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Effects of Time Compression and Time Compression plus Reverberation on the Intelligibility of Northwestern University Auditory Test No. 6

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Abstract

The *Tonal and Speech Materials for Auditory Perceptual Assessment, Disc 1.0* audio compact disc developed in 1992 includes several sets of degraded speech materials, two of which, time compression and reverberation, are described in this paper. The digital techniques used to compress the NU No. 6 materials (female speaker) on an 80386-based computer are described, along with a series of experiments on subjects with normal hearing that document the effects of the time compression on recognition performance. Experiment I examined at 70 dB SPL the effect on word recognition of 45, 55, 65, 70, and 75 percent compressions. Experiment II developed psychometric functions for the 45, 65, and 75 percent time-compression conditions. Experiment III defined the effects that time-compression degradation (45% and 65%) plus reverberation degradation (0.3 sec) had on the recognition performance on the NU No. 6 materials. Based on the experiments, four conditions (45% compression, 65% compression, 45% compression plus 0.3-sec reverberation, and 65% compression plus 0.3-sec reverberation) were selected and recorded on the compact disc. In the compact disc trials, normative data on the four conditions were developed from 120 listeners with normal hearing.

Key Words: Degraded speech, NU No. 6, reverberation, time compression

This paper describes two procedures used to degrade the Northwestern University Auditory Test No. 6 (female speaker) materials that are included on the *Tonal and Speech Materials for Auditory Perceptual Assessment, Disc 1.0* compact disc. The first procedure involved time compression of the speech signals. The second procedure involved a combination of time compression and reverberation of the speech signals.

The rate of speech can be altered in several ways. The rate of speech may be increased (or decreased) either by having the speaker alter the rate of talking (rate of articulation) or by changing the rate of the analog or digital playback with respect to the rate of the recording (Calearo and Lazzaroni, 1957; Bergman, 1980). Speech changed by acceleration or deceleration of the playback rate has a power spectrum and pitch that vary directly with the rate change. A second procedure that changes the presentation rate of speech involves the removal of portions of the speech waveform to shorten the speech sample. This procedure, which typically has been accomplished with an electromechani-

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cal device (Fairbanks and Kodman, 1957), does not alter the power spectrum of the speech sample. Clinically, time-compressed speech materials have been used on a variety of patients with neurologic deficits (Kurdziel et al, 1976; Rintelmann and Lynn, 1983; Mueller et al, 1987). A degradation of the speech signal generally has a greater deleterious effect on patients with central neurologic deficits than on patients with normal central neurologic systems.

Reverberation, which refers to the persistence of an acoustic signal in an enclosure after the sound source has stopped, is quantified as the time required for the amplitude of a signal to decay 60 dB after signal offset. The effects of reverberation on word-recognition performance have been established for a number of years (Knudsen, 1929). Because the persistent sound becomes a masker of later sounds, the general case is that as reverberation time increases, there is a corresponding decrease in word-recognition performance (Steinberg, 1929; Moncur and Dirks, 1967). (Recent reviews are provided by Loven and Collins [1988] and by Helfer and Wilber [1990].)

Many investigations have shown that combinations of speech degradation techniques (e.g., low-pass filtering, time compression, masking, interruption, and reverberation) produce word-recognition performance that is poorer than the simply additive effects of the degradation techniques (Licklider and Pollack, 1948; Martin et al, 1956; Harris, 1960; Finitzo-Hieber and Tillman, 1978; Lacroix et al, 1979). In discussing the effect that multiple degradations have on the understanding of speech, Harris (1960, p. 230) observed that the "picture of high intelligibility with severe distortion does indeed change sharply when one combines two sources (of degradation), each seemingly innocuous in itself."

During the 40 years since the Fairbanks et al (1954) report, speech materials were compressed using electromechanical devices (see, for example, Beasley et al, 1972b; Beasley and Maki, 1976). Because the algorithms and instruments involved with the electromechanical devices were not available and because our laboratory had experience with digital signal processing techniques, we decided to pursue the time compression of speech using a personal computer with an 80386 processor. The time-compression technique that evolved was a combination of in-house routines and a commercial waveform editor (Antex, PCMEDIT). To document the effects that the digital techniques of speech compression had on the recognition performance on the NU No. 6 materials, two experiments were performed on young adults with normal hearing.

The purpose of Experiment I was to examine the effect that five compression ratios (45%, 55%, 65%, 70%, and 75%) had on the word-recognition performance of lists 1 and 4 of the NU No. 6 materials. Based on the data from Experiment I, the focus of the remainder of the project was on two of the five compression ratios, 45 percent and 65 percent. In Experiment II, psychometric functions (percent correct recognition by presentation level) for the four NU No. 6 lists were generated for the 45, 65, and 75 percent compression conditions. To study the effects that time-compression degradation compounded by reverberation degradation had on word-recognition performance on the NU No. 6 materials, Experiment III was conducted, in which psychometric functions were generated for the uncompressed speech materials degraded by 0.3-sec reverberation and for two conditions of compression (45% and 65%) plus 0.3-sec reverberation.

The final form of the compressed materials on the *Tonal and Speech Materials for Auditory Perceptual Assessment, Disc 1.0* compact disc (tracks 14–17, right channel), which was determined from an item analysis of Experiment II, consisted of two lists of 50 words each for both the 45 percent and 65 percent compression conditions. The same compressed words were subjected to the 0.3-sec reverberation and were recorded concurrently on tracks 14–17, left channel. The compact disc trials involved generation of the normative psychometric functions from 120 subjects with normal hearing for these four conditions (45% compression, 65% compression, 45% compression plus 0.3-sec reverberation, and 65% compression plus 0.3-sec reverberation).

METHOD

Material Preparation

The 200 carrier phrases and target words (from the NU No. 6) spoken by a female were digitized from the master analog recording (Revox, Model B77) using a 16-bit analog-to-digital converter (Antex, Model SX-10) at 20,000 samples/sec with an antialaising filter set to 8800 Hz (96 dB/octave rejection). Following the digitization, the lengths of the files were edited

to minimize the file length. (These are the digital masters from which the NU No. 6 materials included on the *Speech Recognition and Identification Materials, Disc 1.1* compact disc were made [Wilson et al, 1990, 1991].)

The speech samples then were processed digitally to define the discard intervals (the portions of the speech samples to be deleted). Based on the earlier work with compressed speech (Fairbanks et al, 1954; Daniloff et al, 1968; Beasley et al, 1972a), a 20- to 25-msec discard interval was selected as the target interval to delete. This discard interval was selected to minimize degradation of the speech signal at the higher compression ratios. The first step in the time-compression scheme used an in-house program to identify and mark the discard intervals on the digital waveform. Because waveform editing was involved at the beginning and end of the discard interval that effectively lengthened the discard interval, an initial 18-msec discard interval was selected as the first approximation of the target 20- to 25-msec discard interval. Table 1 lists the initial retained and discarded intervals established for the respective compression ratios. Thus, for 40 percent compression, 18-msec discarded segments alternated with 27-msec retained segments, whereas for 70 percent compression, 18-msec discarded segments alternated with 7.7-msec retained segments. The 18-msec discard intervals were marked by setting the 360 datum points in each 18-msec interval to zero.

To facilitate the second step in processing, 352 of the 360 zeroed data points in each 18-msec discard interval were eliminated from the data file. Second, the remaining 8 zeroed data points in each discard interval, which were used as a marker of the discard interval, were eliminated from the data file, and the boundaries of the discard intervals (i.e., the waveform just prior to the discard interval and the waveform just after the discard interval) were joined using manual waveform editing techniques with a visual display of the waveforms on the computer monitor (VGA, 640 x 320 point display). The goal in joining the two waveforms was to accomplish a smooth transition between waveforms, which avoided audible clicks caused by abrupt transitions. The following rules were used to join the waveforms:

1. With noise on both sides of the discard interval as with the /s/, /f/, /z/ sounds, the waveforms were joined simply by eliminating the zeroed data points and several adjacent data points; this produced a 20-msec discard interval.
2. With periodic waveforms on both sides of the discard interval, up to one cycle of the waveform and the zeroed data points were eliminated with the waveforms joined at a common point on the cycle, usually at the positive-going or the negative-going zero crossing; this produced a 20- to 25-msec discard interval (the 18-msec zeroed interval plus that part of a cycle required to make the smooth joint).
3. With a periodic waveform adjacent to a noise waveform (or vice versa), the zeroed data points were eliminated and the waveforms were joined at a positive-going or a negative-going zero crossing; this produced a 19-msec to 21-msec discard interval.

Table 1 Target Time Compression Ratio with Corresponding Retained and Discard Intervals

Compression Ratio (%)	*Retained Interval (msec)*	*Discard Interval (msec)*
40	27.0	18
50	18.0	18
60	12.0	18
65	9.7	18
70	7.7	18

Because the majority of splices required more than the 18-msec discard interval, the final compression ratios computed from the lengths of the corresponding data files are about 5 percent longer than the initial target compression ratios (see Table 2). For this reason, the time compressions used in this series of investigations nominally are referred to as 45, 55, 65, 70, and 75 percent. An example of a digitized waveform, "Say the word chief," is shown in Figure 1. In the figure, the top waveform is 0 percent compressed (i.e., unaltered), contrasted to the lower three waveforms that have been compressed by 45, 65, and 75 percent, respectively.

For experiments I, II, and III, the compressed materials were output from the computer via a 16-bit digital-to-analog converter (Antex, Model SX-10) and recorded on digital audio tape or DAT (Sony, Model PCM-2500A). For the reverberation conditions in experiment III and in the compact disc trials, the signal from the computer was passed through a multieffect signal processor (Yamaha, Model

Table 2 Mean Duration and Standard Deviation of Noncompressed Speech Files and Mean Percent of Time Compression and Standard Deviation for NU No. 6 Lists under Compression Ratio Conditions

	0% Compression	Compression (%)				
	(msec)	45	55	65	70	75
List 1						
Mean	1291	43.5	54.3	65.5	70.3	75.5
SD	74	0.9	0.9	1.1	0.9	1.1
List 2						
Mean	1226	44.7		66.6		76.7
SD	78	1.1		0.9		1.5
List 3						
Mean	1238	43.1		64.7		75.7
SD	88	0.9		0.9		1.1
List 4						
Mean	1309	43.7	54.1	65.6	70.9	75.8
SD	70	1.1	0.8	1.1	1.0	1.1

Figure 1 An amplitude (Y) by time (X) display of the digitized waveform "Say the word chief," not compressed, 0 percent, (1070 msec), 45 percent compressed (625 msec), 65 percent (385 msec), and 75 percent (253 msec).

EMP100) prior to being recorded on DAT. The processor was set to the following: (1) type 1 or large-room emulation; (2) delay of 5 msec before the first reflection; (3) depth of 10, which is the number of reflections before a decay of 60 dB; (4) balance of 33 percent, which is the amplitude ratio of the first reflection to the direct signal; and (5) a reverberation time of 0.3 sec, which is the time for the signal to decay 60 dB. Measurements confirmed that 0.3 sec was a good approximation of the reverberation time. For data collection during Experiments I, II, and III, the materials recorded on DAT were reproduced (Sony, Model PCM-2500A) and fed through an audiometer (Grason-Stadler, Model 10) to a TDH-50P earphone encased in a P/N 510C017-1 cushion.

Experiment I

Recognition data for lists 1 and 4 of NU No. 6 in five time-compression conditions (45%, 55%, 65%, 70%, and 75%) were obtained in quiet at 70 dB SPL from 16 listeners (mean age = 24.0 years) with normal hearing (< 20 dB HL, ANSI, 1989). Two randomizations of each word list were made for each of the five compression conditions. Each subject listened to a randomization of list 1 and list 4 under each time-compression condition. The presentation order of the 10 lists for each subject was randomized.

Experiment II

Psychometric functions in quiet for the four lists of NU No. 6 were generated from the data of 18 subjects (mean age = 25.2 years) for three compression ratios (45%, 65%, and 75%). The following levels were used with the respective compression ratios:

1. 45 percent compression: 30, 40, 50, 60, and 70 dB SPL;
2. 65 percent compression: 35, 45, 55, 65, and 75 dB SPL; and
3. 75 percent compression: 50, 60, 70, 80, and 90 dB SPL.

To minimize learning effects, all testing was sequential from the lowest level to the highest level. For each subject and each condition, the order of the four lists was randomized for the first four levels with the list used at the lowest level repeated at the highest level.

Experiment III

In this experiment, psychometric functions were obtained for the NU No. 6 materials in quiet uncompressed (0% compression) with 0.3-sec reverberation, compressed 45 percent with 0.3-sec reverberation, and compressed 65 percent with 0.3-sec reverberation. Seventeen adults (mean age = 23.2 years) with normal hearing, who were new to the study, participated. Word-recognition performance was assessed monaurally at the following levels with the respective conditions:

1. 0 percent compression + 0.3-sec reverberation: 20, 30, 40, 50, 60, and 70 dB SPL;
2. 45 percent compression + 0.3-sec reverberation: 20, 30, 40, 50, 60, and 70 dB SPL; and
3. 65 percent compression + 0.3-sec reverberation: 25, 35, 45, 55, 65, and 75 dB SPL.

As in the previous experiment, all testing was sequential from the lowest level to the highest level. The order of the four lists for each subject and each condition was randomized for the first four levels with the lists used at the lowest levels repeated at the highest levels.

Compact Disc Trials

Psychometric functions were generated during the compact disc trials for each of the four time-compression and reverberation conditions. For the 45 percent compression condition and the 45 percent compression plus 0.3-sec reverberation condition (tracks 14 and 15), levels of 5, 15, 25, 35, 45, and 55 dB HL (25 to 75 dB SPL) were studied. For the 65 percent compression condition and 65 percent compression plus 0.3-sec reverberation condition (tracks 16 and 17), levels of 10, 20, 30, 40, 50, and 60 dB HL (30 to 80 dB SPL) were studied. The materials were presented monaurally. To minimize learning effects, each of the 120 subjects with normal hearing (Noffsinger et al, 1994) listened to only one level of each of the four conditions. Each mean datum point at each level on the psychometric functions, therefore, represents data from 20 different subjects. Thus, with the 120 subjects, combinations of the four compressed/reverberation conditions were evaluated at the same level with only a few (random) subjects.

To simulate clinic conditions, supplemental data were collected from 40 adults (mean age = 27.6 years) with normal hearing. Each subject received the two 45 percent time-compression conditions (compression alone and compression plus 0.3-sec reverberation) (tracks 14 and 15) at 55 dB HL and the two 65 percent compression conditions (tracks 16 and 17) at 60 dB HL. The order of the compression conditions (45% or 65%) was randomized with the compression alone condition always followed by the compression plus reverberation condition.

RESULTS AND DISCUSSION

Experiment I

Recognition data for lists 1 and 4 were obtained from 16 subjects at 70 dB SPL for five compression ratios (45%, 55%, 65%, 70%, and 75%) in quiet. The data, which are depicted in Figure 2, indicated that recognition performance ranged from about 90 percent correct with the 45 percent compression to about 25 percent correct with the 75 percent compression. As the compression ratio increased from 45 percent compression to 65 percent compression, there was a gradual degradation in recognition performance (–1% correct recognition per 1% compression). As the compression ratio increased from 65 to 75 percent, however, there was a more rapid degradation in recognition performance (–2.8% correct recognition per 1% compression). These findings are consistent with an earlier report in that the recognition performance was most affected by time-compression ratios above 60 percent (Beasley et al, 1972a). From these data, three compression ratios (45%, 65%, and 75%) were selected for more detailed investigation in Experiment II.

Experiment II

Psychometric functions for the four lists of NU No. 6 were obtained from 18 subjects for three time-compression ratios (45%, 65%, and 75%) in quiet using 10-dB increments. The functions for the three compression ratios are depicted in Figure 3, along with the function for the uncompressed NU No. 6 words (0%) and the data from Experiment I (filled squares). As the compression ratio increases, the functions become more displaced from the unaltered function, the slopes of the functions become more gradual, the maximum correct recognition is

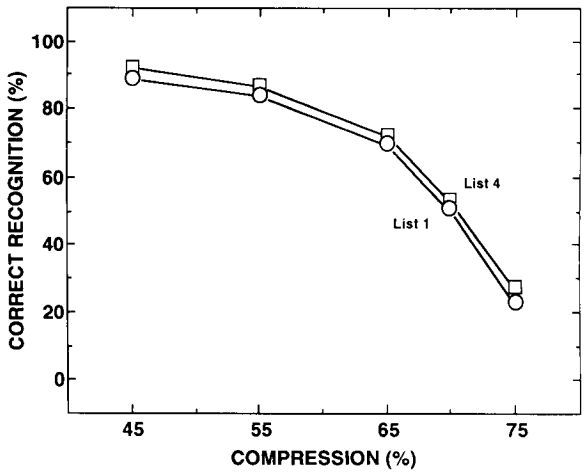

Figure 2 Percent correct recognition (n = 16) for list 1 (circles) and list 4 (squares) of the NU No. 6 materials presented at 70 dB SPL in quiet for the five time-compression ratios in Experiment I.

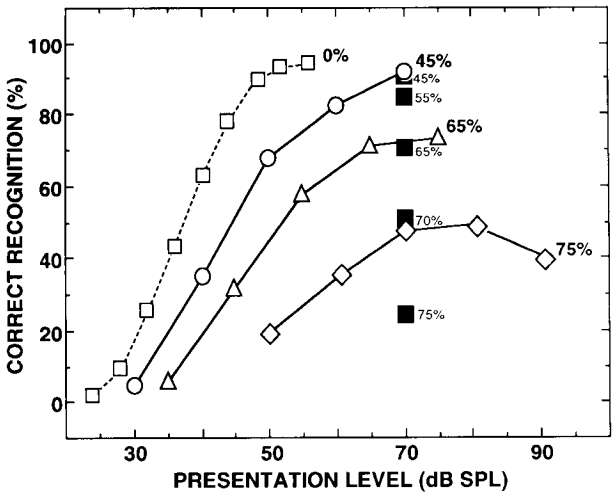

Figure 3 Percent correct recognition (n = 18) for the four lists of NU No. 6 in quiet for three time compression ratios in Experiment II. For reference, the uncompressed NU No. 6 function (squares, 0%) from Wilson et al (1990) is depicted along with the data from Experiment I (filled squares with smaller compression notation) at 70 dB SPL.

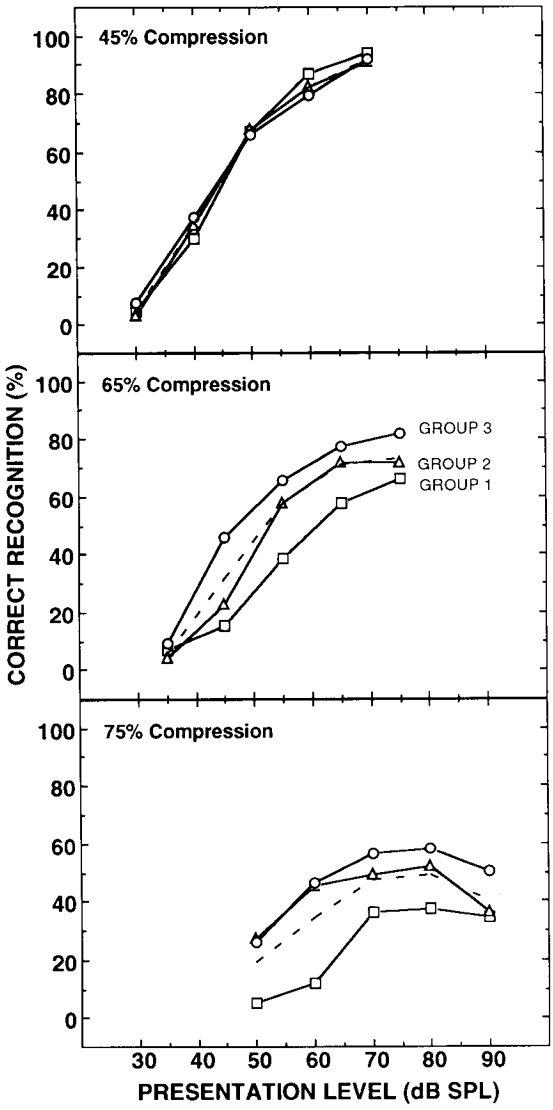

Figure 4 Percent correct recognition for the three time compression ratios in Experiment II grouped by the order in which the compression ratio conditions were presented. Group 1 (circles) received the respective materials first in the order; group 2 (triangles) received the respective materials second in the order; and group 3 (squares) received the materials third. Each group contained six subjects. The dashed lines represent the mean data.

reduced, and there is less agreement with the data from Experiment I obtained at 70 dB SPL. The data in Figure 4 explain this latter point and the effects of learning. In the figure, group 1 represents the subjects who were given a particular condition first, group 2 was given the condition second, etc. The dashed line represents the mean data. As the time-compression ratio increased, the learning effects were more pronounced in that they were minimal at 45 percent compression and maximal at 75 percent compression. In Experiment I, the subjects had less opportunity to learn from the previous measurements than in Experiment II, which may account for the discrepancies in Figure 3 between the data from corresponding conditions of the two experiments.

Finally, an item analysis was performed on the data to establish the percent correct for each of the 200 words for the 45 percent compression condition and for the 65 percent compression condition. For each time-compression condition, the 50 words least often correct and the 50 words most often correct were eliminated from the 200-word pool. The remaining 100 words for each compression condition were randomized into two lists of 50 words each. There were 52 common words between the two compression conditions. (Because these four lists of words contain words from each of the four original lists of NU No. 6 materials, the new randomizations are designated on the compact disc as lists 5A through 8A.)

Experiment III

The mean data from the three conditions of 0.3-sec reverberation (0%, 45%, and 65%) are shown in Figure 5 as the open symbols. For comparison, the mean data from the corresponding conditions from Experiment II without reverberation are depicted in Figure 5 as the filled symbols. The slopes of the functions for the reverberation conditions are more gradual than are the slopes of the functions for the corre-

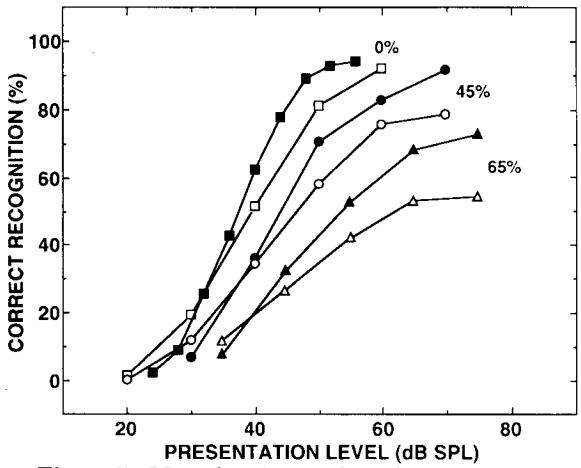

Figure 5 Mean data (n = 17) from the three conditions of 0.3-sec reverberation used in Experiment III are shown as the open symbols. For comparison, the mean data from the corresponding conditions in Experiment II without reverberation are depicted as the filled symbols. The square symbols represent the unaltered data (0%), the circles represent the 45% compression data, and the triangles represent the 65% compression data.

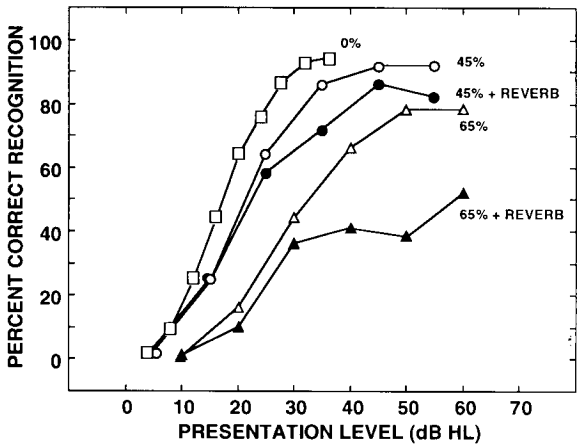

Figure 6 Percent correct recognition obtained from the compact disc trials (20 subjects/datum point) for the 45 percent compression condition (open circles), the 45 percent compression plus 0.3-sec reverberation condition (filled circles), the 65 percent compression condition (open triangles), and the 65 percent compression plus 0.3-sec reverberation condition (filled triangles). The normal, monaural psychometric function for the NU No. 6 materials female speaker (squares) is depicted for reference on the left side of the figure (from Wilson et al, 1990).

sponding condition without reverberation. For example, for the 45 percent compression conditions, the slope of the function without reverberation between the 20 to 80 percent correct points is about 2.4 percent/dB, whereas the slope of the function with reverberation is 1.6 percent/dB.

For each of the three conditions (0%, 45%, and 65% compression), the data for the reverberation condition and the corresponding condition without reverberation are essentially the same below 40 percent correct for 0 percent and 45 percent compression and below 20 percent correct for 65 percent compression). At the higher presentation levels, performance on the reverberation condition is below the performance on the corresponding condition without reverberation. This difference in performance was about 10 percent for 0 percent compression, 8 to 15 percent for 45 percent compression, and 10 to 20 percent for 65 percent compression. In summary, at the lower levels, the reverberated signal was below some critical interference level and thus did not alter word recognition. At the higher levels, the reverberated signal increasingly interfered with word-recognition performance.

Compact Disc Trials

The mean data from the compact disc trials with 120 listeners are presented in Figure 6 and in Table 3. In the figure, the percent correct recognition obtained in the compact disc trials (20 subjects/datum point) are illustrated for the 45 percent compression condition (open circles), the 45 percent compression plus 0.3-sec reverberation condition (filled circles), the 65 percent compression condition (open triangles), and the 65 percent compression plus 0.3-sec reverberation condition (filled triangles). The normal, monaural psychometric function for the NU No. 6 materials with the female speaker (squares) is also depicted (from Wilson et al, 1990). As the speech signal increasingly was degraded, the psychometric functions changed in two ways. First, the functions are displaced to the higher presentation levels. With respect to the function for the uncompressed (0%) NU No. 6 materials, the average displacements calculated at the decade intervals from 20 percent to 80 percent correct[1] were 4.4 dB for the 45 percent compression condition, 6.7 dB for the 45

[1]The mean data for the psychometric functions were fit with third-degree polynomials from which the displacements of the functions and the slopes of the functions were calculated. The following equations represent the functions:

45% compression ($R^2 = 0.99$): $y = -14.557 + 2.6522x + 0.033781x^2 - 0.0008509x^3$;
45% compression + reverb ($R^2 = 0.99$): $y = -8.889 + 1.2848x + 0.070750x^2 - 0.0011556x^3$;
65% compression ($R^2 = 0.99$): $y = -3.133 - 0.6203x + 0.106651x^2 - 0.0012463x^3$; and
65% compression + reverb ($R^2 = 0.92$): $y = -24.067 + 2.6216x - 0.031778x^2 + 0.0001491x^3$.

Table 3 Mean and Standard Deviation Percent Correct Recognition at each of Six Presentation Levels in Compact Disc Trials

	Presentation Level (dB HL)						
	5	*15*	*25*	*35*	*45*	*55*	*(55)*
45% Compression							
Mean	1.1	24.8	63.6	85.4	91.2	93.4	(94.9)
SD	2.8	20.4	13.5	9.6	7.8	6.7	(4.2)
45% Compression + 0.3-sec Reverberation							
Mean	1.3	14.9	58.0	71.0	84.8	84.6	(87.4)
SD	3.4	14.3	22.6	11.7	8.6	12.1	(7.3)
	Presentation Level (dB HL)						
	10	*20*	*30*	*40*	*50*	*60*	*(60)*
65% Compression							
Mean	0.9	14.5	43.0	63.4	75.0	75.0	(75.9)
SD	2.4	11.1	19.1	19.2	19.3	21.8	(10.2)
65% Compression + 0.3-sec Reverberation							
Mean	1.6	9.3	35.4	43.8	39.2	53.4	(55.1)
SD	4.4	14.0	10.2	10.2	14.0	21.8	(10.1)

Each datum point was obtained from 20 listeners with normal hearing. The data in parentheses (far right column) are from the 40 listeners involved in the supplemental study.

percent plus 0.3-sec reverberation condition, and 16.5 dB for the 65 percent compression condition. The function for the 65 percent compression plus 0.3-sec reverberation condition was displaced by > 25 dB between the 20 percent and 50 percent correct points. Second, as the listening task becomes more difficult, the slope of the psychometric function becomes more gradual. The slope of the function for the normal NU No. 6 materials is 4.5 percent/dB (Wilson et al, 1990). The slopes of the functions for the degraded speech conditions between the 20 percent and 80 percent correct points are 2.8 percent/dB (45% compressed), 2.3 percent/dB (45% compressed plus 0.3-sec reverberation), and 2.0 percent/dB (65% compressed). For the 65 percent compressed plus 0.3-sec reverberation condition, the slope of the function was 0.8 percent/dB (evaluated between the 20% and 50% correct points). It is difficult to account for the shape of the function for the 65 percent compressed plus 0.3-sec reverberation condition at the highest presentation levels; probably, the datum point for 50 dB HL is low. Finally, the additive effect of the 0.3-sec reverberation for both the 45 percent compression and the 65 percent compression conditions did not become apparent until the presentation level was ≥ 20 dB HL. Thus, at presentation levels below 20 dB HL, the level of the reverberation signal is below the level required to interfere with word recognition.

The supplemental data from the 40 subjects with normal hearing also are listed in Table 3 (far right column in parentheses). At corresponding levels, the mean recognition data from the supplemental experiment are in excellent agreement with the recognition data from the compact disc trials. Individually, 90 percent of the subjects scored: (1) ≥ 92 percent correct on the 45 percent compression condition; (2) ≥ 82 percent correct on the 45 percent compression plus reverberation condition; (3) ≥ 62 percent correct on the 65 percent compression condition; and (4) ≥ 40 percent correct on the 65 percent compression plus reverberation condition. The differences between the mean performances on the compression alone condition and on the compression plus reverberation condition were 7.5 percent (SD = 5.4%) for the 45 percent compression conditions and 20.8 percent (SD = 8.2%) for the 65 percent compression conditions. The differences in performance on the 45 percent compression and the 45 percent compression plus reverberation conditions ranged from –2 percent to 20 percent, with only one subject having better performance on the compression plus reverberation condition. The differences in performance on the 65 percent condition ranged from 4 percent to 40 percent, with all subjects having better performance on the compression alone condition. At the same presentation levels, 90 percent of the subjects had differences in performances between the

compression and compression plus reverberation that were ≥ 0 percent for the 45 percent compression condition and ≥ 10 percent for the 65 percent compression condition.

The data from the compact disc trials and from the supplemental study define on young adults with normal hearing the effects that two compression ratios (45% and 65%) and that the two compression ratios compounded with 0.3-sec reverberation had on word-recognition performance for the NU No. 6 materials (female speaker). Additional data are needed to define the effects of these speech degradations on the word-recognition performance of patients who are older, patients who have peripheral hearing loss, and patients who have a variety of neurologic impairments.

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REFERENCES

American National Standards Institute. (1989). *Specifications for Audiometers.* (ANSI S3.6-1989). New York: ANSI.

Beasley DS, Forman B, Rintelmann WF. (1972a). Intelligibility of time-compressed CNC monosyllables by normal listeners. *J Audit Res* 12:71–75.

Beasley DS, Maki J. (1976). Time- and frequency-altered speech. In: Lass N, ed. *Contemporary Issues in Experimental Phonetics.* New York: Academic Press, 419–458.

Beasley DS, Schwimmer S, Rintelmann WF. (1972b). Intelligibility of time-compressed CNC monosyllables. *J Speech Hear Res* 15:340–350.

Bergman M. (1980). *Aging and the Perception of Speech.* Baltimore: University Park Press.

Calearo C, Lazzaroni A. (1957). Speech intelligibility in relation to the speed of the message. *Laryngoscope* 67:410–419.

Daniloff R, Shriner T, Zemlin W. (1968). Intelligibility of vowels altered in duration and frequency. *J Acoust Soc Am* 44:700–707.

Fairbanks G, Everitt WL, Jaeger RP. (1954). Method for time or frequency compression expansion of speech. *Trans Inst Rad Eng* AU-2:7–12.

Fairbanks G, Kodman F. (1957). Word intelligibility as a function of time compression. *J Acoust Soc Am* 29:636–641.

Finitzo-Hieber T, Tillman TW. (1978). Room acoustics effects on monosyllabic word discrimination ability for normal and hearing-impaired children. *J Speech Hear Res* 21:440–458.

Harris JD. (1960). Combinations of distortions in speech: the twenty-five per cent safety factor by multiple-cueing. *Arch Otolaryngol* 72:227–232.

Helfer KS, Wilber LA. (1990). Hearing loss, aging, and speech perception in reverberation and noise. *J Speech Hear Res* 33:149–155.

Knudsen VO. (1929). The hearing of speech in auditoriums. *J Acoust Soc Am* 1:56–82.

Kurdziel S, Noffsinger D, Olsen WO. (1976). Performance by cortical lesion patients on 40% and 60% time-compressed materials. *J Am Audiol Soc* 2:3–7.

Lacroix PG, Harris JD, Randolph KJ. (1979). Multiplicative effects on sentence comprehension for combined acoustic distortions. *J Speech Hear Res* 22:247–258.

Licklider JCR, Pollack I. (1948). Effects of differentiation, integration, and infinite peak clipping upon the intelligibility of speech. *J Acoust Soc Am* 20:42–51.

Loven FC, Collins MJ. (1988). Reverberation, masking, filtering, and level effects on speech recognition performance. *J Speech Hearing Res* 31:681–695.

Martin DW, Murphy RL, Meyer A. (1956). Articulation reduction of combined distortions of speech waves. *J Acoust Soc Am* 28:597–601.

Moncur JP, Dirks DD. (1967). Binaural and monaural speech intelligibility in reverberation. *J Speech Hear Res* 1:186–195.

Mueller HG, Beck WG, Sedge RK. (1987). Comparison of the efficiency of cortical level speech tests. *Semin Hear* 8:279–298.

Noffsinger D, Wilson RH, Musiek FE. (1994). Department of Veterans Affairs compact disc recording for auditory perceptual assessment: background and introduction. *J Am Acad Audiol* 5:231–235.

Rintelmann WF, Lynn GE. (1983). Speech stimuli for assessment of central auditory disorders. In: Konkle D, Rintelmann WF. eds. *Principles of Speech Audiometry.* Baltimore: University Park Press, 231–283.

Steinberg JC. (1929). Effects of distortion upon the recognition of speech sounds. *J Acoust Soc Am* 1:121–137.

Wilson RH, Preece JP, Crowther CS. (1991). Enhancement of word-recognition performance with a filtering technique. *J Speech Hear Res* 34:1436–1438.

Wilson RH, Zizz CA, Shanks JE, Causey GD. (1990). Normative data in quiet, broadband noise, and competing message for Northwestern University Auditory Test No. 6 by a female speaker. *J Speech Hear Disord* 55:771–778.