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Consonant Recognition Performance of Hearing-impaired Listeners Using One Linear and Three Nonlinear Hearing Aids

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Abstract

Consonant recognition performance was examined in 18 subjects listening in quiet and speech noise with linear and nonlinear hearing aids. Subjects were divided into three groups by audiometric configuration: flat, moderately sloping, and sharply sloping. Nonlinear amplification schemes included adaptive high-pass filtering (Argosy's Manhattan II, experimentally modified; MANe), MANe circuitry followed by expansion (EXP), and infinite amplitude clipping (IAC). Consonant-to-vowel ratios (CVRs) were calculated for syllables processed through each hearing aid. Performance with the IAC was significantly poorer than with the other amplifiers across audiograms in noise. Intersubject variability in performance was high, even within audiogram groups. High-frequency phonemes were more often audible with the EXP than with the other hearing aids for subjects with moderately and severely sloping audiograms. Output CVRs increased for some phonemes with a nonlinear hearing aid versus linear, but recognition of individual phonemes did not correlate significantly with CVR.

Key Words: Amplification, consonant recognition, consonant-to-vowel ratios (CVRs), expansion, hearing aids, nonlinear signal processing

Simply ensuring the audibility of amplified speech sounds may not always result in good speech recognition performance in noise for patients with sensorineural hearing impairment. Some authors have argued that discrepancies in speech recognition scores among patients with similar audiograms may be due to perceptual distortion and deficits in psychoacoustic processing abilities caused by cochlear damage (e.g., Plomp, 1978). In an attempt to improve speech recognition, especially for listening in noise, a major focus of hearing aid research over the past decade has been the development and evaluation of nonlinear, automatic signal processing (ASP) circuits. A number of ASP approaches have been tried, including various applications of adaptive filtering and compression, but the research literature evaluating the efficacy of these devices has shown mixed results (see Sammeth and Ochs, 1991, for a review).

The most common approach in commercially available ASP hearing aids that are advertised as "noise reduction" has been to reduce gain in the low frequencies as input level increases. This approach has been given the acronym "BILL" (Killion et al, 1990) for "base increases at low levels." One underlying assumption of a BILL-type processor is that longer duration, higher level, low-frequency energy at the input to a hearing aid is primarily noise and that shorter duration, lower level, high-frequency energy is primarily speech. This assumption may be valid for some listening conditions, but with noise such as multitalker babble, the speech and noise spectra largely overlap. As Fabry (1991) has pointed out, any speech energy in the low-frequency region will be reduced concurrently with the noise so that signal-to-noise

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ratio (SNR) will not be improved in any given band.

Another assumption often made with BILL-type processing is that progressive reduction of low-frequency energy at higher input levels may reduce detrimental effects of upward spread of masking. The validity of this assumption is unclear because supportive data are generally lacking (e.g., Bray and Thibodeau, 1992; Rankovic et al, 1992). Finally, it has been noted that BILL-type hearing aids, as well as other ASP approaches, produce fewer distortion products at high input levels than do linear peak-clippers because the hearing aid is less often placed into saturation (Preves, 1990). This reduction in distortion is assumed to be beneficial both in terms of speech recognition and listening comfort.

Researchers recently have examined changes in the temporal waveforms of speech processed by hearing aids (e.g., Preves et al, 1991; Ochs et al, 1992; Teder, 1993), on the assumption that a family of frequency response curves generated with speech spectrum noise may not clearly predict circuit performance for natural syllables. One factor of interest has been consonant-to-vowel ratios (CVRs) at the output of a hearing aid. Picheny et al (1986) found that when speakers were asked to speak "clearly" rather than "conversationally," the result was a change in several acoustic characteristics of their speech, including enhancement of the amplitude of consonants relative to vowels. Laboratory studies have demonstrated 10 percent to 15 percent mean improvements in consonant recognition scores of hearing-impaired subjects with increases in CVRs (e.g., Gordon-Salant, 1987; Montgomery and Edge, 1988), but it is unclear if these results are due to enhancement of suprathreshold cues or to merely achieving audibility of the consonant energy.

The use of fixed high-pass filtering in linear hearing aids alone produces increased CVRs relative to unprocessed speech, but even greater CVR enhancements can be expected with some ASP hearing aids. For example, in an evaluation of four in-the-ear (ITE) hearing aids, three of which included forms of BILL-type processing, Preves et al (1991) reported mean 4-dB to 6-dB improvements in CVRs relative to unaided speech for some, but not all, syllables. Ochs et al (1992) found that the effect on vowel energy of adaptive high-pass filtering in a BILL-type hearing aid was most dramatic in the 1500-Hz region, resulting in increased CVRs relative to linear amplification for some syllables but not for others.

One of the hearing aids in the Preves et al (1991) study incorporated a combination of adaptive high-pass filtering (BILL-type processing) and expansion. Expansion essentially works in a manner opposite to compression, that is, there is an increase in gain as input level increases. In laboratory studies, the use of expansion in hearing aids to enhance low-level consonant energy has produced somewhat equivocal results (e.g., Yanick and Drucker, 1976; Walker et al, 1984). In the Preves et al (1991) study, the output of a BILL-type ASP was expanded, so that expansion primarily acted upon high-frequency energy. This approach resulted in greater CVRs for some high-frequency consonants relative to vowels than did the use of the BILL processing alone.

The current study was intended as a comparative evaluation of three nonlinear hearing aids versus a high-quality linear amplifier. Comparisons included hearing-aid-processed (output) CVRs and patient performance on a consonant recognition task given in quiet and in background noise. Two of the nonlinear hearing aids evaluated used BILL-type processing, one with adaptive high-pass filtering (AHPF) and the other with expansion following the AHPF in an attempt to further increase CVRs.

In the third nonlinear hearing aid, infinite amplitude clipping (IAC) preceded by fixed high-pass filtering was used. In this signal processing approach, fixed high-pass filtering increases the amplitudes of consonants relative to vowels. With subsequent peak clipping, the temporal modulation index is essentially reduced to zero, leaving only the zero crossings of the temporal waveform. Over 4 decades ago, Licklider and Pollack (1948) reported that IAC improved speech understanding compared to linear amplification for normal-hearing subjects listening in a background of white noise. Thomas and Sparks (1971) reported similar results with hearing-impaired listeners, but there has been little follow-up to these works.

METHOD

Subjects

Eighteen hearing-impaired adults (5 females and 13 males), ranging in age from 47 to 84 years (mean age = 73), were paid to participate in this study. Only one ear of each subject was tested, but hearing sensitivity of the nontest ear was equivalent to or poorer than the test ear. All subjects had sensorineural hearing loss (air-bone gaps ≤ 10 dB and normal tympanograms) and no history of retrocochlear pathology. Approximately one-half of the subjects used hearing aids in the test ear at the time of the study, although none used ASP hearing aids.

Subjects were carefully selected to represent three homogenous groups of six subjects each, based on audiometric configuration. Age range and hearing aid usage in the test ear were similar across the three groups. The first group of subjects had relatively "flat" audiogram configurations, defined as thresholds falling within a 20-dB range from 500 to 4000 Hz inclusively. The second group had "moderately sloping" audiograms, defined as mild hearing loss at 500 Hz gradually sloping to a moderate-severe hearing loss at 4000 Hz. The third group had "sharply sloping" audiograms, defined as hearing within normal limits through 1000 Hz, dropping to a moderate-severe to severe hearing loss at 4000 Hz. Mean audiograms for each group, with standard deviation bars, are shown in Figure 1.

Stimuli

Test stimuli for the consonant recognition task consisted of the phonemes /f/, /s/, /t/, /p/, /v/, and /z/, each combined with the vowel /i/ in both initial and final positions. These were selected to include two voiceless fricatives (/f/, /s/), two voiceless stop consonants (/t/, /p/), and two voiced fricatives (/v/, /z/). The consonant-vowel (CV) or vowel-consonant (VC) syllables were spoken with the carrier phrase "I'd like you to circle the word..." by a male speaker with a standard American dialect.

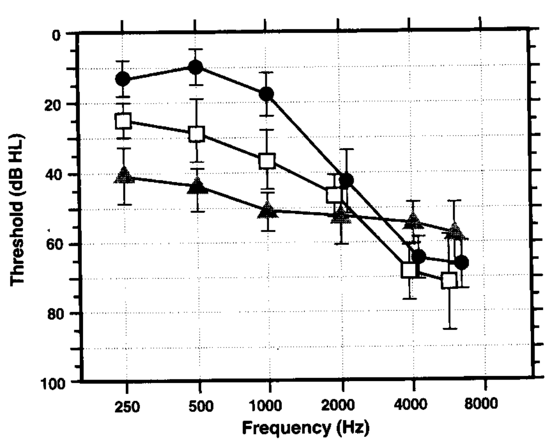

Figure 1 Mean audiograms, with standard deviation bars, for the "flat" (triangles), "moderately sloping" (squares), and "severely sloping" (circles) audiogram groups. Values are slightly offset in the high frequencies to avoid overlap of the standard deviation bars.

For recording of the stimuli, the speaker was seated in a sound booth and produced several samples of each CV or VC stimulus into a Sony ECM-150T electret condenser microphone placed at a distance of 5 inches. The stimuli were initially recorded on a Tascam 22-Z reel-to-reel tape recorder. The best (cleanest) representations of each stimulus were then low-pass filtered at 10 kHz, digitized at 22 kHz using a 12-bit ADC on a Data Translation I/O board, and randomized into lists of syllables for re-recording onto audio cassette tape.

Two stimulus conditions were used: listening in quiet and listening in a background of speech spectrum noise at an SNR of +8 dB. Speech stimuli were calibrated at 70 dB SPL at the input to the hearing aid; thus, actual listening levels were this baseline level plus the gain provided by the hearing aid. For a given stimulus condition and hearing aid, each of the 12 stimuli were presented a total of eight times in randomized order.

Hearing Aids

The hearing aids used in this study were supplied by Argosy Electronics, Inc, and all had a class D amplifier output stage for greater "headroom" (the difference in dB between gain-plus-input level and the level at which saturation begins). The circuitry for all four hearing aids was housed in a small, custom-built, table-top circuit box. The output of this master hearing aid was delivered to a subject's ear via an electrical cord leading to a behind-the-ear (BTE) hearing aid shell. An earhook damper was used in the BTE to place the primary frequency response peak at approximately 3000 Hz, as seen with many ITE hearing aids. This created a smoother insertion gain frequency response than would usually be provided by a BTE hearing aid (which has a primary peak at about 1000 Hz) by filling in the insertion loss dip at about 3000 Hz. Switches on the circuit box allowed quick selection of hearing aid circuit and of preset electroacoustic parameters without removal of the BTE shell from the subject's ear. The four hearing aid circuits evaluated were as follows:

1. *Linear amplifier (LIN).* A commercially available linear hearing aid (Argosy Linear Plus) was used as a comparison condition.
2. *Argosy Manhattan II with experimental modifications (MANe).* The Argosy Manhattan II hearing aid uses BILL-type processing

accomplished with voltage-controlled, adaptive high-pass filtering. The version of this hearing aid that we used was an experimental modification of the commercial version. Specifically, it had a faster, peak-detecting rectifier compared to the slower, averaging rectifier in the commercial Manhattan II, and the preamplifier was placed postfiltering, in order to increase aided CVRs and headroom, respectively (see Preves et al, 1991).

3. *The "Expander" (EXP).* We will use the name "expander" for the second nonlinear hearing aid evaluated, an experimental model that is not yet available on the commercial market. This hearing aid incorporated the circuitry of the MANe, followed by additional circuitry that expanded the output (amplitude expansion). As a result of the reduction in low-frequency energy at moderate-to-high input levels produced by the MANe circuitry, the EXP hearing aid was expected to provide additional increases in CVRs relative to the MANe.
4. *Infinite Amplitude Clipper (IAC).* The third nonlinear hearing aid evaluated, also an experimental model, used infinite amplitude clipping (IAC), implemented with a 50-Hz triangular modulation waveform and comparator, preceded by high-pass filtering. Licklider and Pollack (1948) first suggested adding modulation to the speech waveform before IAC in order to improve sound quality. Depending on the relationship between the amplitude of the modulation waveform and the signal waveform, this processing can result in signal expansion at low input levels and signal compression at high input levels. For the current study, the level of the modulation waveform was adjusted with the use of normal-hearing subjects to that point at which sound quality was considered acceptable, but at which significant consonant emphasis was still perceived.

More detailed descriptions of these nonlinear hearing aids, and block diagrams of their circuitry, can be found in Preves et al (1991).

For the flat and moderately sloping audiogram groups, frequency responses for the LIN, MANe, and EXP hearing aids were set to approximate the prescribed 2-cc coupler gain/frequency response calculated with the National Acoustics Laboratories' revised prescription formula (NAL-r) (Byrne and Dillon, 1986) for a 50-dB SPL input signal. This level was selected in order to match the frequency responses at an input level below the threshold for adaptive processing in the nonlinear hearing aids. Gain/frequency responses were calculated and set for the average audiometric thresholds within each group. Because audiograms within a group were so closely matched and, given the typical degree of error in matching the target gain/frequency response (Sammeth et al, 1993), we believe that this procedure resulted in frequency responses quite similar to those that would have been found had fitting been done on an individual basis. We found that it was necessary to use maximum available high-frequency emphasis tone control settings to achieve prescribed gain in the moderately sloping audiogram group. Therefore, the same frequency responses were also used for the sharply sloping group. In fact, a reasonable argument can be made for supplying slightly greater low-frequency gain to subjects with sharply sloping audiograms who are being fit with a BILL-type hearing aid than that prescribed with formula approaches. Research using subjective judgments suggests that this approach may result in better perceptual sound quality for quiet listening (e.g., Punch and Beck, 1986), yet the adaptive high-pass filter will reduce the gain in high-level noise situations where it is considered undesirable. In addition, fitting to prescribed gain would have resulted in no low-frequency amplification for the sharply sloping group and, thus, little or no difference in frequency response across input levels for the linear versus BILL-type hearing aids.

Figure 2, A and B, illustrates 2-cc coupler frequency responses (with a broadband complex noise input) used for the sloping audiogram groups for the MANe (Fig. 2A) and EXP (Fig. 2B) hearing aids with the 50-dB SPL input used to match the responses, and with a 70-dB SPL input where the effects of adaptive processing are apparent. Note that the higher level stimulus results in an overall reduction in gain for the MANe, with greater reduction in the low frequencies, while the EXP shows reduction in the low frequencies but also increased gain in the high-frequency region. For the IAC hearing aid, the frequency response prior to clipping was set to approximate +12 dB/octave high-frequency emphasis, as recommended by Thomas and Niederjohn (1970), for all three audiogram groups.

Procedures

All testing was completed in a sound-treated booth. Speech and noise were presented from a

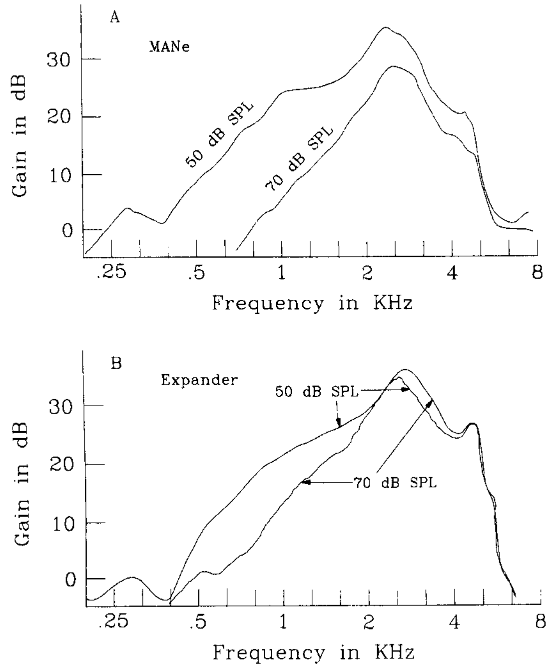

Figure 2 Frequency response curves on the 2-cc coupler for the Manhattan II with experimental modifications (MANe; Part A) and for the EXP hearing aid (Expander; Part B) with broadband stimulus input levels of 50 dB SPL and 70 dB SPL.

single loudspeaker placed at 0° azimuth to the subject and at a distance of 1 meter. The circuit box was placed on a small table behind the chair and the BTE shell was attached to the subject's ear with Comply™ (3M Company) foam earplugs with tubing (#2 for the flat audiogram group and #4, with venting, for the sloping audiogram groups). The nontest ear was occluded with a solid earplug during testing.

Audibility Task. The first task completed was a check of the audibility of the least intense of the test phonemes (the fricatives /s/, /f/, /v/, and /z/) through each of the hearing aids, in both quiet and noise listening conditions. These phonemes were evaluated following the vowel /i/, rather than in an isolated context, to account for any forward masking effects of the preceding vowel. Cassette tape recordings of each of the VC syllables (/is/, /if/, /iv/, and /iz/) repeated at a rate of 1/second were used. A recording was also made of a repeating, isolated /i/, which was spliced from the /fi/ syllable, as a control condition.

Each phoneme recording was played through each hearing aid at least twice (with a random order of the recordings played) for a period of time that covered several VC presentations. Subjects were instructed to raise their hands if they thought that they heard consonant energy at the end of the vowel (regardless of whether or not they could identify the consonant), but not if they thought that they heard the vowel alone. Subjects who raised their hands for the vowel-alone presentation were reinstructed until they could perform the task consistently.

Consonant Recognition Task. Subjects were given response sheets consisting of numbered rows of the letters "f, p, s, t, v, and z," corresponding to the target phonemes. They were instructed to circle the letter corresponding to the sound that they heard either before or after the vowel for each presentation.

The test order of the four hearing aid circuits and two stimulus conditions (quiet vs noise) was randomized. Percent correct scores on the consonant recognition task were subjected to arcsine transformation prior to statistical analysis to homogenize the variance over the range of scores (see Studebaker, 1985). The phoneme data were also entered into individual and audiogram-group confusion matrices, patterned after Miller and Nicely (1955). Phoneme errors for the individual and audiogram group matrices for each condition were descriptively analyzed in terms of the distinctive features of place of articulation, manner of articulation, and voicing. Errors that were multiple in feature, such as identifying /vi/ as /pi/, were counted in all relevant categories.

CVR Measurements. We measured CVRs for each CV and VC token, in quiet, with each hearing aid circuit attached to the ear of a KEMAR mannequin with the same foam earplugs and preset electroacoustic parameters used for each audiogram group. The level of presentation was 70 dB SPL at the hearing aid microphone. The output of the KEMAR Zwislocki coupler was recorded using a Revox A77 reel-to-reel audiotape player. For analysis, the audiotape recordings were routed through a 7.5 kHz low-pass filter and digitized at a sampling rate of 20 kHz. Interactive Laboratory Services (ILS) software was used to mark the boundary between each consonant and vowel, identified as the point at which amplitude changed markedly or the point where aperidodicity either ceased or began. The consonant and vowel portions were separated at the zero crossing closest to the junction, and segment boundaries were verified by listening to the consonant and vowel portions after separation. The rms amplitude was calculated for each segment across its entire duration.

RESULTS

Audibility

Table 1 shows the number of subjects in each audiogram group for whom a given consonant sound was inaudible for each hearing aid and stimulus condition. Not surprisingly, all fricatives were found to be audible in quiet except for four instances in the sharply sloping audiogram group. When subjects were listening in background noise, the /f/ phoneme, which has the highest-frequency energy, was most often inaudible with all hearing aids for subjects with sloping audiograms, while /v/ was most often inaudible for subjects with flat audiograms. The IAC hearing aid produced the greatest number of instances of inaudible phonemes for the sloping audiogram groups. For the sharply sloping audiograms, there were fewer instances of inaudible phonemes with the EXP hearing aid compared with the other circuits.

Consonant Recognition Performance

Group means and standard deviations for overall percent correct with each hearing aid under each listening condition are shown in Figure 3, A–C for each audiogram group. For the quiet listening condition, analysis of variance (ANOVA) on the arcsine transformed data, with

Table 1 Number of Subjects for Whom a Given Consonant Was Inaudible with Each Hearing Aid in Each Listening Condition

	Quiet				*Noise*			
	LIN	*MANe*	*EXP*	*IAC*	*LIN*	*MANe*	*EXP*	*IAC*
Flat Audiograms								
/s/	0	0	0	0	0	0	1	1
/f/	0	0	0	0	1	1	1	1
/v/	0	0	0	0	3	2	2	2
/z/	0	0	0	0	1	2	2	1
Total	0	0	0	0	5	5	6	5
Moderately Sloping Audiograms								
/s/	0	0	0	0	1	2	1	3
/f/	0	0	0	0	2	4	3	3
/v/	0	0	0	0	2	2	1	3
/z/	0	0	0	0	0	0	0	3
Total	0	0	0	0	5	8	5	12
Sharply Sloping Audiograms								
/s/	0	0	0	1	2	2	1	2
/f/	0	1	0	2	4	4	2	3
/v/	0	0	0	0	3	3	2	2
/z/	0	0	0	0	1	1	1	4
Total	0	1	0	3	10	10	6	11

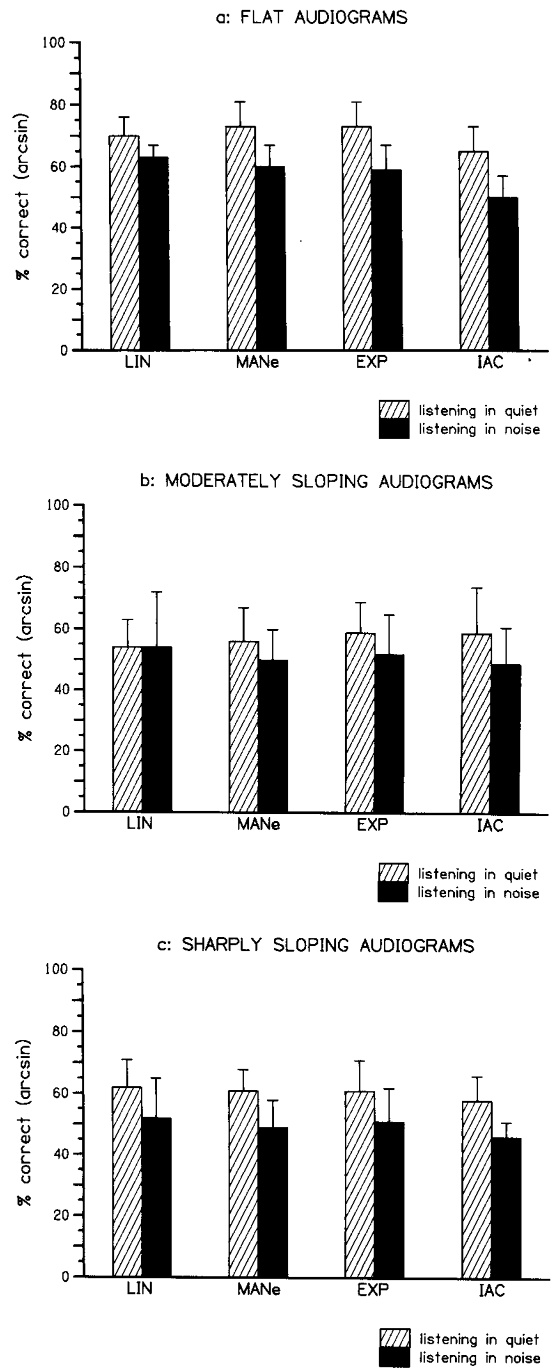

Figure 3 Means and standard deviations of arcsine transformed percent correct scores on the nonsense syllable task for each audiogram group and listening condition (LIN: linear hearing aid; MANe: Manhattan II with experimental modifications; EXP: Expander; and IAC: infinite amplitude clipper).

audiogram group as a between-subjects factor and hearing aid as a repeated factor, revealed a significant effect of audiogram ($p < .05$), but there was no significant effect of hearing aid, and no significant interaction. Newman-Keuls *aposteriori* comparisons revealed that overall performance was significantly better for subjects with flat audiograms than for those with sloping audiograms. For the noise listening condition, an ANOVA revealed a significant effect of hearing aid ($p < .01$), but no significant effect of subject group (audiogram), and no significant interaction. *Aposteriori* comparisons revealed that performance with the IAC was significantly poorer than with the other hearing aids.

Because differences in individuals' performances are sometimes obscured by group mean data, we also examined individual subject data. In fact, despite the close matching of audiograms for each group, there was some notable individual variability in performance, even within a grouping. First, some subjects had better scores across all four hearing aids (indicating greater benefit from amplification) than did others within the same audiogram group. For example, one subject with a moderately sloping audiogram had aided consonant recognition scores in noise that ranged from 77 percent to 99 percent across the four hearing aids, while another subject with a similar audiogram had aided scores in noise ranging from 33 percent to 58 percent across the hearing aids. Second, although the majority of the subjects showed little or no differences in consonant recognition scores across the four hearing aids, there were a few individuals who showed large differences for at least some comparisons. One subject from the flat audiogram group (subject #10) performed much better with the LIN hearing aid (75%) than with the EXP (51%) for listening in noise. In contrast, one subject with a moderately sloping audiogram (subject #6) performed much better in noise with the EXP (75%) than with the LIN (55%). Interestingly, another subject from the moderately sloping audiogram group (subject #2), who not only had nearly identical hearing thresholds but also comparable unaided speech recognition scores (quiet: 80% and 82% for these two subjects, respectively; noise at +8 dB SNR: 58% and 66%) and identical unaided speech MCLs (70 dB HL) and UCLs (95 dB HL), obtained a score of 83 percent correct with both the EXP and LIN hearing aids for listening in noise.

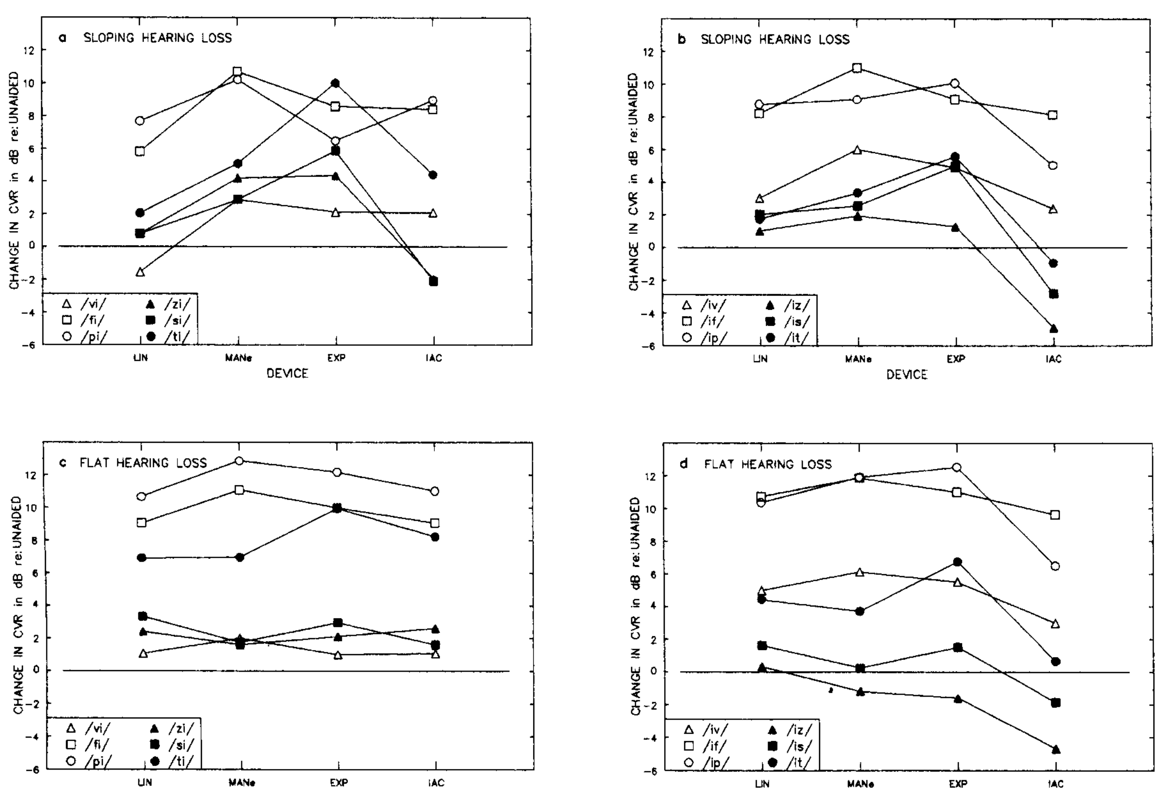

Figure 4 Consonant-to-vowel ratios (CVRs) relative to unaided for the flat and sloping audiogram groups. Panels A and C are for consonant-vowel syllables, and panels B and D are for vowel-consonant syllables.

Consonant-to-vowel Ratios (CVRs)

Results of the CVR measurements on KEMAR for each of the audiogram groups and hearing aids are shown in Figure 4 (parts A and C illustrate the CV syllables and parts B and D illustrate the VC syllables). Each CVR is plotted relative to that measured in the unaided condition. In the unaided condition, as expected, the /f/ phoneme had the lowest CVR, and the /v/ and /t/ had the highest CVRs. In most cases, hearing aid processing increased the level of the consonant relative to the vowel. This is shown in Figure 4 by a positive change in CVR.

Although differences among the hearing aids in terms of output (aided) CVRs were found, the overall range of differences was restricted, with a few exceptions, and the magnitude and direction of the differences varied across consonants. For example, with sloping audiograms, one noticeable difference was the increase in CVR seen for the pre- and postvocalic /t/ with the EXP device relative to the other hearing aids (Fig. 4, solid circles in panels A, B). In this case, the EXP circuit provided a 4-dB to 8-dB increase in CVRs over that seen with the linear device.

This effect on the CVR is shown in Figure 5 for the amplitude-time waveforms of the postvocalic /t/ burst after processing by the LIN, MANe, and EXP circuits. Each waveform is overlaid by a half-Hamming window that marks the onset of the burst and highlights amplitude differences. The rms level of each vowel was digitally equated at 70 dB SPL; therefore, burst amplitude differences were the result of processing by the different hearing aid circuits. Both the MANe and EXP devices increased the level of the burst energy relative to that produced by the LIN device, with the greatest enhancement by the EXP. It should be noted, however, that this pattern of enhancement was not seen for all syllables, presumably because the output CVR produced by these devices depends on the duration, spectral shape, and overall amplitudes of both the consonant and the vowel.

Pearson product-moment correlation coefficients were computed between the mean percent correct scores on each syllable and the CVR values. Correlations were low and nonsignificant both overall and within audiogram groups.

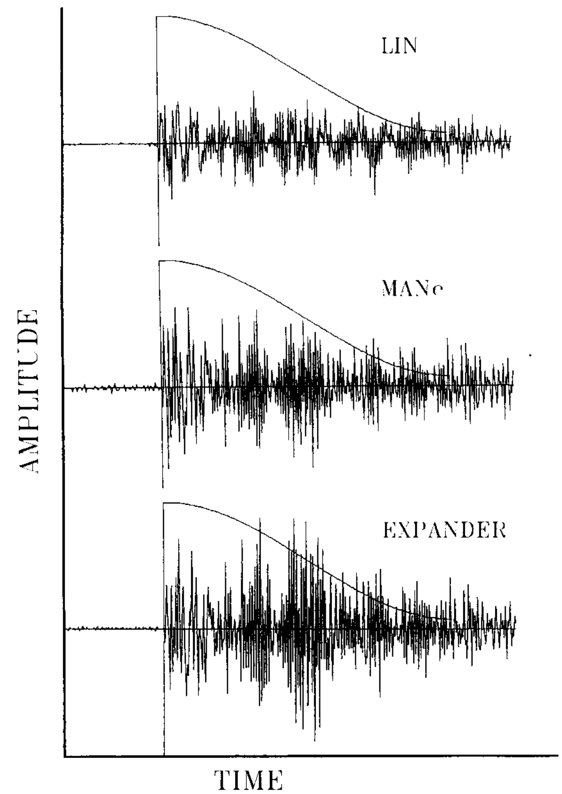

Figure 5 Amplitude-time waveforms of the postvocalic /t/ burst after processing by the LIN, MANe, and Expander (EXP) circuits. Each waveform is overlaid by a half-Hamming window that marks the onset of the burst and highlights amplitude differences. The rms level of each vowel was digitally equated at 70 dB SPL; therefore, burst amplitude differences were the result of processing by the different hearing aid circuits.

Consonant Confusion Analysis

Analysis of the consonant confusion matrices within each audiogram group revealed no clear and consistent error patterns across the hearing aids. As expected, the most common error involved place of articulation, either with or without errors in manner and voicing. The consonant confusion analyses were complicated by the fact that some consonants had been found to be inaudible for some subjects in some conditions. This would have led to random guessing because of the closed-set format. However, even when consonant confusion analyses were restricted to only those subjects and conditions where the consonants had been shown to be audible, different errors were often observed between subjects within an audiogram group while they were wearing a given hearing aid. In most cases, there seemed to be no pattern to the errors but, in a few, the confusions were stable.

As an example of more stable confusions, Figure 6 shows the consonant confusion matri-

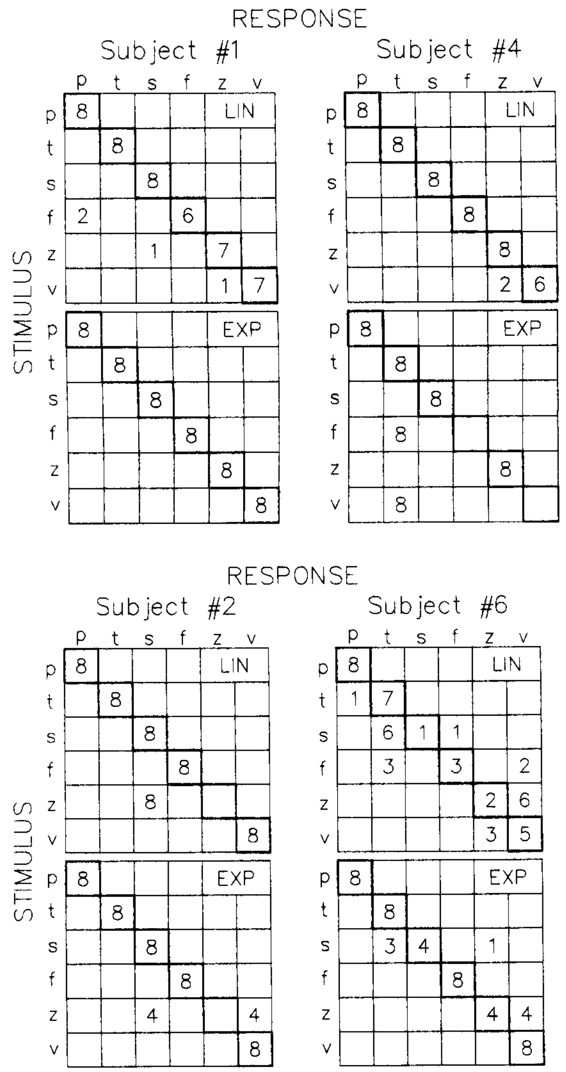

Figure 6 Consonant confusion matrices for quiet listening with the LIN and EXP hearing aids for two pairs of subjects with nearly identical audiograms. Subjects #1 and #4 had flat audiograms, and subjects #2 and #6 had moderately sloping audiograms.

ces for quiet listening for two pairs of subjects with very similar unaided thresholds. All four subjects had demonstrated that all of the consonants were audible in quiet. Subjects #1 and #4 both had flat audiograms. Both of these subjects showed few errors with the LIN, but the EXP introduced some consistent errors involving manner and place in subject #4. Subjects #2 and #6 both had moderately sloping audiograms. Subject #2 performed more similarly across the LIN and EXP, while subject #6 displayed an increase in the number of manner and voicing errors with the LIN relative to the EXP.

DISCUSSION

In this study, the output CVRs we measured showed increases over unaided CVRs, although the values we obtained were somewhat smaller than those previously reported by Preves et al (1991) using the same circuitry, a discrepancy that may be the result of differences in the frequency responses, measurement procedures, or speech stimuli used. Among the hearing aids, differences in output CVRs were also found, although the magnitude and direction of the differences varied across consonants. The lack of a significant correlation between CVRs and percent correct scores on individual phonemes may have been due to the relatively restricted ranges found for both the CVR values and percent correct scores on individual phonemes, rather than to the lack of a relationship per se. The issue of whether enhancing CVRs will improve speech recognition performance still requires further investigation.

There were no statistically significant improvements in group mean percent correct scores on the consonant recognition task in quiet or noise for any of the three nonlinear hearing aids compared to linear. In fact, the IAC hearing aid performed significantly more poorly than the LIN for listening in noise. These data fail to confirm the benefit of IAC versus linear that was previously reported by Thomas and Sparks (1971). In addition, a number of the subjects in our study informally commented that they found the sound quality of speech processed by the IAC hearing aid to be objectionable.

It is also worth noting, however, that the MANe and EXP hearing aids did not perform significantly poorer than the LIN, and there were some individual subjects who appeared to perform better with a nonlinear hearing aid compared with linear. In particular, the experimental EXP hearing aid appeared to show some promise for subjects with sloping hearing losses. The EXP hearing aid increased the instances of audibility of high-frequency phonemes for patients with sharply sloping audiometric configurations, and it seems reasonable to hypothesize that this finding may have resulted from the fact that CVRs were slightly greater overall with the EXP. Based on these limited results, we believe that the EXP hearing aid should be explored further as a nonlinear signal processing algorithm; however, factors such as perceptual sound quality and loudness discomfort should also be evaluated. A few subjects commented that the EXP sounded "tinny," and it is possible that discomfort could result from the high-frequency expansion for some patients with loudness recruitment.

In addition, the relative merits of expanding high-frequency energy rather than simply supplying greater fixed high-frequency gain need to be explored. In this study, we did not allow subjects to adjust the volume control wheels because we wanted to compare purely the effects of processing, holding other factors constant. This raises the possibility that subjects would have preferred to turn the volume up more for one hearing aid circuit than for another. If subjects had, for example, increased the gain via volume control adjustment more for the MANe than for the EXP, differences in high-frequency gain may have been reduced, as well as the number of instances of phoneme inaudibility with the MANe. It is important to keep in mind, however, that frequency response curves for a single input level of a steady-state broadband noise signal do not reflect the dynamic intersyllabic processing differences between these nonlinear hearing aids.

Notable in the data from this study was the variability in performance seen across some subjects within the same audiogram group, either in terms of overall aided performance levels or the performance pattern across hearing aids. This finding suggests that audiogram alone may not always be a good predictor of which patient will perform best with a given amplification approach. While it is possible that performance differences could have been produced by slight differences in audiometric thresholds, real ear resonances, and test variability, it is unlikely that these factors alone account for the relatively large performance differences sometimes seen. Although the majority of the subjects in this study were elderly, it also seems unlikely that aging effects were a primary factor because of the simple nature of the discrimination task. Van Tasell (1993) has recently argued that differences in suprathreshold, psychoacoustic processing abilities in cochlear pathology may only be a significant factor in speech recognition for subjects with hearing losses greater than about 60 dB HL. The next step in resolving this issue would be more in-depth evaluation of young hearing-impaired patients with matched audiograms to see if they perform differently across a set of hearing aids carefully fit to provide equivalent amplification. If such differences are found, further investigation of performance differences on psychoacoustic measures and/or their ability to use available speech cues would be warranted.

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