Veterans Administration

Journal of Rehabilitation Research
and Development Vol. 24 No. 4
Pages 149–160

Multiband compression limiting for hearing-impaired listeners*

DIANE K. BUSTAMANTE and LOUIS D. BRAIDA
Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Abstract—Four multiband compression limiters and two linear amplification systems were compared in terms of the intelligibility of consonant-vowel-consonant (CVC) nonsense syllables for two hearing-impaired listeners over a 30 dB range of input levels. Each system incorporated one of two frequency-gain characteristics and one of three limiting characteristics (no limiting, moderate limiting, or severe limiting). The subjects were instructed to choose overall listening levels that would permit speech spanning the range of input levels to be as intelligible as possible and comfortable for long-term listening. Relative to linear amplification, the overall gain selected by the subjects increased by roughly 5 and 11 dB for the moderate and severe limiter, respectively. With linear amplification, the maximum score, 82 percent correct, was obtained at the highest input level and scores fell roughly 34 percentage points as input level was reduced. With compression limiting, although the maximum scores, 81 percent and 79 percent correct, were obtained at lower input levels, performance was comparable to that with linear amplification. Also, scores spanned a range of only 22 and 9 percentage points across the range of input levels with the moderate and severe limiter, respectively. This benefit was due to the improved scores provided by compression limiting at the low input levels. However, this advantage was offset somewhat by the disadvantage provided by compression at high input levels relative to linear amplification. Error analysis indicated that the spectral degradations introduced by independent compression of 16 frequency bands may have caused the reduced intelligibility at higher input levels.

* This research was supported in part by a grant from the National Institute of Neurological and Communicative Disorders and Stroke, Grant NS12846. Also, DKB was supported in part by fellowships from IBM and Ida Green.

INTRODUCTION

Sensorineural hearing losses are often characterized by a sharp dependence of speech intelligibility on level, resulting from reductions in auditory area. In this study, the ability of compression limiting to reduce this dependence and, thus, increase the overall level of speech intelligibility was explored. Compression limiters, which respond rapidly to input level changes and employ large compression ratios, are designed to protect against high-level sounds (1). However, they also should allow an increase in the range of levels over which speech is intelligible by reducing the level of uncomfortably loud sounds to comfortable levels.

Peak clipping is another form of limiting often found in hearing aids. While a peak clipper saturates at a specific maximum level, resulting in harmonic and intermodulation distortion, a compression limiter is a quasi-linear amplifier whose gain is reduced rapidly when signals exceed a threshold level. Studies to determine the relative intelligibility of compression limited and peak-clipped speech have been conducted with hearing-impaired listeners (3) and with normal-hearing listeners (10). Both studies observed significantly higher intelligibility scores when the limiting was produced by compression rather than by peak clipping. Also, (22) found that peak clipping a signal composed of a target speech signal and five competing speech signals lowered discrimination scores relative to those obtained without clipping. Because harmonic distortion has been found to degrade the performance of hearing

aids (7,8) and because peak clipping produces significantly more harmonic distortion than compression limiting (9), these findings are not surprising.

Although the advantage of compression limiting relative to peak clipping for the purpose of protection from intense sounds is well documented, the ability of compression limiting to improve speech intelligibility for sensorineural hearing-impaired listeners by increasing the effective dynamic range is less well understood. Mangold and Leijon (16) and Laurence et al. (12) have studied the effect of compression limiting on speech intelligibility. Both focused on multiband systems. (Although neither of these studies refers to their devices as multiband compression limiters, their systems can be classified as such given the time constants and compression parameters used.)

Mangold and Leijon (16) evaluated a three-band compression limiting aid preceded by a wideband limiter relative to a three-band linear amplification aid and a conventional aid. Comparisons in terms of speech discrimination measures showed an advantage for three-band compression limiting for some sensorineural hearing-impaired listeners (~ 5–24 percentage point advantage for four subjects, no advantage for three subjects). Similarly, Laurence, et al. (12) evaluated a two-band compression limiting aid preceded by a wideband limiter relative to a two-band linear amplification aid and the subject's own conventional aid. Testing was conducted over a 30 dB range. Comparisons in term of speech intelligibility measures showed small advantages for two-band compression limiting at the highest input level. Averaged across input level, scores with two-band compression were higher than those with linear amplification and the subject's own aid by roughly 17 and 25 percentage points, respectively. These results were very encouraging, but both studies failed to determine whether the wideband limiter, the multiple band compressors, or both stages in combination were responsible for the benefit.

In the present study, multiband compression limiters were compared to linear-amplification systems with carefully chosen frequency-gain characteristics. All systems employed 16 frequency bands. The compression limiters were multiband so as to allow the compression thresholds to be set relative to the subjects' discomfort levels as a function of frequency. Thus, the compression limiters compressed only those suprathreshold sounds in each frequency band which would have exceeded the listeners' discomfort level. The potential of multiband compression limiting to improve speech intelligibility for hearing-impaired listeners was explored by testing two hypotheses. The first hypothesis was that a reduction of the levels of high-energy sounds by compression limiting would allow the listeners to select higher overall gain, thereby increasing the range of comfortable speech levels. The second hypothesis was that an increase in intelligibility would result from this increase in gain. Evaluations were based on speech intelligibility measurements over a wide range of intensity levels, substituting high-level speech for loud environmental sounds.

METHODS

Subjects

Two listeners, each with moderately severe sensorineural hearing losses, relatively flat audiograms, and reduced dynamic ranges were tested. Subject S1, a 61-year-old female, had an acquired bilateral hearing loss; while subject S2, a 24-year-old female, had congenital bilateral hearing loss resulting from cerebral palsy. Air conduction thresholds for 250-millisecond (ms) tone bursts with 25-ms rise/fall times were measured in a two-down/one-up three-alternative adaptive procedure (13) at octave intervals between 125 and 8000 Hz and at 6000 Hz. The results are shown in **Figure 1**. Across the frequencies tested, the average thresholds were 77 and 69 dB SPL for S1 and S2, respectively.

Loudness discomfort levels (LDLs) were measured at octave intervals between 250 and 8000 Hz using a pulsing tonal stimulus (600 ms on, 200 ms off). The 50 percent points on the LDL psychometric functions were determined using an up-down tracking procedure (13), similar to one employed by Morgan, et al. (17). The subjects were instructed to respond positively when the tone reached a level which was uncomfortably loud; specifically, a level to which they would not choose to listen for any length of time. The stimulus intensity was increased following a negative response and decreased following a positive response, in 1 dB steps. The LDL functions (**Figure 1**) were fairly flat across frequency, averaging roughly 100 and 110 dB SPL for S1 and S2, respectively. Using the difference between the

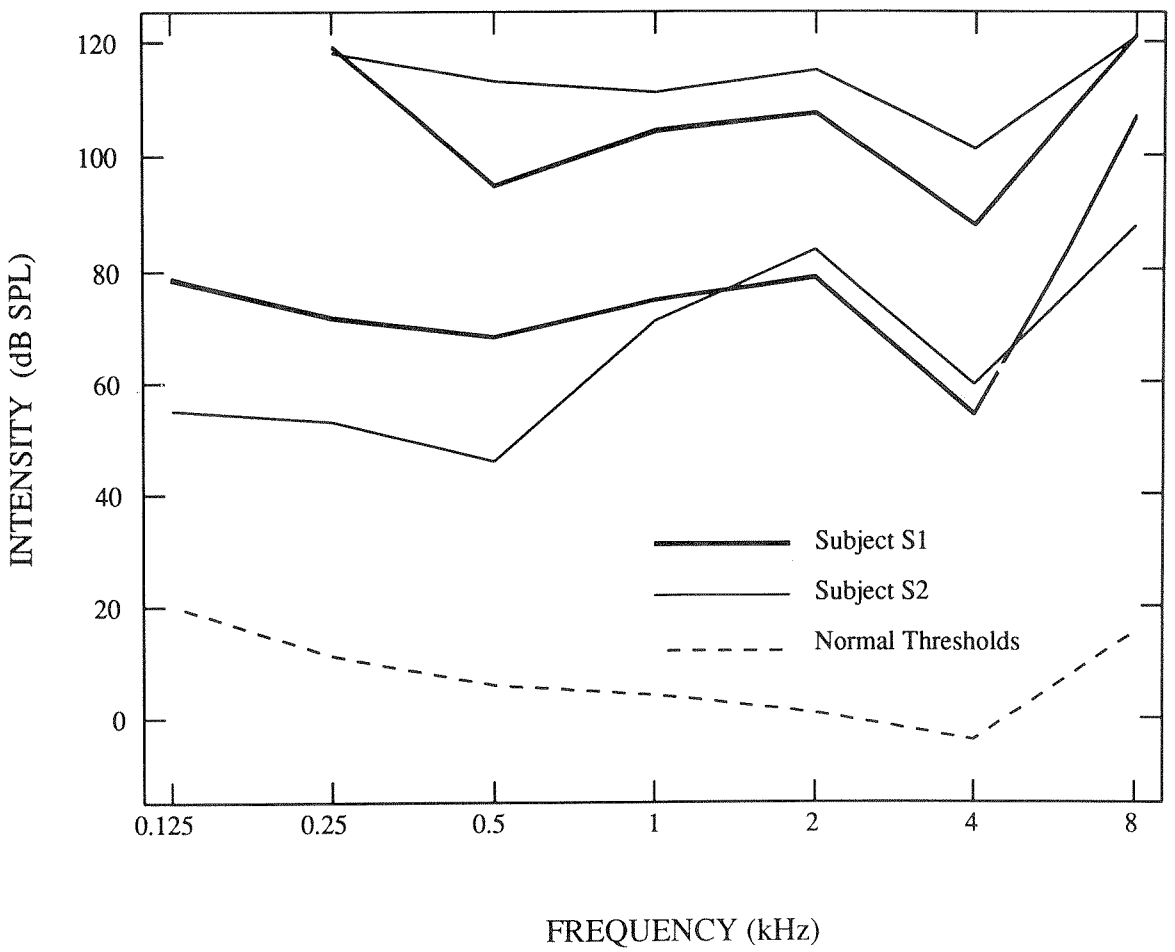

Figure 1.
Pure-tone air conduction thresholds and loudness discomfort levels (LDLs) for subjects S1 and S2. For each pair of curves, the upper curve represents LDLs and the lower curve represents thresholds. The thresholds of a normal-hearing listener are plotted as a reference.

threshold and LDL levels as an estimate of dynamic range, S1 and S2 have dynamic ranges of roughly 25 dB and 40 dB, respectively, above 500 Hz. The dynamic ranges are somewhat wider below 500 Hz, resulting from the higher discomfort levels of S1 and the lower detection thresholds of S2 at low frequencies.

Speech Materials

The speech materials used by Lippmann et al. (15) and DeGennaro (4,6) in their studies of amplitude compression were employed. These materials were consonant-vowel-consonant (CVC) nonsense syllables of the form /ə/-CVC, where /ə/ is the unstressed schwa. Roughly 1600 CVC combinations of 6 vowels, /a,ɛ,I,i,u,U/, and 17 consonants, /p,t,k,b,d,g,f,θ,s,ʃ,v,ð,z,ʒ,tʃ,dʒ,h/ were constructed (/h/ was used only in the initial consonant position; /ʒ/ was used only in the final consonant position). Half of the CVC materials were spoken by a male speaker and half by a female speaker. Recordings were made in a quiet/anechoic setting. The rms level of each CVC was normalized digitally prior to testing.

Systems

All system implementations were employed with a real-time 16-band speech processing system (2). As shown in **Figure 2**, the speech signal was amplified and analyzed by a filter bank (⅓ octave bands from 400–8000 Hz plus a ⅔ octave band at 280 Hz and an octave band at 160 Hz). The envelopes of the filter outputs were measured by rms detectors and the filter outputs were processed by a set of variable

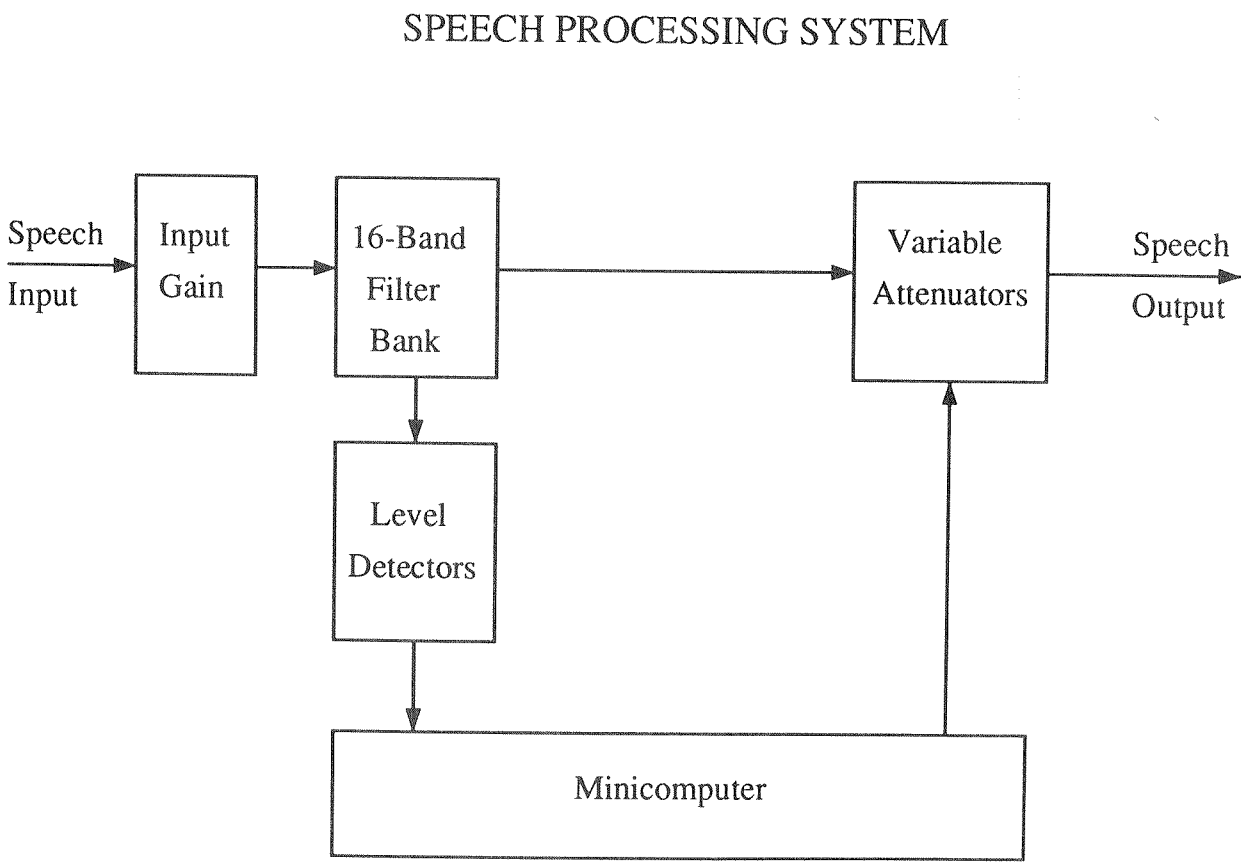

Figure 2.
Block diagram of the speech processing system used for implementing both the linear amplification and compression limiting systems.

attenuators controlled by the detector outputs. The characteristics of the filters and detectors are listed in **Table 1**.

Each subject was tested on speech materials processed by six systems, each employing one of two frequency-gain characteristics and one of three compression characteristics.

The frequency-gain characteristics were specified in the same manner as the two linear-amplification systems studied by Lippmann et al. (15): L1 mirrored the audiogram and L2 attempted to present as much of the speech as possible above the detection threshold and below discomfort levels. The L1 characteristic was determined from the audiogram. The L2 characteristic was specified on the basis of band gains selected by the subjects for each of four separate frequency bands (160–700, 700–1400, 1400–2800, 2800–8000 Hz). For each band, the subjects were instructed to adjust the gain such that the bandpass filtered speech was maximally intelligible

Table 1.
Band center frequencies and level detector time constants of the compression limiting systems.

BAND	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Center Frequency (Hz)	160	280	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300
Detector Time Constant (ms)	18.0	9.4	5.8	4.4	3.4	2.7	2.0	2.0	1.6	1.4	0.9	0.9	0.7	0.7	0.7	0.2

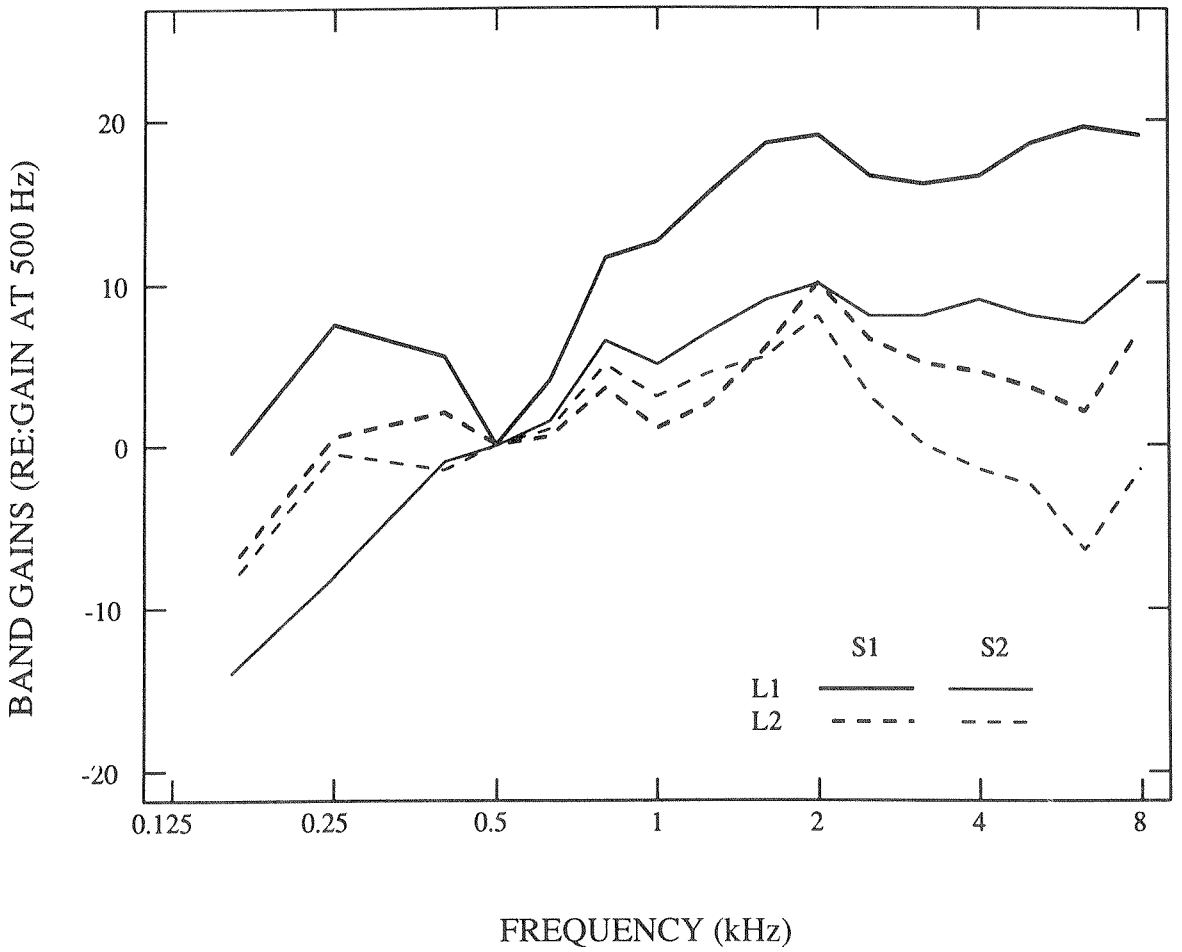

Figure 3.
Frequency-gain characteristics, L1 (solid lines) and L2 (dashed lines) employed in the speech processing systems of subjects S1 (thick lines) and S2 (thin lines).

yet comfortable for long-term listening. The L2 characteristic was derived by smoothing the four selected band gains across the 16 bands of the speech processing system. As one would expect for listeners with flat audiograms, the shapes of the two frequency-gain characteristics were similar (**Figure 3**). However, the L2 characteristic had roughly 10 dB less high-frequency emphasis than the L1 characteristic.

The three compression-limiting characteristics employed in conjunction with each of the two frequency-gain characteristics for each subject were: 1) no limiting (corresponding to linear amplification), 2) moderate limiting, and 3) severe limiting. The latter two characteristics employed different compression thresholds, the levels above which limiting occurs. These thresholds were specified relative to each subject's loudness discomfort levels in each of the 16 frequency bands. The moderate limiters had limiting thresholds set 10 dB and 20 dB below discomfort levels for S1 and S2, respectively. The severe limiters had limiting thresholds set 20 dB and 30 dB below discomfort levels for S1 and S2, respectively. A lower compression threshold was set for S2 because she consistently placed most of the speech energy at a lower level than S1 relative to her discomfort level. With both the moderate and severe limiters, the static compression ratio above the compression threshold in each band was 20:1, while levels below threshold were linearly amplified. However, it should be noted that, because of the dynamic properties of the compression limiters, rapid changes in level were not compressed as effectively as slower changes in level, resulting in wider output level variations than predicted by the static compression characteristics (5).

Testing Procedure

All testing was conducted monaurally in a sound-proof booth using TDH-39 earphone drivers mounted

in GS001 cushions. Because the detection thresholds in the non-test ear were above those in the test ear for both subjects, contralateral masking noise was not used. Each experimental session was roughly 2 to 3 hours long.

A rough model of the levels encountered in conversational speech was provided by presenting the speech materials over a range of levels. Although at this time there are no widely accepted models of the level distributions of everyday speech, measurements made by Pearsons et al. (19) suggest that the speech levels produced by talkers speaking in a "casual" or normal fashion span a range of 18–21 dB. Thus, in order to explore the effect of input level variation, four discrete input levels 10 dB apart (30 dB range) were used. The speech level was varied randomly among these four levels during the listening level determinations. During training and testing, however, the level was fixed at one of the four discrete levels for each block of trials.

Input Gain Adjustment—Prior to the speech intelligibility tests, each subject selected one overall listening level for each of the six systems by adjusting the gain of the amplifier at the input to each system. The subjects were instructed to select a gain which maximized speech intelligibility without causing discomfort. Adjustments were made while listening to CVC nonsense syllables whose levels varied randomly across the four input levels. Two sessions were devoted to gain adjustments for each subject. In each session, the gain for each system was determined as the average of three consecutive gain settings within 4 dB of each other. The gain setting used in the speech intelligibility tests for each system was the average of the adjustments made for that system across the two sessions.

Training—Peterson (20) showed that training can have significant effects on the intelligibility of nonsense syllables for persons with severe sensorineural losses. In his study, initial scores with both linearly amplified and amplitude compressed speech were highly variable. However, after repeated testing with feedback, variability decreased and scores showed a gradual orderly improvement that stabilized after several thousand trials. Therefore, in the present study, 6000 trials with feedback (5 sessions per subject) were used to train the listeners. The first four sessions provided equal amounts of training with each processing system at each of the four listening levels chosen by each subject. However, this resulted in a disproportionate amount of training with linearly amplified speech because at the low input levels the compression limiting systems were effectively linear systems. Thus, additional training was provided with compression limited speech materials at the fifth session by testing all systems at the maximum input level.

Speech Intelligibility Tests—Eight sessions per subject were devoted to speech intelligibility tests. Testing occurred in blocks of 100 trials per system-level-speaker condition. The first 25 trials of each block, presented with feedback, were considered practice and the results were discarded. The 75 trials comprising the actual test were presented without feedback. Each experimental session consisted of 12 testing blocks, one for each of the 6 systems at 2 of the 4 test levels, using materials from one of the two speakers. Each system-level-speaker condition was tested twice and the experimental procedure was structured so that each system was tested at each of the four input levels on four separate occasions to minimize the effects of fatigue and training.

RESULTS AND ANALYSIS

Input Gain Selection

Input gains were selected consistently by both subjects with an average inter-session difference of roughly 2 dB. In general, as the degree of limiting increased, the input gain chosen by the listeners also increased (**Table 2**). Relative to the gains selected with the linear systems, gains were roughly 5 dB higher with the moderate limiters and 11 dB higher with the severe limiters for both subjects.

Table 2.
Input gain in dB of the moderate and severe compression limiters relative to the input gain of the linear amplification system with the corresponding frequency response. Gains were averaged across subjects.

	Relative Input Gains	
Frequency Response	Moderate Limiter	Severe Limiter
L1	5	11
L2	4	11

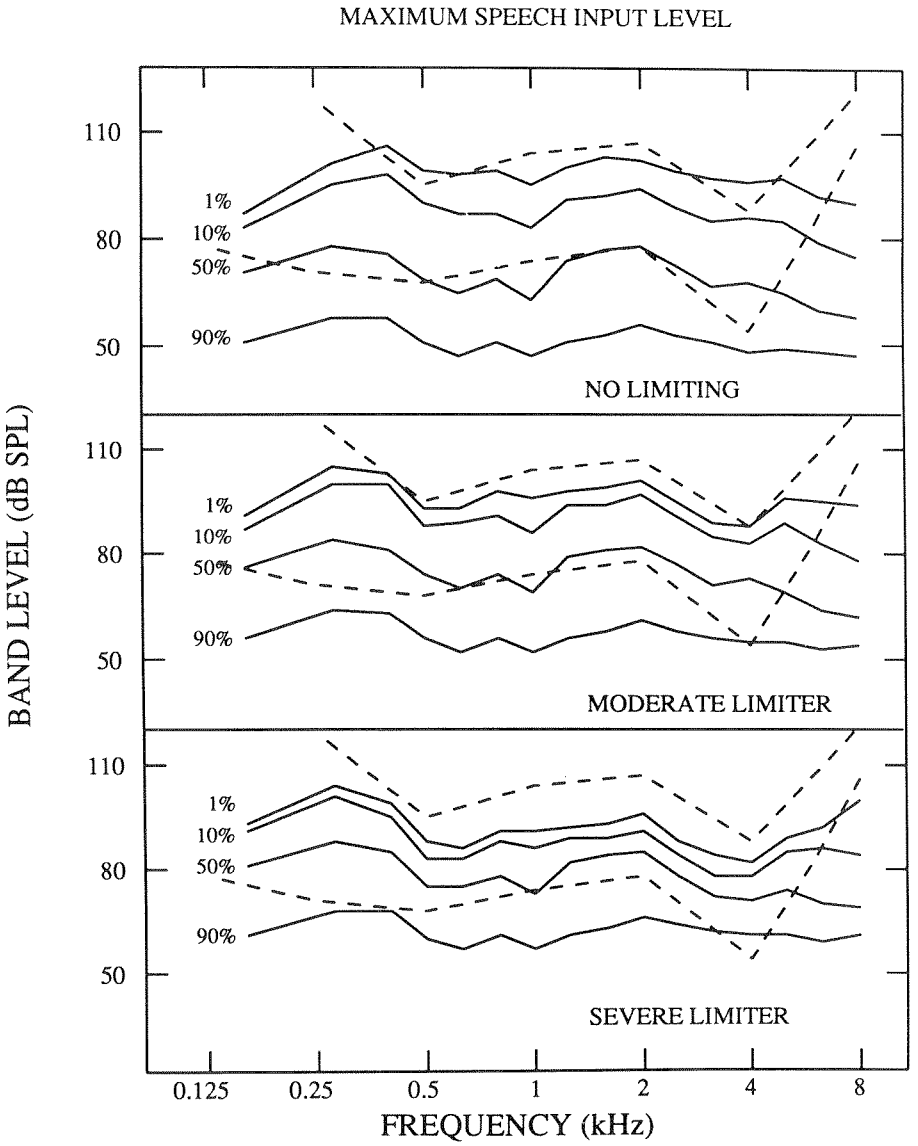

Figure 4a.
Cumulative speech levels measured with the L2 frequency-gain characteristic of subject S1 for all three limiting characteristics: 1, 10, 50, and 90 percent level measurements at the maximum speech input level.

To determine the relationship between the range of speech levels and residual auditory area, speech level distributions were measured as a function of frequency using a speech analysis system (2,11). Speech level distributions are described parametrically in terms of cumulative percent levels, defined as the levels exceeded a certain percentage of the time in each frequency band when speech is present. The 1, 10, 50, and 90 percent cumulative output levels of speech were found for each subject for all 12 system-speaker conditions at the maximum and minimum input levels. Level distributions for each of the three limiting characteristics at the maximum and minimum input level conditions are shown in **Figure 4** for subject S1. These measurements are of a representative speech sample of the male speaker with the L2 frequency-gain characteristic.

Level distributions corresponding to the maximum input level (**Figure 4a**) reveal the extent to which speech materials were compressed with limiting relative to linear amplification. With the moderate limiter, only speech components above the 5 to 25 percent levels at frequencies above 1 to 2 kHz were compressed. With the severe limiter on the other hand, compression was evident in all bands: below 500 Hz, above the 15 to 25 percent levels; in

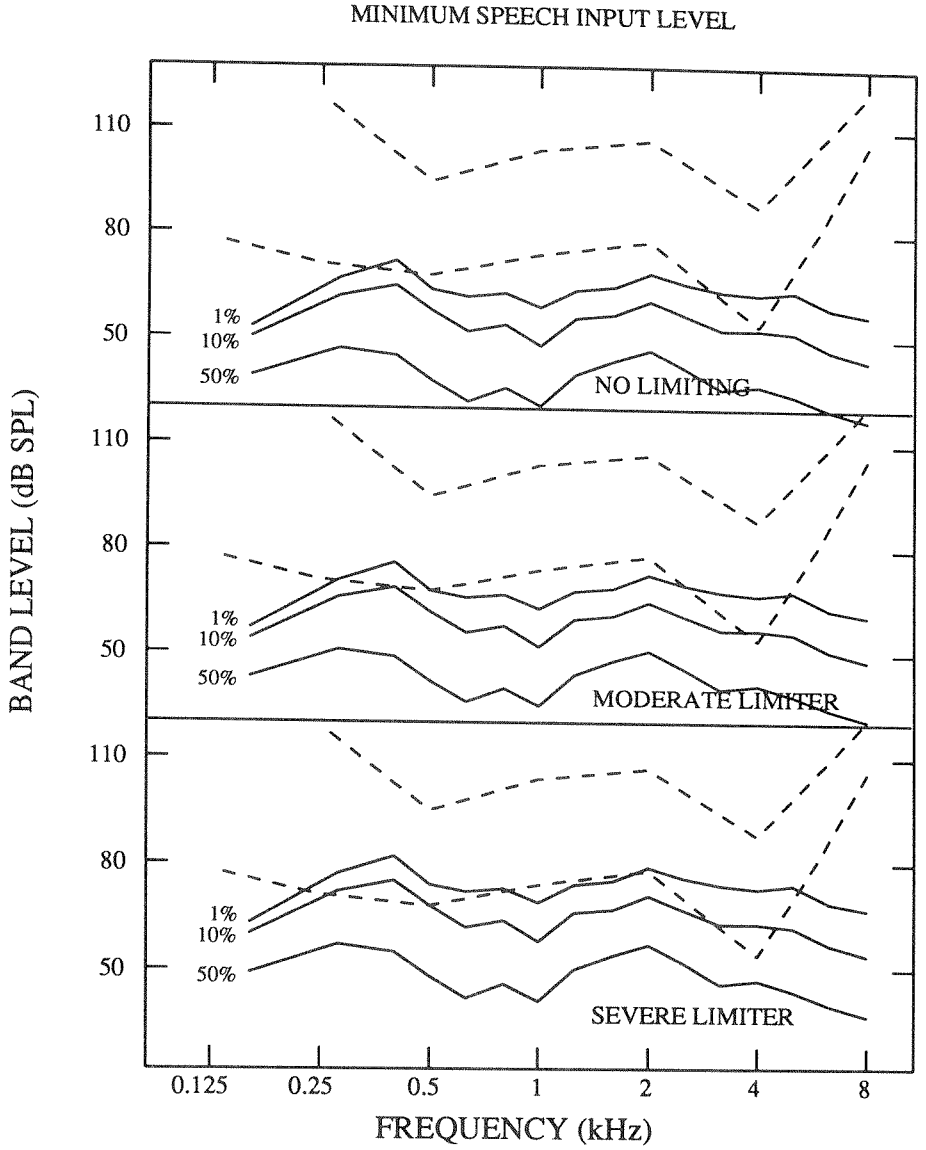

Figure 4b.
1, 10, and 50 percent level measurements at the minimum speech input level. The dashed lines represent the air conduction thresholds and the loudness discomfort levels for subject S1.

the 500–2000 Hz frequency bands, above the 30 to 40 percent levels; and in the 2000–8000 Hz frequency bands, above the 50 to 60 percent level.

Level distributions at the minimum input level (**Figure 4b**) show that the overall level of the low-level speech was highest for the severe limiters and lowest for the linear systems, as expected on the basis of the input gain settings. Also, because a large percentage of the short-term speech levels presented at the minimum input level were below the limiting thresholds, all of the systems behaved as linear amplifiers at this input level.

Analysis of Phoneme Scores

Four types of intelligibility scores were collected from the CVC identification data: initial consonant (C1), final consonant (C2), vowel (V) and overall phoneme scores (average of C1, V and C2 scores). An analysis of variance (14) was performed on these scores with speech input level, frequency-gain characteristic, limiting characteristic, speaker, and subject used as factors.

The analysis of variance indicated that the dominant factors affecting speech intelligibility were input level and the interaction between input level

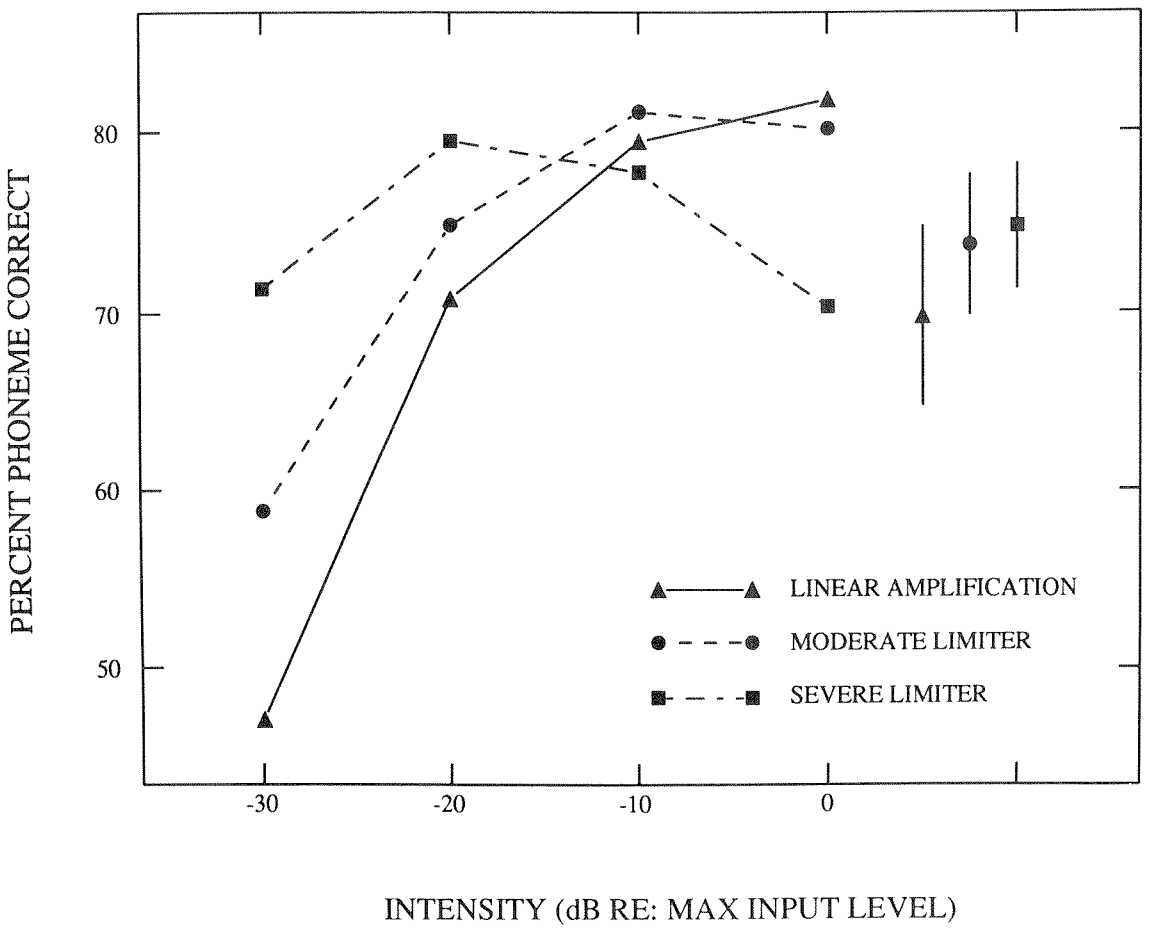

Figure 5.
Phoneme scores for each compression limiting condition at the four speech input levels. Vertical bars at the right show the mean and standard deviation of the phoneme scores across the 30 dB range of input levels for each limiting condition.

and the limiting characteristic, accounting for roughly 50 percent and 25 percent of the variance, respectively. In general, the gain, speaker, and subject factors and their interactions with other factors were either insignificant or accounted for less than one percent of the variance. Consequently, the phoneme scores plotted in **Figure 5** are averaged across gain, speaker, subject and session (i.e. each plotted point represents an average of 16 data points).

The effects of input level, and of limiting as a function of level, on the phoneme scores are evident in **Figure 5**. With the linear system and the moderate limiter, phoneme scores decreased as input level decreased. However, the decline was smaller with the moderate limiter. With the severe limiter, phoneme scores were more independent of level, yielding higher scores at the lower input levels but lower scores at the higher input levels than the other systems.

At low input levels, average phoneme scores increased dramatically as the degree of limiting increased (by 12 and 24 percentage points with the moderate and severe limiters, respectively). Although the maximum scores did not vary greatly as a function of the limiting characteristic (82, 80 and 79 percent correct for the linear system, moderate limiter and severe limiter, respectively), the range of scores achieved with these systems did (34, 22, and 9 percentage points, respectively). Thus, the limiting systems reduced the level dependence of speech intelligibility by an impressive amount for these listeners.

Analysis of Consonant Confusions

At the lower input levels, the compression limiters provided higher gain than the linear systems, and

also functioned roughly as linear amplifiers. Thus, the intelligibility benefits with compression limiting at these levels may have been solely due to audibility differences.

At the maximum input level, scores with the compression limiters were generally poorer than with the linear systems. At this level, although the delivered peak (1 percent) levels were comparable across the three processing conditions, a significant portion of the speech levels were compressed (**Figure 4a**) with the moderate and severe limiters.

To determine which speech contrasts were degraded by compression limiting, consonant errors (which were much more common than vowel errors) were analyzed in terms of feature-information transfer (18). Four features were considered: voicing, manner of articulation, stridence, and place of articulation. Unconditional percent transmitted information scores were derived from confusion matrices for each limiting condition at the maximum input level condition. Separate analyses indicated that there were only small differences between subjects, and that the features chosen were relatively independent (21).

The results, summarized in **Table 3**, indicate that transmission of the features voicing and manner was nearly equal under all three limiting conditions at the maximum input level condition. However, transmission of the features stridence and place was significantly degraded (14 to 18 percentage points) with severe limiting relative to that with linear amplification or moderate limiting.

Table 3.
Percent transmitted information scores for the features, voicing, stridence, manner, and place of articulation for the three speech processing systems at the maximum speech input level.

	Percent Transmitted Information		
Feature	**Linear Amplification**	**Moderate Limiter**	**Severe Limiter**
Voicing	88	86	82
Stridence	75	74	57
Manner	80	83	78
Place	51	48	37

DISCUSSION

The Perception of Compression Limited Speech

Of the many variables studied, only input level and limiting characteristic were found to have significant effects on speech intelligibility. The major effect of input level on speech intelligibility was expected: phoneme scores declined as the input level was reduced. This effect was observed across the entire 30 dB range of input levels with linear amplification and moderate limiting, and also across the lower 10 dB range of levels with severe limiting. Thus, for these hearing-impaired listeners, reduction of the input level generally reduced audibility and degraded speech intelligibility.

Compression limiting had two major effects on speech intelligibility relative to linear amplification: 1) scores were increased at the low input levels, and 2) scores were reduced at the high input levels. At low input levels, speech typically fell below the limiting thresholds and was processed in the same manner as linearly amplified speech. However, the effective gain of the limiting systems was greater than that of the linear systems, resulting in higher output levels and, thus, improved speech intelligibility at the low input levels. On the other hand, at the maximum input level, phoneme scores with the moderate and severe limiter were 2 and 10 percentage points, respectively, below those with linear amplification.

The declines in intelligibility with compression limiting at the high input levels were accompanied by reduced transmission of all consonant features, although stridence and place were affected far more than manner and voicing. Since both the stridence and place features distinguish consonants differing primarily in terms of spectral cues, these results suggest that 16-band compression limiting degrades spectral information. Thus, in this case, the theoretical benefits of using multiple bands were not realized.

Comparisons with Previous Research

The results of the error analysis with the 16-band compression limiter used in the present study for the maximum input level condition were very similar to those previously obtained by Lippmann (15) and DeGennaro (4,6) with 16-band syllabic compression. In all cases, perception of the consonant features stridence and place were degraded by 16-band compression. These findings suggest that the spectral flattening resulting from independent compres-

sion of 16 bands is deleterious to the intelligibility of certain speech sounds.

The three-band and two-band compression hearing aids studied by Mangold and Leijon (16) and by Laurence et al. (12), respectively, were similar in function to that of the present study in that both systems compressed frequency bands independently with compression parameters appropriate for limiters. However, it is not clear whether these systems compressed band level variations to the same extent as did the systems of the present study because band nor level measurements were not reported in either study.

Mangold and Leijon (16) obtained positive results for five of the seven subjects tested. However, the advantages observed may have been due primarily to overall gain differences. As in the present study, a higher overall gain may have been provided with compression limiting than with overall amplification, resulting in increased speech intelligibility scores at moderate input levels. For example, had testing in the present study been conducted only at 20 dB below the maximum input level, an 8 percentage point advantage would have been observed for the severe limiter.

Laurence et al. (12) conducted testing over a 30 dB range of levels, as in the present study, and obtained somewhat similar results: compression of high level sounds allowed listeners to increase the overall input gain relative to linear amplification, which in turn resulted in improved audibility and intelligibility of low-level speech sounds. However, the relative performance of compression limiting and linear amplification at the maximum input level differed: Laurence et al. found compression limiting to be superior to linear amplification—in the present study it was inferior. This difference in results may be due to system differences and/or experimental differences.

System differences include the following: 1) Laurence's compression aid employed a wideband compression limiter prior to multiband processing whereas the present system did not; and 2) Laurence's compression and linear aids employed two frequency bands while the present system employed 16. The wideband compression limiter in the Laurence aid may have reduced the percentage of time that the band compressors operated in the compression mode. Also, a two-band compressor might produce less severe distortions of short-term spectral shape (e.g., peak-valley structure) than a 16-band compressor. In addition, a two-band linear aid may not be as effective a reference system as a 16-band linear aid.

Experimental differences included the following. 1) Laurence's subjects had an average dynamic range of 43 dB, 10 dB wider than the average range of those of the present study. (This value is the average of the maximum of the left and right ear dynamic ranges for each subject as the Laurence system was binaural.) 2) Laurence's study employed sentences as test materials while the present study used CVC nonsense syllables. Also, the present study may have tested at higher input levels than did Laurence relative to the compression thresholds. This would result in greater compression action at the highest input levels and, consequently, increased distortion. In general, these differences served to make the task more difficult in the present study than in Laurence's. Thus, it is possible that the studies merely measured different points along very similar performance functions.

CONCLUSIONS

In summary, multiband compression limiting allowed increased overall gain relative to linear amplification by reducing the level of high-energy speech sounds. This resulted in greater audibility and, consequently, greater intelligibility of low-level speech sounds relative to that with linear amplification. However, at high input levels 16-band compression limiting degraded intelligibility relative to linear amplification, reducing the benefit of multiband compression limiting for hearing-impaired listeners. Error analysis suggested that these degradations may have been due to spectral distortions resulting from independent compression of multiple frequency bands. Thus, the intelligibility benefits observed with compression limiting relative to linear amplification may have been due only to the increased overall gain allowed by the compression system rather than to the frequency-dependent nature of the compression functions. Comparable benefits might have been achieved with a wideband compression limiter or with a wideband AGC followed by a wideband compression limiter. Furthermore, a system such as one of these might prove superior, providing the same advantage as multiband compression limiting at low input levels without the disadvantage at high levels.

REFERENCES

1. **Braida LD, Durlach NI, Lippmann RP, Hicks BL, Rabinowitz WM, and Reed CR:** *Hearing Aids—A Review of Past Research on Linear Amplification, Amplitude Compression and Frequency Lowering.* American Speech-Language-Hearing Association Monographs Number 19, 1979.
2. **Coln MCW:** *A Computer Controlled Multiband Amplitude Compressor.* Master's Thesis, Massachusetts Institute of Technology, Cambridge, MA, 1979.
3. **Davis H, Stevens SS, Nichols RH, Hudgins CV, Peterson GE, Marquis RJ, and Ross DA:** *Hearing Aids—An Experimental Study of Design Objectives.* Cambridge: Harvard University Press, 1947.
4. **DeGennaro SV:** *The Effect of Syllabic Compression on Speech Intelligibility for Normal Listeners with Simulated Sensorineural Hearing Loss.* Master's Thesis, Massachusetts Institute of Technology, Cambridge, MA, 1978.
5. **DeGennaro SV, Krieg KR, Braida LD, and Durlach NI:** Third-octave analysis of multichannel amplitude compressed speech. *Proceedings of IEEE International Conference on Acoustics Speech and Signal Processing,* 1981.
6. **DeGennaro SV, Braida LD, and Durlach NI:** Multichannel syllabic compression for severely impaired listeners. *J Rehabil Res Dev* 23:1, 17–24, 1986.
7. **Harris JD, Haines HL, Kelsey PA, and Clack TD:** The relation between speech intelligibility and the electro-acoustic characteristics of low-fidelity circuitry, *J Auditory Res* 1:357–381, 1961.
8. **Jerger J, Speaks C, and Malmquist C:** Hearing aid performance and hearing aid selection. *J Speech Hear Res* 9:136–149, 1966.
9. **Krebs:** Output Limiting and Related Harmonic Distortion, *Oticongress 2,* 1972.
10. **Kretsinger EA and Young NB:** The use of fast limiting to improve the intelligibility of speech in noise. *Speech Monographs* 64–69, 1960.
11. **Krieg KR:** *Third-Octave Band-Level Distributions of Amplitude Compressed Speech.* Bachelor's Thesis, Massachusetts Institute of Technology, Cambridge, MA, 1980.
12. **Laurence RF, Moore BCJ, and Glasberg BR:** A comparison of behind-the-ear high-fidelity linear hearing aids and two-channel compression aids, in the laboratory and in everyday life. *Brit J Audiol* 17:31–48, 1983.
13. **Levitt H:** Transformed up-down methods in psychoacoustics. *J Acoust Soc Am* 49:467–477, 1971.
14. **Lindman HR:** *Analysis of Variance in Complex Experimental Designs.* San Fancisco: W.H. Freeman and Company, 1974.
15. **Lippmann RP, Braida LD, and Durlach NI:** Study of multichannel amplitude compression and linear amplification for persons with sensorineural hearing loss. *J Acoust Soc Am* 69:2, 524–534, 1980.
16. **Mangold S and Leijon A:** Programmable Hearing Aid with Multichannel Compression. *Scand Audiol* 8:121–126, 1979.
17. **Morgan DE, Wilson RH, and Dirks DD:** Loudness discomfort level: Selected methods and stimuli. *J Acous Soc Am* 56:2, 577–581, 1974.
18. **Miller GA and Nicely PE:** An analysis of perceptual confusions among some English consonants, *J Acous Soc Am* 27:2, 301–315, 1955.
19. **Pearsons KS, Bennett RL, and Fidell S:** *Speech Levels in Various Environments.* BBN Report No. 3281, 1976.
20. **Peterson PM:** *Further Studies of Perception of Amplitude-Compressed Speech by Impaired Listeners.* Master's Thesis, Massachusetts Institute of Technology, Cambridge, MA, 1980.
21. **Wang MD and Bilger RC:** Consonant confusions in noise: A study of perceptual features. *J Acoust Soc Am* 54:1248–1260, 1973.
22. **Young LL, Goodman JT, and Carhart R:** Effects of whitening and peak-clipping on speech intelligibility in the presence of a competing message. *Audiol* 18:1, 72–79, 1979.