Journal of Speech and Hearing Research, Volume 27, 483–493, December 1984

EFFECTS OF REDUCING LOW-FREQUENCY AMPLIFICATION ON CONSONANT PERCEPTION IN QUIET AND NOISE

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The aim of this study was to assess the effect of low-frequency amplification on speech recognition performance by hearing-impaired listeners. Consonant identification performance by subjects with flat hearing losses and high-frequency hearing losses was assessed in three different hearing aid conditions, in quiet and noise. The experimental hearing aids all provided extra high-frequency amplification but differed in the amount of low-frequency amplification. The results showed that listeners with flat hearing losses benefited by low-frequency amplification, whereas subjects with high-frequency hearing losses exhibited deteriorating scores in conditions with greatest low-frequency amplification. Analyses of phonetic feature perception and individual consonant recognition scores revealed subtle interactions between hearing loss configuration and amplification contour.

High-pass amplification has received increasing attention in recent years as a viable fitting for listeners with high-frequency hearing losses (Schwartz, Surr, Montgomery, Prosek, & Walden, 1979) and wide-band hearing losses (Harford & Fox, 1978). In these amplification schemes, a wide-band hearing aid receiver is used to provide amplification above 5000 Hz, and a high-pass filter is used to minimize amplification of the low frequencies. Coupling the hearing aid to an open or vented earmold further reduces amplification in the low frequencies and may create additional high-frequency resonances to enhance the high-frequency gain. Although success has been reported with the use of extended high-frequency amplification in comparison with conventional (narrow-band) frequency-response hearing aids, comparatively little is known about the effect of severely restricting amplification of the low frequencies in these hearing aid fittings. Undoubtedly, the configuration of a listener's hearing loss and the stimulus-response parameters have some influence on the extent to which low-frequency amplification will affect performance.

The rationale for employing high-pass amplification is two-fold: to provide maximum enhancement of the weak, high-frequency spectral cues in the speech signal and to reduce upward spread of masking by attenuating the more intense low-frequency energy in the speech spectrum. Listeners with selective high-frequency hearing losses appear to be particularly good candidates for this type of amplification because they demonstrate poor recognition of consonant phonemes conveyed by high-frequency cues (Owens, Benedict, & Schubert, 1972) and they demonstrate a susceptibility to upward spread of masking (Danaher, Osberger, & Pickett, 1973). Indeed, investigations of hearing aid contours that result in maximum speech recognition performance by listeners with sloping hearing losses have shown consistently that high-pass amplification (between 1000 or 2000 Hz and 6300 Hz) is critical for achieving optimum performance (Kamm, Dirks, & Carterette, 1982; Pascoe, 1975; Schwartz et al., 1979; Skinner, 1980). This result has been shown for a variety of speech tests presented in noise, including high-frequency word lists, the California Consonant Test (CCT), NU-6, selected voiceless consonants, and the Synthetic Sentence Identification Test (SSI) (Kamm et al., 1982; Pascoe, 1975; Schwartz et al., 1979).

The application of high-pass amplification to listeners with flat sensorineural hearing losses is less tenable. These listeners may be unable to detect low-frequency cues necessary for consonant identification and, therefore, may require some amplification in the low frequencies. A study by Owens et al. (1972) showed that subjects with flat hearing losses exhibited errors for consonants conveyed by low-frequency information and by high-frequency information. Further, perception of sonorance, a (low-frequency) dimension identified for normal listeners and those with high-frequency losses, was not evident for listeners with flat hearing losses (Walden & Montgomery, 1975).

Listeners with flat hearing losses also may not exhibit upward spread of masking. This measurement is dependent on the listener's unmasked thresholds in quiet and the masker intensity (Humes, 1983b). Measurements of threshold shift produced by equivalent high-intensity maskers (>100 dB SPL) show that normal and hearing-impaired listeners with flat losses exhibit similar spread-of-masking patterns, based on average data (Humes, 1983b; Martin & Pickett, 1970). However, when masked thresholds are measured, some impaired listeners may demonstrate an excessively asymmetrical masking pattern (deBoer & Bouwmeester, 1974). In addition, if the masker is adjusted to produce equivalent effective masking levels for all subjects, then listeners with both flat and high-frequency sensorineural losses show more spread of masking than do normals. This is due to the higher masker levels presented to the impaired subjects (Humes, 1983b; Jerger, Tillman, & Peterson, 1960). Comparisons of threshold shift produced by maskers of equivalent SPL in listeners with different hearing loss configurations have indicated that listeners with flat losses do not show as severe upward spread of masking effects as do listeners with high-frequency sensorineural losses (Danaher et al., 1973; Martin & Pickett, 1970). However,

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sizable between-subject variability has been noted in the data obtained from impaired ears (Danaher & Pickett, 1975; Martin & Pickett, 1970). Our contention, therefore, is that listeners with flat hearing losses may benefit from some low-frequency amplification without experiencing excessive spread of masking effects at typical levels of aided conversational speech.

Amplification of the low frequencies may also benefit hearing-impaired listeners by improving the quality of amplified sound. Paired-comparison preference judgments of amplified sound quality have shown that normal-hearing listeners and listeners with gradually sloping sensorineural hearing losses consistently prefer electroacoustic responses characterized by low-frequency energy (Punch & Beck, 1980; Punch et al., 1980). Magnitude estimations of amplified speech quality by hearing-impaired listeners with gradually sloping hearing losses have confirmed this finding for speech presented at levels below 100 dB SPL (Tecca & Goldstein, 1984). These reports suggest that low-frequency amplification should be considered in a hearing aid fitting to improve the hearing aid user's subjective reaction to the aid.

It is apparent that methodological parameters, especially the stimulus, presence of background noise, and listener's task, have a substantial influence on the measured effects of various hearing aid frequency responses on hearing-impaired listeners' performance. Most standardized speech tests presented in quiet have been ineffective in demonstrating performance differences with different hearing aid frequency responses (Harford & Fox, 1978; Schwartz et al., 1979). However, in noise, performance changes across different amplification contours are more often observed (Harford & Fox, 1978; Jerger & Hayes, 1976; Pascoe, 1975), although not with all tests (Kamm et al., 1982).

The evaluation of subtle effects of low-frequency amplification requires a test that will be sensitive to changes in perception of low-frequency as well as high-frequency stimuli. Thus, tests such as the California Consonant Test, the Nonsense Syllable Test, and Pascoe's high-frequency word list, constructed to elicit the errors of listeners with high-frequency hearing losses, will not suffice. Instead, a test that assesses recognition of all possible consonants should be able to demonstrate subtle performance changes. In addition, measures of total performance on a particular test can only provide gross information regarding changes in speech recognition performance as the amplification spectrum is altered. It is possible for a listener's total score to remain stable in two hearing aid conditions, but for the pattern of errors to change dramatically. A detailed analysis of error patterns would enable us to determine whether recognition of certain consonants is affected differentially under varying hearing aid spectral contours.

The preceding review suggests that extended high-frequency amplification may improve speech recognition for many hearing-impaired listeners, but that severe reduction of low-frequency amplification may not be warranted in all cases. The low-frequency part of the speech spectrum is rich in acoustic information cueing consonant identity and also contributes to the perceived quality of amplified speech. The purpose of this study was to evaluate whether selectively reducing the amount of low-frequency amplification has a significant effect on the speech recognition performance of hearing-impaired listeners. Specifically, the study sought to determine whether low-frequency attenuation reduces the scores of listeners with flat hearing losses and improves the scores of listeners with high-frequency hearing losses. Consonant recognition responses were used to evaluate total performance changes across experimental conditions, as well as to observe subtle changes in specific patterns of performance as the amount of low-frequency amplification was manipulated.

METHODS

Subjects

Two groups of 10 subjects each, selected from the University of Maryland Hearing Clinic population, participated in the experiment. The listeners in Group I had bilateral mild or moderate sensorineural hearing losses with flat audiometric configurations, defined as thresholds within 15 dB of each other from 250 through 4000 Hz. The subjects in Group II had hearing thresholds within normal limits through 1000 Hz, which sharply sloped to a sensorineural hearing loss of 40 dB or more at 4000 Hz and above, bilaterally. The mean audiometric configurations for the two groups of listeners are presented in Figure 1. Speech recognition scores on a standard phonetically balanced word list (NU-6; Northwestern University Auditory Test No. 6–Tillman & Carhart, 1966) were greater than 70% for all subjects. Tympanometric screening was conducted for all subjects to ensure that

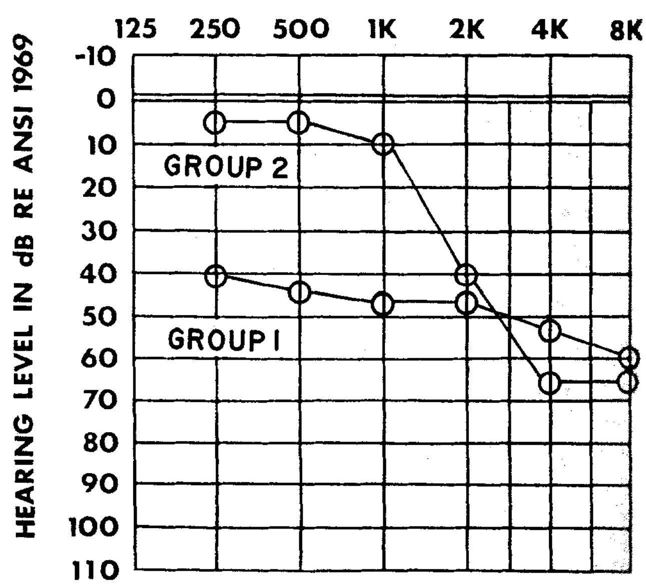

FIGURE 1. Mean audiometric configurations for subjects with flat sensorineural hearing losses (Group 1) and subjects with high-frequency sensorineural hearing losses (Group 2).

they were free of significant middle-ear disease. Subjects assigned to the two groups were matched in age. Those in Group I were aged 26–71 ($\bar{x}$ = 56.6 years); those in Group II were aged 23–69 ($\bar{x}$ = 54.4 years). All subjects had been hearing aid users for at least 6 months prior to the study.

Hearing Aids

Three experimental hearing aids were selected for this study on the basis of frequency response curves measured according to the ANSI (1982) standard. These electroacoustic measurements were made in a hard-walled 2-cm³ coupler (B & K DB-0138) and an acoustic test chamber (Phonic Ear HC 2400). During measurement, the volume of each hearing aid was set at the Reference Test Gain position, and an input sweep tone of 60 dB SPL was presented. The three hearing aids were similar in providing high-frequency amplification from 2000 through 6300 Hz, but they differed in the amount of amplification provided below 2000 Hz.

The first hearing aid (Oticon E15P1) had a wide-band frequency range of 400–6300 Hz and a flat frequency response from approximately 800 to 6000 Hz. This aid was designated as the *Flat Frequency Response* hearing aid, or FFR. The second hearing aid (Oticon E11HC) had a high-frequency emphasis from 2000 to 6300 Hz and a "gradual" low-frequency attenuation rate of 12 dB/octave below 2000 Hz (designated as *Gradual Low-Frequency Response*, or GLFR). The third hearing aid (Oticon E17HC) also had a high-frequency emphasis from 2000 to 6300 Hz, but a "sharp" low-frequency attenuation rate of approximately 24 dB/octave below 2000 Hz (called the *Sharp Low-Frequency Response*, or SLFR). The frequency responses of the three experimental hearing aids are presented in Figure 2.

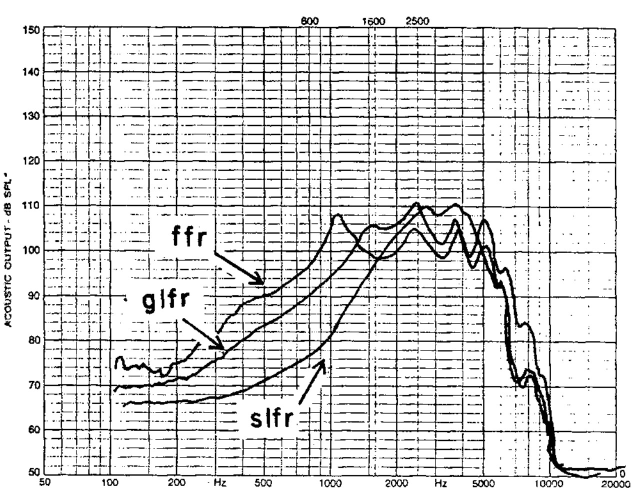

FIGURE 2. Frequency response curves of the three experimental hearing aids, measured in a 2-cm³ coupler with a 60-dB SPL input sweep tone, according to the ANSI (1982) standard. ffr = flat frequency response hearing aid: glfr = gradual low-frequency response hearing aid; slfr = sharp low-frequency response hearing aid.

Stimuli

A broad set of speech stimuli were selected for this study. They consisted of 19 consonants paired with the vowel /a/ in a CV format. The consonants were /b,d,g, p,t,k,m,n,f,θ,v,ð,s,ʃ,z,j,l,r,w/. The 19 CV syllables were recorded by a male speaker of General American dialect. To enable control of the levels and presentation intervals of the stimuli, they were modified by computer adjustment as follows. The recorded CVs were digitized onto a PDP-12 laboratory computer (11.43-kHz rate) and adjusted in level so that their peak RMS levels, calculated in a 20-ms time window, were equivalent. The digitized stimuli were then randomized, converted to analog signals (11.43-kHz rate), low-pass filtered at 5000 Hz (48 dB/octave attenuation rate), and recorded on analog tape. Five different test tapes were prepared. In each test tape were 190 items composed of 10 randomizations of the 19 CV syllables.

The 12-talker babble recorded in the SPIN test (Speech Perception in Noise—Kalikow, Stevens, & Elliott, 1977) was used as the background speech competition in this experiment.

Apparatus and Calibration

The stimuli and masker were recorded onto two separate channels of magnetic tape. During the experiment, they were played back on an Otari MX5050B tape recorder and routed separately to two Hewlett-Packard 350D attenuators. The stimuli and masker were then mixed (Coulbourn audio-mixer amplifier), amplified (Crown D150 amplifier), and presented to the subject via a single loudspeaker (JBL Model 4311). The loudspeaker was positioned 1.8 m from the subject's head, at the same height as the listener's ear, and at 0° azimuth. All testing was conducted in an IAC double-walled sound-insulated chamber.

Calibration was conducted prior to each experimental session. The CV stimuli were calibrated so that the level of a peak-equivalent calibrating vowel, /a/, produced 70 dB SPL at the location of the listener's head. The overall level of the babble was calibrated to produce 64 dB SPL at this same location, to create a signal-to-noise ratio (S/N) of +6 dB.

Procedures

During the experiment, each experimental hearing aid was coupled to the subject's test ear by a custom-made shell earmold. This occluding earmold was used to control for acoustic modifications of the amplified signal which can occur with different coupling schemes (Cox, 1979). The test ear for each subject was the ear that usually received amplification. An EAR hearing protector was placed in the unaided ear during all testing. This plug provides approximately 30–35 dB of attenuation from 500 through 8000 Hz (Humes, 1983a).

Consonant identification was assessed while subjects wore each of the three hearing aids, in both quiet and a background of babble (+6 dB S/N). The order of listening conditions was randomized across subjects. Prior to listening with each hearing aid, the volume control of the hearing aid was adjusted for each subject by a bracketing procedure, so that the level of speech spectrum noise presented at 70 dB SPL was comfortably loud. The gain developed by each hearing aid at the subject's comfort volume setting was assessed after each experimental condition was completed. Gain was measured across frequency in a 2-cm^3 coupler with a 60-dB SPL input sweep tone.

For each experimental condition, the subject was required to identify each CV syllable in a written, closed-choice response format. The order of stimulus presentations was varied across experimental conditions. Prior to data collection, the subjects received practice in identifying the stimuli in quiet, when presented under earphones at a comfortably loud listening level. All testing was completed in two sessions of 45 min each.

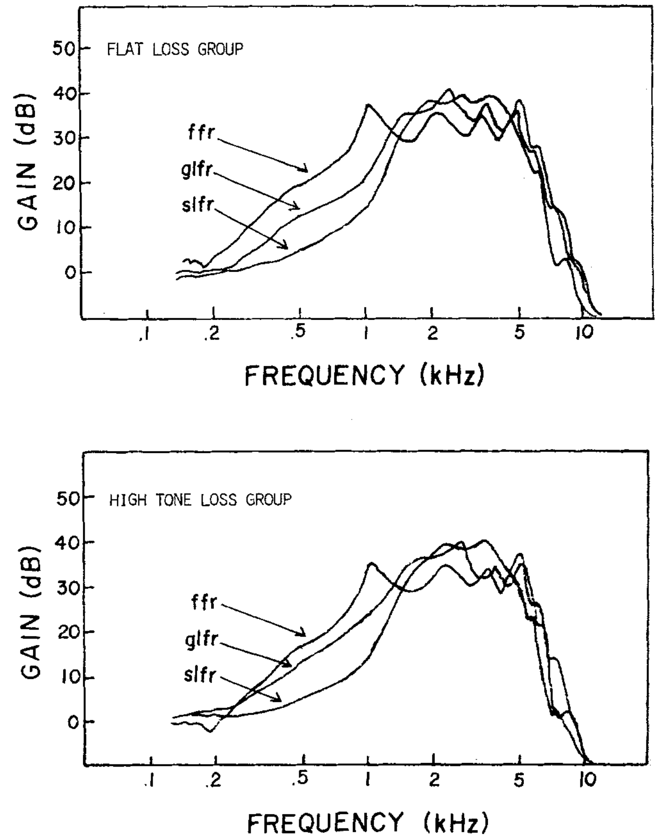

FIGURE 3. Gain of the three experimental hearing aids, measured electroacoustically with a 60-dB SPL input sweep tone, after comfort volume adjustment by subjects with flat hearing losses (top) and subjects with high-frequency hearing losses (bottom).

RESULTS

A. *Gain Measures*

The gain of each hearing aid was assessed after volume adjustment to determine if the two subject groups had different gain in the low and high frequencies. Figure 3 presents the mean electroacoustic gain values. It is apparent that the gain of each hearing aid was similar for the two subject groups. Figure 3 also shows that the gain of the three hearing aids was substantially different in the low frequencies and approximately equivalent in the mid and high frequencies. Notably, the FFR hearing aid provided greater gain in the low frequencies and slightly less gain from 2000 Hz through 5000 Hz than the other two hearing aids. The GLFR and SLFR aids exhibited different gain values primarily below 1500 Hz.

B. *Condition Effects*

The individual raw scores, as well as the means and standard deviations for each subject group in each listening condition, are presented in Table 1. To determine the effects of hearing aid condition and noise condition on nonsense syllable recognition, the raw scores of all subjects in each listening condition were subjected to an analysis of variance with one between-subjects factor (subject group) and two within-subjects factors (hearing aid and noise condition). The ANOVA results revealed a significant main effect of noise condition ($F = 231.43$, $df = 1$, $p < .001$), and this variable was not involved in any interactions. A significant Group × Hearing Aid interaction was also found ($F = 6.58$, $df = 2$, $p < .005$). A simple main effects analysis of this interaction showed that subjects with high-frequency losses performed significantly better than the subjects with flat losses while wearing the GLFR hearing aid ($F = 4.45$, $df = 1$, $p < .05$) and the SLFR hearing aid ($F = 6.58$, $df = 1$, $p < .01$). The analysis of this interaction also revealed a significant performance effect across hearing aid conditions for the high-frequency hearing loss group ($F = 12.352$, $df = 2$, $p < .001$), but no significant differences in performance with the three hearing aids for the flat configuration hearing loss group. Post hoc multiple comparison testing (Newman-Keuls) revealed that the subjects with high-frequency sensorineural hearing losses performed significantly better with the GLFR and SLFR hearing aids than with the FFR hearing aid.

The results suggest that in quiet and noise conditions, the subjects with flat hearing losses performed equally well with the three hearing aids, regardless whether the low frequencies were amplified (as in the FFR hearing aid), moderately attenuated (as in the GLFR hearing aid) or severely attenuated (as in the SLFR hearing aid). Conversely, subjects with high-frequency hearing losses did demonstrate significant performance differences according to the low-frequency amplification characteristics, with best performance obtained in conditions with some low-frequency attenuation.

Subjects with high-frequency losses obtained significantly higher scores than subjects with flat losses in the two hearing aid conditions with the greatest low-frequen-

TABLE 1. Nonsense syllable recognition scores from subjects with flat hearing losses (Group I) and high-frequency losses (Group II), with the FFR hearing aid (flat frequency response), GLFR hearing aid (gradual low-frequency response), and SLFR hearing aid (sharp low-frequency response) in quiet and noise.

	FFR, Quiet		*FFR, Noise*		*GLFR, Quiet*		*GLFR, Noise*		*SLFR, Quiet*		*SLFR, Noise*	
Subject	*Raw score*	*%*	*Raw score*	*%*	*Raw score*	*%*	*Raw score*	*%*	*Raw score*	*%*	*Raw score*	*%*
Group I												
1	117	65.0	75	41.67	85	47.2	62	34.44	46	25.56	58	32.22
2	104	57.77	82	45.56	110	61.11	72	40.0	131	72.78	86	47.78
3	110	61.11	64	35.56	94	52.22	83	46.11	95	52.78	66	36.67
4	82	45.56	35	19.44	109	60.55	45	25.0	83	46.11	46	25.56
5	131	72.78	95	52.78	115	63.89	102	56.67	126	70.0	68	37.78
6	135	75.0	91	50.56	139	77.22	75	41.67	140	77.78	80	44.44
7	128	71.11	90	50.0	111	61.67	69	38.33	121	67.22	97	53.89
8	78	43.33	67	37.22	88	48.89	72	40.0	95	52.78	59	32.78
11	106	58.89	73	40.56	130	72.22	83	46.11	134	74.44	86	47.78
17	112	62.22	68	37.78	138	76.67	76	42.22	142	78.89	56	31.11
$\bar{x}$	110.3	60.98	74.0	41.11	119.9	62.16	73.9	41.06	111.3	61.83	70.2	39.0
SD	19.2	10.56	17.4	9.73	19.4	10.77	14.8	8.22	30.9	17.15	16.3	9.1
Group II												
9	135	75.0	60	33.33	132	73.33	83	46.11	111	61.67	75	41.67
10	134	74.44	101	56.11	157	87.22	105	58.33	157	87.22	110	61.11
12	111	61.67	74	41.11	140	77.78	98	54.44	128	71.11	112	62.22
13	81	45.0	25	13.89	115	63.89	55	30.56	111	61.67	63	35.0
14	143	79.44	82	45.56	146	81.11	92	51.11	157	87.22	121	67.22
15	118	65.56	75	41.67	132	73.33	97	53.89	129	71.67	99	55.0
16	125	79.44	78	43.33	141	78.33	105	58.33	151	83.89	101	56.11
18	81	45.0	46	25.56	108	60.0	63	35.0	79	43.89	67	37.22
19	102	56.67	65	36.11	119	66.11	82	45.56	135	75.0	77	42.78
20	161	89.44	85	47.22	144	80.0	105	58.33	154	85.56	117	65.0
$\bar{x}$	119.1	66.17	69.1	38.39	133.4	74.11	88.5	49.17	131.2	72.89	94.2	52.33
SD	26.0	14.46	21.5	11.93	15.4	8.53	18.0	9.86	25.4	14.12	21.7	12.07

cy attenuation. This finding contrasts with previous reports of better performance by subjects with flat losses than by subjects with high-frequency losses on a nonsense syllable test (Dubno, Dirks, & Langhofer, 1982). The higher scores of subjects with high-frequency losses in the current study are attributed to the benefit that these listeners received from high-pass amplification.

There was substantial intersubject variability. An examination of individual scores in the flat hearing loss group (Table 1) revealed that the performance of 6 of 10 subjects was clearly better with one of the hearing aids. For 3 subjects, best performance was with the SLFR hearing aid, for 2 subjects it was with the GLFR hearing aid, and for the remaining subject it was with the FFR hearing aid. One subject obtained a recognition score with the FFR hearing aid that exceeded the scores obtained with the SLFR and GLFR hearing aids by 40% and 18%, respectively. This subject had a moderately severe flat hearing loss (pure-tone average = 65 dB HL), and therefore required amplification of the low frequencies to receive low-frequency cues for consonant identification. The performance trends of the other five subjects in this group did not appear to be related to degree of hearing loss, subtle idiosyncracies in audiometric configuration, or volume adjustment. The performance of two subjects in the high-frequency group deviated from the group's average performance of relatively poor scores in FFR conditions and equivalent scores in GLFR and SLFR conditions. One subject scored 14% better with the FFR hearing aid than with the SLFR hearing aid; the other subject scored 17% better with the GLFR hearing aid than with the SLFR hearing aid. Both subjects had sharply sloping hearing losses above 1000 Hz and probably required more amplification in the region between 1000 and 2000 Hz than was provided by the SLFR hearing aid.

C. *Perceptual Feature Analysis*

The results of the ANOVA demonstrated group, hearing aid, and noise effects based on total performance scores. We were also interested in detailing how the different hearing aid contours affected perception of the important consonant features by the two subject groups in both quiet and noise conditions. To accomplish this, confusion matrices were prepared separately for the two subject groups, in each of the three hearing aid conditions and the two listening conditions. Twelve matrices resulted, each representing 1,900 observations of the subjects in one group. A high value in an off-diagonal cell of a confusion matrix indicates that the stimulus presented was misperceived by the subjects of a hearing loss group.

The 12 matrices were submitted to the Individual Differences Scaling (INDSCAL) algorithm of the ALSCAL-4 program (Young & Lewyckyj, 1979). The INDSCAL procedure has been thoroughly described by other investigators (Carroll & Chang, 1970; Danhauer & Singh, 1975; Walden & Montgomery, 1975; Wish & Carroll, 1973). The INDSCAL algorithm used the data from the 12 pooled confusion matrices to create a spatial representation of the stimulus objects. This configuration depicts the "hidden structure" underlying all the listeners' psychological judgments of the stimuli, in two or more dimensions. The dimensions are interpreted according to the consonant features which best account for the arrangement of the stimuli. Thus, the *group stimulus space* reflects the consonant feature dimensions that were used by all subjects in perceiving the stimuli. INDSCAL also constructed a *condition space*, which is plot of points representing the experimental conditions. The fitted weights of the condition space indicate the importance of the various dimensions of the group stimulus space for each condition. The ALSCAL-4 program uses an iterative, alternating least squares procedure to determine the stimulus coordinates and condition weights which account for the maximum possible variance in the data.

Solutions were obtained in two through five dimensions, which were examined in two ways. First, the important features that were common in all conditions were identified from the group stimulus space. Second, the salience of these features to each subject group in each listening condition was determined from the condition space. Thus, a description of how the two subject groups' perceptions of the stimuli varied in the different listening conditions can be deduced from these solutions.

Stimulus Configuration

The INDSCAL group stimulus space for the 12 "conditions" revealed readily interpretable dimensions for the four-dimensional solution. In addition, the solution in four dimensions accounted for greater amounts of variance than solutions in fewer dimensions and approximately the same amount of variance as the five-dimensional solution. This solution in four dimensions accounted for 66.2% of the variance in the subjects' proximities data, indicating that the solution fit the data reasonably well.

The four-dimensional stimulus configuration is depicted in Figure 4. This configuration represents the perceptual weightings of the stimuli that were common to all listening conditions for both groups of subjects.

The stimuli may be interpreted as representing three clusters on Dimension 1 (D1): the fricatives /θ,f,v,ð/, the plosives and sibilants /b,d,g,p,t,k,z,r,s,ʃ/, and the nasals and glides /w,l,m,n,j/. Thus, D1 primarily distinguishes different *manner* classes of articulation. D2 displays the stimuli /m,n,p,t,b,f,w,v,l,r,θ/ near the top of the space and

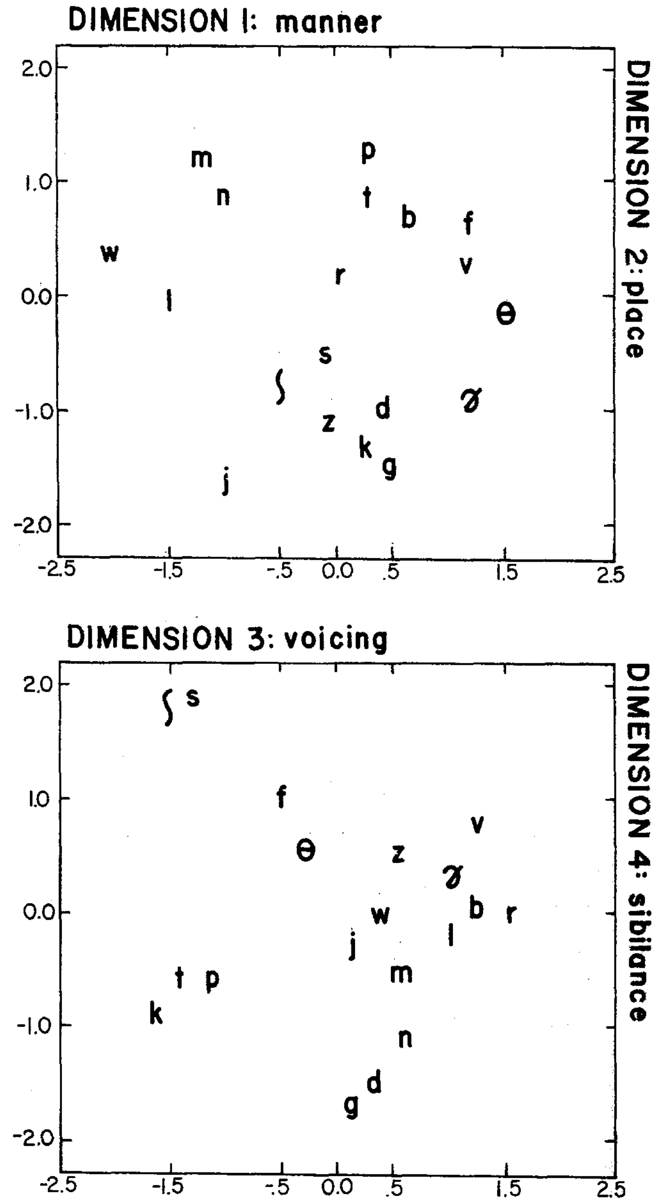

FIGURE 4. Group stimulus configuration in four dimensions, which is common to all subjects in all listening conditions. D1 = manner, D2 = place, D3 = voicing, D4 = sibilance.

the stimuli /s,ʃ,d,ð,z,k,g,j/ near the bottom of the space. The most obvious characteristic of this pattern is that the members of each manner class are ordered according to place of articulation. Specifically, the front-place consonants of each class appear closer to the top of the space than the mid or back-place consonants. D2 is therefore labeled as *place*. The arrangement of stimuli on D3 demonstrates that the voiced stimuli /r,v,b,l,ð,w,z,m,n,j, d,g/ are separated from the voiceless stimuli /p,t,k,θ,s, f,ʃ/. The distinguishing feature for this stimulus pattern clearly is *voicing*, which is the label assigned for D3. Finally, D4 displays a stimulus configuration in which the stimuli /ʃ,s/ are separated from the other phonemes. It appears that the *sibilance* characteristics among these phonemes can account for this stimulus pattern.

The dimensions retrieved by INDSCAL are similar to those reported by other investigators. Doyle, Danhauer, and Edgerton (1981) used SINDSCAL (a version of INDSCAL) to analyze normal and hearing-impaired listeners' consonant confusions on a nonsense syllable task. Three dimensions were interpreted from performance on each of two lists: voicing, place, and sibilance (List A); and voicing, place, and frication (List B). That a manner dimension was not observed may be attributed to the limited stimulus items included in each list (Doyle et al., 1981). INDSCAL also has been applied to hearing-impaired listeners' similarity judgments (Danhauer & Lawarre, 1979; Danhauer & Singh, 1975; Walden & Montgomery, 1975). Dimensions of importance identified in these studies correspond with dimensions retrieved in the present study, despite differences in listening task. Walden and Montgomery labeled the four dimensions in their solution as *sibilance, stop* (ordered according to place), *sonorance*, and *manner of production*. Hearing-impaired listeners used the features *sibilancy, place, voicing, plosive,* and *stop/continuant* in a study by Danhauer and Singh (1975). Perceptual features of consonants employed by hearing-impaired listeners appear to be consistent, regardless of task, amplification, and noise conditions.

Condition Space

The output of INDSCAL provides a plot of the relative weightings of each dimension in the various listening conditions. These weights indicate the importance of each consonant feature dimension to each group of subjects when identifying the stimuli in the different listening conditions. Statistically, the condition weights reflect the proportion of variance in the pooled (condition) matrix which can be accounted for by that dimension. Figure 5 presents the derived condition weights. The effect of hearing aid, listener group, and environmental condition, relative to the stimulus dimensions, can be discerned from these data. However, it should be noted that numerical differences in these weights do not necessarily imply statistical differences.

Overall, the condition weights indicate that subjects with high-frequency losses used manner, voicing, and

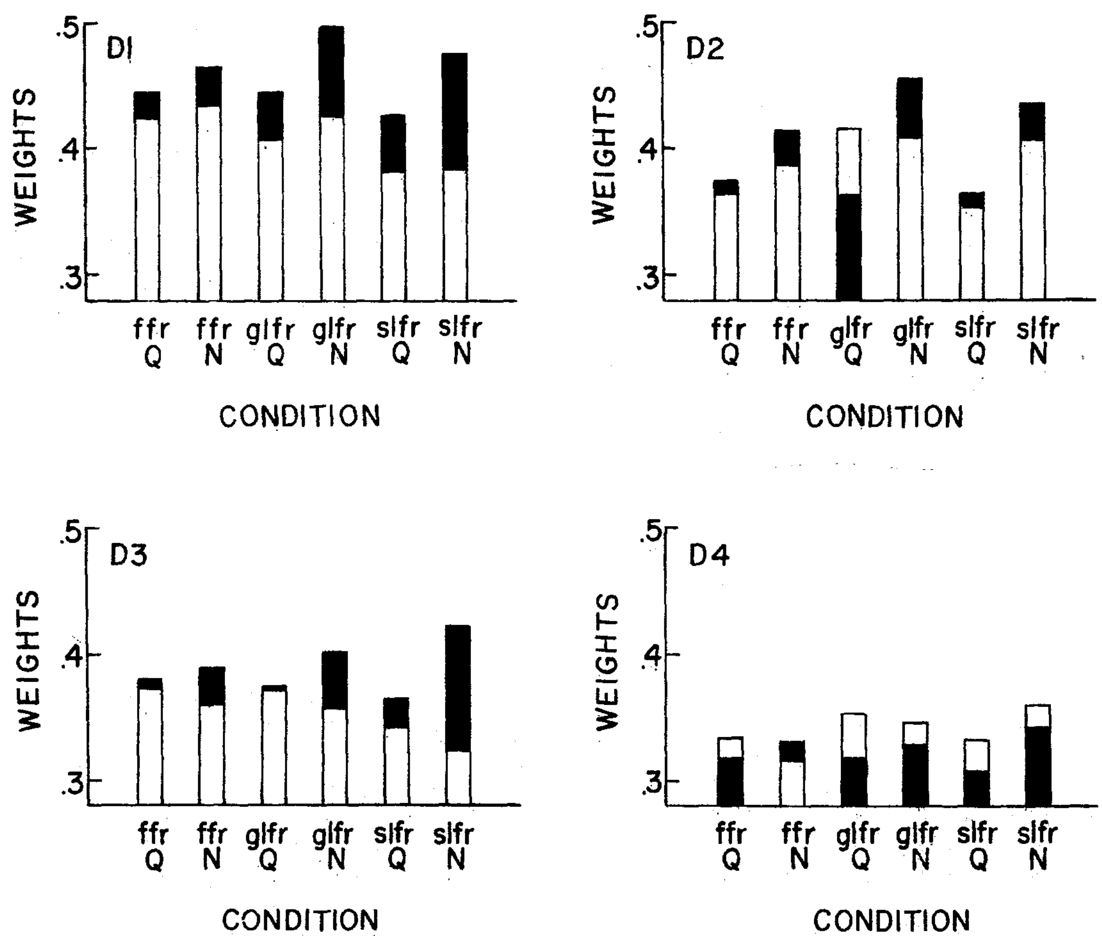

FIGURE 5. Weights for dimensions 1–4 of the group space, obtained by each subject group in quiet and noise in the three hearing aid conditions. The weights indicate the importance of each dimension to the two subject groups for each condition. Filled bar = subjects with high-frequency losses; open bar = subjects with flat hearing losses. ffr = flat frequency response hearing aid; glfr = gradual low-frequency response hearing aid; slfr = sharp low-frequency response hearing aid.

place cues more extensively than subjects with flat losses, and subjects with flat losses used sibilance cues more extensively than subjects with high-frequency losses. Each dimension had numerically larger weights in noise conditions than in quiet conditions, reflecting the greater variance among stimulus confusions in noise. The various features were perceived differentially by the two subject groups while wearing the different hearing aids, suggesting that low-frequency amplification plays an important role in perception of different phonetic features.

The weights for D1 reveal that subjects with high-frequency sensorineural losses used manner cues more extensively than subjects with flat losses. Further, the manner feature was more salient in noise conditions than quiet conditions for each subject group. Perception of manner was most prominent for listeners with high-frequency losses when using hearing aids with moderate or severe low-frequency reduction. Subjects with flat hearing losses used manner cues most extensively when wearing the FFR hearing aid. For each group, weights on D1 were lowest in the quiet condition with the SLFR hearing aid.

The place dimension (D2) is also more salient in noise conditions than in quiet conditions. In noise, place cues are used more by subjects with high-frequency sensorineural losses than by subjects with flat losses. However, in quiet, subjects with flat losses either exhibit higher or equivalent weights compared to subjects with high-frequency losses. Interestingly, the place dimension was most salient for both groups in noise while wearing the hearing aids that reduced low-frequency amplification (GLFR and SLFR) but least salient in quiet while wearing the SLFR hearing aid.

The voicing dimension (D3) contributed more to identification of the stimuli by subjects with high-frequency losses than by subjects with flat losses. Voicing was apparently more salient in noise than in quiet for listeners with high-frequency losses, but was more salient in quiet than in noise for listeners with flat losses. The weights of the three hearing aid conditions presented in noise are clearly different for the two groups of subjects on this dimension. Subjects with high-frequency losses used voicing cues most extensively while wearing hearing aids with low-frequency reduction (SLFR and GLFR); subjects with flat hearing losses used voicing cues most prominently with hearing aids that have low-frequency amplification (FFR and GLFR). This dimension contributed least to the identification responses of the flat hearing loss subjects in noise while wearing the SLFR hearing aid.

The fourth dimension, sibilance, was most salient for subjects with flat hearing losses while wearing the SLFR and GLFR hearing aids. It was least salient for subjects with high-frequency losses listening in quiet conditions. However, these same subjects did use sibilance cues to some extent while wearing the SLFR hearing aid in noise. These results suggest that the perceptual salience of sibilance was less for subjects with high-frequency losses than for subjects with flat losses. The finding that sibilance contributes little to perceptual judgments by subjects with high-frequency losses is consistent with the results of other studies assessing speech perception by listeners with different audiometric configurations (Walden & Montgomery, 1975).

D. Consonant Recognition

To examine further the effects of varying the amount of low-frequency amplification on consonant recognition, a percentage correct score for each of the 19 consonants was calculated. These individual phoneme recognition scores were obtained by summing the individual consonant scores from the 10 subjects in each hearing loss group for each condition. Each score represents the frequency of correct identifications for 100 observations of the stimulus phoneme. These scores are presented in Tables 2 and 3.

Table 2 displays the consonant recognition scores obtained from listeners with flat audiometric contours. In quiet, these subjects achieved higher scores while wearing the FFR hearing aid than while wearing the GLFR or SLFR aids for the front-place phonemes /b,p,v,w/ and /l/. However, recognition of the mid and back-place phonemes /g,t,k,n/ was lower with this same hearing aid compared to scores obtained with the other aids. Identification scores for most phonemes were similar when these subjects wore the GLFR and SLFR hearing aids, with the exception of the consonants /b,z,f,r/. Large differences in scores (greater than 20%) are observed across at least two hearing aid conditions for the stop consonants /b,g,t,n/ and the glide /l/. These data confirm that individual consonant identification scores can change dramatically as low-frequency amplification contours are manipulated. This effect was not reflected in the total percent correct recognition scores.

In noise, subjects with flat losses obtained similar consonant recognition scores while wearing the three different hearing aids for most phonemes (Table 2). Moderate score differences (>10%) are observed for several consonants, indicating that the FFR hearing aid was useful for perception of the glides /w, l/, the SLFR hearing aid was useful for perception of the voiced plosive /d/, and the GLFR hearing aid improved identification of the consonants /p,z/

Consonant recognition scores of subjects with high-frequency hearing losses are shown in Table 3. Large differences in scores obtained with the three hearing aids in quiet (≥20%) are seen for the phonemes /g,t,n,ʃ/. Scores for these phonemes were consistently poorest when subjects with high-frequency losses wore the FFR hearing aid. However, only small differences among scores for these phonemes, with the exception of /t/, are seen with the GLFR and SLFR hearing aids.

Recognition performances of subjects with high-frequency losses, listening in noise, are also shown in Table 3. The data indicate considerable differences in recognition of specific phonemes, especially /d,g,m,n,ʃ,j,l/ across the three hearing aid conditions. Recognition of these consonants was consistently poorest while the subjects

TABLE 2. Mean % correct recognition scores of individual consonant phonemes obtained by subjects with flat hearing losses in quiet and noise, across the three hearing aid conditions. Phonemes whose scores exceed a 20% difference among at least two hearing aid conditions are underscored. FFR = flat frequency response, GLFR = gradual low-frequency response, SLFR = sharp low-frequency response.

Phoneme	*Quiet condition*			Phoneme	*Noise condition*		
		Hearing aid				*Hearing aid*	
	FFR	*GLFR*	*SLFR*		*FFR*	*GLFR*	*SLFR*
b	85	49	61	b	40	32	32
d	85	88	81	d	77	79	92
g	43	74	71	g	18	29	26
p	78	65	62	p	24	40	22
t	21	48	50	t	5	11	13
k	33	42	51	k	19	12	11
m	93	85	83	m	62	66	57
n	6	33	40	n	19	18	28
s	43	33	33	s	33	34	24
z	42	44	60	z	23	27	14
ʃ	100	99	100	ʃ	90	97	95
f	92	98	86	f	67	57	57
v	38	21	23	v	12	11	11
θ	8	6	6	θ	8	13	10
ð	17	21	17	ð	8	4	8
w	62	58	50	w	42	31	32
j	99	99	98	j	80	81	86
r	72	75	64	r	47	43	43
l	93	79	69	l	61	53	42

with high-frequency hearing losses wore the FFR hearing aid. The SLFR and GLFR hearing aids yielded similar recognition performance for most of the consonant phonemes, with the exceptions of /r/, /v/, and /p/. These consonants were identified with highest accuracy when these subjects wore the SLFR hearing aid. It is apparent that overall performance by subjects with high-frequency hearing losses is best with hearing aids with some low-frequency reduction, which is due to large part to improvements in identification of voiced stops and glides.

DISCUSSION

The results of this study have shown that incorporating low-frequency amplification in extended high-frequency emphasis hearing aids differentially affects speech perception performance by hearing-impaired listeners with different audiometric configurations. Although no significant differences in overall recognition performance were found for listeners with flat hearing losses across the different hearing aid contours, a feature analysis (INDSCAL) revealed that two of the features perceived by all listeners were most salient to listeners with flat losses when using hearing aids with some low-frequency amplification. Further, an examination of specific phoneme recognition scores obtained from these listeners indicated that identification of difficult-to-perceive consonants was often better with the hearing aid providing the most low-frequency amplification. For subjects with high-frequency sensorineural hearing losses, overall recognition scores were significantly better with the high-pass hearing aids than with the wide-band hearing aid. These results were confirmed by the feature analysis, in which it was shown that all four dimensions had the highest numerical weights in noise with hearing aids that attenuated the low frequencies. These subjects also showed poorest identification of consonant phonemes that had large score differences across the three hearing aids while wearing the FFR aid. For those few phonemes that were identified with different accuracy while subjects wore the two high-pass hearing aids, performance was usually higher with the aid that most severely limited low-frequency amplification.

The major conclusions of this experiment generally support those of previous investigations. Specifically, the finding that reduction of low-frequency amplification improves speech recognition performance by listeners with high-frequency sensorineural hearing losses also has been reported by Kamm et al. (1982), Pascoe (1975), Schwartz et al. (1979), and Skinner (1980), using different experimental paradigms. One surprising result of the present investigation, which is contrary to these earlier reports, was that recognition scores varied significantly across different hearing aid contours in quiet as well as in noisy listening environments. We attribute this occurrence to the stimulus materials used in the experiment, because large differences in consonant identification scores were observed across hearing aid contours for phonemes that were not typically represented in the materials of other investigators.

That hearing-impaired listeners with flat hearing losses did not demonstrate significant changes in gross performance as low-frequency amplification was manipulated is in agreement with the results of a recent study by Kamm et al. (1982), in which the NST was presented. However,

TABLE 3. Mean % correct recognition scores of individual consonant phonemes, obtained by subjects with high-frequency hearing losses in quiet and noise, across the three hearing aid conditions. Phonemes whose scores exceed a 20% difference among at least two hearing aid conditions are underscored. FFR = flat frequency response, GLFR = gradual low-frequency response, SLFR = sharp low-frequency response.

Phoneme	*Quiet condition*			*Phoneme*	*Noise condition*		
	Hearing aid				*Hearing aid*		
	FFR	*GLFR*	*SLFR*		*FFR*	*GLFR*	*SLFR*
b	78	72	64	b	31	29	32
d	74	78	84	d	46	70	62
g	62	82	87	g	9	26	36
p	60	70	64	p	48	44	59
t	22	63	45	t	6	16	12
k	94	79	80	k	34	28	25
m	100	98	100	m	68	88	90
n	16	50	49	n	22	46	44
s	46	52	39	s	39	43	38
z	64	65	73	z	30	32	38
ʃ	71	93	90	ʃ	37	88	90
f	88	87	84	f	65	71	65
v	25	31	32	v	23	14	26
θ	13	22	24	θ	5	14	22
ð	44	45	56	ð	16	28	29
w	56	59	48	w	33	38	37
j	92	100	99	j	67	89	84
r	92	86	95	r	40	28	43
l	93	92	99	l	72	91	92

when the SSI was presented in that same study, subjects with flat hearing losses performed best with the amplification contour that included the most low-frequency enhancement. This result was also supported by our data, when they were analyzed according to feature perception and individual consonant recognition. We contend that hearing-impaired listeners with flat losses can benefit by low-frequency amplification for consonant perception without severe deleterious effects. This conclusion conflicts somewhat with Harford and Fox's (1978) tentative assertion that extra high-frequency amplification in conjunction with reduction of low-frequency amplification is advantageous for listeners with flat hearing losses. However, unlike the present investigation, Harford and Fox did not directly investigate the effects of reducing low-frequency amplification while maintaining the favorable high-frequency amplification contour. In other words, the positive effects reported by Harford and Fox could have been attributed more to the extended high-frequency emphasis than to the low-frequency reduction.

The patterns of feature weights also reflect subtle perceptual differences between the two groups of listeners while wearing the different hearing aids. Subjects with high-frequency hearing losses perceived all four features in noise more extensively with hearing aids having low-frequency reduction than with the FFR hearing aid. Presumably, amplification of the low frequencies was extraneous for perception of features cued by high-frequency information, such as sibilance, place, and manner. For voicing, a feature distinguished primarily by low-frequency content, listeners with high-frequency losses probably received the information without additional low-frequency amplification because of their normal thresholds in the low frequencies. For all four features, then, the addition of low-frequency amplification reduced perceptual salience, and therefore may have caused upward spread of masking. In addition, the slight reduction in high-frequency gain developed by the FFR hearing aid may have served further to reduce the availability of high-frequency cues. Subjects with flat hearing losses perceived the place and sibilance features more extensively while wearing the GLFR and SLFR hearing aids than the FFR hearing aid. Again, amplification of the low frequencies may have served to reduce detection of the relevant high-frequency information inherent in these features. However, the flat hearing loss subjects used the manner and voicing cues most extensively while wearing the FFR hearing aid. Amplification of the low frequencies was therefore necessary for these subjects to perceive low-frequency voicing cues and to receive the low-frequency cues that contribute to distinguishing the various manners of articulation.

In conclusion, the results of this investigation suggest that listeners with flat hearing losses do benefit by amplification of the low frequencies, when incorporated into an extended high-frequency amplification contour. Conversely, extensive amplification of the low frequencies is not warranted for subjects with selective high-frequency losses. Evaluation of performance by feature analysis or consonant recognition analysis provided more detailed information about the subtle effects of hearing aid-hearing loss interactions than did an examination of total percent correct recognition scores.

ACKNOWLEDGMENTS

The study presented in this paper was supported in part by a Postdoctoral Research Award from the American Speech-Language-Hearing Foundation and Psi Iota Xi Sorority, and by a Biomedical Research Support Grant (No. RR-07042) from the University of Maryland. The computer time for this project was partially supported through the facilities of the Computer Science Center at the University of Maryland. The author is grateful to Grace Yeni-Komshian for her valuable comments on an earlier draft of this manuscript. Appreciation is also expressed to the Oticon Corporation for the generous loan of the hearing aids used in this experiment.

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Received June 24, 1983
Accepted March 7, 1984

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