared to the second evaluation in 14 of 20 cases. The most discouraging result of the Walden et al. (1983) study was the lack of agreement in 60% of the cases between the recommendation resulting from the hearing aid evaluation and user preference after wearing the aids in everyday life situations.

An alternative or adjunct to the word recognition approach is to measure aided sound-field thresholds and select the hearing aid that produces the most desirable results. One can question what constitutes the optimum set of aided sound-field thresholds. While several studies have provided limited data on this issue (Pascoe, 1975; Skinner, 1980), the answer is far from clear. Do we want gain equal to one-half the hearing loss? One-third the hearing loss? Is the shape of the aided audiogram more important than the absolute hearing thresholds? Should the long-term speech spectrum be amplified to most comfortable loudness level (MCL) regardless of the aided threshold that results?

A second problem with sound-field thresholds is variability. Hawkins, Montgomery, Prosek, and Walden (1985) examined the test-retest variability of aided thresholds and expressed the results in critical differences. Table 1 shows the critical differences at six test frequencies and four confidence levels. These values represent the dB differences that must be observed between two sets of aided thresholds to be confident at a set probability level that a difference is real and not due to test-retest variability. For instance, two thresholds at 1000 Hz would have to differ by greater than 15 dB to be certain 95 times out of 100 that this difference is not due to testing variability. If a larger error can be tolerated (e.g., being sure only 80 out of 100 times), a 10-dB difference can be accepted as reliably indicating differences between aids.

Table 1

Critical Differences (dB) for Aided Sound-Field Thresholds

	Frequency (kHz)					
p	.25	.5	1	2	3	4
.05	12	16	15	15	16	17
.10	10	13	13	13	14	14
.20	8	10	10	10	11	11
.30	6	8	8	8	9	9

In addition to being a rather variable measurement, aided thresholds can be contaminated by internal circuit noise of the hearing aid and/or ambient environmental noise (Macrae, 1982; Macrae & Frazer, 1980; Rines, Stelmachowicz, & Gorga, 1984). When persons have regions of normal or near-normal hearing, the circuit noise and/or ambient noise acts as a masker, and the aided thresholds can be a masked instead of an absolute threshold. As a result, functional gain can be substantially underestimated in regions of good unaided hearing. Macrae (1982) suggested that when unaided thresholds are better than 30 dB HL, aided thresholds may be inaccurate. The minimum hearing loss that can be evaluated without masking of aided thresholds depends upon an interaction of aid noise, room noise, and unaided hearing threshold.

A final difficulty with aided sound-field thresholds is restriction of frequency-specific information. Time constraints typically allow testing only at octave or, at best, half-octave intervals. Many peaks and valleys in the response curve may go unnoticed when testing is done at such widely spaced frequencies.

In addition to, or in place of, word recognition scores and aided sound-field thresholds, a common evaluation method is to solicit comments regarding sound quality and intelligibility. There are three major problems with such an approach as typically carried out in a sound booth. The first problem is a simple one of auditory memory. If any significant time intervenes between hearing aid comparisons, the reliability of the judgments is poor, and they do not agree well with those obtained in a classic paired-comparison method (Schum & Collins, 1985). To ensure reliability, comparisons must be made in a rapid A-B-A-B paradigm.

The second problem relates to the effect of sound booth acoustics on quality judgments. In a sound booth, the greater the low-frequency gain, the better the quality judgment (Punch & Beck, 1980). This relationship holds true even for listeners with normal low-frequency hearing and a significant high-frequency hearing loss (Schwartz et al., 1979). Few clinicians would probably agree that real-world performance and success with a hearing aid is directly related to the amount of low-frequency gain.

A third, related problem with the subjective opinion approach is that the rank order of hearing aid preferences for both quality and intelligibility is different in a sound booth than in a reverberant room when a paired-companion technique is used (Logan, Schwartz, Ahlstrom, & Ahlstrom, 1984).

ALTERNATIVE HEARING AID SELECTION AND EVALUATION METHODS

Achieving validity in hearing aid selection requires procedures that (a) take into account important variables and (b) have predictive validity for real-world functioning with hearing aids. What follows are some personal opinions as to what directions we could take in this pursuit.

Consider first the selection of SSPL90. A potentially valid procedure should include the following: (a) situate the person in a sound field so that head and body diffraction effects are present; (b) make measurements through an actual hearing aid; (c) include the person's earmold in the sound delivery system; (d) instruct the listener so that the LDL is not obtained at an inappropriately low level (thus restricting the dynamic range) or at a level so high that loudness discomfort will result; and (e) most importantly, calibrate the whole delivery system in dB SPL re a 2-cm^3 coupler so that the LDL is directly applicable to the SSPL90 data on the hearing aid specification sheet.

We have recently developed a procedure for determining SSPL90 which attempts to take into account the variables that were just described. In this procedure the person wears an actual hearing aid, the output of which is calibrated in a 2-cm^3 coupler. Table 2 summarizes the first phase, calibration. First, a Knowles Electronics Manikin for Acoustic Research (KEMAR) is placed in the calibrated spot in the sound field and a ½-in. microphone is located above the pinna at the typical site of a hearing aid microphone. For each test frequency the SPL at the hearing aid microphone position is determined for various HL dial readings on the audiometer. The clinician will then know the actual SPL entering the hearing aid at the point of loudness discomfort. Second, the volume control wheel on a peak clipping hearing aid with a high SSPL90 (greater than 125 dB SPL) is taped at a rotation providing approximately 25-30 dB of gain in the 500-3000 Hz region. The actual gain at each test frequency (500, 1000, 2000, 3000, and 4000 Hz) is then carefully measured in a 2-cm^3 coupler.

Testing begins with the person seated in the calibrated spot. The high-output hearing aid with the fixed volume control is connected to his/her

Table 2

Calibration Procedures for the LDL Procedure Used to Select SSPL90

I. SOUND FIELD
  A. Place a KEMAR or a person in sound field.
  B. Determine SPL at the location of the hearing aid microphone for a given HL dial reading at each frequency.
  C. Calculate corrections from HL to SPL.

II. HEARING AID
  A. Use a high-output peak clipping aid.
  B. Set and tape the volume control wheel for 25-30 dB of 2-cm^3 coupler gain.
  C. Measure and record the 2-cm^3 coupler gain at each test frequency.

custom earmold, and the non-test ear is plugged. The following instructions are given:

> We need to do a test that will help me decide where to set the amplifier on the hearing aid. We want to set it so that sounds don't get so loud that they are uncomfortable. If we set it too high, sounds could get too loud, and you probably wouldn't want to wear the hearing aid.
>
> You will hear some tones through the loudspeaker, and after each one I want you to tell me which of the loudness categories on this sheet best describes the tone to you. [Hand them the loudness chart. See Table 3.] So after each tone, tell me if it was "Comfortable," or "Comfortable But Slightly Loud," or "Loud, But O.K.," or "Uncomfortably Loud," etc.
>
> I will be zeroing in on this "Uncomfortably Loud" category, because that's where we want the hearing aid to stop. We want to keep the sound down in this region [point to the three "Comfortable" categories] and not let the sound get up into here [point to the three top categories]. So for each tone, tell me which category it falls into. Understand?

Table 3

Loudness Level Chart Used in Instructions for the LDL Procedure

Levels of Loudness
Painfully Loud
Extremely Uncomfortable
Uncomfortably Loud
Loud, But O.K.
Comfortable, But Slightly Loud
Comfortable
Comfortable, But Slightly Soft
Soft
Very Soft

Starting with an intensity of 45 dB HL (approximately 80 dB SPL in the ear canal), an ascending method of limits is used with a 2-dB step size. The lowest intensity that produces a judgment of "Uncomfortably Loud" on two of three presentations is the LDL. Frequency-modulated tones (5%, 5 Hz) centered at 500, 1000, 2000, 3000, and 4000 Hz are used as the stimuli. After the LDL in dB HL has been determined for each stimulus, it is converted to dB SPL at the hearing aid microphone. The 2-cm^3 coupler gain is added to the input SPL at the microphone to give the output in a 2-cm^3 coupler at the point of loudness discomfort. This value is used to select the SSPL90 from the hearing aid specification sheet. This procedure takes approximately 5-10 minutes per ear. Preliminary validation data described by Hawkins, Walden, Montgomery, and Prosek (1985) indicated that the procedure prescribed SSPL90 values which resulted in close to optimally wide dynamic ranges in the majority of hearing-impaired listeners.

Following electroacoustic measures are evaluation procedures that attempt to relate to aspects of real-world functioning. Our chances for developing a procedure with predictive validity may increase if we include some of the major variables from real-world communication that affect speech intelligibility; namely, reverberation, noise, visual cues, and test material. The most relevant material may be continuous discourse, as it is most representative of everyday communication. If hearing-impaired people listen to continuous discourse in reverberant environments while watching the speaker's face and must extract the speech signal from a background of noise, then it seems imperative that selection of the optimal hearing aid be accomplished in just this situation.

At Walter Reed Army Medical Center we use a room having typical dimensions (15 ft × 18 ft) and moderate reverberation time (0.5 sec). The patient is seated 6-8 ft from a video monitor that displays the image of a person reading a passage of continuous discourse. Speech spectrum noise emanates from three loudspeakers located behind and at both sides of the listener (90°, 180°, and 270°).

To facilitate the speech-in-noise tasks, we have developed, with the help of the Biomedical Engineering Laboratory at Walter Reed Army Institute of Research, an acoustic valve. It allows a rapid paired-comparison method to be used clinically with two behind-the-ear hearing aids. A picture of a prototype is shown in Figure 2. By moving the switch to one side or the other, one of two hearing aids is connected through to the earmold. This allows rapid user comparisons in an A-B-A-B format with the actual hearing aids and user earmold. The device has a negligible effect (less than 2 dB) on the gain and frequency response when compared to a straight tube of the same length.

Two hearing aids are selected which the clinician believes could be appropriate for the patient's needs. The SSPL90 is set based on the LDL procedure described earlier. Both aids are connected to the acoustic valve. One objective and three subjective measures are made. The objective test consists of

Figure 2. Acoustic switching valve developed at Walter Reed Army Medical Center for rapid clinical paired-comparison judgments between two hearing aids at the same ear.

measuring insertion gain with a probe-tube microphone in the ear canal. This measurement provides the electroacoustic equivalent of functional gain across frequency. Preliminary studies (Popelka, 1984) indicated close agreement between functional gain and insertion gain measured with a probe tube in the ear canal. With the use of the valve, insertion gain can be measured for both hearing aids in less than 5 min. Tone control and/or earmold changes may be made at this time and the measurement repeated to obtain the most desirable results.

Following measurement of insertion gain, the subjective tests are performed. The first consists of sound quality judgments using the valve in an A-B-A-B paired-comparison paradigm. The sound quality dimensions on which the two aids are compared are shown in Table 4. These dimensions were derived through a series of studies by Gabrielsson and colleagues in Sweden (for a summary, see Gabrielsson & Sjögren, 1979). The patient is seated in the reverberant room, with a video monitor showing a male talker reading continuous discourse, presented at a signal-to-noise ratio of + 12 dB. For each pair of bipolar adjective pairs, the patient switches back and forth between the two aids and provides a preference judgment. Following these judgments, the patient compares the two aids in terms of perceived speech intelligibility, again via the A-B-A-B paradigm.

Table 4

Adjective Pairs Used In Paired-Comparison Sound Quality and Intelligibility Judgments of Hearing Aids

	Quality of Speech	
Distinct	______________	Blurred
Mild/Calm	______________	Sharp
Airy/Open	______________	Shut Up/Closed
Bright	______________	Dull
Quiet	______________	Noisy/Hissing
Clear	______________	Hazy
Near	______________	Far
Full	______________	Thin
	Understanding of Speech	
Understood none of the words	______________ Understood half of the words	Understood all of the words

In the final subjective test the listener views a female talker on the video monitor reading a passage of continuous discourse. Two approaches are being experimented with at this time. In the first, the patient is given an attenuator which controls the level of the noise from the three loudspeakers. With the speech kept constant at 65 dB SPL, the patient adjusts the noise attenuator until he/she "understands 50% of what is being said" or "just follows the conversation." There are data suggesting that such a task can be done with very good test-retest reliability (Speaks, Parker, Harris, & Kuhl, 1972; Gray & Speaks, 1978; Walker & Byrne, 1985). The measure the procedure provides is a signal-to-noise ratio, not a percent correct score. This is an efficient procedure, as it takes less than 1 min per trial. The second approach uses a fixed signal-to-noise ratio, +10 to +14 dB. The patient rates the intelligibility of the speech sample on a scale from 1 to 10, similar to that described by Cox and McDaniel (1984). The aid is recommended which yields the lowest signal-to-noise ratio or the highest intelligibility rating. These tests can also be performed without visual cues, with the difference between auditory-only and auditory-plus-visual providing an index of how well the person is utilizing visual information in signal-to-noise ratio terms.

To summarize, the proposed hearing aid selection and evaluation procedure includes the following: (a) measurement of LDLs in dB HL and conversion to dB SPL to allow selection of appropriate SSPL90 characteristics from hearing aid specifications; (b) use of an acoustic valve to couple two hearing aids at a time to the same ear via the person's earmold; (c) measurement and adjustment of insertion gain across frequency using an ear canal probe-tube microphone system; (d) speech quality comparisons along eight dimensions using the acoustic valve during an auditory-visual presentation of continuous discourse (S/N = +12 dB) in a reverberant room; (e) estimate of speech intelligibility using the paired-comparison method as in (d); and (f) measurement of the signal-to-noise ratio necessary to just follow the conversation with auditory-only and auditory-plus-visual cues for two hearing aids. With the acoustic valve, total testing time is less than 1 hour. Although there has been no validation of this procedure, we are suggesting that the data it produces have more potential than a series of scores on monosyllabic word lists and/or a set of aided sound-field thresholds.

HEARING AID PERFORMANCE AND ADAPTATION

Can any test or series of tests at the selection stage correlate highly with performance or preferences at some future point in time? If a hearing loss has been present for some time, we can probably assume that the person's "central processor" has learned to extract information from the degraded neural signal in an optimal fashion. When a hearing aid is introduced, the input to the central processor is suddenly changed. An adaptation and learning period may be necessary before optimum cue extraction is again established. When we do a comparative evaluation, however, we are making the assumption that the rank order of hearing aids on performance measures at the selection stage will be maintained throughout any learning or adjustment period. Barfod (1979) discussed this issue at length in the following way:

> The fitting of a hearing aid means a sudden change of the input to the recognition device. This change can have two effects, one improving and one degrading speech perception. On the one hand, speech perception will tend to improve because an increased amount of information is presented to the recognition device; on the other hand, speech perception can deteriorate due to the increased mismatch of the recognition device and the input code. An immediate degradation in speech perception will result if the latter effect dominates at the time when the hearing aid is fitted . . . the patient may be so sensitive to the abrupt change of sound quality that he rejects the hearing aid and in principle "chooses as best a peak amplifier or one which accentuates most of the frequencies he already can hear best; and, paradoxically, he frequently says he hears poorly with the amplifier with which he actually hears best" (according to intelligibility measurements) [Watson and Knudsen, 1940].
>
> Consequently, when a hearing aid is first given to a patient there will most likely exist a mismatch between the code of the input to the recognition device and the performance of this device. This mismatch will gradually decrease as a result of adaptation, if adaptation is possible. The literature supplies little information on adaptation periods for hearing aid wearers. In our experience, the learning period for new and motivated hearing aid wearers last from a few weeks to half a year or longer.
>
> Experimental hearing aids are often evaluated using some kind of intelligibility measurement. Usually, some training is performed and, occasionally,

> the progress in training is reported. Due to the intermittent nature of the experiment, the main part of this training aims at making the subject acquainted with the test procedure, rather than providing an adaptation to the experimental hearing aid. Conclusions based on "instant" experimental intelligibility measurements are therefore contaminated with a possible interaction of a mismatched recognition device. This aspect increases the number of imperfections inherent in using laboratory experiments to predict every day behavior and emphasizes the importance of real-life testing of experimental hearing aids. (p. 438 and 439)

Regardless of the validity of such an argument, it serves to remind us that people do learn, change, and adapt, and we must be cognizant of this as we evaluate our selection assumptions and procedures and plan follow-up procedures.

ASSESSING THE OUTCOME

Perhaps the most difficult of all problems in hearing aid research is that of determining effectiveness of the hearing aid. The most commonly used terms in this area have been benefit, satisfaction, and success (Demorest, 1984). Unless we have a valid means of assessing these properties, we will never be able to move forward in comparing different frequency responses, signal processing schemes, rehabilitation procedures, or other aspects of hearing aid fitting.

There are two basic approaches to assessing the "final outcome," objective and subjective. The objective approach might examine word recognition scores, aided sound-field thresholds, or a speech-in-noise and reverberation task like the one described earlier. While these measures might hold some potential for quantifying benefit, it is uncertain whether they would bear any relationship to the hearing aid user's perception of benefit, satisfaction, or success. Indeed, a major problem is how these three terms are used and defined (Demorest, 1984). For instance, suppose we choose the term "satisfaction." What hearing aid users expect from a hearing aid could well affect their response. In one case, there could be a hearing aid user with high occupational demands on hearing, and as a result, high expectations from a hearing aid. This individual might receive *excellent benefit* but still be *dissatisfied* with the hearing aid because speech is not understood normally. In contrast is the hearing aid user who does not expect much from the aid and does not receive much, but when asked if satisfied, would respond affirmatively. In other words, there could be *little benefit,* but reported *satisfaction.*

It is clear that there are many attitudes, expectations, and feelings that comprise the success, satisfaction, and benefit concepts. We propose the following approach to the objective quantification of overall hearing aid performance while attending to the subjective perception of benefit:

1. Make an objective measurement of some aspect of performance that relates to real-world performance by duplicating real-world conditions

of noise, reverberation, and visual cues.

2. Obtain an index of communication needs, demands, and importance through an instrument such as the Communication Profile for the Hearing Impaired (Demorest & Erdman, 1984).
3. Assess the subjective reactions of the hearing aid user via a self-report inventory such as the Hearing Aid Performance Inventory (Walden, Demorest, & Hepler, 1984).

Using a combination of these three types of measures, it may be possible to obtain a clearer picture of what a hearing aid is providing the hearing-impaired person than can be obtained with only word-recognition test scores or aided sound-field thresholds. Until this range of approaches is developed and has some proven validity, it will be difficult to truly validate our hearing aid selection and evaluation procedures.

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