Prediction of Benefit from Linear Hearing Aids in Nonreverberant Listening Environments

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Abstract

Hearing aid benefit, defined in terms of improved speech intelligibility, was measured for 16 elderly hearing-impaired subjects. Twelve conditions were tested, simulating a range of daily situations from typical home environments to moderate-sized social gatherings, and assuming a small talker-listener distance (thus maintaining essentially nonreverberant listening conditions). Each subject was fitted with the same type of programmable hearing aid. The goals were to develop a model for the prediction of benefit based on hearing loss, listening environment, and amplification variables, and to assess the potential accuracy of the model. Two models were developed using multiple linear regression analyses. The prefitting model used data that would be available before a hearing aid fitting, that is, audiogram and listening environment data. This model, although potentially useful as a counseling tool, was relatively inaccurate. Six of the 16 subjects yielded benefit data that were consistently different from the model's predictions. The postfitting model used information that could be obtained during a hearing aid fitting about audibility changes resulting from amplification. This model produced more accurate, but still imperfect predictions of benefit. Benefit obtained by three subjects deviated substantially from the predictions of the postfitting model. It was concluded that a model producing fairly accurate benefit predictions must encompass additional variables beyond those considered here. Nevertheless, these models may be useful for prediction of typical benefit for potential hearing aid wearers.

In everyday life, hearing aid wearers must function in a variety of listening environments, each with its own combination of signal to noise ratio, speech level, reverberation characteristics, talker intelligibility, etc. Each of these variables has an impact on the amount of benefit that an individual will realize from amplification. Because hearing aid benefit is complex, it is not possible at this time to accurately predict the amount of benefit that can be expected from a particular hearing aid fitting in various types of listening environments. The process of hearing aid fitting could be considerably refined if validated methods were available to predict benefit. This article reports an initial attempt to develop a model to predict benefit from linear hearing aids in nonreverberant listening environments.

Although there are numerous reports summarizing the subjective opinions of hearing aid wearers about the help provided by their hearing aids, relatively few objective data have been reported to indicate the benefit obtained by typical hearing aid wearers in listening conditions similar to those of daily life. In one such study, Cox and Alexander (1991) reported hearing aid benefit obtained in three typical listening environments. Benefit was defined as improvement in intelligibility of conversationally produced connected speech when amplification was used. The three environments studied were similar to a typical living room, a classroom lecture, and a cocktail party, respectively. Two of these listening environments, the living room and the cocktail party, produced results that motivated the follow-up experiment that is described in the present article.

Cox and Alexander (1991) found that hearing aid benefit was relatively large for the living room environment, but negligible for the cocktail party. Although these objective data were consistent with subjective reports of hearing aid benefit in daily life (e.g., May, Upfold, & Battaglia, 1990; Walden, Demorest, & Hepler, 1984), the sizable difference in objective benefit between living room and party environments was puzzling because both listening environments involved face-to-face communication with full visual cues under acoustic conditions that allow essentially full intelligibility for normal hearing listeners (Pearsons, Bennett, & Fidell, 1977). Also, because the talker-listener distance was small in these situations, both listening environments were essentially nonreverberant. On the other hand, because the two environments were configured to emulate real life conditions, they differed on several variables, including talker level and signal to noise ratio. In addition, a variety of hearing aids was used in the study, introducing the possibility of variations in hearing aid-related distortion; data reported by Studebaker and Marincovich (1989) suggest that distortion could be a factor influencing hearing aid

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benefit, even for properly functioning hearing aids. Finally, Cox and Alexander (1991) used matched groups of hearing-impaired subjects in the different environments. Despite efforts to control relevant variables, between-group differences on uncontrolled variables might have significantly affected the results.

A follow-up study was performed to explore more fully the determinants of objective benefit from linear hearing aids in nonreverberant listening situations. In this study, all subjects were fitted with the same hearing aid to control hearing aid-related variables such as distortion effects. To eliminate the problems of group matching, all subjects were tested under all conditions. The variables of talker level and signal to noise ratio were systematically varied through the range spanned by typical nonreverberant listening situations. The goal of the project was to explore the effects on benefit of hearing loss variables (pure-tone average and audiogram slope), environment variables (talker level and signal to noise ratio), and amplification variables (audibility changes in low-, mid-, and high-frequency regions). Based on these data, we planned to develop a model for predicting hearing aid benefit in typical nonreverberant listening situations and to assess the residual errors associated with the model for this group of subjects.

Method

Subjects

Sixteen hearing-impaired listeners were tested. Their average age was 76.2 years (SD = 6.4, range = 66-85). All had bilateral sensorineural hearing loss. On the basis of case history information, hearing loss etiologies were assumed to be either presbycusis, noise-induced, or a combination of these two. Two subjects had never owned a hearing aid. Six owned hearing aids, but used amplification less than 4 hr/day. The remaining eight were experienced in hearing aid use, reporting consistent use of amplification for 4 to 16 hr/day extending over a period of 4 to 15 years.

The group was fairly homogenous in terms of hearing loss, with mild to moderate losses sloping toward the high frequencies. Thirteen had bilaterally symmetrical audiograms; three audiograms were bilaterally asymmetric. Figure 1 illustrates the test ear audiograms of each subject.

Hearing Aid Fitting

Each subject was fitted monaurally with the same type of programmable over-the-ear hearing aid (Widex Q8) coupled to the ear using a custom earmold, vented if appropriate. The test ear was the better ear if the two ears were different; the aided ear if the subject was a monaural amplification user; the preferred ear if neither of these conditions applied; or the right ear if neither ear was preferred. There were 6 right and 10 left test ears. The instrument was configured for linear amplification and the frequency response was individually adjusted to match the frequency gain prescription produced by the National Acoustics Laboratory (NAL) procedure (Byrne & Dillon, 1986). Measurements of insertion gain were performed to verify that the fitting produced results that were reasonably similar to the prescriptive goals. Root-mean-square differences between prescribed and fitted insertion gains were 6.6, 2.7, 4.2, and 4.3 dB at 0.5, 1.0, 2.0, and 4.0 kHz, respectively. Individual differences for each subject may be found in Appendix A. For all subjects, the maximum output was set to the highest value (high-frequency average SSPL90 = 118 dB SPL in a 2 cm^3 coupler). Calculations and measurements of hearing aid performance indicated that, during testing, momentary saturation occurred rarely, if ever.

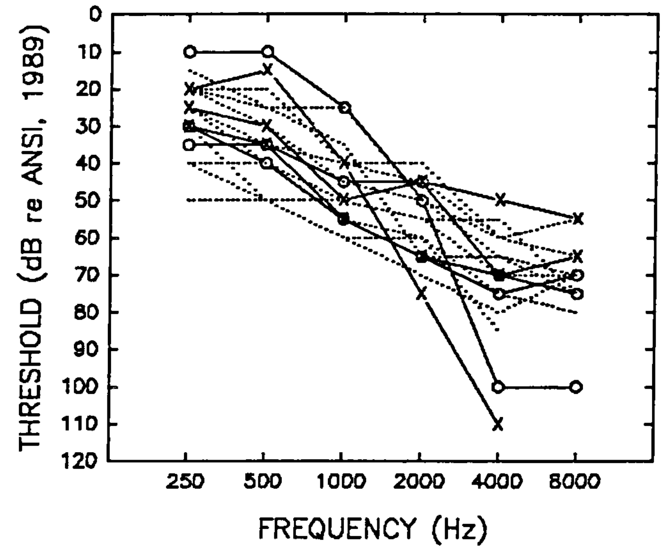

Figure 1. Audiograms of the test ear of each subject. Subjects whose audiograms are depicted with *solid lines* and *symbols* yielded anomalous benefit data (see text).

Hearing Aid Benefit Measure

Hearing aid benefit was quantified in terms of the difference between aided and unaided scores for the Connected Speech Test (CST). This test was developed as a vehicle for assessing intelligibility of conversationally produced everyday speech. Its recording and standardization have been fully described in previous publications (Cox, Alexander, & Gilmore, 1987; Cox, Alexander, Gilmore, & Pusakulich, 1988, 1989). The talker is a female who produces speech of average intelligibility. Her long-term average 1/3-octave band speech spectrum is given in Appendix A, compared with the corresponding speech spectrum assumed in the NAL procedure. The competing message for the CST is a six-talker speech babble.

The test is composed of 10-sentence passages about common topics. Before a passage is presented, the listener is shown a word describing the passage topic. A passage is presented one sentence at a time. After each sentence, both speech and babble are halted while the subject repeats the sentence or as much of it as he/she understood. Subjects are instructed to repeat every word exactly as heard. Each passage contains 25 scoring words. The test is scored in terms of the number of scoring words correctly repeated. Percent correct scores are transformed into rationalized arcsine units (rau) to minimize the relationship between mean score and variance (Studebaker, 1985). The rau scale extends from -123 to +123. Within the range from about 12 to 88, rau scores are close to the corresponding percentage scores.

The CST passages can be grouped into 12 sets of 4 passages, all sets being essentially equal in intelligibility for normal hearing and most hearing-impaired listeners. In the present study, one set of four CST passages (100 scoring words) was used in each test. The test was administered without visual cues.

Audibility Measurements

In each test condition, the ear canal sound pressure levels of speech and babble were measured separately using a probe microphone system (Etymotic ER-7). The output of the probe microphone was amplified using a sound level meter (Larson-Davis, model 800B) and delivered to a spectrum analyzer (Hewlett Packard 3561A). Ear canal RMS sound pressure levels were determined in 14 1/3-octave bands from 250 to 5000 Hz. In aided conditions, the probe tube was inserted into the ear canal via a specially drilled bore in the earmold. For measurements in unaided conditions, an additional earmold was made for each subject. This earmold was constructed to provide a minimal conduit to hold the probe tube in the ear canal without otherwise occluding the ear canal. For each subject, the probe tube was inserted to the same depth in both aided and unaided conditions (25-30 mm beyond the tragus) and it remained in place throughout intelligibility testing. Audibility of the target speech in each condition was assessed by comparing the ear canal sound pressure levels of speech, competing babble, and threshold-level tones in each 1/3-octave band. Amplification provided by the hearing aid was calculated in terms of the change in speech audibility between aided and unaided tests.

Procedures

Testing was performed in a 1.9 × 1.8 × 1.9 m audiometric test room lined with sound-absorbing foam. Ambient noise in the test room was 53 dBC/19 dBA. The target speech was presented from a small loudspeaker (Realistic Minimus 7) located 1.2 m in front of the subject. The multitalker babble was split and delivered from four identical small loudspeakers mounted in the corners around the listener at azimuths of 45, 135, 225, and 315. The frequency response of the reproduction system was essentially flat from 150 Hz to at least 13 kHz. During all tests, the nontest ear was plugged using a compressible foam earplug. The location of the subject's head was visually monitored and controlled using a headrest.

Calibration levels for speech and babble were measured at the listener's position in the unobstructed sound field. Twelve listening conditions were tested: all combinations of three talker levels of 55, 60, and 65 dBA Leq (overall sound pressure levels were about 3 dB higher than the dBA Leq level) and four signal to babble ratios (SBRs) (1, 3, 5, and 7 dB). In each listening condition, both speech intelligibility benefit and audibility changes were measured.

Data were collected in four sessions. The first session was used to assess the subject's aided preferred listening level and to permit practice listening to amplified speech via the newly fitted hearing aid. A CST passage was played repeatedly in the sound field. The subject wore the experimental hearing aid and was directed to listen, but not to repeat the words. Each of the 12 combinations of talker level and SBR was presented in turn. During the presentation of each condition, the subject was asked to indicate his/her preferred listening level for that listening environment by instructing the experimenter to raise or lower the hearing aid's volume control setting. After a preferred setting was established for a particular condition, the ear canal level of speech-plus-babble in 14 1/3-octave bands was measured using the probe microphone. After all conditions had been presented, the overall preferred level in each 1/3 octave was estimated by averaging the preferred levels in that band across the 12 test conditions. The outcome of this session was a set of 14 1/3-octave band average preferred listening levels. These were used in subsequent sessions as the target listening levels in aided tests.

Sessions 2, 3, and 4 were used for benefit and audibility testing. Each session encompassed both aided and unaided testing in all of the SBR conditions, presented in random order, for one talker level. The order of presentation of talker levels was randomized across subjects. Half of the subjects were tested first in an unaided condition. The other half were tested first in an aided condition. In each aided condition, the volume control of the hearing aid was adjusted so that the level of speech-plus-babble in each 1/3-octave band was as close as possible to the average preferred listening level established in session 1. The RMS difference between preferred and actual listening levels across the range from 250 to 4000 Hz was typically about 3.0 dB.

Ten to 12 practice CST passages were administered at the beginning of each test session. Whenever SBR conditions were changed, 4 additional practice passages were completed before data collection. When listening condition was changed from aided to unaided or vice versa, 10 to 12 practice passages were presented to reorient the subject to the new condition.

Results

For each listening condition, hearing aid benefit was computed by subtracting the intelligibility score in the unaided test from the intelligibility score in the corresponding aided test. Each subject yielded benefit data in 12 listening conditions. Figure 2 illustrates the mean benefit obtained in each combination of talker level and SBR. Inspection of this figure indicates that benefit was greatest for the low talker level and progressively less for middle and high talker levels. Furthermore, within a talker level, benefit tended to decrease as SBR changed from +7 dB to +1 dB. To determine the significance of these trends, the data were subjected to repeated measures analysis of variance with two variables (talker level and SBR). The results revealed significant effects for talker level [$F(2, 30) = 11.6$, $p < 0.01$] and SBR [$F(3, 45) = 11.5$, $p < 0.01$]. Post hoc testing, with the Student-Newman-Keuls test at $\alpha = 0.05$, indicated that significantly less benefit was obtained at the high talker level, whereas benefit did not differ significantly for the middle and low talker levels. The four SBRs produced two categories of benefit with results at +7 and +5 dB significantly higher than those at +3 and +1 dB.

During each test (aided or unaided), ear canal levels of speech and babble were measured separately. Subsequently, audibility in each 1/3-octave band was computed as follows: (1) pure-tone threshold was converted to the equivalent 1/3-octave band level [as recommended by Pavlovic (1987)], (2) this value was combined by power addition with the babble level, and (3) the result was subtracted from the 1% peaks of the talker's speech. Next, audibility change resulting from amplification was assessed for each listening condition by subtracting the audibility in the unaided test from the audibility in the corresponding aided test in each 1/3-octave band. Finally, the audibility change data were reduced to low-, mid-, and high-frequency regions: low-frequency audibility change was determined by summing data for the five bands from 250 to 630 Hz and dividing the result by five, producing a value in decibels per 1/3-octave band in this frequency region. A similar procedure was followed to generate mid-frequency (800-1600 Hz) and high-frequency (2000-5000 Hz) audibility changes.

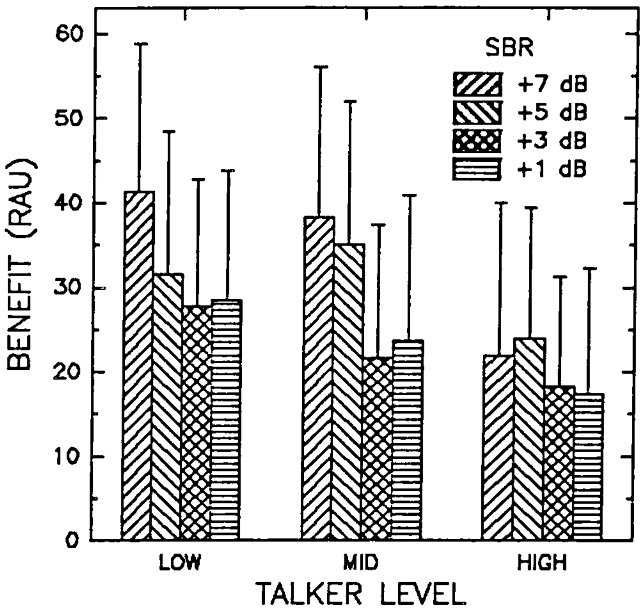

Figure 2. Mean hearing aid benefit obtained in each combination of talker level and SBR. Error bars give 1 SD. Low=55 dBA Leq, mid=60 dBA Leq, high=64 dBA Leq.

Figure 3 depicts mean audibility changes resulting from amplification (i.e., the difference in audibility between aided and unaided conditions). Data are given in the three frequency regions for each combination of talker level and SBR. As this figure reveals, audibility changes were greatest in the midfrequency region and least in the low-frequency region. Overall trends are seen for audibility changes to decrease as talker level increased and as SBR decreased. Results for each frequency region were subjected to repeated measures analysis of variance with the variables talker level and SBR. Student-Newman-Keuls post hoc testing ($\alpha = 0.05$) was used to explore significant main effects. The results indicated that audibility changes declined significantly with each decrease in SBR for all three frequency regions. In addition, audibility changes were significantly greater for the low talker level than for the high talker level in both the mid- and

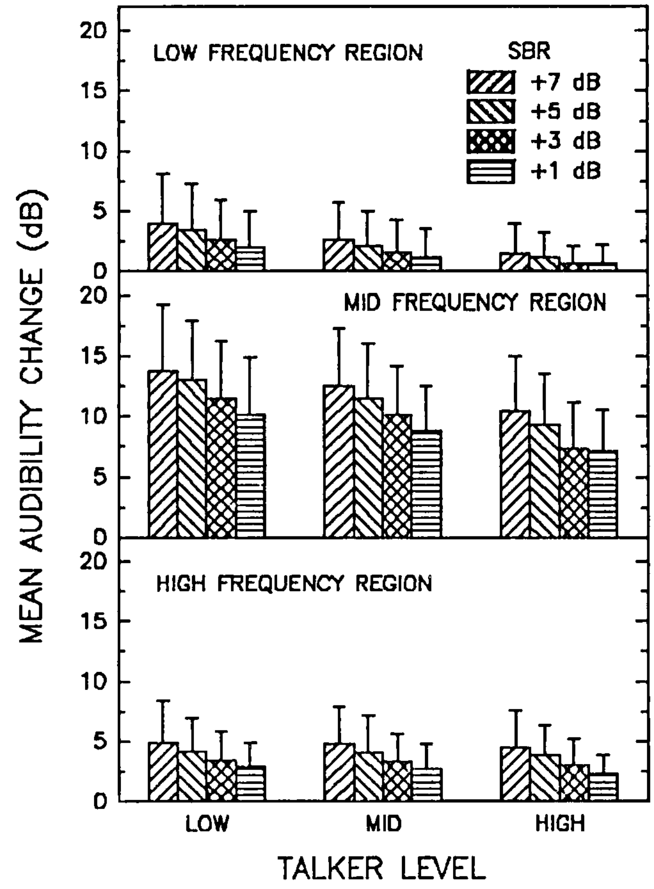

Figure 3. Mean audibility changes resulting from amplification. Data are decibels per 1/3-octave band in low-, mid-, and high-frequency regions for each combination of talker level and SBR. Error bars give 1 SD.

low-frequency regions. However, in the high-frequency region, mean audibility changes did not vary significantly across talker levels.

The primary goal of this study was to explore the development of a model to predict benefit (as measured by the CST) based on audiogram, environment, and amplification variables. This was addressed by conducting stepwise multiple linear regression analyses. Most of the analyses were performed using the combined data from all 16 subjects for all 12 conditions. Inclusion of several data sets from each subject in the multiple regression analyses had the substantial advantage of allowing investigation of the contributions of individual subjects, as discussed below. However, one problem that can occur with this procedure is the generation of multicolinear independent variables, which, if present, could lead to an inaccurate result. Multicolinearity was assessed by examining the intercorrelations among the independent variables and by employing a statistical analysis program (SPSS/PC+) that tested the tolerance of each independent variable before allowing it to enter a regression equation. For all analyses, a relatively stringent criterion was adopted for entry into the equation (significant F change ≤ 0.01). Table 1 shows the linear correlation coefficients among the variables. None of the correlations between independent variables was high. The highest correlations were seen among pure-tone average [PTA; mean pure-tone threshold (dB HL re ANSI, 1989) at 500, 1000, and 2000 Hz], audiogram slope (dB/octave), and A-lo and A-mid (audibility changes in low- and mid-frequency regions, respectively). A-mid was the variable correlating most highly with benefit.

In the first multiple regression analysis, we evaluated the accuracy of benefit predictions based on variables that would be known or projected before the hearing aid fitting. These include hearing loss, as reflected in audiogram slope and PTA, and listening environment, reflected in SBR and talker level [it is possible, using published data, to estimate both talker level (TKR) and SBR in many typical daily listening situations (eg., Pearsons et al, 1977; Teder, 1990)].

A multiple regression encompassing hearing loss and environment variables was performed. The results indicated that three of the four variables contributed significantly to prediction of benefit and together accounted for 31% of the variance in benefit. The variables were PTA (16.8%), TKR (7.8%), and SBR (6.5%). The regression equation to predict benefit in rationalized arcsine units was

$$\text{Benefit (rau)} = 0.59\ (\text{PTA}) - 1.8\ (\text{TKR}) + 1.99\ (\text{SBR}) + 66 \tag{1}$$

Because the data file included nonindependent data sets, the standard error of estimate (SEE), computed in the usual way, provided an optimistic estimate of the goodness-of-fit of this equation to the data for the 16 subjects. In an attempt to generate a more realistic estimate of the SEE, the corpus was

Table 1. Linear correlation coefficients among variables. Slope, audiogram slope (dB/octave); Tkr, talker level; A-lo, audibility change in the low-frequency region; A-mid, audibility change in the midfrequency region; A-hi, audibility change in the high-frequency region; Ben, hearing aid benefit.

	Slope	Tkr	SBR	A-lo	A-mid	A-hi	Ben
PTA	−0.60	0	0	0.59	0.68	0.17	0.41
Slope		0	0	−0.33	−0.52	−0.43	−0.33
Tkr			0	−0.27	−0.29	−0.07	−0.28
SBR				0.18	0.29	0.30	0.26
A-lo					0.53	−0.04	0.48
A-mid						0.44	0.64
A-hi							0.30

subdivided into 12 separate data files, each composed of one set of data, randomly chosen, from each subject. The SEE associated with equation 1 was then computed for each of the 12 data files and the 12 SEEs were combined. Using this approach, the SEE for equation 1 was 15.4 rau.

In evaluating the size of the SEE, it is important to consider the expected variability of the benefit data due to factors such as CST passage set equivalence and measurement error. It would be unreasonable to expect the SEE of a prediction equation drawn from these data to be smaller than the expected measurement errors in the data themselves. To assess errors in the benefit measurements, the SD of the distribution of repeated benefit measurements for a typical individual was determined, based on the SD of repeated scores for hearing-impaired listeners responding to four CST passages (Cox et al, 1988). The value established was 7.8 rau. This value reflects earphone listening conditions. An additional source of variability in the present study was that associated with sound field listening. Because subject position was carefully monitored, this variability component was not expected to be large. Overall, it seems reasonable to estimate the SD of repeated benefit measurements for a typical individual in this study as 10 rau.

Comparing the SEE for equation 1 (15.4 rau) with the expected variability of the actual benefit measurements (SD = 10 rau), it is clear that equation 1 falls considerably short of predicting benefit as accurately as we would wish (with fairly accurate benefit prediction, the SEE would approach the expected error of measurement). We concluded that benefit prediction based on hearing loss and environmental variables was not very precise for the group of subjects taken as a whole.

As mentioned above, because the data file contained several data sets from each subject, it was possible to investigate the extent to which subjects were similar to each other in terms of the accuracy with which the independent variables could be used to predict benefit. To allow the evaluation of individual subjects, an indicator variable was created for each subject and included in regression analyses. If a particular subject performed systematically differently from most other subjects, the variable representing that unique subject appeared in the multiple regression equation.

Additional multiple regression analyses, including subject indicator variables, were performed. The results revealed that variables representing 6 of the 16 subjects appeared in the regression equations. This result indicated that the performance of these 6 individuals was not well described by a model based on PTA, SBR, and TKR. Three of these, shown in Figure 1 with O-symbols, consistently obtained substantially less benefit than predicted whereas the other three, also shown in Figure 1, with X-symbols, consistently obtained substantially more. Examination of Figure 1 indicates that the anomalous subjects could not be distinguished from the rest of the group based on audiogram data.

Next, the analyses explored the improvement in benefit prediction that could be obtained when amplification data were available. These types of data could be gathered at the time of the hearing aid fitting. A stepwise multiple regression analysis was performed, including the data on audibility changes in low-, mid-, and high-frequency regions as well as the hearing loss and environment variables. The results indicated that two variables made a significant contribution to the prediction of benefit and together accounted for 44% of the variance in benefit. The variables were A-mid (41%) and A-lo (3%). The regression equation is given below.

$$\text{Benefit (rau)} = 1.97\,(\text{A-mid}) + 1.15\,(\text{A-lo}) + 4.5 \tag{2}$$

The SEE associated with equation 2, computed in the same manner as described for equation 1, was 14.1 rau, a value somewhat smaller than that seen for equation 1.

To explore the performance of individual subjects, the multiple regression analysis including hearing loss, environment, and audibility data was repeated with the addition of subject indicator variables. On this occasion, three subjects were singled out by the analyses as presenting unusual results. Furthermore, when these subjects' effects were isolated by the analysis, the regression equation for the remaining 13 subjects simplified to

$$\text{Benefit (rau)} = 2.16\,(\text{A-mid}) + 7.5 \tag{3}$$

and the SEE was reduced to 13.2 rau. Each of the three anomalous subjects obtained consistently less benefit than predicted by equation 3. The same three subjects produced abnormally poor performance when equation 1 was used to predict benefit (Fig. 1).

Discussion

Cox and Alexander (1991), using linear hearing aids, a similar prescriptive procedure, and similarly impaired subjects, measured mean hearing aid benefit of 23 rau in a living room type of listening environment and -1 rau in a cocktail party type of setting. In the present study, these environments were simulated in an audiometric test room. The condition with low talker level and 7 dB SBR corresponded to the living room type of environment, and the condition with high talker level and 1 dB SBR was analogous to the party environment. Inspection of Figure 2 reveals that mean hearing aid benefit in these two conditions was 41 rau in the simulated living room and 17 rau in the simulated cocktail party. Thus, in both listening environments, mean benefit in the present study was 18 rau more than in the previous study.

One might speculate that this difference between studies arose because the present study was conducted in simulated rather than real listening environments. However, Cox, Alexander, and Rivera (1991) found that nonreverberant listening environments could be simulated very accurately in an audiometric test room and that speech intelligibility was essentially the same in the real and simulated conditions. As a result, the use of simulated listening environments does not seem likely to be responsible for the difference in outcome between studies.

The explanation for this difference probably lies in the treatment of the nontest ear, which differed in the two investigations. In the previous study, subjects listened with the nontest ear open, as occurs in daily life. Because their hearing losses were generally symmetrical, this resulted in binaural listening in unaided tests. During aided testing, however, any contribution from the nontest ear would be reduced because of the asymmetry produced by monaural amplification. In the present study, in order to control audibility changes, subjects were restricted to monaural listening by plugging the nontest ear in both aided and unaided tests. This difference between the two investigations produced the potential for a binaural advantage during unaided testing in the earlier study, but not in the present study. During aided testing, on the other hand, conditions in the two studies were more alike. Assuming a CST performance-intensity function slope of 8.5 rau/dB, as found by Cox et al (1988), the benefit difference between studies of 18 rau is equivalent to a SBR change of 2.1 dB. This value can quite reasonably be attributed to the unaided binaural advantage that was available in the earlier study, but not in the present study.

Once the difference in unaided listening conditions is accounted for, the outcomes of the two studies are rather consistent. These considerations suggest that the equations from the present study are probably directly applicable to: (1) persons with asymmetric hearing loss and monaural amplification on the better ear, and (2) individuals with symmetric hearing loss and binaural amplification (assuming equal binaural advantage in aided and unaided conditions). On the other hand, if the equations are used to predict benefit when a monaural hearing aid is used with a symmetric hearing loss, it will be necessary make a correction to account for the loss of binaural advantage when moving from unaided to aided listening. Although further research is necessary to fully explore this issue, comparison of the results of Cox and Alexander (1991) to those of the present study suggests that the loss of binaural listening when the hearing aid is worn will result in a reduction in benefit of 18 rau, on average.

Two models to predict benefit were developed from the regression analyses: one that could be used before the hearing aid fitting (the prefitting model) and one that could be used after a hearing aid was fitted and measurements were made of audibility changes resulting from amplification (the postfitting model). The prefitting model, exemplified by equation 1, requires only a knowledge of the subject's audiogram and a description of listening environments in which benefit prediction is desired. The disadvantage of this model is its lack of precision. Thirty-eight percent of the subjects were shown to yield an amount of benefit that deviated systematically from its predictions. These types of results are well known to practicing audiologists who often find that their initial informal prediction of likely benefit is substantially surpassed or undershot by individual clients. Thus, the use of the prefitting model should probably be restricted to counseling about results obtained by typical hearing aid wearers.

Nevertheless, the model could be useful within this constraint. For example, an individual with symmetrical hearing loss and PTA = 45 dB who works as a sales clerk in a department store may wish for an estimate of the benefit that a typical hearing aid wearer would obtain in that situation. If we assume (1) that this individual would wear a monaural linear hearing aid, fit rather accurately according to the NAL prescriptive method, and (2) the mean talker level and SBR in the department store are 58 dBA Leq and +4 dB, respectively (Pearsons et al, 1977), then the predicted benefit would be about 14 rau (32 rau from eq. 1 minus 18 rau to account for the loss of binaural listening, as discussed above). As long as neither aided nor unaided intelligibility scores approach the extremes of the measurement range, 14 rau would be similar to 14%.

If a benefit prediction is desired after a hearing aid is fitted, the postfitting model (eq. 2) would be appropriate. One potential disadvantage of this model is its requirement for an estimate of the extent to which amplification improves the audibility of the speech signal in the listening environments of interest. However, these data are not difficult to obtain using an in situ output probe microphone measurement procedure similar to the one described by Cox and Alexander (1990), combined with listening environments simulated in an audiometric test room, as described by Cox et al (1991).

Because it includes information derived from the individual hearing aid fitting, it is reasonable to expect that the postfitting model would produce a more accurate prediction of benefit than the prefitting model. This expectation is supported by the smaller SEE associated with equation 2 than with equation 1. Furthermore, in equation 2, variables describing mid- and low-frequency audibility changes with amplification replaced the variables for hearing loss (PTA), talker level (TKR), and SBR that appeared in equation 1. We may conclude that when audibility change data were available, these three variables (PTA, TKR, and SBR) became superfluous for benefit prediction. However, it is important to note that this conclusion applies only to conditions in which subjects are accurately fitted to the NAL prescription and gain is then adjusted to the preferred listening level for the simulated environment.

It is also of interest to note that when audibility change was available as the predictor of benefit, none of the subjects consistently obtained more benefit than predicted. Thus, the three subjects whose performance surpassed that predicted by equation 1 were not unusual when evaluated using equation 2. This outcome suggests that, after gain adjustment to the preferred listening level, the audibility changes achieved by these subjects were relatively large, resulting in relatively large benefit. The results for these three subjects demonstrate the kinds of improvements in benefit prediction that can be realized with a model that incorporates individualized amplification variables. The predominance of audibility variables in determining benefit is consistent with a report by Studebaker and Marincovich (1989), who determined that importance-weighted audibility accounted for 90 to 95% of the variance in recognition of hearing aid-processed nonsense syllables by normal-hearing listeners.

Audibility changes in the high-frequency region were not predictive of benefit, despite the fact that fairly large changes were observed and intersubject variability was sizable, as shown in Figure 3. This outcome was somewhat surprising because conventional wisdom holds that improvements in high-frequency audibility are essential in securing adequate hearing aid benefit for many individuals. Hearing aid prescriptive methods have tended to place considerable importance on high-frequency gain, at least since the work of Pascoe (1975) demonstrated that improved high-frequency gain was associated with increased recognition of high-frequency-loaded monosyllabic words. Why, then, was increased high-frequency audibility not specifically associated with greater hearing aid benefit in the present study? Several issues should be considered in attempting to answer this question.

First, the type of speech used as the test material may have influenced the result. Studebaker, Pavlovic, and Sherbecoe (1987) have reported that audibility in the high-frequency region is less important for speech understanding when the test material is continuous discourse rather than monosyllabic words. In fact, their study suggests that low-frequency audibility is at least as important as high-frequency audibility for understanding connected speech similar to that of the CST.

Second, two recent studies (Cox & Alexander, 1992; Gatehouse, 1992) have reported that hearing aid benefit increases over the first few months of hearing aid use. Other studies have also reported that even when speech cues are audible, they may not be utilized by hearing-impaired listeners (e.g., Stelmachowicz, Lewis, Kelly, & Jesteadt, 1989; Turner & Robb, 1987; Zeng & Turner, 1990). Both groups of studies are consistent with a hypothesis that ability to utilize newly audible high-frequency speech cues develops over a period of time. This hypothesis suggests that although high-frequency audibility change may not be predictive of benefit soon after the hearing aid is fitted (as occurred in the present study), this variable may become more significant after the hearing aid has been worn for 10 to 12 weeks.

It is troublesome to reconcile the above hypothesis with the fact that eight of the subjects were experienced hearing aid wearers. Presumably, their own hearing aids provided some high-frequency audibility (we did not compare the high-frequency gain of these subjects' own hearing aids with that of our experimental instrument). However, it is probable that, due to careful fitting procedures, the experimental hearing aid supplied more high-frequency gain than the subjects' own hearing aids. Gatehouse (1992) reported that several weeks of adjustment were necessary before the benefits of increased high-frequency gain could be measured, even among experienced hearing aid wearers.

Last, it should be noted that if high-frequency audibility were strongly associated with midfrequency audibility, this could explain its failure to appear in equation 2 in addition to A-mid. However, Table 1 reveals that the relationship between A-mid and A-hi was weaker than that between A-mid and A-lo, both of which did appear in the equation.

Although equation 2, based on audibility, was a more accurate predictor of benefit than one based on hearing loss and environmental variables (eq. 1), it is important to keep in mind that 19% of the hearing-impaired subjects in the present study yielded benefit data that were not consistent with the predictions of equation 2. All of these subjects obtained substantially less benefit than the audibility-based model would predict. This outcome suggests that, for a fairly large proportion of hearing aid wearers, measures of audibility change alone will not allow an accurate prediction of benefit in various environments. Furthermore, it was not possible to identify these subjects in advance: they were not remarkable in terms of audiograms (Fig. 1), etiology of hearing loss (noise induced = 2, presbycusis = 1), age (65, 68, and 84), or other demographic variables that were considered. None of the three was a regular hearing aid wearer, although one of them owned a hearing aid that he reported wearing < 4 hr/day. The two others did not own hearing aids. We must conclude that one or more additional, unmeasured variables were operating to restrict the benefit available to these three individuals.

Several investigators have suggested that auditory resolution variables are related to speech understanding and/or hearing aid benefit in the elderly hearing impaired. For example, Gatehouse (1991) reported that frequency resolution accounted for a substantial proportion of the variance in benefit from experimental amplification. Also, Humes and Christopherson (1991) reported that temporally based processing accounted for a significant proportion of the variance in speech intelligibility of elderly hearing-impaired listeners. These results are consistent with a hypothesis that unusually poor auditory resolution abilities may have been responsible for the limited benefit obtained by the three subjects who were not well described by equation 2. Additional research will be necessary to evaluate this hypothesis.

When the three aberrant subjects were removed from consideration, equation 3 emerged as the best predictor of benefit for the remaining 13 individuals. Because it applies only to a subset of the subjects, equation 3 could not be widely applied in practice. Nevertheless, this equation is interesting because it yields the most accurate predictions of benefit that could be obtained with this subgroup of typical subjects, based on the independent variables selected for study. Even this equation was associated with a relatively large SEE (but it should be kept in mind that variability associated with the speech intelligibility measurements accounts for some of the apparent inaccuracy of these equations, as noted earlier). This outcome indicates that, even for typical subjects, benefit predictions based on hearing loss and environmental and amplification variables alone was not very precise. Future research should develop methods to include other variables, such as auditory resolution or cognitive abilities, that might make a significant contribution to the prediction of hearing aid benefit.

Conclusions

Overall, the results of this study indicate that benefit from linear hearing aids in nonreverberant listening environments can be predicted in a general way from audiogram and environment variables. Predictive accuracy is improved if individualized amplification variables are available. However, benefit could not be predicted with even moderate accuracy for 3 of the 16 subjects, or about 19%. Further research is needed to explore the applicability of the prefitting and postfitting models to a larger number of hearing aid wearers as well as to include additional variables in an attempt to improve the predictions. Other issues of future concern include the extension of the models to listening conditions not yet tested, such as compression hearing aids and reverberant listening situations.

In the meantime, if equations 1 and 2 are used to provide general estimates of benefit, it is necessary to keep certain limitations in mind. These models apply only to linear hearing aids with gain prescriptions derived using the NAL procedure and SSPL90 settings high enough to prevent significant distortion of speech delivered at the preferred listening level. In addition, the predictions apply to amplification used in listening situations in which the talker-listener distance is quite small (to maintain nonreverberant listening conditions). Furthermore, the application is specific to elderly individuals with mild to moderate sensorineural hearing loss. Finally, care should be taken to correct the results for loss of binaural listening when a monaural hearing aid is used with a bilaterally symmetrical hearing loss.

The talker levels used in this study cover the range of levels from normal conversation to raised voice. Also, the SBRs span those found in typical home environments to moderate-sized social events (Pearsons et al, 1977; Plomp, 1977). These probably encompass many of the situations in which hearing aids would be worn. However, speech levels higher than those used in this study have been reported in transportation vehicles and large gatherings (e.g., Teder, 1990). Extrapolations of the equations to situations with speech levels or SBRs outside the range used in this study should be made with caution.

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Appendix

Table A1. Differences between prescribed and fitted insertion gain (dB) for each subject at four frequencies.

	Frequency (kHz)			
Subject	0.5	1.0	2.0	4.0
1	−3	2	3	0
2	−16	−2	6	1
3	−3	4	1	−4
4	0	0	−3	0
5	0	−4	0	1
6	−1	2	4	0
7	2	−5	6	−4
8	−7	4	−3	5
9	−14	−2	5	−8
10	−5	0	4	−8
11	−5	1	2	−5
12	0	3	−7	−8
13	−10	−3	7	0
14	−2	2	2	−1
15	−4	−2	0	0
16	1	2	5	−4

Table A2. Long-term average RMS ⅓-octave band speech spectrum of the CST talker compared with the speech spectrum assumed in the NAL procedure. Overall level = 70 dB SPL.

⅓-Octave Frequency	CST Talker	NAL Spectrum
200	63	63
250	65	62
315	48	60
400	59	62
500	61	61
630	61	58
800	57	55
1000	55	50
1250	54	51
1600	53	51
2000	48	49
2500	47	48
3150	44	47
4000	40	48
5000	39	45
6000	44	46