Dimensions of Hearing Aid Outcome

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Abstract

Dimensions of hearing aid outcome are explored in this paper. First, a variety of hearing aid outcome measures is defined including objective and subjective performance, objective and subjective benefit, satisfaction, and use. Following the definition of these terms, factor analysis is described as a statistical tool that can be of assistance in establishing the number and nature of the relevant dimensions of hearing aid outcome. Next, the results from three recent studies that included a variety of measures of hearing aid outcome are examined and factor analysis is applied to the data from each study. This examination leads to the conclusion that hearing aid outcome is a multidimensional construct, rather than unidimensional. The most complete description of hearing aid outcome will be obtained when including at least one measure of aided speech recognition performance, one or more measures of objective benefit in speech recognition, one or two subjective measures of sound quality or listening effort, and one measure of either subjective benefit, satisfaction, or use.

Key Words: Factor analysis, hearing aid benefit, hearing aid outcome, hearing aid satisfaction, hearing aid usage

Abbreviations: COSI = Client-Oriented Scale of Improvement; CST = Connected Speech Test; HAPI = Hearing Aid Performance Inventory; HHIE = Hearing Handicap Inventory for the Elderly; ITC = in the canal; PHAB = Profile of Hearing Aid Benefit; REAR = real-ear aided response; REIG = real-ear insertion gain; REUR = real-ear unaided response

C urrently, there is much interest in the measurement and quantification of hearing aid outcome (Humes et al, 1996; Mueller, 1997). In general, "outcome" refers to the measurable effect, either real or perceived, of the hearing aid on the wearer's hearing disability or hearing handicap (Weinstein, 1997). Outcome can be either positive or negative. That is, the use of a hearing aid by the wearer can either increase or decrease the hearing disability or handicap.

Researchers, clinicians, consumers, and various third-party representatives have begun recently to focus greater attention on the issue of hearing aid outcome. Researchers have developed a keener interest in this concept as they have become involved increasingly in attempts to document the hypothesized benefits of various electronic circuits or signal-processing schemes developed by hearing aid manufacturers. Their increased involvement in recent years

can be traced, in many cases, to more stringent regulations adopted by the Food and Drug Administration in the early 1990s. The regulations require hearing aid manufacturers to document marketing claims regarding product performance and benefits scientifically, especially those regarding improved speech understanding, often with clinical research conducted at multiple test sites. Clinicians and consumers, on the other hand, are interested in such research for the most accurate and complete picture regarding the relative costs and benefits of various hearing aid technologies. Finally, various third-party payers, including state and federal agencies, insurance companies, labor unions, and health maintenance organizations, also want to know whether additional costs of a particular technology can be justified by additional enhancements to the wearer's communication abilities prior to approving reimbursement.

OVERVIEW OF HEARING AID OUTCOME MEASURES

A wide variety of hearing aid outcome measures have been developed over the past couple of decades. Most of these measures can

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be categorized as measures of aided performance, benefit, satisfaction, or use. In many cases, both objective and subjective metrics are available for each type of outcome measure. Aided performance refers to the scores or measures obtained from the hearing aid wearer in the aided condition. Aided performance can be measured objectively or subjectively, that is, either requiring or not requiring the wearer to express an opinion or judgment regarding the hearing aid's function. Results can be compared to various norms established for these same measures from large samples of normal-hearing or hearing-impaired persons to assist in establishing claims that aided performance "has been returned to normal" or "is superior to that achieved with technology X" in similar patients. A wide range of aided performance measures can be used, including measures of speech recognition performance, loudness, and sound quality. Performance can also be quantified in purely acoustic terms in which one is describing the hearing aid's performance in a coupler or on the patient, rather than the wearer's performance with the hearing aid. Probably the most common measurement of this type is the real-ear aided response (REAR; Mueller, 1992), in which the aided sound pressure level output of the hearing aid is measured in the wearer's ear canal. Most often, however, performance outcome measures refer to the performance of the hearing aid wearer while wearing the instrument(s). Examples of an objective measure of aided performance include speech recognition scores in any of a variety of listening conditions and using any of the many tests of speech recognition available, ranging from nonsense syllables to sentences in connected discourse. Such measures are referred to as "objective," even though a response is required from the wearer, because the responses can be scored as correct or incorrect. Subjective measures of performance, on the other hand, rely entirely on the wearer's judgment or opinion and have no external reference for evaluation. Examples of subjective performance measures include loudness judgments (whether accomplished by scaling, category rating, or matching), quality judgments (clarity, harshness, spaciousness, etc.), and perceived disability or handicap.

In contrast to measures of aided performance, hearing aid benefit is established by comparing aided performance to unaided performance within the same wearer or group of wearers. Benefit expresses the magnitude or degree of change from unaided to aided listening.

Most often, it is calculated as a difference score, rather than a ratio or proportion. It can be positive, negative, or neutral, depending on the relative effect the hearing aid has on performance. Objective measures of benefit include real-ear insertion gain (REIG = REAR − REUR) and changes in speech recognition scores associated with hearing aid use. Just as with aided speech recognition performance, there are many combinations of listening conditions that can be used to measure benefit in speech recognition. For example, any of the following listening condition variables can affect aided performance, unaided performance, and the benefit derived by subtracting these measures: speech level, speech material (nonsense syllables, monosyllabic words, sentences, etc.), background (type, spectrum, level, signal-to-noise ratio), response format (open or closed response set, written or oral responses), and the azimuth for the speech and noise signals. Specification of each of these variables is required as part of the measurement process. Combinations of listening condition variables are sought that maximize the reliability and validity of the measurements for a particular individual's age and hearing impairment. For objective benefit, test conditions must be identical in the aided and unaided conditions so that the effect of the hearing aid can be ascertained.

Subjective measures of benefit can also be obtained as well. Hearing aid wearers can provide sound-quality judgments, for example, for a variety of stimuli with and without their hearing aids with the goal of improving sound quality in the aided condition. Hearing handicap can be assessed prior to and after a period of hearing aid use with the difference indicating the subjective benefit or relative change in self-perceived handicap. The Hearing Handicap Inventory for the Elderly (HHIE; Ventry and Weinstein, 1982) has proven useful in this regard (Newman and Weinstein, 1988; Malinoff and Weinstein, 1989). Hearing aid wearers can also be asked to establish subjectively their aided and unaided performance in a variety of specified listening situations with the difference providing a subjective measure of benefit. The Profile of Hearing Aid Benefit (PHAB; Cox et al, 1991) and, more recently, the abbreviated version of this instrument, the APHAB (Cox and Alexander, 1995), have both proven useful in this regard. In this approach, unaided and aided performance are either assessed at two different points in time (before and after a period of hearing aid use) or at one point in time after hearing aid use, but requiring the wearer to recall how he or she

functioned without the hearing aid in that same listening situation prior to hearing aid use.

Another approach to measuring subjective benefit is simply to ask the hearing aid wearer how much benefit or "help" is provided by the hearing aid in a variety of listening situations after he or she has been fit with hearing aids. That is, rather than asking how well he or she performed in each situation, both aided and unaided, and then subtracting the two measures to determine the effect of the hearing aid, the wearer is simply asked how much benefit is provided. Again, the reference is based on the wearer's memory of performance in this same situation without the hearing aid, but "benefit" is directly scaled in this approach, rather than scaling performance twice (i.e., aided and unaided) and then deriving benefit indirectly by subtracting these two estimates of performance. Probably the most frequently used measure of this type is the Hearing Aid Performance Inventory (HAPI; Walden et al, 1984). Two abbreviated versions of the HAPI have also been developed (Schum, 1992; Dillon, 1994).

Recent trends in the development of these subjective measures of hearing aid performance and benefit have been to weight benefit estimates for a particular listening situation according to the wearer's estimated frequency of occurrence or the self-perceived importance of that listening situation (Gatehouse, 1994; Dillon et al, 1997). That is, it may not be simply the amount of benefit that is provided in a hypothetical communication situation that is important but also how frequent or important that hypothetical situation is to the hearing aid wearer. In the extreme, a hypothetical standardized set of communication situations is not employed in subjective scales of this type. Rather, open-ended scale items are tailored to each person's particular communication needs and experiences, based on individual assessments of their frequency or importance, with benefit assessed for each of these conditions following use of amplification. The Client-Oriented Scale of Improvement (COSI; Dillon et al, 1997) is one recent example of a scale of this type.

Hearing aid satisfaction is another outcome dimension that can be measured. Since satisfaction is an internalized construct defined exclusively by the hearing aid wearer, measures of satisfaction are necessarily subjective. It has been suggested, however, that it may be possible to derive more objective measures of satisfaction by tallying events such as the number of return visits, either for repair or adjustment,

following hearing aid delivery (Walden, 1982). In this case, it is assumed that the more frequent the return visits to resolve complaints, the less satisfied the hearing aid wearer.

Measures of hearing aid satisfaction have evolved over the past several decades. Probably the most extensive measures of satisfaction available currently are those developed for use by Kochkin in a series of consumer surveys referred to as MarkeTrak (Kochkin, 1992, 1995). The most recent version of this survey partitions satisfaction into several components including satisfaction with the physical features of the instrument (size, comfort of fit, ease of use, ease of care), with its performance in various listening situations, and with the quality of services provided. Satisfaction is established by asking the hearing aid wearer to assign a number to each item representing the degree of satisfaction or dissatisfaction with that particular aspect of the hearing aid, its performance, or the services provided. That scale ranges from 1 to 5 with 1 representing "very dissatisfied" and 5 representing "very satisfied."

Hearing aid use represents another possible measure of hearing aid outcome. Both objective and subjective measures of hearing aid use have been developed. In subjective estimates, the wearer is asked to report typical or average use of the hearing aid, usually in hours per day, at some measurement time following hearing aid delivery. The accuracy of this global estimate of typical use can be enhanced by requesting the wearer to keep a daily log or diary of the hours the hearing aid was used. This information can then be used to compute an average amount of use in hours per day. Some subjective estimates of use do not require actual estimates of use in hours per day but assess the "frequency" of use for a variety of listening situations. An item in this type of measurement might be structured as follows: "You are watching television alone at home. In this situation, you use your hearing aid ... (all of the time, most of the time, sometimes, rarely, never)." The objective is not to derive an absolute estimate of how much time the hearing aid is used on a daily basis. Rather, the intention is to determine the relative use of the hearing aid(s) across various listening situations.

Objective measures of hearing aid use are also available. Some hearing aids, for example, have electronic circuits within them that can be used to establish the number of hours the hearing aid was on (Haggard et al, 1981; Humes et al, 1996). Another method involves measuring changes in the weight of oxide batteries over time

(Fino et al, 1992). It should be noted that although these methods offer more objective means to estimate the number of hours the hearing aid circuit was active, this does not necessarily mean that this is the time the hearing aid was actually worn by the wearer. It is not uncommon for people to forget to turn their hearing aids off when they remove them. This would tend to bias objective measures of use toward higher values than subjective estimates. However, when both types of measures have been obtained from the same group of wearers, the objective and subjective estimates are correlated strongly with one another, but the subjective estimates tend to be higher than those measured objectively (Haggard et al, 1981; Humes et al, 1996).

ARE ALL OF THESE OUTCOME MEASURES NEEDED?

Somewhat surprisingly, few studies have been conducted that sought to measure hearing aid performance, benefit, satisfaction, and use in the same group of hearing aid wearers. Several studies have examined various subsets of these measures with the most common approach being to either measure hearing aid performance and benefit (e.g., Cox and Alexander, 1992) or satisfaction and use (e.g., Carstairs, 1963; Kapteyn, 1977a, b). As a result, some fundamental issues regarding outcome measures for hearing aids have been ignored and remain unresolved. For instance, is it the case that "hearing aid outcome" is a unidimensional construct? That is, are all hearing aid outcome measures assessing the same thing? If so, then all measures would be highly correlated and, when subjected to factor analysis, would load heavily on the same, single factor. The development of separate measures of performance, benefit, satisfaction, and use reflect the clinical and research communities' belief that these are, in fact, independent aspects of outcome that must be measured separately. If this is the case, then it should be possible to confirm experimentally by obtaining a variety of outcome measures from the same group of hearing aid wearers and performing a factor analysis on the data. (The results of three such analyses are presented later in this paper.)

Assuming for the moment that hearing aid outcome is not unidimensional but has several independent dimensions associated with it, another important issue to be addressed is the association among the various dimensions of outcome. One simple possibility, for example, is that there are several separate dimensions of hearing aid outcome, but they are sufficiently positively associated such that high aided performance tends to lead to high benefit, which tends to lead to high satisfaction, which, in turn, leads to high amounts of use. Clearly, though, the situation may not be so straightforward. Consider, for the moment, just two outcome measures, unaided and aided speech-recognition performance, and the relative benefit derived from these measures. Who is likely to be more satisfied with their hearing aids, a person with a 70 percent unaided speech recognition score in noise who improves to normal performance of 90 percent in the aided condition (20% benefit) or a person with unaided scores of 20 percent in the same listening condition who improves to aided performance of 70 percent (50% benefit)? Which person is more likely to use his or her hearing aid(s) the most? If aided speech recognition performance in noise is the most critical predictor of satisfaction and use, then the first person would be the correct answer. If the relative speech recognition benefit obtained in that same listening condition is the most important determinant of satisfaction and use, then the second person would be the correct answer. Of course, it is conceivable that neither speech recognition performance in noise nor the relative speech recognition benefit in noise would be the primary determinants of satisfaction and use. They may contribute partially or not at all to satisfaction and use. Perhaps the quality of sound, ease of operation, and cosmetics will be more important determinants of satisfaction and use. It is not at all clear, moreover, that higher hearing aid satisfaction will lead to higher hearing aid use. In the example above, for instance, it could be that the second individual is less satisfied with the hearing aid's performance than the first individual, given aided speech recognition performance of 70 percent, but continues to wear the hearing aid because it at least restores function to a minimally acceptable level (70% aided vs 20% unaided). That is, the need is greater for the second individual, and this may determine use more than satisfaction.

FACTOR ANALYSIS AS A TOOL TO ASSIST IN IDENTIFYING DIMENSIONS OF OUTCOME

So, how many measures of hearing aid outcome are needed and what should each measure? To answer this question, one typically

makes use of existing knowledge to develop measures designed to tap what are believed to be relevant and independent dimensions or aspects of hearing aid outcome. The relevance of a particular dimension is often validated through studies of successful and unsuccessful hearing aid wearers. Those measures most helpful in distinguishing successful from unsuccessful hearing aid users have the greatest relevance and would appear to tap important dimensions of outcome. Measures that also delineate wearers' preferences for one type of hearing aid technology over another would also be considered more relevant or important. In the absence of sufficient data to guide the selection of relevant dimensions and measures of those dimensions, the investigator and clinician will need to rely on well-conceived rationales, models, or hypotheses to guide the selection process.

Currently, a number of hypothetically relevant dimensions of outcome have been proposed by various investigators, and the most common of these were defined previously in this paper. These include objective and subjective measures of aided performance, benefit, satisfaction, and use. A fundamental question to be addressed at this early stage in the evolution of hearing aid outcome measures is whether all of these measures are necessary. That is, are there redundancies among these measures such that not all of them need to be measured? If so, how many independent dimensions of hearing aid outcome are there and what measures of each dimension might be used in the clinic or the laboratory?

One objective, statistical approach to addressing these questions makes use of factor analysis. Although there are many different types of factor analysis, probably the most common type used in audiology and hearing science has been principal-components factor analysis (Kim and Mueller, 1990, 1991). In this approach, the correlations among the variables in the data set are used to identify common underlying "factors" responsible for the observed correlations. The typical method of principal-components factor analysis seeks to establish the number of orthogonal or independent factors needed to account for individual variations in performance among participants through the examination of the correlation matrix generated for all possible pairs of variables. Variables highly correlated with one another are identified as sharing a common underlying factor. Once each factor has been identified, factor or component weights are established for each variable on each identified factor. Factor weights or load-

ings can range from –1.0 to 1.0 with the magnitude of the weight indicating the strength of its loading on each factor. From these loadings, the factors are then interpreted or labeled with a name that reflects the nature of the variables loaded on each factor. The number of factors identified can range from a minimum of one to a maximum corresponding to the total number of variables included in the analysis. The goodness of fit of the resulting factor solution is identified by the percentage of variance accounted for by the solution while keeping a statistic known as the eigenvalue above a minimally acceptable value of 1.0. (The meaning and importance of this eigenvalue criterion are discussed below.)

Consider the following hypothetical example for measures of hearing aid outcome. Imagine that the following hearing aid outcome measures are all obtained from a group of study participants: (1) two measures of aided speech recognition performance (e.g., monosyllabic words in noise and in quiet); (2) two measures of objective benefit derived by comparing these aided speech recognition scores to unaided speech recognition scores for the same conditions; (3) one measure of aided hearing handicap (e.g., HHIE); (4) one subjective measure of reduction in hearing handicap derived from aided and unaided handicap scores; (5) one subjective measure of benefit (e.g., HAPI); (6) three subjective measures of aided performance, all focusing on aided sound quality; (7) two measures of hearing aid satisfaction, one for the instruments and their function, the other for quality of services provided; and (8) one subjective measure of hearing aid use (daily logs of use). This represents a total of 13 measures of hearing aid outcome.

Figure 1 displays three hypothetical results for the principal-components factor analysis. In Figure 1A, all 13 variables are loaded positively on a single factor with factor weights ranging from about 0.45 to 0.75. This one factor, however, accounts for only 20 percent of the variance in the data set.

Figure 1B illustrates a hypothetical situation at the other extreme. Here, 13 factors have been identified, with a separate outcome variable loading on each factor. (Figure 1B actually only shows the first, second, third, and thirteenth factors in the solution.) In this case, 100 percent of the variance is accounted for by these 13 factors and each factor accounts for 1/13 or 7.7 percent of the total variance. This is always the case in factor analysis when the number of
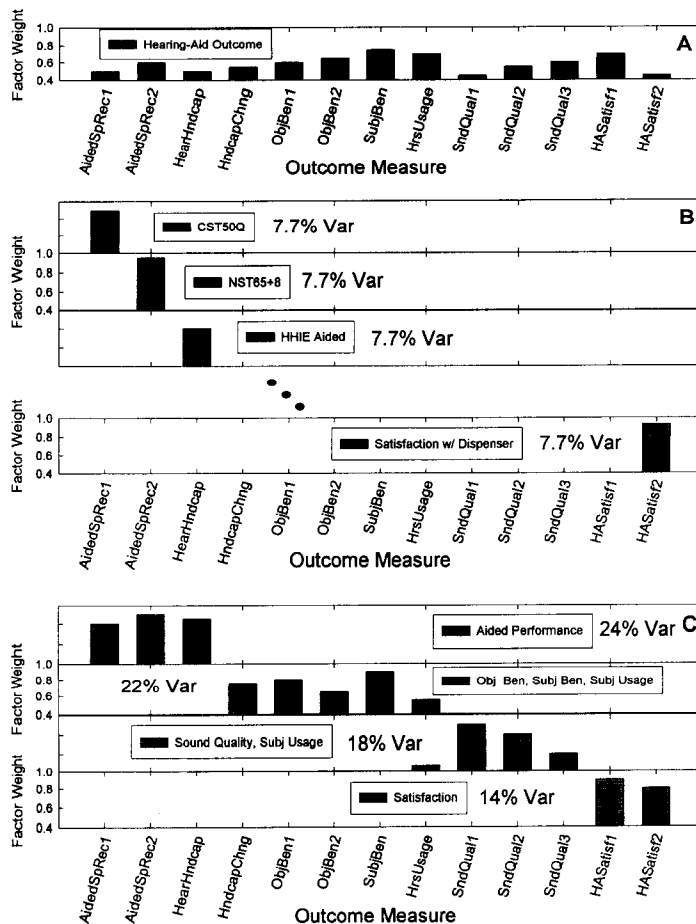
Figure 1 Illustration of a range of possible results of principal-components factor analyses applied to 13 measures of hearing aid outcome. A, One hearing aid outcome factor emerges with all 13 outcome measures weighted moderately on this factor. B, Thirteen independent factors emerge from the principal-components analysis, one for each of the 13 outcome measures with each factor accounting for 1/13th or 7.7 percent of the total variance. C, Four factors are identified with various outcome measures weighted highly on various factors. The factor is interpreted or labeled according to the type of measures weighted highly on it. The percentage of total variance accounted for by each factor is indicated again in each panel.

factors identified equals the number of variables and illustrates why it is not possible to rely solely on the percentage of variance accounted for in determining the goodness of fit. A negative practical consequence of this factor solution would also be that nothing has been gained by identifying common underlying factors associated with various subsets of variables. That is, if one has 13 measured variables available from each participant, there would be no advantage in terms of data reduction to use the 13 identified factors. Rather, each of the 13 measured variables would represent an independent aspect of hearing aid outcome that must be measured separately.

Finally, the hypothetical results depicted in Figure 1C illustrate a more typical result from principal-components factor analysis. Here, four factors were identified with a total variance accounted for of 75 percent while keeping the eigenvalue above 1.0. The eigenvalue constraint (eigenvalue > 1.0) is a common one for factor analyses. The eigenvalue is the ratio between the variance accounted for by the factor and the portion expected by an n-factor solution applied

to n variables. In this hypothetical example with 13 outcome variables, in a 13-factor solution, each factor would explain 1/13 or 7.7 percent of the total variance. Thus, in this example, as long as the variance explained by a factor exceeds 7.7 percent, then the eigenvalue (x/7.7) will be greater than 1.

The factor solution also indicates how much variance each factor, in this case each of the four factors, accounts for alone. This can be helpful to the investigator in further exploring the underlying factor structure. For example, consider two different factor solutions, both accounting for a total of 75 percent of the variance (while keeping the eigenvalues above 1.0). Examination of one solution revealed that each factor explained about the same amount of variance (about 18%–19% per factor). In the other factor solution, on the other hand, the first three factors each accounted for 24 percent of the variance with the fourth factor explaining only an additional 3 percent of the variance. This being the case, the investigator may elect to force the factor analysis to a three-factor solution to further reduce the complexity of the factor struc-

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ture while accounting for about the same amount of variance (72% vs 75% total variance explained by the three-factor vs the four-factor solutions).

In the hypothetical four-factor solution depicted in Figure 1C, each factor was depicted as accounting for about the same amount of variance. In addition, by examining the factor weights or loadings for each variable and factor, it is possible to interpret or establish meaningful labels for each of the identified factors. For example, notice that both of the aided speech recognition performance measures load highly (weightings > 0.6) on Factor 1, as does the aided hearing handicap score. No other variables are loaded highly on Factor 1 and these three measures do not load highly on any of the other three factors. As a result, Factor 1 could be easily interpreted or labeled as an aided performance factor. Because principal-components analysis seeks orthogonal or independent factors, the aided performance factor is entirely independent from the other three factors in this solution. It represents one of four separate and independent aspects of hearing aid outcome. In like manner, labels for the remaining three dimensions in Figure 1C could be established. Factor 2 could be interpreted as a factor associated with objective benefit, subjective benefit, and subjective use, Factor 3 as a sound quality and subjective use component, and Factor 4 as a satisfaction factor. Thus, from this hypothetical factor analysis, four independent aspects or dimensions of hearing aid outcome would emerge with only one outcome variable, subjective use, associated with more than one factor. If the 13 × 13 correlation matrix for all of the hearing aid outcome variables (on which the factor solution is based) was examined, strong correlations would be seen among all of those variables loaded on the same factor with weak correlations to all other variables. An important implication of this hypothetical four-factor solution is that one would only need four measures of hearing aid outcome, one from each factor or dimension of outcome, to quantify hearing aid outcome and not the full set of 13 variables. With several measures loaded on the same factor, the best choice among variables to represent that particular dimension of hearing aid outcome is usually the variable with the highest factor weight for that particular factor. This assumes that each variable is itself a reliable measurement. To the extent that this is not true, then multiple variables associated with a particular factor should be included and pooled to provide a more reliable (greater number of items) composite measure associated with that factor or dimension.

The foregoing paragraphs provide only a cursory overview of factor analysis and its possible application to measures of hearing aid outcome. The focus here, for example, has been on a particular type of factor analysis, principal components, in which each factor in the solution is independent from all other factors. There are, however, other factor extraction procedures that can be used, including some that extract related, rather than independent, factors. Moreover, within each factor extraction method, there are several choices as to how the factors in the solution might be rotated to optimize the solution. For example, even if an investigator selects the principal-components factor extraction technique to select independent factors, the independence of the factors in the solution can be effectively negated by selecting an oblique rotation of the axes. Further discussion of factor analysis as a statistical tool is beyond the scope of this brief article. However, examples of principal-components factor analysis applied to speech recognition performance in elderly listeners with impaired hearing can be found in Humes et al (1994) for standard varimax rotation of the factors and in Jerger and Chmiel (1997) for oblique rotation of the factors.

APPLICATION OF FACTOR ANALYSIS TO THREE RECENT STUDIES OF HEARING AID OUTCOME

In a recent study (Humes et al, 1997), 110 hearing aid wearers were fit binaurally with in-the-canal (ITC) hearing aids. The instruments could be set for linear amplification or BILL-processing mode. In the latter mode, the frequency response of the hearing aid was level dependent such that greater gain was applied to the low frequencies at low input levels and progressively less was provided as the input level increased. Factor analysis of the hearing aid outcome measures from this study are confined to those obtained for the linear setting. All participants in the Humes et al (1997) study were new hearing aid users. However, half began the study with the BILL circuit, rather than the linear circuit. These participants, therefore, had 6 to 8 weeks experience with hearing aids prior to being switched to the linear setting for the remainder of the study (another 4–6 weeks). In general, however, the entire group of 110 hearing aid wearers can be considered inexperienced or new users of linear amplification. This was confirmed by the lack of a significant effect of

hearing aid type (linear vs BILL) and order of evaluation (linear-BILL vs BILL-linear sequence) on the outcome measures in that study.

The resulting principal-components factor solution for the outcome measures included in Humes et al (1997) is provided in Figure 2. A total of 42 measures of hearing aid outcome from all 110 study participants served as the input to the factor analysis. Of these 42 measures, 32 were measures of speech recognition in noise, either the aided performance or the objective benefit (aided minus unaided scores). Each of these 42 variables is listed along the abscissa in Figure 2. Each of the panels represents a separate factor that emerged from the analysis. The vertical bars in each panel depict the factor weights of each variable for the factor represented in that panel. For clarity, only factor weights greater than 0.40 are depicted in each panel of this figure (and subsequent figures, as well). The percentage variance accounted for by each factor and the label assigned by the author to that factor (located within the box in each panel) are also indicated in each panel.

The variables listed along the abscissa of Figure 2 are coded as follows. First, the two rightmost variables represent a measure of subjective benefit (HAPI) and subjective estimates of the daily hours of hearing aid use taken from

logs or diaries used by the participants (hours/use). All of the other measures listed along the x-axis were obtained in one of eight factorial combinations of two noise types (c = cafeteria noise or b = babble), two speech presentation levels (60 or 75 dB SPL), and two signal-to-noise ratios (+5 or +10 dB). Two tests of speech recognition, the Connected Speech Test (CST; Cox et al, 1988) and the Northwestern University Auditory Test No. 6 (NU-6; Tillman and Carthart, 1966), served as test materials. Beginning with the leftmost variable along the abscissa, the first eight variables represent aided CST scores for each of the eight listening conditions and the next eight variables represent aided NU-6 scores for the same set of conditions. Next, the measures of objective benefit derived from the previous 16 variables by subtracting the corresponding unaided speech recognition scores are provided. Finally, the remaining outcome variables listed along the abscissa of Figure 2 represent a subjective estimate of aided performance in which participants were required to indicate "listening effort" or the "ease of listening" on a scale from 0 to 100 (with 100 corresponding to very easy listening and 0 representing very difficult listening).

The focus of the study by Humes et al (1997) was on differential effects of linear versus BILL processing on speech recognition performance
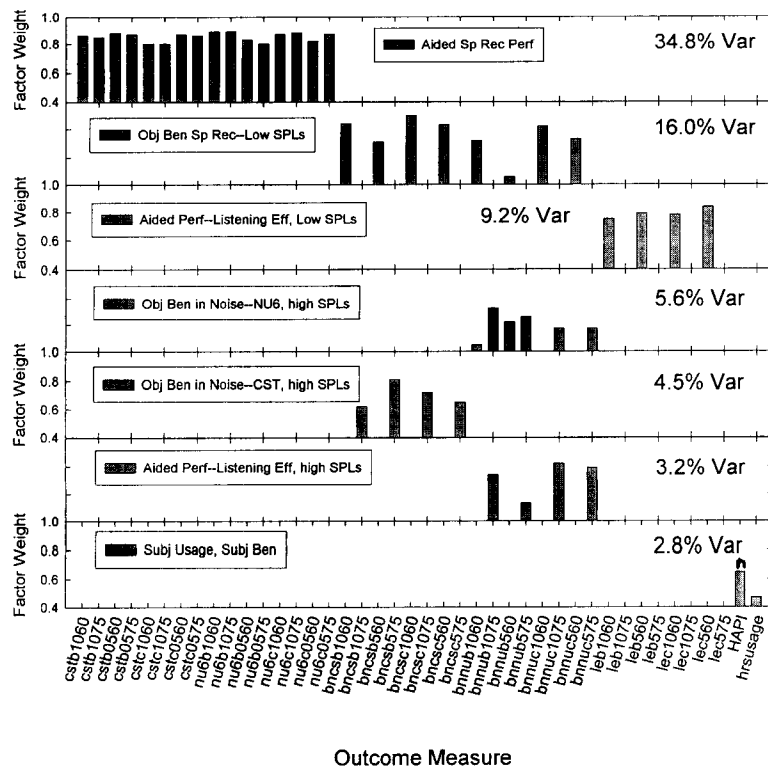

Figure 2 Results of the principal-components factor analysis applied to the 42 outcome measures obtained from 110 new users of linear ITC hearing aids. Factor labels and percentages of total variance accounted for are indicated in each panel. An n located above the vertical bar in a panel indicates that the actual factor weighting was negative, rather than positive.

Outcome Measure

and benefit in noise. As a result, the outcome measures were overloaded with this type of outcome variable. The resulting factor analysis shown in Figure 2 reflects this emphasis on speech recognition performance in noise. When the 42 outcome measures were subjected to a principal-components factor analysis, Figure 2 reveals that only seven independent factors were needed to account for 76.1 percent of the variance in the data. In other words, seven variables, appropriately selected, could have been as informative regarding hearing aid outcome as the entire set of 42 variables, although at the possible expense of measurement precision or reliability. The single largest factor that emerged and accounted for 34.8 percent of the variance (top panel) was labeled an aided speech recognition performance factor. Note that all 16 of the aided speech recognition measures (all CST and NU-6 scores represented on the left portion of the abscissa) loaded very high (factor weights > 0.8) on this factor and no other variables had factor loadings greater than 0.4 for Factor 1. Moreover, it is apparent that aided speech recognition scores were never weighted above 0.4 on any other factor. Thus, the 16 speech recognition scores obtained from each participant were highly correlated across subjects and one such score would have sufficed. Comparable results have been reported for unaided speech recognition results from elderly hearing-impaired listeners across a comparably diverse range of listening conditions and test materials (Humes et al, 1996).

The factor loadings for the second factor, labeled objective benefit for speech recognition at low levels, accounted for 16.0 percent of the total variance and represent a second independent dimension of hearing aid outcome. This factor is labeled as such because the variables with high loadings on this factor are measures of speech recognition benefit obtained for the 60 dB SPL presentation level. All eight of these variables have a factor loading > 0.4. As shown in the fourth and fifth panels of Figure 2, other factors associated with measures of objective benefit emerged and accounted for an additional 5.6 and 4.5 percent of the variance, respectively. From these results, it appears that objective benefit is an aspect of hearing aid outcome separate from aided performance (first factor) and one in which it is necessary to make finer distinctions as to the conditions under which benefit is measured. It appears that both the presentation level and the materials affect objective measures of benefit such that the benefit

measured at low sound levels for one type of test material is not necessarily correlated with that measured at higher sound levels or for different test materials. Similarly, as can be seen in Figure 2, the third and sixth factors that emerged were related to listening effort obtained at low and high sound levels, respectively. Thus, subjective estimates of listening effort represent an aspect of hearing aid outcome distinct from measures of aided speech recognition performance and objective benefit, despite obtaining all of these measures from an identical set of eight listening conditions. Finally, the remaining independent dimension of hearing aid outcome that emerged from these data is shown in the bottom panel of Figure 2 and was interpreted as a subjective benefit and subjective use factor. The n located just above the factor weight for the HAPI measure of subjective benefit indicates that the factor loading was actually negative. This means that the two measures weighted on the seventh factor were correlated but inversely related. Lower HAPI scores (the hearing aid being judged to be more helpful) were associated with higher amounts of hearing aid use. A similar inverse association between HAPI scores and hearing aid use has been noted previously (Humes et al, 1996).

In a follow-up study conducted approximately 1 year after the conclusion of the study by Humes et al (1997), 55 of that study's participants with mild or moderate hearing loss were evaluated with linear and two-channel wide dynamic range compression ITC hearing aids fit binaurally. Again, the factor analysis will only be presented for the results obtained with the linear circuit. The outcome measures obtained in this study were modified from the prior study as follows. First, half of the previous listening conditions were eliminated by obtaining all measurements in the babble background only (rather than babble and cafeteria noise). Second, two additional listening conditions were added for speech recognition measures: 50 and 60 dB SPL in quiet. This represented a total of six listening conditions for all speech recognition testing. Subjective listening effort measures were also obtained in all six listening conditions. Subjective measures of benefit (HAPI) and daily hours of use were again measured in this study. In addition to these measures, subjective judgments of sound quality using the procedures of Gabrielsson et al (1988) were obtained for aided listening with 10-second speech samples presented in each of the six listening conditions described above.

Given the smaller sample of participants in this study compared to the previous study (55 vs 110) and the still large number of outcome variables (40) used here, the number of variables was reduced by deriving various composite measures from the original set of outcome variables. The factor solution of the prior study's outcome measures guided the creation of the composite variables used in this study. For example, the 12 aided measures of speech recognition were reduced to two scores, one being the mean score for all conditions using lower presentation levels (50 or 60 dB SPL) and the other representing the mean score for conditions making use of a 75 dB SPL presentation level. Similarly, the original 12 measures of objective benefit were reduced to four measures, each representing the mean for one of the following grouping of test conditions: CST in quiet (50 and 60 dB SPL), CST in noise (60 and 75 dB SPL with +5 and +10 dB SNR), NU-6 in quiet, and NU-6 in noise. Two subjective estimates of listening effort were generated by computing a geometric mean for all quiet conditions and for all noise conditions. Two geometric means were also generated for the sound-quality judgments: one for the loudness judgments and the other for the other seven quality dimensions. Loudness was treated separately because it appeared to be the only dimension of the eight quality measures in which higher ratings were not necessarily better (i.e., a 10 on the loudness scale would mean "too loud" and a 1 would be "too soft"). Finally, two additional measures identical to those from the prior study were HAPI scores and daily hours

of use calculated from entries in the wearer's daily logs of use.

Figure 3 depicts the results of the factor analysis on the resulting 12 measures of hearing aid outcome for this study. Four factors emerged and accounted for a total of 72.4 percent of the variance. The first factor accounted for 21.6 percent of the variance and was interpreted as a factor associated with sound quality and listening effort in noise. Both types of measure associated with this factor represent subjective estimates of sound perception in aided listening conditions, either the quality of the amplified sound or the effort expended by the listener to understand amplified speech. The second factor, aided speech recognition performance and listening effort in quiet, accounted for almost as much variance (21.2%) as the first factor. The third factor, objective benefit in quiet, accounted for 15.6 percent of the variance in outcome measures whereas the fourth factor, subjective use, subjective benefit, and objective benefit in noise, accounted for 14.0 percent of the variance.

There are several similarities in the factor structures depicted in Figures 2 and 3. First, aided speech recognition performance emerged as a major factor in both analyses. Second, objective benefit and subjective listening effort again emerged as condition-specific factors. That is, there does not appear to be one objective benefit factor on which all measures of objective benefit load. Finally, subjective measures of benefit (HAPI) and hearing aid use are associated with the same factor and one that accounts for the
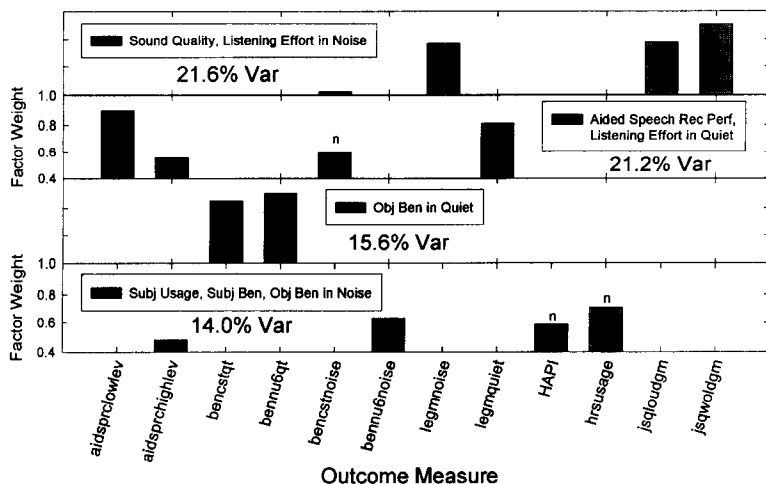

Figure 3 Results of the principal-components factor analysis for 12 outcome measures obtained from 55 experienced users of linear ITC instruments. Factor labels and percentages of total variance accounted for are indicated in each panel. An n located above the vertical bar in a panel indicates that the actual factor weighting was negative, rather than positive.

smallest portion of the variance among outcome measures. These similarities are of special note in that the 55 subjects in the follow-up study were also in the first study and the same linear hearing aids were worn by the participants in both studies. However, the participants, who were new hearing aid users in the initial study, had about 1 year of experience with amplification by the start of this follow-up study. The common features of the factor solutions that emerged from the data for both studies suggest that the relevant dimensions of hearing aid outcome apply to both new and experienced users of hearing aids.

Figure 4 depicts the interim results of a principal-components factor analysis for an ongoing study of hearing aid outcome measures. Results shown in this figure are for 51 hearing aid wearers with mild-to-moderate sloping high-frequency sensorineural hearing loss ranging in age from 60 to 89 years. Outcome measurements were obtained following 4 to 6 weeks of use of binaural, in-the-ear, linear (Class D) instruments with output-limiting compression. Many of the outcome measures shown along the abscissa are composite measures derived from a larger set of outcome variables. For example, the two rightmost variables represent hearing aid satisfaction as measured with the MarkeTrak IV satisfaction instrument (Kochkin,

1995). When examining outcome measures based on a larger number of hearing aid satisfaction subscales (satisfaction with cosmetics, aided performance, ease of use, costs and expenses, dispenser knowledge, quality of service, etc.), two independent satisfaction measures emerged: one related to satisfaction with all aspects of the hearing aids as instruments, such as comfort/fit, costs, performance, etc. (HAShaid) and one that involved dispenser-related variables only, such as dispenser knowledge, quality of service, etc. (HASdispnsr). The final set of outcome variables included in the factor analysis consisted of (1) two measures of aided speech recognition performance (CST at 50 dB SPL in quiet; CUNY NST [Levitt and Resnick, 1978] at 65 dB SPL in noise at a +8 dB SNR); (2) two measures of objective benefit derived by subtracting unaided performance on these two measures of speech recognition from the corresponding aided scores; (3) one measure of perceived hearing handicap (subjective aided performance; HHIE); (4) one measure of reduction in perceived handicap based on the difference between unaided and aided HHIE scores (subjective benefit); (5) one measure of subjective benefit based on the HAPI; (6) one measure of subjective use computed from daily logs of hearing aid use; (7) three measures of aided sound quality (the geometric mean of the loudness judgments for 65 dB SPL speech in
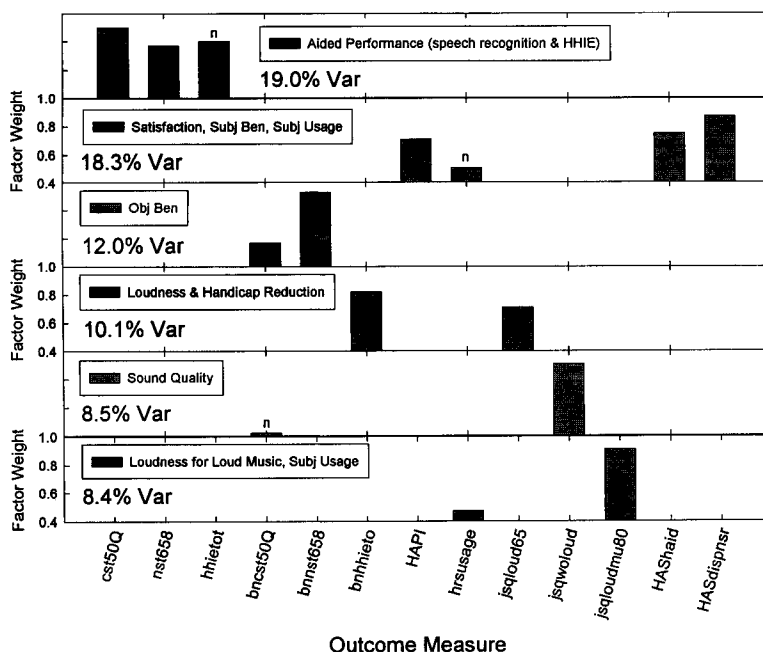

Figure 4 Illustration of the six principal components that emerged from the factor analysis of 13 outcome measures from a study with 55 users of Class D linear in-the-ear hearing aids. Factor labels and percentages of total variance accounted for are indicated in each panel. An n located above the vertical bar in a panel indicates that the actual factor weighting was negative, rather than positive.

quiet and noise and for music at 65 dB SPL; loudness for music at 80 dB SPL; and geometric mean of the seven other quality scales from the prior study computed across all four of these listening environments); and (8) two measures of hearing aid satisfaction (one expressing satisfaction with the instruments and the other with the dispenser and dispenser's services). This resulted in a total of 13 measures of hearing aid outcome for the 51 hearing aid wearers in this study.

As can be seen in Figure 4, six factors emerged from the principal-components analysis. These factors accounted for a total of 76.3 percent of the variance in these outcome measures. Once again, aided speech recognition performance emerged as a primary factor, in this case, accounting for 19.0 percent of the variance. Next, however, is a factor unique to this analysis representing hearing aid satisfaction, along with subjective use and subjective benefit (HAPI) and accounting for 18.3 percent of the variance. Although the association of performance on the HAPI and subjective estimates of use with the same factor was observed in both of the prior factor analyses (Figs. 2 and 3), here, hearing aid satisfaction, a new variable not included in the other two studies, is also loaded on this factor. The next factor, accounting for 12.0 percent of the total variance in the outcome measures, represents objective benefit, with both measures of speech recognition benefit loading on this factor. The fourth factor emerging in this analysis is interpreted as loudness and handicap reduction. This factor accounts for 10.1 percent of the variance. Next is a sound-quality factor accounting for 8.5 percent of the variance. The final factor in this analysis is also unique to this study and links hours of use with the perceived loudness of music presented at 80 dB SPL. This factor accounts for 8.4 percent of the variance.

The factors identified in Figure 4 again share some common features with those identified in the earlier analyses (Figs. 2 and 3). First, all three analyses revealed multiple independent factors underlying the various hearing aid outcome measures. The number of independent factors varied from four to seven across studies. Clearly, hearing aid outcome is multidimensional, not unidimensional. Second, the resulting factor solutions were good fits, accounting for 72.4 percent to 76.3 percent of the variance. This indicates that hearing aid outcome has a well-defined underlying structure. Third, aided speech recognition performance emerged as a major component of hearing aid outcome in all

three analyses. Fourth, objective benefit and sound quality or listening effort appear to be separate aspects of hearing aid outcome. Fifth, subjective estimates of hearing aid use, subjective benefit in a variety of listening situations (HAPI), and hearing aid satisfaction appear to be related to the same underlying outcome factor.

Several common dimensions or components of hearing aid outcome emerged in the factor analyses from the three studies examined. These common components appear to apply to both new and experienced hearing aid wearers. All three studies examined here, however, made use of linear amplification (with either a Class AB or Class D amplifier) with gain matched to targets generated by the NAL-R formula (Byrne and Dillon, 1986). Future factor analyses should be extended to other hearing aid technologies to confirm the importance of the same dimensions of outcome for these technologies. In addition, most of the results obtained here were from hearing aid wearers who had used their instruments for 4 to 6 weeks. As a result, it should be confirmed that the factors of relevance following short-term hearing aid use remain the most relevant following extended periods of use. Recall, however, that the same basic factors emerged in the first study (Fig. 2) and in the follow-up study conducted after using amplification for about 1 year (Fig. 3). This suggests that the factor structure that emerges after 4 to 6 weeks of use may be stable through the first year of hearing aid use. In addition, there is evidence that many of the outcome variables from the third study are themselves stable over at least a 6-month period following hearing aid delivery (Humes et al, 1996). It is likely, therefore, that the factor structure underlying these variables would also be stable.

Once the number of independent outcome dimensions has been further confirmed, a significant "next step" will be to determine the importance or relevance of each independent dimension. That is, from the foregoing factor solutions, it appears that sound-quality measures assess an aspect of hearing aid outcome separate from that assessed via aided speech recognition. However, are both of these dimensions of hearing aid outcome of equal importance? Which dimension is most likely to differentiate successful from unsuccessful hearing aid users?

Once the importance or relevance of various dimensions of hearing aid outcome has been established, a reasonable subsequent step would be to attempt to predict a hearing aid wearer's performance along each relevant outcome dimen-

sion from information obtained prior to hearing aid delivery or during the 30-day trial period. Consider, for example, the measurement of aided speech recognition, a component that emerged repeatedly in the foregoing analyses as a significant dimension of hearing aid outcome. It would not be at all surprising if the aided speech recognition score was found to be predictable by one or more of the following variables: (1) puretone thresholds, (2) age, (3) gain of the hearing aids, or (4) unaided speech recognition performance. All of these measures are easily obtainable prior to or during the first 30 days of hearing aid use. Of course, aided speech recognition performance can itself be directly measured during the first 30 days of use. Other dimensions of outcome, however, may be less predictable. Hearing aid satisfaction, for instance, may depend on a complex combination of severity of hearing loss, perceived handicap or need for assistance, aided sound quality, reliability or dependability of the instruments, and the personality of the wearer. Many of these variables, if found to be accurate predictors of hearing aid satisfaction, could also be measured during the first 30 days and used to predict satisfaction. Through studies such as these, the performance along dimensions of hearing aid outcome that have been identified and validated as being relevant may one day be predicted from measures obtained prior to hearing aid delivery.

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