Hearing Aid Benefit in Everyday Environments

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ABSTRACT

Hearing aid benefit was measured for three matched groups of eleven hearing-impaired subjects, each serving in one typical listening environment. Benefit was quantified in terms of improvement in intelligibility score for the Connected Speech Test. Each subject was individually fitted with three hearing aids, differing in nominal frequency response slope by a total of 8 dB/octave. Research questions centered on the amount of benefit typically realized in everyday environments and the interactions of this benefit with frequency response and/or visual cues. Results revealed: (1) mean benefit in a living-room type setting was about 24% and significantly greater than in a reverberant setting (7%) and a noisy setting (−1%); (2) despite the relatively large mean difference in benefit between the reverberant and noisy environments, the difference was not statistically significant ($p > 0.05$); (3) the addition of visual cues did not change hearing aid benefit in any tested environment; (4) there was no significant overall trend for any of the three different frequency-response slopes to give superior benefit in any environment; (5) 76% of the subjects achieved significantly different benefit ($p < 0.05$) in at least one hearing aid condition when data were considered on an individual basis; and (6) articulation indices in the aided conditions did not successfully predict the observed within-subject benefit differences. Benefit was significantly related to speech reception threshold in the living-room environment. However, in the less favorable environments, benefit and hearing loss were not related despite the fact that benefit varied considerably across subjects. (Ear Hear 12 2:127–139)

FOR THE MAJORITY of adults with postlingually acquired hearing loss, the most desired outcome of hearing aid use is improved ability to understand speech in everyday life (Barcham & Stephens, 1980; Golabek, Nowakowska, Siwiec, & Stephens, 1988; Hagerman & Gabrielsson, 1984). Thus, the benefit provided by a hearing aid is largely determined by the extent to which it facilitates everyday communication. In recognition of this, hearing aid selection procedures typically aim to prescribe an instrument that will maximize speech understanding. There are now a large number of different hearing aid prescription methods, all of which attempt to achieve this goal.

Because improved communication is the primary goal of amplification, comparison of different hearing aid prescription methods and the validation of any particular hearing aid fitting both call for quantification of aided speech understanding or aided benefit (benefit is defined as the difference between aided and unaided speech understanding). Traditionally, this has involved either objective measurement of speech understanding within a clinical/laboratory setting (e.g., determining the percentage of monosyllabic words correctly repeated), or subjective measurement of speech understanding in everyday settings through the use of self-assessment tools such as questionnaires. Each type of measurement has advantages and drawbacks.

Objective measurements in the laboratory setting, typically an audiometric test room, are easy to administer in a controlled manner. Variables such as frequency response can be manipulated and the effect on speech understanding can be measured. The main problem with this type of measure is the uncertainty with which the results can be generalized to everyday life settings containing background noise and reverberation as well as different talkers, speech materials, gain settings, and so forth. Investigations that have attempted to determine the relationship between laboratory measurements of aided speech understanding and self-assessed aided benefit have usually not found a high correlation between these two types of data (Berger & Hagberg, 1982; Haggard, Foster & Iredale, 1981; Oja & Schow, 1984). This outcome suggests that the traditional measurements of aided speech understanding may not result in accurate estimates of the amount of benefit to be expected in everyday living.

Self-assessment inventories have been widely used in attempts to quantify hearing aid benefit in everyday life (Hutton & Canahl, 1985; Walden, Demorest & Hepler, 1984; and others). In this approach, subjects respond to items that solicit their opinions about the extent to

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which the hearing aid improves their functioning in a variety of situations. The main advantage of self-report data is high content validity. When the questions directly address everyday situations in which speech understanding can be a problem, this type of measure may result in valid quantification of hearing aid benefit. However, it is not known whether the typical hearing aid wearer is able to estimate accurately the benefit derived from hearing aid use. Scherr, Schwartz, and Montgomery (1983) concluded that their respondents were actually judging absolute intelligibility in the various situations rather than assessing the contribution of the hearing aid to that intelligibility. In this event, self-assessed hearing aid benefit would appear least in situations with poor inherent intelligibility (e.g., noisy settings). Also, factors not relevant to the hearing aid's benefit (subject expectations, memory for benefit, attitude toward impairment) may influence an individual's self-reported benefit. The importance and pervasiveness of these nonauditory factors in responses to questionnaires about hearing aid benefit have not been reported.

There appear to be no documented studies in which hearing aid benefit has been measured objectively in everyday environments. These kinds of data are desirable for several reasons. First, despite all the effort that has been expended in laboratory measurement of hearing aid benefit, we do not know the percentage of improvement in everyday speech understanding that typically can be anticipated as a result of hearing aid use in various types of situations. Second, objective data on benefit in everyday settings could be used for criterion validation of both laboratory-measured and self-assessed benefit. Finally, objective measurements of hearing aid benefit in everyday settings can combine the best features of the laboratory and self-report approaches described above: variables such as hearing aid frequency response and access to visual cues can be controlled and their effects can be assessed in realistic acoustic settings.

The investigation described here was undertaken as a result of these considerations. Aided and unaided speech understanding were measured for hearing-impaired listeners in three typical listening environments. These environments are representative of most of the acoustic settings in which hearing aid wearers function daily. The talker and speech stimuli were chosen to maximize the generalizability of the results to other everyday settings.

In addition, the contribution of visual cues to hearing aid benefit was assessed. Haggard et al (1981) found that objectively measured hearing aid benefit (improvement in speech understanding) was less when visual cues were available to the listener than when they were not, but not significantly so. However, Walden et al (1984) reported a significant increase in self-assessed hearing aid benefit when visual cues were available.

Moreover, frequency response slope was varied in an attempt to explore a hypothesis that the optimal frequency response is different in different acoustic environments. This hypothesis was suggested by the outcome of several previous studies. Lindblad, Haggard, and Foster (1983) presented data suggesting that the optimal frequency response is different when visual cues are available versus unavailable. Harris and Goldstein (1979) and Logan, Schwartz, Ahlstrom, and Ahlstrom (1984) reported data showing that the hearing aid that scored best in a naturally reverberant room was not always the best-scoring aid in an audiometric test room. These observations suggest that a hearing aid that is optimal in one setting, such as a typical living room, may not be optimal in another everyday setting such as a lecture hall.

The primary research questions may be summarized as follows:

1. How much benefit is typically obtained in everyday settings from newly fitted hearing aids; that is, what percentage of improvement in speech understanding can be anticipated?
2. Is hearing aid benefit different in different environments or is the typically reported difference in self-assessed benefit due to variations in absolute performance rather than in benefit?
3. Is hearing aid benefit more, less, or the same when the talker's face is visible as it often is in real life situations?
4. Is the optimal frequency-response slope different; (a) in different environments, or (b) in the same environment when visual cues are available?

METHOD

Subjects

Three groups of 11 subjects each served in the study. They are referred to as groups A, B, and C, according to the acoustic environment in which they served. The groups were matched as closely as possible in terms of audiometric configuration, speech reception threshold, word discrimination, and age. Each group comprised 5 individuals with speech reception threshold (SRT) <40 dB HL (re: ANSI, 1969) and 6 persons with SRT = 40 to 60 dB HL. Audiogram slopes from 500 to 4000 Hz were divided into three groups: flat = ±7 dB/octave; moderately sloping = 8 to 19 dB/octave; sharply sloping = 20+ dB/octave. Groups A and C contained 2 flat, 6 moderately sloping, and 3 sharply sloping. For group B the tallies were 2, 5, and 4, respectively. Figure 1 illustrates composite audiograms for test ears in each group. *Open symbols* portray the subjects with SRT <40 dB. *Filled symbols* portray the subjects with SRT = 40 to 60 dB. All hearing losses were essentially sensorineural. Most of the subjects had bilaterally symmetrical audiograms, five had SRTs more than 15 dB different in the two ears. Thirty-two of the subjects were 55 to 83 years old, one subject was 36. The mean ages of the groups were 72, 69, and 64, respectively. Mean SRTs were 41, 40, and 37, respectively. Mean monosyllabic word discrimination scores in quiet were 77, 72, and 77%, respectively.

All of the subjects were hearing aid candidates, in the author's opinion. However, not all were hearing aid wearers. Each group contained three or four persons who did not use amplification. The rest had worn hearing aids for varying periods. All of the subjects had been hearing impaired for at least several years. Most of the subjects were rather vague about the etiology of their impairments, although about half

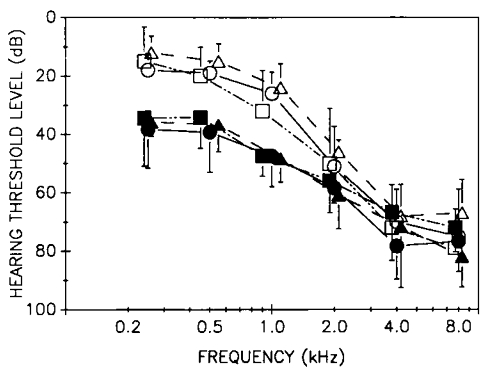

Figure 1. Composite audiograms for subjects. *Open symbols* portray subjects with SRT <40 dB HL. *Filled symbols* portray subjects with SRT = 40 to 60 dB HL. Environment A subjects are shown with *circles*, environment B subjects are shown with *triangles*, environment C subjects are shown with *squares*. Error bars give 1 SD.

were able to report some history of noise exposure, especially to gunfire. Because of the lack of clear precipitating factors, it was presumed that most of the subject's hearing losses were due to presbycusis, perhaps combined with noise exposure. Near and far vision was screened for all subjects. Near vision ranged from 20/20 to 20/30. Far vision ranged from 20/20 to 20/80.

Hearing Aids

Three frequency gain prescriptions, encompassing eight test frequencies from 250 to 6300 Hz, were derived for each subject. The first followed the MSU hearing aid prescription procedure, version 3.0 (Cox, 1988). This prescription, and the hearing aid chosen to implement it, are identified as HAO. The second frequency gain prescription differed from that of HAO by −4 dB/octave. This negative slope prescription and hearing aid are identified as HAN. The third frequency gain prescription differed from that of HAO by +4 dB/octave. This positive slope prescription and hearing aid are identified as HAP. Thus, the three prescriptions for each subject covered a slope range of 8 dB/octave.

The gain values of the HAN and HAP prescriptions were adjusted in an attempt to maintain equal loudness among the three prescriptions despite their differing slope. Gain was adjusted for the HAN and HAP prescriptions so that the average gain at 1000, 1600, and 2500 Hz was equal to the analogous average for the HAO prescription. This strategy was derived from data reported by McDaniel (1988) in which hearing-impaired listeners adjusted the gain of three hearing aids differing from each other by a total of 6 dB/octave until amplified speech shaped noise was equally loud with all three instruments.

Earmolds were obtained for each subject; they were vented if this would have been appropriate in normal clinical practice. Each subject was fitted monaurally with three different hearing aids, one for each prescription. In cases of symmetrical hearing loss, the fitted ear was chosen randomly. Most of the subjects with assymetrical hearing loss were fitted in the better ear but one subject was fitted in the poorer ear (for this subject, the better ear was plugged during all testing).

All hearing aids were over the ear, nondirectional, linear, analog, or hybrid digital instruments in good working order. A total of 18 different hearing aid models were used in fitting the 33 subjects. Each fitting was validated using an in situ output probe microphone procedure that has been fully described elsewhere (Cox & Alexander, 1990). Earmold modifications and damping elements were used as necessary to improve the match between the prescription and the fitting. The quality of the match between prescription and fitting was expressed in terms of the RMS error at five test frequencies between 500 and 2500 Hz. Mean RMS errors in decibels (with standard deviations in parentheses) were 4.71(1.62), 4.47(2.03), and 4.24(2.03) for HAN, HAO, and HAP, respectively.

The maximum output of each hearing aid was set at its highest value. This was considered appropriate because none of the testing involved high level signals and we wished to avoid the interpretation problems that could arise if the dynamic range of the amplified signals was restricted.

Stimuli

Speech understanding in the three environments was quantified using the Connected Speech Test (CST). This test, its recording and standardization, has been fully described in previous publications (Cox, Alexander, & Gilmore, 1987; Cox, Alexander, Gilmore, & Pusakulich, 1988, 1989). Briefly, the talker for this audiovisually recorded test is a female who has been empirically determined to produce speech of average intelligibility (Cox et al, 1987). The test is composed of 10 sentence passages about common topics. The listener is informed of 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 passages are grouped into eight sets of six passages. All sets are essentially equal in intelligibility for normal hearing and most hearing-impaired listeners. The test may be presented audiovisually or audio-only.

The competing message for the CST is a six-talker speech babble. In this study, the competing babble channel was split and delivered to four loudspeakers to produce the background noise in each environment. This resulted in background noise sources that were correlated to some extent when they reached the listener's ear. Normal hearers could profit from correlated noise sources, using interaural phase and intensity differences to reduce the effective level of the competition. However, because the hearing-impaired subjects were listening monaurally, this factor is not considered to have compromised the validity of the test environments. In addition, even when listening binaurally, hearing-impaired individuals often cannot utilize interaural cues in the same way as normal-hearing listeners do (Cox & Bisset, 1984).

Environments

Three everyday environments were defined for evaluation. Both theoretical considerations and the data of Walden et al (1984) suggest that these environments place distinctly different demands on the listener and together represent a large proportion of the everyday listening situations experienced by the typical hearing aid wearer. In each environment, the data of Pearsons, Bennett, and Fidell (1977) were used to determine appropriate speech and background noise levels, as well as appropriate talker-listener distance. The levels and distances used were those reported by Pearsons et al to be maintained by talkers and listeners in everyday environments to allow essentially complete intelligibility for conversations in that setting. In all environments, the signal source was located in the middle of the room.

Environment A represented a communication situation in which speech is at normal or casual conversational level, visual cues are fully available, and background noise and reverberation are relatively low. Examples of environment A include face to face conversation in a typical living room or quiet office. The level of the CST passages was 55 dB L_{eq} (L_{eq} = equivalent continuous dBA level) and the multitalker babble was delivered at 48 dB L_{eq} (both measured beside the listener's ear). The talker-listener distance was 1 m (well inside the critical distance). This environment was implemented in a 6.2 × 5.8 × 2.9 m room for which the reverberation times as a function of frequency are shown in Table 1. The room was carpeted, with acoustical tile ceiling and several small pieces of furniture.

Environment B represented a communication situation in which external environmental noise is low but speech cues are reduced because of reverberation, low speech intensity, or limited or absent visual cues. Examples of environment B include listening as an audience member to a lecture delivered in an unamplified classroom, communicating over a distance, and listening to someone whose face is not visible. The talker-listener distance was 5 m (considerably beyond the critical distance). When measured beside the listener's ear, the CST passages were delivered at 63 dB L_{eq} and the multitalker babble was delivered at 55 dB L_{eq}. This environment was implemented in a small auditorium, 18 × 6.1 × 3.2 m (ceiling lowered to 2.6 m in the front one-third of the room). Reverberation times for environment B as a function of frequency are shown in Table 1. The room was uncarpeted with hard walls and acoustical tile ceiling. It contained classroom chairs and several tables.

Environment C represented a communication situation where external environmental noise is relatively high, speech levels are somewhat raised, and visual cues are available. Examples of environment C include face to face communication at a social event with numerous people present and communication with a clerk in a busy store. In addition to the data of Pearsons et al (1977), the report of Plomp (1977) was considered in selecting the speech to babble ratio in this environment. The level of the CST passages was 64 dB L_{eq} and the multitalker babble was delivered at 62 dB L_{eq} (both measured beside the listener's ear). The talker-listener distance was 1.0 m (well inside the critical distance). This environment was implemented in a 5.8 × 6.9 × 2.9 m, hard-walled room with carpet, acoustical tile on the ceiling, and containing several tables and nonupholstered chairs. The reverberation times as a function of frequency are shown in Table 1.

Instrumentation and Procedure

Data were collected in four 1 to 2 hr test sessions for each subject. The first session was devoted to measurement of basic audiological data, including thresholds, SRT, monosyllabic word score, and highest comfortable loudness levels. Earmold impressions were made and the three prescriptions were generated. During session two, the three hearing aids were fitted and verified with probe microphone measurements. After the fitting session, 2 cm^3 coupler gain was recorded for each fitted hearing aid. Both sessions were conducted in a double walled, sound-treated audiometric test room.

Sessions three and four were conducted in the everyday environment to which the subject was assigned with each subject serving in only one environment. In each environment, the "talker" was a small loudspeaker (Realistic minimus-7). Four other identical small loudspeakers were placed symmetrically around the subject at distances of approximately 1, 4, and 1 m in environments A, B, and C, respectively. These produced the multitalker babble.

The CST was reproduced from optical laser disk. Each audio channel was replayed, (Panasonic model TQ2024F or Sony model 1500 laser disk player) attenuated, amplified, and fed to the appropriate loudspeaker(s). The frequency response of the entire reproduction system, measured in a highly damped audiometric test room, was flat ±5 dB from 150 Hz to 15 kHz. The video output was routed to a 33 cm (diagonal) color monitor (Panasonic model CT-1330M). This produced a color image slightly smaller than life-sized. Delivery and scoring of the CST was controlled by a laptop microcomputer (Zenith 181 or 183). The experimenter was located 1 to 2 m from the subject and keyed in the scoring words correctly repeated by the subject after each sentence was presented.

Each subject listened under eight conditions which were counterbalanced and distributed over the two final sessions. The eight conditions included listening unaided and with hearing aids HAN, HAO, and HAP for both audiovisual and audio-only stimuli presentations. One set of six passages was administered in each condition. Data collection in each condition was preceded by a practice session of approximately 15 min. In the aided conditions, subjects adjusted the gain of the hearing aid during the practice period. To make this adjustment, they were instructed first to bracket, and then to select, the gain setting they would normally prefer in everyday listening in the test environment. They were permitted to change the setting as often as desired during the practice period until they decided on the preferred setting. After data collection, 2 cm^3 coupler gain was measured at the chosen volume setting. Hearing aid gain was always selected using audio-only stimuli and no adjustments were made when visual cues were added. After the gain setting was finalized, several additional practice passages were administered with the hearing aid at its final settings in the audio or audiovisual mode for the subsequent test condition. During the practice session, subjects were generally presented 6 to 10 passages. An additional two practice passages were presented when changing between audio and audiovisual modes.

Table 1. Reverberation time (sec) as a function of frequency for the rooms used to implement the three listening environments.

Frequency (Hz)	Environment A	Environment B	Environment C
125	0.648	1.255	0.867
250	0.521	1.064	0.708
500	0.295	0.809	0.470
1000	0.520	0.699	0.487
2000	0.610	0.677	0.592
4000	0.537	0.715	0.487

RESULTS

Raw data were the percentage of correct repetitions of CST scoring words in each condition. To homogenize the variances of these percentage data, all values were transformed into rationalized arcsine units (raus) before analysis as described by Studebaker (1985). The scale for rationalized arcsine units extends from −23 to 123. Values in the range from 20 to 80 are within about one unit of the corresponding percentage score.

Unaided Speech Understanding in each Environment

Mean CST scores for unaided conditions (audio and audiovisual combined) in each environment were 52.3, 44.9, and 80.5 rau for environments A, B, and C, respectively. It may seem surprising to observe the best unaided performance in environment C, the setting with the poorest signal to babble ratio (SBR). However, this outcome is more easily understood when the actual audibility of the speech signal in each environment is considered. This is illustrated in the three panels of Figure 2. These panels show the mean 1/3 octave band levels of hearing thresholds, highest comfortable loudness (HCL) levels, multitalker babble, and CST passages in each environment.* All data are expressed in terms of sound pressure level at approximately a midear canal location. Data from the probe microphone fitting session, measurements made in the listening environments, and acoustic transformations from the free-field to eardrum (Shaw, 1974) and within the ear canal (Dirks & Kincaid, 1987), were used to derive these values. For thresholds and HCLs, data were available at seven 1/3 octave bands from 250 through 4000 Hz and values were interpolated for 1/3 octave bands between these limits.

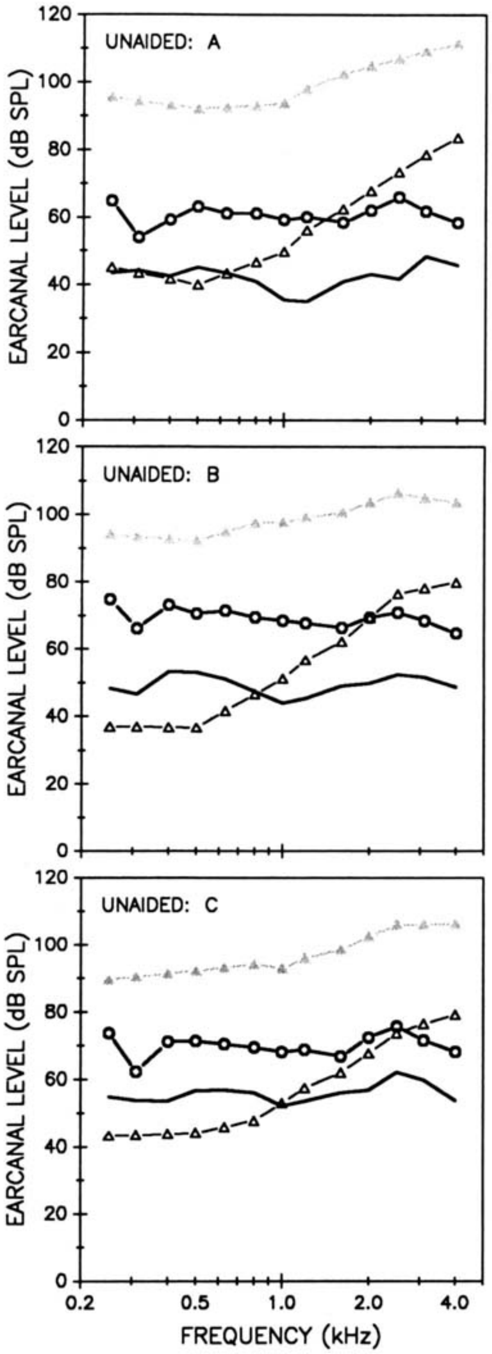

Figure 2. Mean 1/3 octave band levels of hearing thresholds (*open triangles*), highest comfortable loudness (*shaded triangles*), multitalker babble (*solid line*), and speech peaks (*open circles*) in each environment. All data expressed in ear canal sound pressure level.

As Figure 2 illustrates, the audibility of the CST passages in each 1/3 octave band was limited by hearing threshold or babble, whichever was higher. Because of the relatively high signal level in environment C, the bandwidth of audible signal was widest in this environment. This relatively better audibility probably accounts for most of the difference between unaided scores in environments A and C. The relatively low unaided score in environment B could be attributed principally to the effects of reverberation on intelligibility.†

In this study, the main focus was on the difference between aided and unaided intelligibility performance. Unaided CST scores in all environments fell close enough to the middle of the −23 to 123 rau scale that significant changes in performance could be detected, if present.

Hearing Aid Benefit in each Environment

Hearing aid benefit was quantified by subtracting the unaided CST score from the aided CST score in each condition. Note that for audiovisual presentations, benefit was quantified as the difference between audiovisual unaided and audiovisual aided scores. Benefit was determined for each hearing aid in each environment for both audio and audiovisual conditions. When averaged across environments, hearing aids, and presentation mode, the typical amount of hearing aid benefit was a very modest 10.3 rau.

To explore the effects of environments, frequency response slopes and presentation mode, the benefit data were entered into a repeated measures analysis of variance with one between-group factor (environment) and two within-group factors (hearing aid condition and mode of presentation). The only significant main effect

* All data are in RMS levels except the CST passages. These are shown in terms of peak levels (RMS + 12 dB).

† Recall that the talker-listener distance in environment B was substantially greater than the critical distance whereas the listener was less than the critical distance from the talker in environments A and C. Thus, B was the only environment in which reverberation was a significant factor in the received signal.

was that of environment [F(2,30) = 13.5, $p = 0.0002$]. There were no statistically significant interactions.

Figure 3 illustrates the benefit obtained for each hearing aid in each environment, averaged across audio and audiovisual presentation modes. Examination of this figure reveals that mean benefit obtained in environment A was between 23 and 25 rau for all hearing aids (SD = 20.1 rau), in environment B mean benefit ranged from 6 to 10 rau (SD = 9.8 rau), and in environment C benefit was negligible on average, falling between 0 and −2 rau (SD = 10.4 rau). Post hoc testing using the Student-Newman-Keuls procedure ($\alpha = 0.05$) indicated that benefit obtained in environment A was significantly greater than that realized in environments B and C, whereas environments B and C were not significantly different from each other.

To facilitate exploration of the relationships between hearing aid benefit and audiometric variables, benefit for each subject was averaged across the three hearing aids and two presentation modes, resulting in a single benefit measure. Correlations were computed between this average benefit for each subject and subjects' speech reception thresholds, word discrimination scores, ages, audiogram slopes and thresholds at 500 Hz and 2 kHz. Only one statistically significant correlation emerged. There was a modestly strong relationship between SRT and average benefit for subjects listening in environment A [$r(9) = 0.76$, $p < 0.01$]. The relationship between SRT and benefit was not significant in the other two environments. Figure 4 illustrates the mean benefit data as a function of SRT for listeners in each environment. The regression line is shown for environment A data but not for the other two environments. The trend in environment A data was toward an increase in benefit as SRT increased. In the other two environments, even though a wide range of SRTs was represented, there was no systemic trend for benefit to be related to SRT.

Effect of Visual Cues on Hearing Aid Benefit

In the analysis of variance reported above, the main effect of presentation mode did not produce a significant F value or any significant interactions. This indicates that within a given environment, hearing aid benefit was essentially the same in both audio and audiovisual stimulus conditions. Figure 5 shows the benefit obtained in each presentation mode in each environment, averaged across hearing aid conditions. This figure demonstrates that the benefit observed in the different environments was similar for both audio and audiovisual stimuli. If there is a trend in these data, the trend is for benefit to be less in the audiovisual mode than in the audio mode.

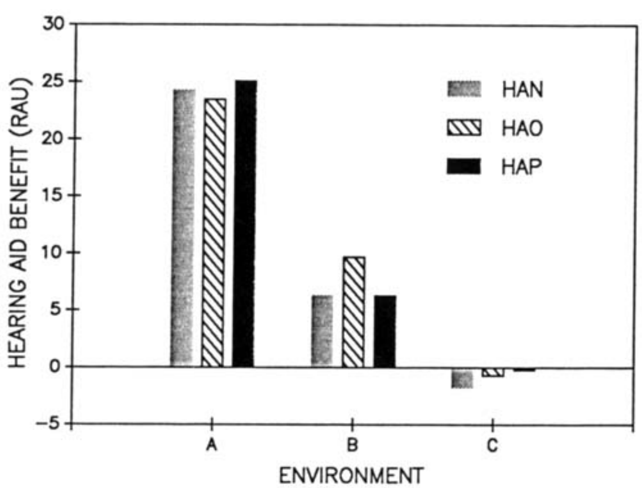

Figure 3. Mean benefit for each hearing aid in each environment.

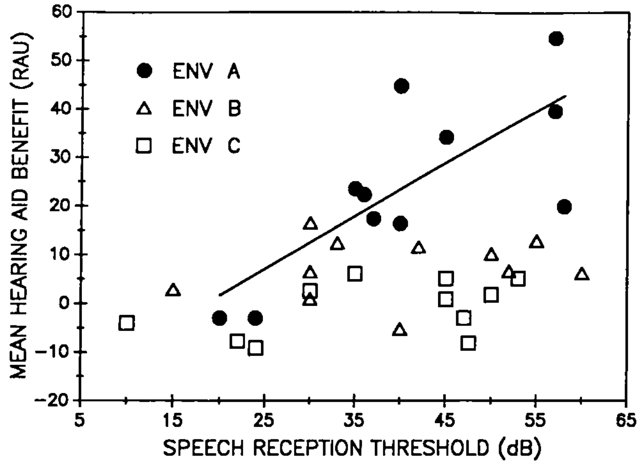

Figure 4. Mean benefit as a function of SRT for subjects listening in each environment. The regression line is shown for environment A data.

Effect of Frequency Response Slope on Hearing Aid Benefit

Because the main effect of hearing aid condition in the analysis of variance was not significant, these data indicate that the three hearing aids produced essentially the same average benefit in these everyday environments in spite of the nominal frequency response slope difference among them of 8 dB/octave. It should be kept in mind that the gain control for each instrument was adjusted to the level that the subject felt he/she would prefer in everyday use of that instrument in the tested environment. Presumably, these adjustments achieved a compromise, for each subject, between the demands of loudness comfort and the need for speech intelligibility. These adjustments would be expected to reduce the differences between hearing aids that might be observed if volume controls were not adjusted by the subjects.‡

The finding that there were no significant differences in benefit among three hearing aids with considerably different frequency/gain characteristics is more readily understood when the actual audibility of the speech signal is compared across hearing aid conditions. This

‡ Because this study was attempting to measure hearing aid benefit that would be obtained under conditions of actual use, adjustment of the volume control by the hearing impaired listener was essential to the validity of the procedure.

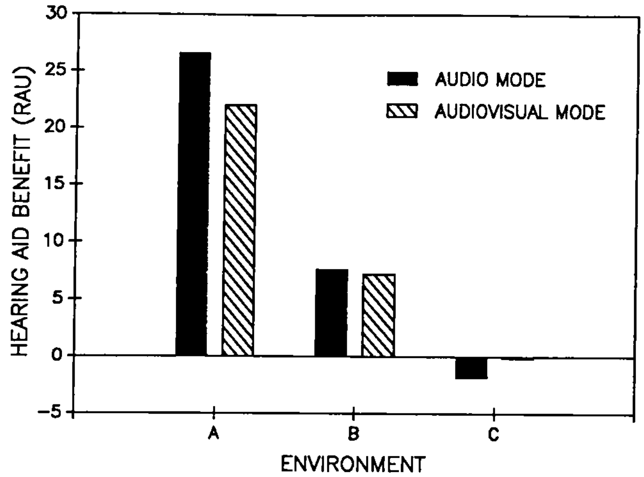

Figure 5. Mean benefit for each stimulus presentation mode in each environment.

comparison is available in Figures 6, 7, and 8 for environments A, B, and C, respectively. These figures illustrate mean amplified speech peaks, mean amplified babble, mean thresholds and mean HCL levels, all referenced to a midear canal location, for each hearing aid. Ear canal probe microphone measurements, coupler and in situ measurements of hearing aid gain, measurements made in the listening environments, and acoustic transformations from the free-field to eardrum (Shaw, 1974), and within the ear canal (Dirks & Kincaid, 1987), were combined to derive these values.

Examination of Figure 6 indicates that for all three hearing aid conditions used in environment A, both speech and babble were amplified to suprathreshold levels. The only exceptions are seen at the highest frequencies, where babble levels are slightly below threshold levels for HAO and HAN. These data show that despite the differences in frequency response slope, mean SBR in each 1/3 octave band was almost identical for all three hearing aids. Figures 7 and 8, depicting the analogous results for hearing aids in environments B and C, are consistent with Figure 6. They reveal that, after hearing aids were adjusted to preferred levels, the mean SBR in each 1/3 octave band was almost the same for the three hearing aid conditions. Again, small differences among conditions occurred in the highest frequency bands.

These results indicate that, when averaged across subjects, the audibility of the amplified speech signal was very similar for all three hearing aids in each environment. It is not surprising, therefore, that each hearing aid produced, on average, about the same speech intelligibility.

Hearing Aid Benefit for Individual Subjects

Even though there were no significant group trends for a particular hearing aid condition to produce more benefit, this does not preclude the possibility of significantly different benefit among the three hearing aids for individual subjects. If different hearing aid conditions were optimal for different subjects, these effects would tend to cancel when data were averaged across subjects.

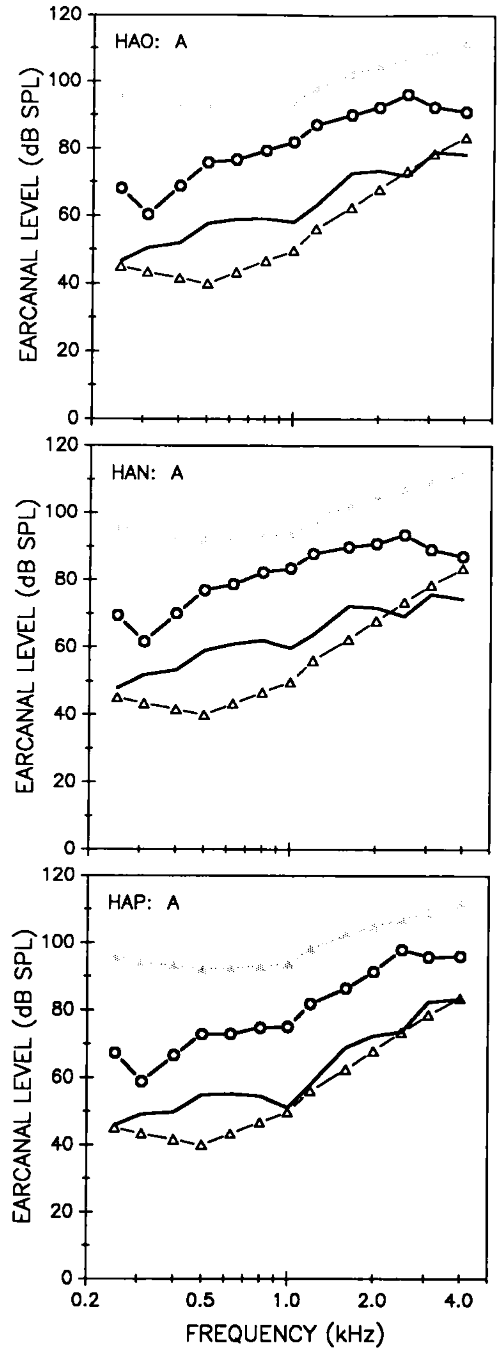

Figure 6. Mean 1/3 octave band levels of hearing thresholds (*open triangles*), highest comfortable loudness (*shaded triangles*), amplified multitalker babble (solid line), and amplified speech peaks (*open circles*) for each hearing aid in environment A. All data expressed in ear canal sound pressure level.

To explore the results for individual subjects, score differences among hearing aid conditions were evaluated for each subject. The results are illustrated in Figure 9. In this figure, score differences between HAN and HAO are shown as the *triangles* and score differ-

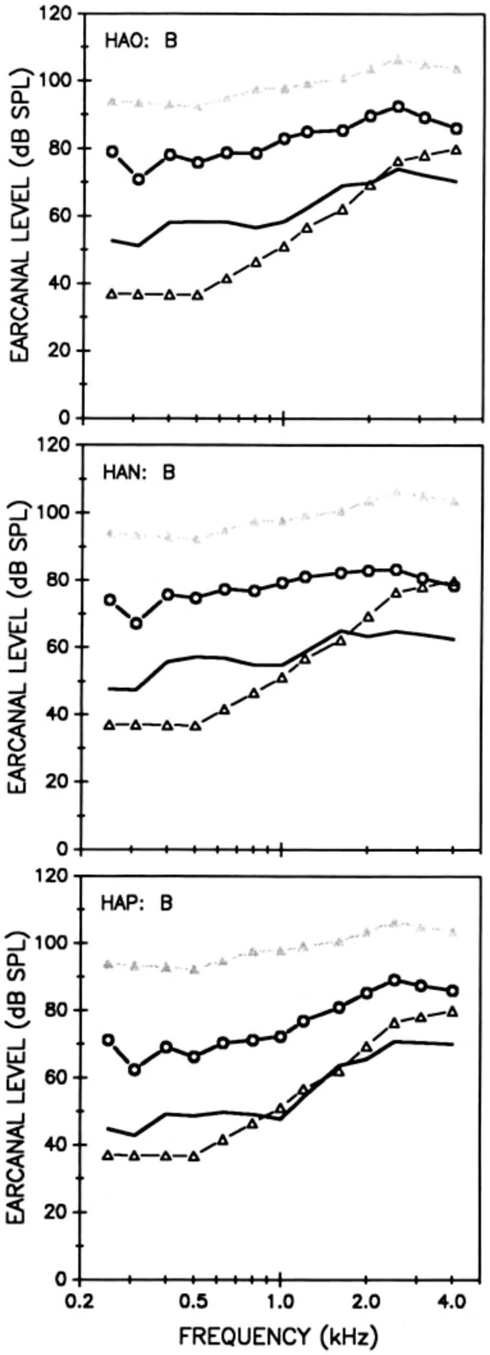

Figure 7. Mean 1/3 octave band levels of hearing thresholds (*open triangles*), highest comfortable loudness (*shaded triangles*), amplified multitalker babble (*solid line*), and amplified speech peaks (*open circles*) for each hearing aid in environment B. All data expressed in ear canal sound pressure level.

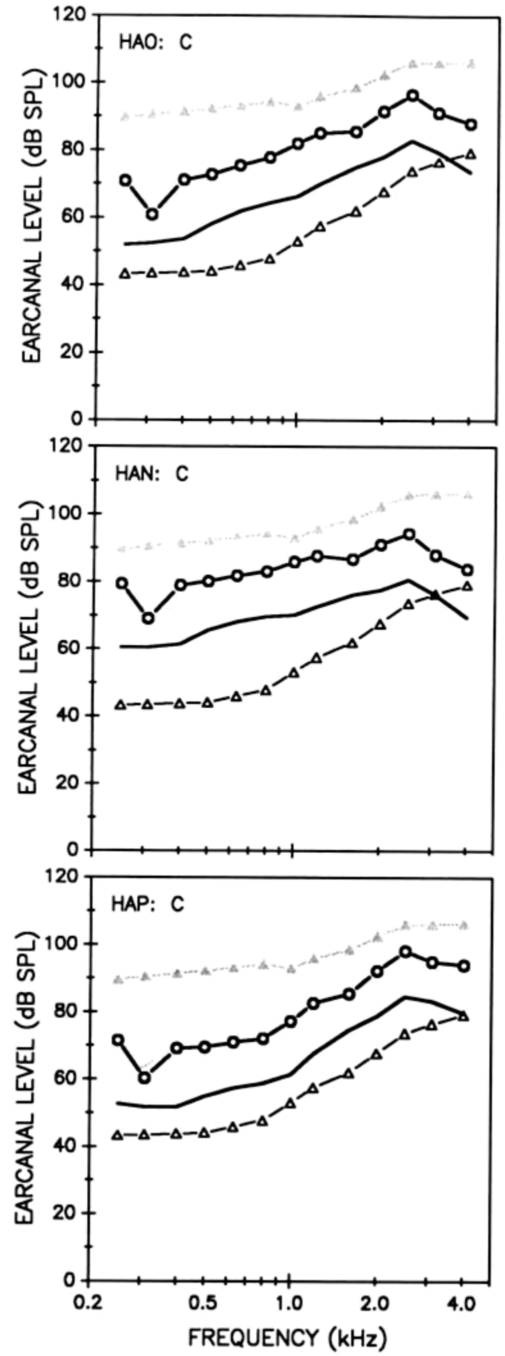

Figure 8. Mean 1/3 octave band levels of hearing thresholds (*open triangles*), highest comfortable loudness (*shaded triangles*), amplified multitalker babble (*solid line*), and amplified speech peaks (*open circles*) for each hearing aid in environment C. All data expressed in ear canal sound pressure level.

ences between HAP and HAO are shown as the *circles* (score differences between HAP and HAN may be derived by comparing their respective symbols on the figure). *Filled symbols* give data for audiovisual presentations and *open symbols* portray data for audio-only presentations. The 95% critical difference for six-passage CST scores obtained from hearing-impaired listeners is 12.2 rau (Cox et al, 1989). These critical differences are marked on the figure using *dashed lines.* Data points that appear above the *upper dashed line* or below the *lower dashed line* in each panel signify a condition in which there was a significant difference in benefit between HAO and one of the other hearing aids for an individual subject. For example, an *open triangle*

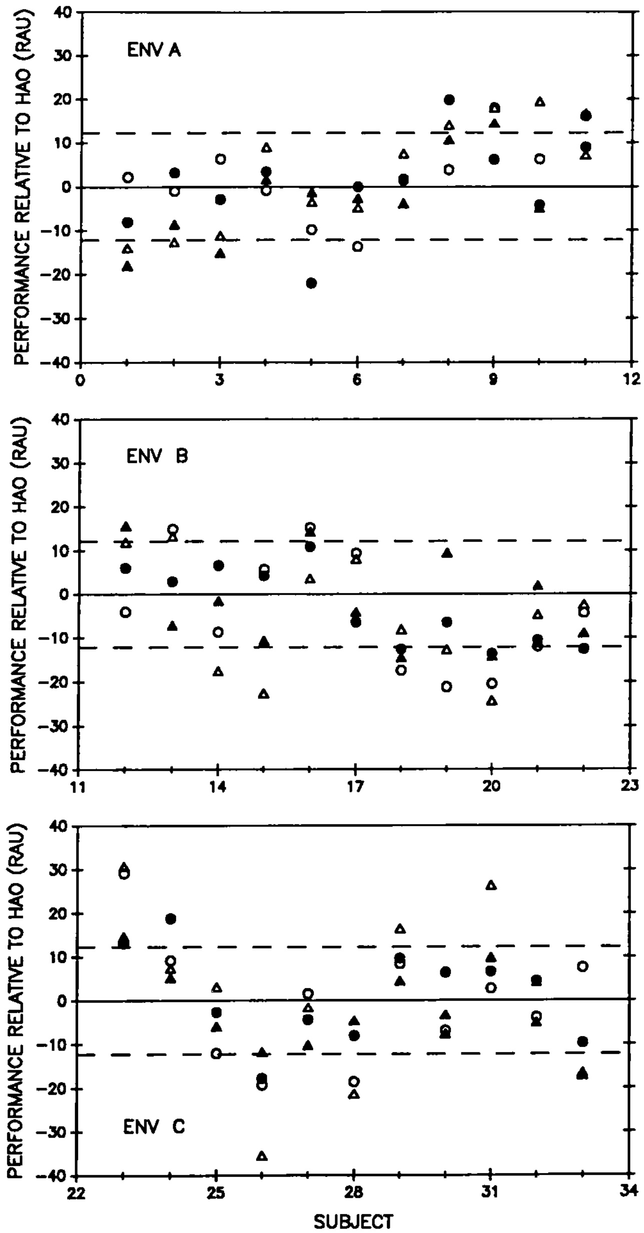

Figure 9. Intelligibility score differences between HAN and HAO (*triangles*) and between HAP and HAO (*circles*) for each subject. *Filled symbols* give data for audiovisual stimuli and *open symbols* portray results for audio-only stimuli. Ninety-five percent critical differences are shown as the *dashed lines*.

appearing above the *dashed line* for a particular subject indicates that the score in the HAN condition was significantly better than that in the HAO condition in the audio presentation mode for this subject. Because the data are evaluated using a 95% critical difference, we can expect that an apparently significant difference will occur by chance on about 5% of the comparisons. Since each panel shows 44 independent comparisons, 2 to 3 differences larger than the critical difference can be expected to occur by chance alone.

Figure 9 shows that there were only eight subjects for whom no significant differences were noted among hearing aids. In each environment, there were a few more significant differences observed in the audio mode than in the audiovisual mode; there were a total of 17 significant differences involving the audiovisual mode compared to 27 significant differences involving the audio mode. Inspection of these data for individual subjects reveals that no slope condition was consistently superior in any environment: some subjects performed better with HAN, some with HAO, and some with HAP.

Skinner and Miller (1983) reported that, for listening conditions that differed in bandwidth, speech intelligibility for hearing-impaired listeners was proportional to the articulation index (AI) in each condition. Others have also reported that, when hearing-impaired listeners respond to speech under several different conditions, the AI values for the various conditions may result in accurate ranking of the conditions' speech intelligibility (Kamm, Dirks, & Carterette, 1982). These results suggested that the AI in the various hearing aid conditions might provide insight into the significant differences observed between these conditions for individual subjects. Thus, the relationship between speech intelligibility and articulation index was explored retrospectively.

There are several different approaches to the computation of an articulation index (ANSI, 1969; Pavlovic, 1987; Pavlovic & Studebaker, 1984) but all are based on the essential notion that intelligibility is primarily determined by the audibility of the speech signal in each of several contiguous frequency bands, with each band's contribution weighted by the importance of that band to speech understanding. In the present study, RMS levels of speech and babble were measured in the test environments in 1/3 octave bands from 250 Hz to 4.0 kHz. Audibility in each of the thirteen 1/3 octave bands was estimated using procedures based on the recommendations of Pavlovic (1987). Corrections to RMS levels to determine speech peaks were those reported by Pavlovic (1987). Speech levels higher than the HCLs did not contribute to the AI. The importance function for continuous discourse materials reported by Studebaker, Pavlovic, and Sherbecoe (1987) was used to weight each 1/3 octave band. Only data obtained in the audio presentation mode were used in these analyses.

Two approaches were taken to evaluate the relationship between calculated AI values and measured intelligibility performance. The first was to determine whether significant score differences between hearing aid conditions, as reflected in Figure 9, were paralleled in the articulation indices. That is, when intelligibility was significantly different between two hearing aid conditions, did the hearing aid condition with the better score also have the higher AI? Of the 66 independent comparisons between pairs of hearing aids, there were 27 significant differences. For 13 of these pairs, the condition with the higher score also had the higher AI.

For the remaining 14 pairs, the condition with the higher score had the lower AI.

In the second analysis of these data, the three hearing aid conditions were ranked in terms of intelligibility score and AI for each subject (disregarding the statistical significance of differences among conditions). A comparison of rankings for each subject revealed that the condition with the highest score also had the highest AI for 11 subjects. For the remaining 22 subjects, the hearing aid condition with the highest intelligibility score did not have the highest articulation index.

These results suggested that for these hearing aids operating in typical listening conditions, the AI was not a useful predictor of the condition that would result in the highest intelligibility. An example is shown in Figure 10. This figure depicts the threshold and HCL 1/3 octave band levels for one subject who served in environment A. In addition, speech peak and RMS babble levels are given for each hearing aid condition. The AIs for HAN, HAO, and HAP were 0.487, 0.491, and 0.454, respectively. The intelligibility scores for the same conditions were 60.6, 74.7, and 76.9 rau, respectively. Thus, even though the AIs suggested that HAP should produce the lowest score, HAN actually yielded significantly lower scores than HAO or HAP.

DISCUSSION

In a study of self-assessed hearing aid benefit reported by Walden et al (1984), it was found that hearing aid wearers reported receiving the most benefit from their instruments in quiet listening environments with the talker relatively close, similar to our environment A. The least self-reported benefit was registered for noisy situations similar to our environment C. Benefit in situations with reduced speech cues, similar to our environment B, was between these two extremes. Very similar results have been reported by Birk Neilsen (1980) and by Scherr, Schwartz, and Montgomery

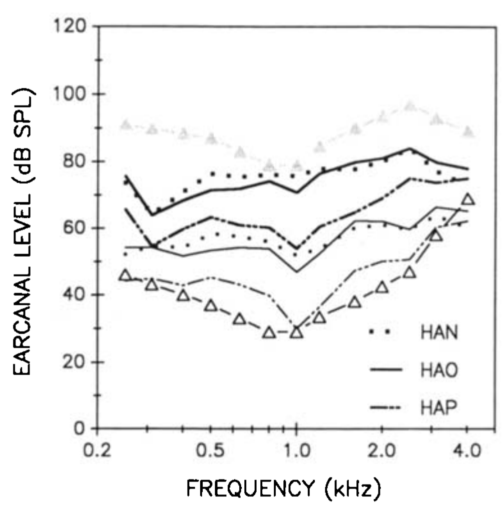

Figure 10. Hearing thresholds (*open triangles*), highest comfortable loudness (*shaded triangles*), amplified speech peaks (*heavy line*), and amplified multitalker babble (*light line*), for each hearing aid as worn by one subject. All data expressed in ear canal sound pressure level.

(1983). The latter authors questioned the validity of their data because the results were not consistent with the data obtained during the hearing aid fitting: At the time the hearing aids were fitted, clinical data suggested that benefit would be greatest in noisy situations and least in quiet settings.

The results of the investigation reported here are consistent with the self-reports of hearing aid benefit in everyday environments. Our subjects obtained the most benefit from their hearing aids in the favorable listening situation of environment A and the least benefit in the situation with highest background noise, environment C. Benefit in the reverberant situation (environment B) was intermediate in magnitude.

The typical subject obtained 20% or more improvement in intelligibility in environment A. This is considerably more than the 10% improvement in intelligibility noted by Haggard et al (1981) in a laboratory test. These authors were surprised that their subjects reported sizable hearing aid benefit in daily life despite the small benefit measured in the clinical setting. The results of the present study suggest that, in fact, sizable benefit can be realized in daily life in environment A settings.

Plomp proposed a model in which hearing loss was viewed as composed of an attenuation component and a distortion component (1978). He maintained that, because only the attenuation component could be reduced by amplification, hearing aids would be of negligible benefit in everyday situations where the background noise exceeded 50 dB(A). In testing the model, Duquesnoy and Plomp (1983) measured hearing aid benefit for 10 individuals with hearing losses similar to those of subjects in this study. Their mean data correspond closely with those obtained in this study: Benefit in a situation similar to environment A was about 2 dB (equivalent to about 23 rau for the CST) and zero benefit was measured in a situation similar to environment C.

Previous studies that have attempted to correlate reported benefit in daily life with hearing loss or SRT have produced somewhat equivocal findings. Hutton and Canahl (1985) reported a modest increase in self-assessed benefit as hearing loss increased. However, others have noted that reported hearing aid benefit appeared to be independent of extent of hearing loss (Birk Neilsen, 1974; Kapteyn, 1977; Scherr et al, 1983). Results of the present study (Fig. 4) suggest that the relationship of benefit to hearing loss depends on the listening environment. Benefit was significantly related to hearing loss only in the favorable listening situation of environment A. In less favorable listening environments (B and C), benefit and hearing loss were not related despite the fact that, in both environments, mean benefit varied considerably across subjects. Thus, the relationship between self-reported benefit and hearing loss is likely to be markedly influenced by the type of listening situations that are considered.

The finding that benefit was not significantly influenced by the presence of visual cues is consistent with the report of Haggard et al (1981). Our data (Fig. 5) agree with those of Haggard et al in indicating that benefit was less in the presence of visual cues than without them but the difference between presentation modes was not significant. This outcome suggests that a valid assessment of hearing aid benefit can probably be made using speech samples presented without visual cues. However, Walden et al (1984) reported that self-assessed benefit was greater for situations where visual cues were available. This apparent discrepancy between measured benefit and self-reported benefit for speech with visual cues should be explored further. It may be that the visual-cues-available situations assessed by Walden et al were inherently more favorable than the visual-cues-unavailable settings. If so, this could account for the difference between the two sets of data.

Overall, there was no evidence to support the finding reported by Lindblad et al (1983) that the optimal frequency response for understanding speech without visual cues was different from the optimal frequency response when visual cues were available. The different outcomes of the two studies may be related to the fact that frequency responses were individually fitted in the present study and all of the tested conditions were potentially useful hearing aid fittings. In contrast, Lindblad et al (1983) used the same set of frequency responses for all subjects and the response conditions were much more different from each other than the nominal 8 dB/octave in the present study.

The most disappointing outcome of the present study was the general lack of hearing aid benefit in the environment C (noisy) setting. Negligible or limited benefit in noisy everyday environments has been reported consistently by hearing aid wearers. However, at least two factors have caused clinicians to doubt the validity of these reports: (1) Clinical or laboratory measurements of aided and unaided speech intelligibility often suggest that intelligibility should improve in noisy settings, and (2) several investigations of the relationship between audibility (quantified using an articulation index) and speech intelligibility for hearing-impaired listeners have shown that improved audibility is usually associated with improved intelligibility (Kamm, Dirks, & Bell, 1985; Pavlovic, 1984). Thus, a reported lack of hearing aid benefit in noisy environments has often been attributed to inability of the hearing-impaired listener to judge hearing aid benefit separately from the difficulty of the listening task and/or to failure of the hearing aid to amplify speech to audible levels. Neither of these explanations can be applicable in the present study. The audible bandwidth was dramatically improved in environment C when the hearing aids were worn (*cf.* Fig. 8 and *bottom panel* of Fig. 2). Nevertheless, the typical subject obtained no benefit in this environment and about half of the subjects actually performed more poorly with the hearing aid than without it.

These results suggest that improvement in audibility per se was not predictive of hearing aid benefit in this typical noisy listening situation.[§] Several studies have shown that even though speech cues are audible, they may not be fully exploited by many persons with sensorineural hearing impairment. Turner and Robb (1987) reported that full audibility of spectral cues for stop-consonant recognition did not produce normal recognition of stops for many hearing-impaired subjects. Stelmachowicz, Lewis, Kelly, and Jesteadt (1989) reported that withdrawal of high-frequency masker components did not improve speech intelligibility performance for their hearing-impaired subjects. They suggested that listeners with sensorineural hearing impairment may actually use primarily low-frequency or temporal cues for speech recognition. Zeng and Turner (1990) found that hearing-impaired listeners were not able to utilize formant transition cues for fricative recognition even though these cues were audible. The results of the present study in environment C are consistent with this work in suggesting that, under some circumstances, hearing-impaired subjects may not be able to profit from speech cues even though these are audible.

Why was hearing aid benefit so much greater in environment A than in environment C? This outcome was probably due to a combination of factors. For the typical listener in environment C, amplification substantially increased audibility for signals above 1000 Hz and also raised the sensation level (but not the SBR) of signals in the 500 to 1000 Hz region. In environment A, amplification resulted in increased audibility above 630 Hz for the typical listener. In addition, the sensation level of speech and babble in the 250 to 1000 Hz region was increased. Moreover, the SBR was about 5 dB more favorable in the environment A setting. Although the better SBR in environment A probably accounted for some of the advantage in this setting, the increased sensation level of low frequency (250–500 Hz) speech cues also may have been a salient factor.

Data obtained in environment B were qualitatively different from those in the two other environments in several ways. Despite the fact that measurements of signal and babble levels suggested that unaided audibility in environment B was the best of the three environments, intelligibility was actually the worst in this setting. Although nominal signal to babble ratio in environment B was similar to that of environment A, hearing aid benefit in environment B was much lower than in environment A and not statistically distinguishable from that in environment C. These results are undoubtedly due to the temporal smearing of speech that resulted from reverberation in environment B.

Much investigative effort has been directed toward exploring the relative efficacy of different hearing aid frequency-gain prescriptions. Several workers (Byrne, 1987; Skinner, 1988) have pointed out that different procedures often result in different prescribed frequency-gain curves. Different prescriptive fittings often

[§] It should be recalled that the three test environments were structured in such a way that normal-hearing listeners are able to maintain essentially full intelligibility for conversational speech. This has been confirmed with measurements of CST intelligibility for normal hearers in each environment. Thus, the listening situation in environment C was not especially difficult by everyday standards.

produce significant differences in speech perception when tested in the laboratory (Benedict, Punch, Lasky, & Chi, 1989; Byrne, 1986; Humes, 1986; Sullivan, Levitt, Hwang, & Hennessey, 1988). However, when different prescriptive fittings are compared in daily life settings, significant differences are typically not observed among them (Sammeth, Bess, Bratt, Peek, Logan, et al 1989; Stroud & Hamill, 1989). In the present study, no significant differences in benefit were seen among the three frequency responses in any of the everyday environments. Examination of Figures 6, 7, and 8 clearly reveals that this outcome was obtained because, when subjects were given the freedom to choose the gain setting of each instrument, they typically chose settings that amplified both speech and background noise to suprathreshold levels. Thus, the audibility of the speech signal was almost equal in the three conditions, producing very similar average scores for all hearing aids. Since the three test environments were typical of daily life listening situations, these results are consistent with those studies indicating that there are no significant differences among many frequency gain prescriptions in terms of speech intelligibility produced in everyday life settings.[‖]

These data suggest that significant differences in benefit from hearing aid fittings based on different prescriptive procedures could only be expected when: (1) the background noise is so low, or (2) the dynamic range is so narrow, that the noise remains mostly below threshold when speech is amplified to the preferred level. The results of this study lead to the prediction that, except under these atypical conditions, there will not be significant differences among most frequency-gain prescription formulae when hearing aids are used under everyday conditions. These group data suggest that moderate differences in frequency responses slopes may be less important than previously thought.

Finally, although the main focus of this investigation was the typical hearing aid benefit observed for groups of subjects under different conditions, the individual results cannot be ignored. Despite the fact that there were no significant trends for a particular hearing aid condition to be superior, overall, in any of the environments, many significant differences were observed among hearing aid conditions for individual subjects.

It was disappointing to note that articulation indices were generally not predictive of the differences among hearing aid conditions for individuals, even when significant speech intelligibility differences were observed. At first, this result may seem inconsistent with the reports of Kamm et al (1982) and Skinner and Miller (1983), which both noted that differences in AI were moderately predictive of differences in speech intelligibility for hearing-impaired subjects. However, in the former study, this result was obtained after averaging data across subjects and the experimental frequency responses differed more from each other than did the hearing aid frequency responses used in this investigation. In the latter study, the range of AIs for which intelligibility data were obtained for each subject was much greater than in the present study. These factors certainly contributed to the differences in outcome between those investigations and the one reported in this paper. Overall, the results of the present study employing real hearing aids used under everyday conditions suggest that the articulation index approach (as used in this investigation) would be of questionable value in selecting, for a particular individual, which of several hearing aid fittings would produce the best speech intelligibility in everyday listening.[¶]

To explain the significant within-subject benefit differences, two hypotheses are under consideration. They are: (1) that benefit was affected by distortion products produced by the hearing aids, despite the fact that all had low harmonic distortion by standard measures, and (2) that benefit differences for some subjects resulted from inconsistent adjustments in the listening level for amplified speech across the three hearing aids.

In support of the first hypothesis, Studebaker and Marinkovich (1989) reported that hearing aid-generated harmonic distortion measured under real-use conditions was different from that measured using standard procedures. Also, differences among hearing aids in harmonic and intermodulation distortion measured under real-use conditions contributed to a discrepancy between measured speech intelligibility performance and performance predicted from the AI. It seems possible that similar electroacoustic differences among hearing aids were a factor in the present study, influencing performance in a manner that could not be predicted from a consideration of the AI.

In support of the second hypothesis, it was noted that about 40% of the subjects in this study chose listening levels for amplified speech that differed substantially across the three hearing aid conditions. Figure 10 shows an example of this: the listening level chosen for HAP was substantially below that for HAN and HAO. Studies have established that speech intelligibility is strongly related to listening level in many hearing-impaired individuals and that there is usually an optimal range of levels within which the highest scores are obtained (Gutnick, 1982; Skinner, 1980). These findings suggest that hearing aid benefit will be maximized when the gain control is set to produce speech within this optimal listening range. It follows that in the present study, the three hearing aids used by a particular subject should have been adjusted to produce similar levels. Indeed, 60% of the subjects in the present study did adjust all three instruments to produce similar listening levels. It seems likely that inappropriate gain adjustments may have resulted in reduced benefit in some conditions for the subjects who adjusted the hearing aids to widely varying levels.

‖ Examination of comparisons of frequency-gain prescriptions made by Skinner (1988, pp 179–187) suggest that, after normalization, they do not differ from each other more than the three responses tested here.

¶ Assuming that the hearing aids being compared are all reasonable choices for the individual in question, based on current thinking about hearing aid fitting.

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