J Am Acad Audiol 11: 214–223 (2000)

Improving Audibility with Nonlinear Amplification for Listeners with High-Frequency Loss

Pamela E. Souza*
Robbi D. Bishop*

Abstract

In contrast to fitting strategies for linear amplification that have been frequently refined for listeners with different degrees of hearing loss, we know relatively little about the effects of nonlinear amplification for differing audiometric configurations. The purpose of the current study was to determine whether increases in audibility with nonlinear amplification improved speech recognition to a comparable degree for listeners with sloping sensorineural loss as for a comparison group of listeners with flat sensorineural loss. Consonant recognition was examined as a function of audibility with wide dynamic range compression amplification and with linear amplification. For linearly amplified speech, listeners with flat and sloping loss showed similar improvements in recognition given the same increases in audibility. Results for nonlinearly amplified speech indicated that the listeners with flat loss showed a greater rate of improvement as audibility increases than the listeners with sloping loss. This difference is largely due to superior performance by the listeners with sloping loss for low-audibility speech in comparison to equivalent group performance for high-audibility speech.

Key Words: Amplification, compression, hearing loss, nonlinear

Abbreviations: AAI = Aided Audibility Index, LDL = loudness discomfort level, MCR = modified compression ratio, VCV = vowel-consonant-vowel, WDRC = wide dynamic range compression

The majority of hearing aid wearers exhibit a sloping audiometric pattern, with poorer high-frequency thresholds. These listeners are at a disadvantage because crucial high-frequency speech cues are partially or completely inaudible. The conventional solution for these listeners is a linear hearing aid with a frequency-gain response that improves audibility of high-frequency speech cues. However, even within a given frequency, band speech levels vary by at least 30 dB (Fletcher, 1953; Skinner, 1988). This range is considerably increased by the variety of sound levels in different listening situations. For listeners with sloping loss, this variation in speech levels, coupled with a reduced high-frequency dynamic range, may limit the ability to restore audibility without discomfort or distortion from higher-level speech.

Multichannel compression amplification offers an attractive option for improving speech audibility in listeners with sloping loss. When speech varies over a range of input levels, compression can improve recognition by placing greater amounts of the speech signal in the range between threshold and discomfort (Moore and Glasberg, 1986; Souza and Turner, 1998). Use of more than one compression channel allows the audiologist to maximize audibility by accommodating variations in threshold and dynamic range across frequency. Because improved speech audibility can be linked to better speech recognition (Skinner, 1980), the greater audibility offered by multichannel compression is assumed to provide an advantage over linear amplification for listeners with sloping loss.

There is increasing evidence that some listeners with sloping loss may receive limited benefit from improved high-frequency audibility, at least for linearly amplified speech. Hogan

*Department of Speech and Hearing Sciences, University of Washington, Seattle, Washington

Reprint requests: Pamela E. Souza, Department of Speech and Hearing Sciences, University of Washington, 1417 NE 42nd St., Seattle, WA 98105

and Turner (1998) provided increasing amounts of high-frequency information to listeners with sloping loss by varying low-pass filter cut-offs. Although increased high-frequency audibility improved speech recognition for most listeners, it produced either no improvement or a decrement in speech recognition for some listeners. These listeners tended to be those with greater amounts of high-frequency loss. In another study, Turner and Cummings (1999) obtained performance-intensity functions for a group of listeners with sloping or flat sensorineural loss. Although all listeners scored better as presentation level increased, listeners with sloping loss showed little change in performance when increases in level specifically improved audibility of high-frequency speech cues. Listeners with flat loss did not show the same effect. Previous work also suggests that maximizing audibility in the high frequencies can actually result in lower recognition scores for some listeners with sloping sensorineural loss (Murray and Byrne, 1986; Rankovic, 1991).

It is not clear whether the same effects apply to improved audibility with nonlinear hearing aids. The acoustic characteristics of nonlinearly amplified speech are fundamentally different from those of linearly amplified speech. The most notable differences, particularly with higher compression ratios and/or shorter time constants (Verschuure et al, 1995), are an overall reduction in speech range coupled with alterations in the gross time-intensity variations, or amplitude envelope, of the speech signal. In the linear amplification studies described above, the listeners who showed the least benefit from improved high-frequency audibility were those with the most hearing loss and, presumably, the smallest dynamic range. Providing maximal audibility of low-level cues to these listeners may have involved higher-than-comfortable linear gain that resulted in discomfort or distortion. Alternatively, restricting linear gain to avoid discomfort can reduce audibility of low-level speech cues. For example, Hogan and Turner (1998) noted that some recognition deficits in their study were due to high presentation levels. It is possible that nonlinear amplification, which can improve audibility of low-level speech without overamplification of high-level speech, would not produce similar effects. In that case, we might expect that listeners with sloping versus flat loss would show the same increase in performance as audibility improves. Alternatively, if listeners with sloping loss are simply unable to use audibility improvements, we might see the same pattern with nonlinear amplification as seen in previous linear amplification studies. The purpose of the current study was to determine whether increases in audibility with wide dynamic range compression (WDRC) amplification improved speech recognition to a comparable degree for listeners with sloping sensorineural loss as for a comparison group of listeners with flat sensorineural loss.

METHOD

Participants

Participants included 10 listeners with sloping sensorineural loss, aged 43 to 80 years (mean age 62.1 years), and 10 listeners with flat sensorineural loss, aged 34 to 94 years (mean age 65.6 years). All listeners were tested monaurally, had normal immittance results with no significant air–bone gaps in the test ear, and were native English speakers. Loudness discomfort levels (LDLs) were obtained for each listener using the procedure suggested by Hawkins et al (1987). Mean audiometric thresholds and LDLs (re: ANSI, 1996a) for the two listener groups are shown in Figure 1.

Stimuli

Consonant recognition was assessed using a set of vowel-consonant-vowel (VCV) nonsense syllables. Each syllable contained the common

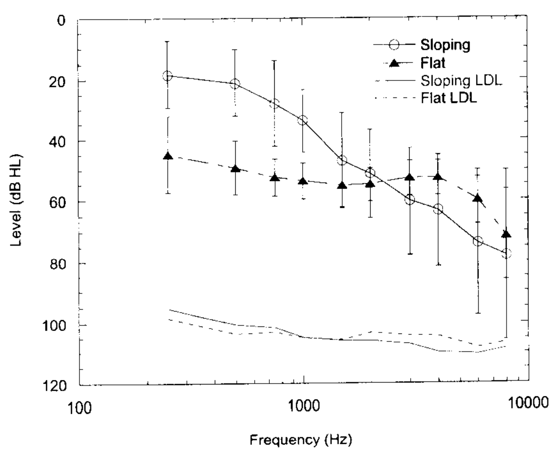

Figure 1 Mean hearing thresholds for listeners with sloping (open circles) and with flat loss (filled triangles). Error bars represent ± 1 SD about the mean. Mean loudness discomfort levels are shown for listeners with sloping loss by the solid line and for listeners with flat loss by the dashed line.

vowel /a/ and 1 of 16 consonants: /p, t, k, b, d, g, m, n, f, s, ʃ, v, ð, θ, z, ʒ /. Each VCV was spoken by four talkers (two males and two females) and was digitally recorded on a Pentium Pro computer. To provide a range of speech audibility, the entire set of 64 speech tokens was presented at low (55 dB SPL), moderate (70 dB SPL), and high (85 dB SPL) input levels. Each speech token at each presentation level was separately amplified by linear amplification and by nonlinear amplification.

Amplification Parameters

To create the nonlinearly amplified stimuli, speech stimuli were processed by a laboratory-based two-channel WDRC amplification system. The system was designed as an input compression amplifier. First, each VCV was digitally filtered into a low-pass and a high-pass channel. Each channel was then digitally compressed. The compression algorithm is more fully described in Souza and Turner (1996). Briefly, for each digital waveform point, the rms of the previous 15 msec was calculated. If this rms value exceeded 45 dB SPL, the point value was adjusted to yield the specified compression ratio. This scheme resulted in a kneepoint of 45 dB SPL, an attack time of 8 msec, and a release time of 15 msec as defined by ANSI (1996b). The channel cut-off frequency was 1500 Hz with compression ratios of 2:1 in the low-frequency channel and 5:1 in the high-frequency channel. The compression parameters were representative of those possible with current hearing aids. However, to explore the magnitude of the impact of nonlinear processing, these parameters were slightly more extreme than those selected by most clinical audiologists.

After compression processing, the digital signal was converted to an analog signal (Tucker-Davis Technologies AP2) and gain was provided using an external analog amplifier (Crown D75). To improve audibility of high-frequency cues, the analog signal was also routed through an equalizer (Rane GE-30) to provide high-frequency emphasis before presentation to the listeners. The frequency-gain response is described in detail below.

Three linear amplification conditions were created using the same speech input levels as used for the WDRC-amplified stimuli. The linearly amplified speech received the same processing as described above with the exception of the digital compression algorithm. This resulted in a total of six VCV conditions for each listener.

Speech Audibility and Frequency-Gain Response

Speech audibility can be expressed in several ways: for example, as ⅓-octave band sensation levels relative to the listener's thresholds. To examine the relationship between improved audibility and recognition, it is more convenient to use an audibility measure that can express speech audibility in a single value. In this case, we used the Aided Audibility Index (AAI) (Stelmachowicz et al, 1994). The AAI can be used to quantify audibility of both linearly amplified and WDRC-amplified speech (Souza and Turner, 1999). The AAI ranges from 0.0 to 1.0. An AAI of 0.0 indicates that the entire range of speech levels is below the listener's threshold. An AAI of 1.0 indicates that the entire range of speech levels is audible to the listener. The calculated AAI depends on a frequency-importance function that describes the contribution of each band to recognition and on the signal level (speech peaks minus listener threshold) in each of several frequency bands. Several recent articles provide a detailed description of the AAI calculation (Stelmachowicz et al, 1994, 1998; Souza and Turner, 1999). For convenience, the calculation formulas used in the current study are provided in the Appendix.

The frequency gain response was chosen as follows. First, our intent was to present the entire range of speech input levels (low, moderate, and high) so that loud speech was not uncomfortable and soft speech was at least partially audible. Second, we wanted to provide a similar range of audibility (i.e., AAI) across listener groups. Third, we wanted to maintain a relationship such that compression amplification would result in better audibility of low-intensity speech than linear amplification without compromising audibility of higher-intensity speech.

To meet these goals, we first selected a frequency-gain response that would provide a similar range of AAIs for each listener group. The same frequency shaping was used for all listeners. The frequency-gain response was selected to maximize high-frequency audibility, with approximately a 6-dB roll-off below 2 kHz. Because our intent was to examine recognition under controlled conditions rather than to simulate all of the complex interactions seen in wearable hearing aids (i.e., changes in frequency response with input level and/or high-level limiting), we purposely did not use an individually prescribed frequency response. Use of the same frequency response across listeners offered a

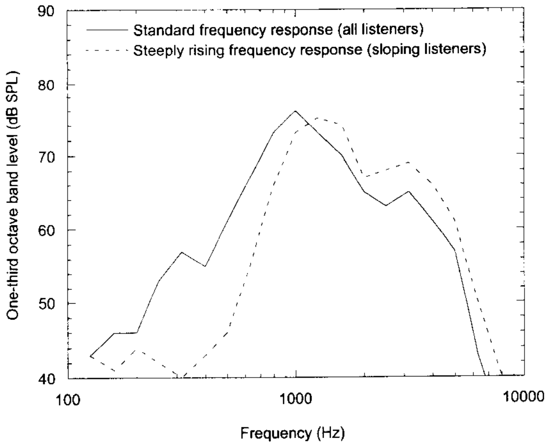

Figure 2 Comparison of the standard frequency response (solid line) provided to all listeners and the steeply rising frequency response (dashed line) presented to a subset (n = 7) of the listeners with sloping loss.

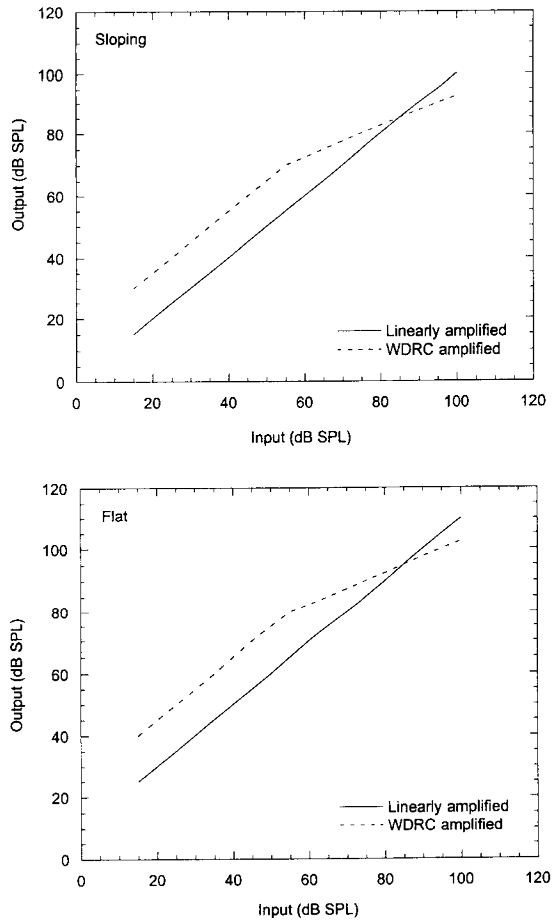

Figure 3 Input-output functions for listeners with sloping loss (top panel) and flat loss (lower panel).

straightforward means of controlling audibility in each group and also allowed us to compare the effect of a broad- versus high-pass frequency response as described below. Although variations in frequency response that also change gain may affect speech recognition (Lutman and Clark, 1986; Van Tasell and Yanz, 1987), most data indicate that the shape of the frequency response has little effect on recognition when audibility is controlled (Byrne, 1986; Humes and Hackett, 1990; Horwitz et al, 1991; Leijon et al, 1991; van Buuren et al, 1995).

Some previous work suggests that listeners with sloping loss may show lower recognition scores due to upward spread of masking when too much low-frequency emphasis is provided (Gordon-Salant, 1984). To be sure that reduced performance for listeners with sloping loss, if it occurred, was not due to this effect, we retested 7 of the 10 listeners with sloping loss with a more steeply rising high-frequency emphasis response. Figure 2 shows a comparison of the two frequency responses. The shape of the steeply rising high-frequency emphasis condition was adjusted to provide the same mean AAIs as the standard frequency response when presented at the same output levels.

Table 1 Presentation Levels (in dB SPL) for Listeners with Sloping Loss

Input Speech	*Linearly Amplified*	*WDRC Amplified*
High	85	85
Moderate	70	77.5
Low	55	70

Presentation levels for the listeners with sloping loss (Table 1) were selected as follows. In pilot testing, we determined that a presentation level of 85 dB SPL[1] was rated as loud but comfortable by listeners with sloping loss. Accordingly, for this group, presentation of the highest input level was fixed at 85 dB SPL for both types of amplification. For linearly amplified speech, lower input levels were dictated by the linear input-output function (Fig. 3, top). Presentation levels for the compression-amplified speech were selected using the following criteria. Because presentation levels were based on long-term rms, which for these stimuli was dominated by low-frequency energy, a 2:1 compression ratio was used to select presentation levels

[1]All levels refer to sound levels at the output of the system (e.g., after amplification and high-frequency emphasis) presented through a Sennheiser HD 25-SP headphone mounted in a NBS-9A coupler.

Table 2 Presentation Levels (in dB SPL) for Listeners with Flat Loss

Input Speech	*Linearly Amplified*	*WDRC Amplified*
High	95	95
Moderate	80	87.5
Low	65	80

for the compression-amplified speech. With application of a 2:1 compression ratio, a 15-dB difference in input level (as seen between the high- and moderate-level inputs) would result in a 7.5-dB difference in output level.

As shown in Table 1, we chose to match output levels of the two amplification conditions at the highest input level. Setting the speech levels in this way maintains the desired objective of WDRC, that is, WDRC should result in better audibility of low-intensity speech without compromising audibility of higher-intensity speech. This scheme mimics a situation in which a listener sets a linear or WDRC hearing aid so that loud speech is not uncomfortable, then makes no further adjustments for soft or moderate speech levels. In a clinical situation, more gain would typically be applied at lower input levels with peak clipping or compression limiting used to control output at the highest input level. Because use of output limiting may distort acoustic cues and confound results of audibility changes, we deliberately avoided its use in this study.

Recall that we wanted to provide a similar range of audibility for each group. In pilot testing, the group with flat loss rated speech at 95 dB SPL as loud but not uncomfortable. Accordingly, for both types of amplification, the highest level input was presented at 95 dB SPL to listeners with flat loss. Presentation levels of the remaining conditions are shown in Table 2 and were set according to the input-output relationships shown in the lower panel of Figure 3.

Test Procedures

To obtain speech recognition scores, each participant was seated in a double-walled sound booth and listened to the speech presented monaurally through Sennheiser HD 25-SP headphones. Contralateral masking was used if necessary to eliminate responses from the nontest ear. In a single run, each listener heard the 64 VCVs (16 consonants × 4 talkers) presented in a random order. After presentation of each VCV, the listener pushed a button to select the consonant heard in a 16-alternative forced-choice paradigm. To account for practice effects, each participant completed repeated runs with feedback until asymptotic performance was achieved. Asymptotic performance was defined as scores within 5 percent of each other on four consecutive runs without continuing to increase. For example, consecutive scores of 40, 45, 50, and 45 percent were considered asymptotic; consecutive scores of 40, 45, 50, and 55 percent were not. Listeners typically required 8 to 10 runs to reach asymptotic performance in each condition. A final percent correct score was then taken as the average of scores from the last two runs in a test condition. Final data consisted of six scores (three levels of linearly amplified speech and three levels of nonlinearly amplified speech) for each listener.

RESULTS

Audibility of Amplified Speech

An AAI was calculated for each participant data point, based on the listener's thresholds and ⅓-octave band levels of the speech in that condition. Mean AAI values for each group are shown in Table 3. Although mean AAIs for the flat and sloping loss groups are not identical, a similar range of audibility was provided to each group. Table 3 also shows a comparison of AAI values for the two frequency responses provided

Table 3 Group Mean AAI Values for Each Amplification Condition and Presentation Level

	Linear			*Compression*		
	Input			*Input*		
Amplification Type	*Soft*	*Moderate*	*High*	*Soft*	*Moderate*	*High*
Flat	.20	.57	.84	.54	.76	.81
Sloping (standard frequency response)	.26	.53	.75	.48	.63	.70
Sloping (steeply rising response)	.23	.50	.75	.49	.65	.72

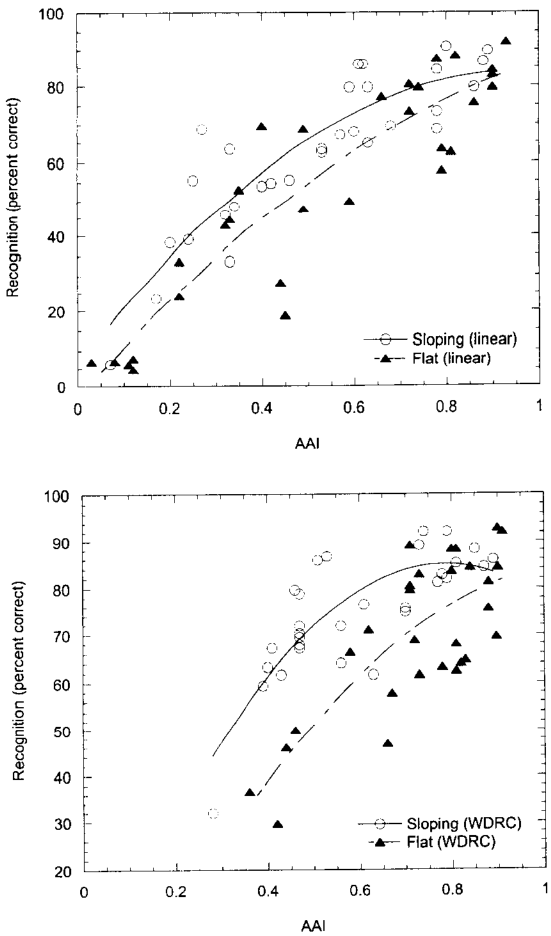

Figure 4 Recognition plotted as a function of audibility for each group. Results for linearly amplified speech are shown in the top panel and results for compression-amplified speech in the lower panel. In each case, open circles represent data from listeners with sloping loss; filled triangles represent data from listeners with flat loss.

to the group with sloping loss. Values for the two responses are very similar, differing by .03 or less for each presentation level and amplification type.

Relating Improved Audibility to Performance

To determine how audibility improvements affect performance, consonant recognition is plotted as a function of audibility in Figure 4. The top panel compares performance of the two groups for linearly amplified speech processed using the standard frequency response. The best-fit second-order polynomial regression line is also shown for each group. For both groups, the AAI is monotonically related to the percent correct score. On average, the listeners with sloping loss score slightly higher than the listeners with flat loss. Slopes of the best-fit lines are very similar for both groups, suggesting that both groups show similar improvements in recognition given the same increases in audibility of linearly amplified speech.

The lower panel compares performance of the two groups for compression-amplified speech processed using the standard frequency response. At low-to-moderate AAIs, increases in audibility result in a rapid growth in recognition score, with generally better performance by the listeners with sloping loss. At AAIs greater than 0.70, performance for the sloping group shows a tendency to asymptote, even with continued increases in audibility. In contrast, performance for listeners with flat loss continues to improve even at high AAIs. These data suggest that the benefits of improved audibility may be limited for listeners with sloping loss.

To answer these questions, the data shown in Figure 4 were transformed for linearity by taking the logarithm of the AAI (Draper and Smith, 1981). The line slope describes the relationship between audibility and recognition for a given group and test condition. By comparing slopes of the fitted lines (Snedecor and Cochran, 1980), we can determine whether this relationship differs for listeners with flat versus sloping loss.

Results for linearly amplified speech indicated that both listener groups show the same rate of improvement as audibility increases ($F[1, 56] = 3.72$, $p > .05$). Results for nonlinearly amplified speech indicated that the listeners with flat loss show a greater rate of improvement as audibility increases than the listeners with sloping loss ($F[1, 56] = 15.77$, $p < .01$). One important issue illustrated in Figures 4 and 5 is that the greater rate of improvement for listeners with flat loss is a factor of their reduced performance at low AAIs. The data predict that for nonlinearly amplified speech at an AAI of 0.50, a listener with flat loss would score only 50 percent correct, whereas a listener with sloping loss would score approximately 70 percent. When the AAI is increased to 0.90, both listeners achieve about 82 percent performance. These results suggest that when maximal audibility can be achieved with a nonlinear aid, there is little difference in aided performance between the groups. However, when less-than-maximal audibility is provided, performance for listeners with flat loss is reduced relative to a group with sloping loss.

Individual Threshold Effects

Although the AAI takes into account the effect of frequency by incorporating frequency importance weighting, it does not specifically address differences in low- versus high-frequency audibility. To explore these issues, a low-frequency (0.25, 0.5, 1 kHz) and a high-frequency pure-tone average (2, 3, 4 kHz) were calculated for each participant. Within each group of listeners, Pearson product-moment correlations were obtained between pure-tone average and recognition scores for each test condition. Results are shown in Table 4.

The greater rate of improvement for the flat loss group is a consequence of the fact that the sloping loss group achieved higher speech recognition scores at low audibility. One possibility is that the better performance of listeners with sloping loss at low AAIs is due simply to their better low-frequency hearing, rather than the configuration of their loss per se. For both sloping loss and flat loss listeners, better low-frequency thresholds were significantly correlated with better low-level speech recognition. At higher input levels, the degree of low-frequency loss had no effect on performance.

Since previous work suggested that listeners with greater amounts of high-frequency loss perform more poorly than those with less high-frequency loss, we might expect that poorer high-frequency thresholds would be associated with poorer recognition performance in listeners with sloping loss. Results of the correlation analysis for the sloping loss group demonstrate that the degree of high-frequency loss is linked to performance. The greater the loss in the high frequencies, the poorer the recognition scores for all test conditions. Interestingly, this is not true of the listeners with flat loss, who show no relationship between high-frequency hearing thresholds and recognition.

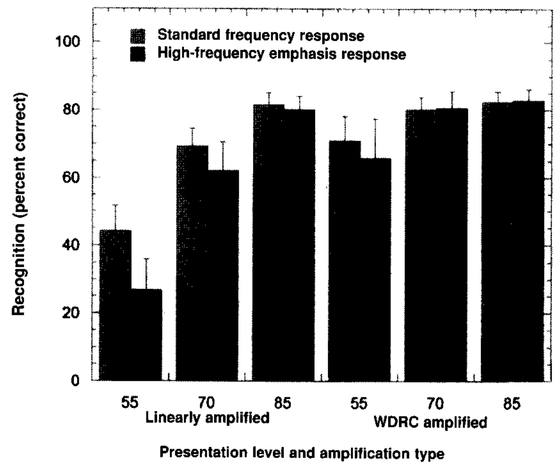

Figure 5 Comparison of mean recognition scores for each frequency response. Results for the standard response are shown by the gray bars and for the steeply rising high-frequency emphasis response by the black bars. Error bars represent ± 1 standard error about the mean.

Effects of Frequency Shaping

The effect of the steeply rising frequency response for the listeners with sloping loss is illustrated in Figure 5. In general, there was little difference between scores obtained with the

Table 4 Correlations between Low-Frequency Pure-Tone Average (LFPTA), High-Frequency Pure-Tone Average (HFPTA), and Performance (Percent Correct)

			Flat		*Sloping*	
PTA	*Condition*	*Input Level*	*r*	*p*	*r*	*p*
LFPTA	Linear	Low	−.941	<.001	−.698	.025
		Moderate	−.617	.057	−.468	.173
		High	−.623	.054	−.476	.164
	WDRC	Low	−.797	.006	−.788	.007
		Moderate	−.565	.089	−.356	.313
		High	−.460	.181	−.320	.367
HFPTA	Linear	Low	−.341	.334	−.589	.073
		Moderate	.107	.768	−.728	.017
		High	.043	.906	−.726	.017
	WDRC	Low	.034	.925	−.903	<.001
		Moderate	−.034	.925	−.743	.014
		High	.170	.638	−.731	.016

Table 5 Results of Analysis of Variance on the Effect of Frequency Response for Listeners with Sloping Loss

Source	*df*	*F*	*p*
Frequency response	1, 6	3.82	.098
Amplification type	1, 6	149.74	<.001
Input level	2, 12	23.47	<.001
Frequency response × amplification type	1, 6	4.67	.074
Frequency response × input level	2, 12	5.40	.021
Amplification type × input level	2, 12	27.38	<.001
Frequency response × amplification type	2, 12	0.72	.509

steeply rising, high-frequency emphasis response versus the standard frequency response. Although audibility of the two responses was essentially equivalent (see Table 3), at the lowest input level, recognition was slightly better with the standard response than the high-frequency emphasis response. To analyze these results, data were submitted to a three-way, repeated-measures analysis of variance (Table 5). Although there was no difference between the two frequency responses across all conditions ($F [1, 6] = 3.82$, $p = .098$), the effect of frequency response depended on presentation level ($F [2, 12] = 5.40$, $p =.021$). Accordingly, we examined the effect of the frequency response separately at each presentation level. The frequency response made no difference to recognition at high ($F [1, 6] = .56$, $p = .705$) or moderate ($F [1, 6] = .84$, $p = .395$) input levels. At the lowest input level, performance was slightly better with the standard frequency response ($F [1, 6] = 7.61$, $p = .033$). This result, plus the significant correlation between low-frequency thresholds and recognition, suggests that performance is largely influenced by low-frequency audibility. However, because performance for listeners with sloping loss was also correlated with high-frequency thresholds, the impact of high-frequency audibility improvements cannot be dismissed.

DISCUSSION

The specific purpose of this project was to determine if the increases in audibility possible with nonlinear amplification provided the same benefit (in terms of improved recognition) for listeners with sloping loss as for listeners with flat loss. In a broader sense, this project addresses the issue of how nonlinear amplification affects listeners with differing audiometric configurations. The main finding was that listeners with sloping loss show smaller improvements in recognition for nonlinearly amplified speech given the same increase in audibility as a listener with flat loss. In contrast, both groups showed the same benefit from improved audibility of linear speech.

The consequences of nonlinear amplification can be viewed in two ways. First, a steeper function for listeners with flat loss could occur if scores for the flat loss group are reduced at low-to-moderate AAIs. As seen in the lower panel of Figure 4, scores for both groups reach a maximum of about 82 percent. At low-to-moderate AAIs, scores for the group with flat loss are approximately 20 percent poorer than for listeners with sloping loss. These results suggest that when maximal audibility can be achieved with a nonlinear aid, there is little difference in aided performance between the groups. However, when less-than-maximal audibility is provided, performance for listeners with flat loss is reduced relative to a group with sloping loss.

Second, the same relationship between groups would be seen if nonlinear amplification reduced scores for listeners with sloping loss at high AAIs. One possibility is that listeners with sloping loss are more susceptible to acoustic changes in nonlinearly amplified speech. For example, speech with the highest output AAIs was processed at the highest input level relative to the kneepoint. In other words, the highest AAI speech received the most extreme compression and thus the greatest alteration of time-amplitude cues. Because the ability to use temporal cues can be mediated by loss of high-frequency sensitivity (e.g., Fitzgibbons, 1983; Bacon and Viemeister, 1985; Formby and Muir, 1988; Bacon and Gleitman, 1992), it is possible that the listeners with sloping loss were more susceptible to such changes.

Finally, it is important to consider the differences between this structured, laboratory-based study and use of nonlinear hearing aids in real-life situations. For the purposes of this study, audibility was controlled and listeners were not permitted to make their own volume adjustments. The data shown here suggest that differences with nonlinear amplification due to audiogram configuration would be greatest for listeners who listen at reduced volume settings (i.e., lower AAIs). Additionally, although we took care to ensure that presentation levels were not uncomfortable, no output limiting was used. In practice, use of peak clipping or compression limiting and the availability of a volume control might alter audibility.

As a final caution, any interpretation of results should consider the specific processing parameters used in this study. Because the effect of nonlinear amplification on speech depends on the compression parameters, these results may not generalize to other types of compression (e.g., compression limiting or other compression parameters). Future work should focus on the extension of these results to wearable hearing aids.

Acknowledgments. Support for this project was provided by the Deafness Research Foundation. The authors would like to thank Chris Turner for many helpful discussions about this project, and Christine Kim for her help with data collection. A portion of this work was presented at the 1999 American Academy of Audiology convention, Miami, FL.

REFERENCES

American National Standards Institute. (1996a). *Specifications for Audiometers.* (ANSI S3.6-1996). New York: ANSI.

American National Standards Institute. (1996b). *Specification of Hearing Aid Characteristics.* (ANSI S3.22-1996). New York: ANSI.

Bacon SP, Gleitman RM. (1992). Modulation detection in subjects with relatively flat hearing losses. *J Speech Hear Res* 35:642–653.

Bacon SP, Viemeister NF. (1985). Temporal modulation function in normal-hearing aid hearing-impaired listeners. *Audiology* 24:115–134.

Byrne D. (1986). Effects of frequency response characteristics on speech discrimination and perceived intelligibility and pleasantness of speech for hearing-impaired listeners. *J Acoust Soc Am* 80:494–504.

Draper NR, Smith H. (1981). *Applied Regression Analysis.* 2nd Ed. New York: John Wiley and Sons.

Fitzgibbons PJ. (1983). Temporal gap detection in noise as a function of frequency, bandwidth, and level. *J Acoust Soc Am* 74:67–72.

Fletcher H. (1953). *Speech and Hearing in Communication.* Princeton, NJ: D. Van Nostrand.

Formby C, Muir K. (1988). Moduation and gap detection for broadband and filtered noise signals. *J Acoust Soc Am* 84:545–550.

Gordon-Salant S. (1984). Effects of reducing low-frequency amplification on consonant perception in quiet and in noise. *J Speech Hear Res* 27:483–493.

Hawkins DB, Walden B, Montgomery A, Prosek RA. (1987). Description and validation of an LDL procedure designed to select SSPL90. *Ear Hear* 8:162–169.

Hogan CA, Turner CW. (1998). High-frequency audibility: benefits for hearing-impaired listeners. *J Acoust Soc Am* 104:432–441.

Horwitz AR, Turner CW, Fabry DA. (1991). Effects of different frequency response strategies upon recognition and preference for audible speech stimuli. *J Speech Hear Res* 34:1185–1196.

Humes L, Hackett T. (1990). Comparison of frequency response and aided speech-recognition performance for hearing aids selected by three different prescriptive methods. *J Am Acad Audiol* 1:101–108.

Leijon A, Lindkvist A, Ringdahl A, Israelsson B. (1991). Sound quality and speech reception for prescribed hearing aid frequency responses. *Ear Hear* 12:251–260.

Lutman ME, Clark J. (1986). Speech identification under simulated hearing-aid frequency response characteristics in relation to sensitivity, frequency resolution and temporal resolution. *J Acoust Soc Am* 80:1030–1040.

Moore BCJ, Glasberg BR. (1986). A comparison of two-channel and single-channel compression hearing aids. *Audiology* 25:210–226.

Murray N, Byrne D. (1986). Performance of hearing-impaired and normal hearing listeners with various high-frequency cut-offs in hearing aids. *Aust J Audiol* 8:21–28.

Pavlovic CV. (1989). Speech spectrum considerations and speech intelligibility predictions in hearing aid evaluations. *J Speech Hear Disord* 54:3–8.

Rankovic CM. (1991). An application of the articulation index to hearing aid fitting. *J Speech Hear Res* 34: 391–402.

Skinner MW. (1980). Speech intelligibility in noise-induced hearing loss: effects of high-frequency compensation. *J Acoust Soc Am* 67:306–317.

Skinner MW. (1988). *Hearing Aid Evaluation.* Englewood Cliffs, NJ: Prentice Hall.

Snedecor GW, Cochran WG. (1980). *Statistical Methods* 7th Ed. Ames, IA: Iowa State University Press.

Souza PE, Turner CW. (1996). Effect of single-channel compression on temporal speech information. *J Speech Hear Res* 39:901–911.

Souza PE, Turner CW. (1998). Multichannel compression, temporal cues, and audibility. *J Speech Hear Res* 41:315–326.

Souza PE, Turner CW. (1999). Quantifying the contribution of audibility to recognition of compression-amplified speech. *Ear Hear* 20:12–20.

Stelmachowicz P, Lewis D, Kalberer A, Creutz T. (1994). *Situational Hearing Aid Response Profile Users Manual (SHARP, v 2.0).* Omaha, NE: Boys Town National Research Hospital.

Stelmachowicz PG, Dalzell S, Peterson D, Kopun J, Lewis DL, Hoover BE. (1998). A comparison of threshold-based fitting strategies for nonlinear hearing aids. *Ear Hear* 19:131–138.

Stone MA, Moore BCJ. (1992). Syllabic compression: effective compression ratios for signals modulated at different rates. *Br J Audiol* 26:351–361.

Turner CW, Cummings KJ. (1999). Speech audibility for listeners with high-frequency hearing loss. *Am J Audiol* 8:47–56.

van Buuren RA, Festen JM, Plomp R. (1995). Evaluation of a wide range of amplitude-frequency responses for the hearing-impaired. *J Speech Hear Res* 38:211–221.

Van Tasell DJ, Yanz JL. (1987). Speech recognition threshold in noise: effects of hearing loss, frequency response, and speech materials. *J Speech Hear Res* 30:377–386.

Verschuure J, Maas AJJ, Stikvoort E, de Jong RM, Goedegebure A, Dreschler WA. (1995). Compression and its effect on the speech signal. *Ear Hear* 17:162–175.

APPENDIX

AAI Formula for Linearly Amplified Speech

$$AAI = [\sum_{i=1}^{8} I_i\,(LTASS_i + 15 - THRESHOLD_i)]/30$$

where $LTASS_i$ = long-term average speech spectrum level at frequency i

$THRESHOLD_i$ = listener's hearing threshold at frequency i

I_i = band importance value at frequency i (Pavlovic's [1989] nonsense syllable values)

AAI Formula for WDRC-Amplified Speech

$$AAI = [\sum_{i=1}^{8} I_i\,[\,LTASSi + (15/MCR_i) - THRESHOLD_i]/(30/MCR_i)]$$

where $LTASS_i$ = long-term average speech spectrum level at frequency i

$THRESHOLD_i$ = listener's hearing threshold at frequency i

I_i = band importance value at frequency i (Pavlovic's [1989] nonsense syllable values)

MCR_i = modified compression ratio at frequency i. The higher the compression ratio, the more the speech peaks are reduced. Because the compression ratio for speech does not reach the compression ratio measured with a steady-state signal (Stone and Moore, 1992), the specified compression ratio of the hearing aid is first transformed into a modified compression ratio (MCR). The MCRs were 1.25:1 in the low-frequency bands (for an ANSI-specified 2:1 compression ratio) and 3.5:1 in the high-frequency bands (for an ANSI-specified 5:1 compression ratio).