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Recognition of Multiply Degraded Speech by Young and Elderly Listeners

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This study investigated the hypothesis that age effects exert an increased influence on speech recognition performance as the number of acoustic degradations of the speech signal increases. Four groups participated: young listeners with normal hearing, elderly listeners with normal hearing, young listeners with hearing loss, and elderly listeners with hearing loss. Recognition was assessed for sentence materials degraded by noise, reverberation, or time compression, either in isolation or in binary combinations. Performance scores were converted to an equivalent signal-to-noise ratio index to facilitate direct comparison of the effects of different forms of stimulus degradation. Age effects were observed primarily in multiple degradation conditions featuring time compression of the stimuli. These results are discussed in terms of a postulated change in functional signal-to-noise ratio with increasing age.

KEY WORDS: speech recognition, aging, reverberation, time compression, noise

The age-related decline in understanding degraded speech has been well documented (Dubno, Dirks, & Morgan, 1984; Gordon-Salant & Fitzgibbons, 1993; Helfer & Wilber, 1990). One hypothesis of the effects of aging postulates that with increased age there is a decrease in the listener's functional signal-to-noise ratio (SNR) (Salthouse, 1985). This decline in functional SNR could result from a reduction in internal signal strength or an increase in the level of neural noise, which together are presumed to reduce an older person's ability to encode a signal. Although this hypothesis is difficult to examine empirically, it may provide a useful framework for evaluating the performance of older listeners on speech recognition tasks.

In a recent study (Gordon-Salant & Fitzgibbons, 1995), we utilized a physical SNR metric as an operational estimate of a listener's functional SNR. This "equivalent SNR index" referenced the percent-correct performance of an individual listener in a specific stimulus distortion condition to that physical SNR needed to produce the same performance level for undegraded speech among a group of young listeners with normal hearing. The use of the index allowed phenomenal comparisons about the effects of different types of stimulus distortions on listener performance.

In the previous study, recognition performance of young and elderly listeners was compared across a range of conditions involving undegraded and temporally degraded speech. Comparisons of performance, when converted to the equivalent SNR index, revealed that elderly listeners with normal hearing performed more poorly than younger listeners with normal hearing in the mild degrees of temporal speech distortion. In conditions involving moderate and severe forms of temporal distortion, however, elderly listeners with and without hearing loss performed more poorly than younger listeners with matched hearing sensitivity. To the extent that derived estimates of equivalent SNR reflect a listener's functional SNR, these results suggest that elderly listeners with normal hearing operate at a reduced functional SNR for a

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range of signal degradation conditions. However, for listeners with hearing loss, an age-related reduction in equivalent SNR becomes evident only in more severe forms of speech distortion.

One type of real-world listening situation that might prove particularly difficult for elderly listeners is the combination of different forms of speech degradation. Multiply degraded speech conditions can consist of combinations of two or more forms of acoustic distortion, or the combination of one form of speech distortion and noise. Previous studies have shown that elderly listeners with normal hearing or minimal hearing loss perform more poorly than younger listeners with normal hearing for recognizing reverberant speech presented in noise (Harris & Reitz, 1985; Helfer & Wilber, 1990). The effects of age among listeners with hearing loss in these combined degradation conditions remain obscure because of the lack of a younger control group with hearing loss or inadequate methods of matching the hearing sensitivity of younger and older listeners. Other types of combined speech degradations, in addition to reverberation and noise, can occur in daily listening situations, including listening to rapid speech in noise or listening to rapid speech in reverberant environments. The effects of these combined forms of signal degradation on the performance of young and elderly listeners has not yet been evaluated.

The purpose of the current investigation was to examine the effects of multiple stimulus degradations on speech recognition performance of young and elderly listeners. The experimental hypothesis was that elderly listeners operate with a reduced functional SNR compared to younger listeners, particularly on difficult speech recognition tasks. If this is the case, then elderly listeners should experience more difficulty recognizing speech degraded by multiple forms of degradation than younger listeners, because multiple degradations act to reduce the acoustic redundancy inherent in the speech stimulus. The equivalent SNR index was applied for examining speech recognition performance in single and multiple forms of speech degradation. The use of this index permitted several key comparisons to be made: the relative difficulty of different combinations of speech degradation, the independent effects of age and hearing loss, and the relative performance deficits in single versus multiple forms of speech degradation. Additionally, use of the equivalent SNR index allowed a preliminary evaluation of the hypothesis that age is accompanied by a reduction in functional SNR.

Method

Participants

There were 40 listeners, divided into four groups of 10 participants each: elderly listeners with normal hearing (age 65–76; pure tone thresholds ≤ 15 dB HL re ANSI, 1989 from 250–4000 Hz), young listeners with normal hearing (age 18–40 years; pure tone thresholds comparable to those for Group 1), elderly listeners with hearing loss (age 65–76 years; mild-to-moderate sloping sensorineural hearing loss), and young listeners with hearing loss (age 18–40 years; hearing sensitivity matched as closely as possible to that of the participants in Group 3). Mean audiograms of the four groups are shown in Figure 1.

Stimuli

The stimuli were the eight lists of low-predictability (LP) items from the Revised Speech Perception in Noise Test (R-SPIN; Bilger, Nuetzel, Rabinowitz, & Rzeczkowski, 1984). These stimuli were presented in undistorted form and in one of three forms of speech distortion: (a) time compression (which simulates some of the temporal characteristics of rapid speech), (b) reverberation, or (c) time compression + reverberation. The single forms of time compression and reverberation were implemented by computer algorithms described previously (Gordon-Salant & Fitzgibbons, 1993). Briefly, the time-compression algorithm extracted quasi-alternate waveform sections (between 5 and 15 ms duration) at zero crossing points and abutted the remaining sections using a weighting function to create gradual rise-fall times between sequential speech samples. The reverberation simulation software, based on the image method for simulating small-room acoustics (Allen & Berkley, 1979), calculated the impulse response of a simulated room. This was then convolved with the digitized speech sample to produce a reverberant version of the input signal. The combined reverberant + time-compressed stimuli were produced by first creating the time-compressed sentences and then convolving these sentences with the appropriate impulse response to simulate the reverberation. Subsequent to stimulus modification, all of the stimuli and the calibration tone were equated for RMS speech level. The modified stimuli were converted back into analog form and recorded on digital-audio tape (DAT).

A fixed time-compression ratio of 40% was used for the

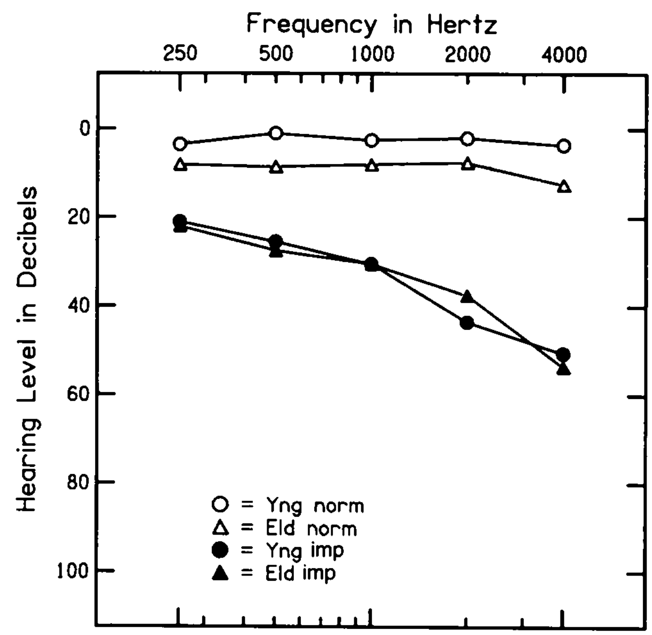

FIGURE 1. Mean audiograms of the four groups.

time-compressed stimuli, and a fixed reverberation time of 0.3 s was used for the reverberant speech stimuli. The combined condition used these degrees of distortion as well. These conditions were selected on the basis of previous testing indicating that these degrees of distortion produced an overall average of approximately 70% correct recognition in young and elderly listeners with hearing loss (Gordon-Salant & Fitzgibbons, 1993). This performance level was chosen in order to avoid floor effects that could obscure observation of further performance decrements associated with addition of a second form of stimulus distortion.

A background noise was used for some of the conditions, either as a single form of speech degradation or in combination with the temporal distortions of speech. This noise was the 12-talker babble of the R-SPIN test. The noise was presented at a fixed SNR of +16 dB, selected because this was the SNR that produced an average correct recognition performance score of 70% by listeners with hearing loss during previous testing (Gordon-Salant & Fitzgibbons, 1995).

Procedure

Seven conditions were presented to each participant. The first condition was the presentation of the undistorted LP-SPIN sentences in quiet. In three conditions, single forms of speech degradation were presented: the undistorted LP-SPIN sentences in the noise at +16 dB SNR, the LP-SPIN sentences distorted by 40% time compression, and the reverberant LP-SPIN sentences with a 0.3 s reverberation time. In addition, there were three conditions employing combined forms of speech distortion: the time-compressed sentences (40% time-compression ratio) presented in noise (+16 dB S/N ratio), the reverberant sentences (0.3 s reverberation time) presented in noise (+16 dB S/N ratio), and the combined time-compressed-reverberant sentences.

The seven listening conditions were presented in a randomized order to each participant. In addition, random assignment was made of SPIN list to listening condition.

During the experiments, the speech signal was played from a DAT recorder/player (SONY PCM 2500), routed to an amplifier (Crown D-75), attenuator (Hewlett-Packard 350D), audio mixer-amplifier (Colbourn S284), second attenuator (Hewlett-Packard 350D), and delivered to a single insert earphone (Etymotic ER-3A). In the noise conditions, the multitalker babble was played from a second channel of the DAT and was separately amplified, attenuated, and delivered to the audio mixer-amplifier. The speech signal was always presented at 90 dB SPL, as measured in a 2-cm^3 coupler. The level of the noise, when presented, was 74 dB SPL, as measured in the 2-cm^3 coupler. The signal and noise were delivered monaurally to the listener's better ear for listeners with hearing loss, and to the right ear for listeners with normal hearing.

The participant's task was to write the final word of each LP-SPIN sentence on an answer sheet. Participants were seated in a double-walled sound-attenuating booth during the experiments. All testing was completed within 2 hours.

Results

The mean percent-correct recognition scores of the four groups in each of the seven listening conditions are shown in Table 1. The percent-correct scores of the individual participants in each condition were converted to an equivalent SNR metric. The equivalent SNRs were derived by measuring the R-SPIN scores (undistorted, low-probability sentences presented at 90 dB SPL) of listeners with normal hearing at multiple SNRs, and then generating a performance curve relating percent correct to SNR using a cumulative logistic function of the form described by Equation 1:

$$PC = \frac{1}{1 + e^{-2\cdot\left(\frac{S/N-a}{b}\right)}} \qquad (1)$$

where S/N is the S/N ratio of the signal and noise condition in dB, and a and b are the intercept and slope parameters with derived values of 4.99 and 8.12, respectively. The fitted function was then used to convert the percent-correct scores from other participants in other speech conditions to the corresponding SNR that produced equivalent performance levels. On the asymptotic portion of the function, 22dB was selected as the S/N ratio that produced a perfect (100%) correct recognition score. The equivalent SNRs were used as the dependent variable for analysis of variance

TABLE 1. Mean percent-correct recognition scores (and standard deviations) of the four groups in the seven listening conditions.

	Participant group			
Condition	YNG NORM	ELD NORM	YNG IMP	ELD IMP
Undistorted - Q	98.8 (1.9)	98.8 (1.9)	86.8 (10.5)	88.4 (10.7)
Undistorted - N	92.8 (5.6)	88.8 (8.6)	72.4 (20.4)	67.2 (16.7)
Time-Comp. - Q	100.0 (0.0)	90.4 (6.8)	66.8 (23.1)	72.8 (15.6)
Reverberant - Q	89.6 (8.5)	84.4 (6.1)	77.6 (12.5)	74.8 (13.1)
Time-Comp. - N	78.4 (10.5)	63.2 (16.2)	56.8 (23.3)	42.4 (23.6)
Reverberant - N	79.6 (8.1)	70.8 (8.4)	66.8 (14.1)	57.2 (20.5)
Time-Comp. + Reverb.	69.6 (15.5)	44.8 (19.7)	37.2 (20.6)	26.0 (21.4)

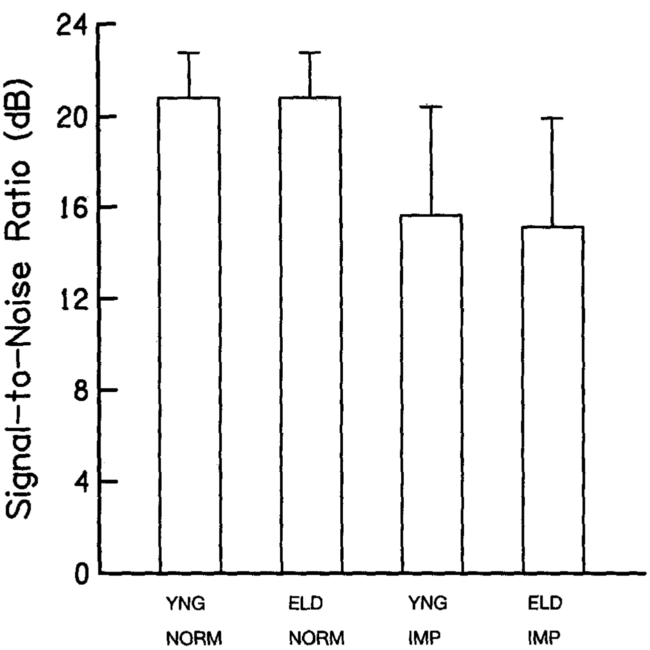

FIGURE 2. Mean equivalent SNRs of the four groups for undistorted speech presented in quiet.

procedures after determining that the assumption of homogeneity of variances was met.

The mean equivalent SNRs of the four groups for the undistorted SPIN sentences presented in quiet are shown in Figure 2. A one-way analysis of variance (ANOVA) showed a significant main effect of participant group ($F = 7.35$, $df = 3, 39$, $p < .01$). Multiple comparison tests (Student-Newman-Keuls) showed a significant difference ($p < .05$) between mean performance of the two groups with hearing loss compared to the two groups with normal hearing. Figure 2 indicates that the listeners with hearing loss exhibited lower equivalent SNRs, reflecting poorer performance, than listeners with normal hearing in the undistorted listening condition.

Performances of the four groups in the six conditions with single or multiple degradations are shown in Table 2. An analysis of covariance (ANCOVA) was used to evaluate the data, with the speech recognition score for undistorted speech as the covariate. This procedure was used in order to remove the systematic differences in speech recognition scores for undistorted speech among listeners with normal hearing and hearing loss. A split-plot factorial design was used with two between-subjects factors (age and hearing loss) and one within-subjects factor (distortion condition). Table 3 presents the resulting ANCOVA table. The table indicates that there were significant main effects of age, hearing, and condition, as well as significant interactions between the hearing and condition factors and the age, hearing, and condition factors.

TABLE 3. Summary of ANCOVA results of age, hearing, and condition effects and interactions.

Source of variation	*F*	*df*	*p*
Age	14.47	(1, 35)	.001
Hearing	7.53	(1, 35)	.010
Age × Hearing	1.50	(1, 35)	.229
Condition	78.47	(4, 144)	.000
Age × Condition	.81	(4, 144)	.541
Hearing × Condition	7.96	(4, 144)	.000
Age × Hearing × Condition	2.74	(4, 144)	.021

Subsequent analyses were conducted to determine the significance of factors contributing to the three-way interaction. Results of these analyses are shown in Table 4. Initially, age effects for the two hearing loss groups in each of the distortion conditions were assessed. Age effects were significant for listeners with normal hearing and hearing loss in the combined distortions involving time compression and noise, and time compression and reverberation. Age also exerted a significant influence among listeners with normal hearing for time-compressed speech presented in quiet. Thus, age effects were most prominent in conditions featuring some form of time compression. The age effects reflected lower (poorer) equivalent SNRs for the elderly listeners compared to the younger listeners.

Similar analyses were conducted to determine the conditions and age groups for which hearing loss exerted a significant influence. The effect of hearing loss was significant for both young and elderly listeners in the single-distortion conditions involving noise only and time compression only. Additionally, the effect of hearing loss was significant for younger participants in the combined time-

TABLE 2. Mean equivalent S/N ratios (and standard deviations) of the four participant groups in the six degraded conditions.

	Participant group			
Condition	YNG NORM	ELD NORM	YNG IMP	ELD IMP
Undistorted - N	16.2 (3.2)	14.5 (3.5)	10.2 (5.5)	8.4 (3.5)
Time-Comp. - Q	22.0 (0.0)	15.1 (4.0)	8.8 (5.3)	9.6 (3.4)
Reverberant - Q	15.2 (4.9)	12.2 (2.4)	10.7 (3.4)	10.1 (3.7)
Time-Comp. - N	10.9 (3.3)	7.6 (3.4)	6.7 (5.0)	3.5 (4.6)
Reverberant - N	10.9 (2.3)	8.8 (1.7)	8.4 (3.8)	6.4 (3.9)
Time-Comp. + Reverb.	8.6 (2.9)	4.2 (3.6)	2.6 (3.9)	−0.5 (5.0)

TABLE 4. *F* values for simple-simple main effects analyses of age × hearing × condition interaction.

Source	*F*	*df*	*p*
Age with Norm Hrg × Noise	1.31	(1, 215)	.25
Age with Hrg Imp × Noise	1.75	(1, 215)	.19
Age with Norm Hrg × TC-Q	21.21	(1, 215)	.00
Age with Hrg Imp × TC-Q	.16	(1, 215)	.69
Age with Norm Hrg × RT-Q	3.81	(1, 215)	.05
Age with Hrg Imp × RT-Q	.27	(1, 215)	.60
Age with Norm Hrg × TC-N	4.81	(1, 215)	.03
Age with Hrg Imp × TC-N	5.02	(1, 215)	.03
Age with Norm Hrg × RT-N	1.93	(1, 215)	.17
Age with Hrg Imp × RT-N	2.11	(1, 215)	.15
Age with Norm Hrg × TC-RT	8.58	(1, 215)	.00
Age with Hrg Imp × TC-RT	4.68	(1, 215)	.03
Hearing with ELD × Noise	5.55	(1, 215)	.02
Hearing with YNG × Noise	4.80	(1, 215)	.03
Hearing with ELD × TC-Q	3.97	(1, 215)	.04
Hearing with YNG × TC-Q	45.49	(1, 215)	.00
Hearing with ELD × RT-Q	.03	(1, 215)	.86
Hearing with YNG × RT-Q	1.47	(1, 215)	.23
Hearing with ELD × TC-N	1.14	(1, 215)	.29
Hearing with YNG × TC-N	1.03	(1, 215)	.31
Hearing with ELD × RT-N	.00	(1, 215)	.98
Hearing with YNG × RT-N	.01	(1, 215)	.93
Hearing with ELD × TC-RT	2.01	(1, 215)	.16
Hearing with YNG × TC-RT	4.66	(1, 215)	.03
Cond. with ELD × Norm Hrg	23.86	(5, 180)	.00
Cond. with YNG × Norm Hrg	30.70	(5, 180)	.00
Cond. with ELD × Hrg Imp	21.67	(5, 180)	.00
Cond. with YNG × Hrg Imp	11.26	(5, 180)	.00

compressed + reverberant speech condition. Listeners with hearing loss obtained lower equivalent SNRs than listeners with normal hearing in these conditions, reflecting poorer performance for the participants with hearing loss than for participants with normal hearing.

Finally, the effect of listening condition was assessed for both age groups and hearing groups. Listening condition was significant for both elderly and younger listeners and for participants with and without hearing loss. Mean performance across the six different distortion conditions, shown separately for each group in Figure 3, was compared using the Student-Newman-Keuls procedure. In the figure, conditions producing equivalent scores share a common shading. It appears that the different groups varied somewhat in the specific patterns of performance across the different conditions. Nevertheless, poorest performance was found for all groups in the combined time-compressed + reverberant speech condition; and best performance generally was found in the time-compressed speech condition in quiet, the reverberant speech condition in quiet, and the undistorted speech condition in noise.

Discussion

The main hypothesis explored in this study was that elderly listeners experience excessive difficulty compared to younger listeners in recognizing multiply degraded speech. The results partially supported the experimental hypothesis. Elderly listeners with normal hearing and with hearing loss exhibited poorer performance than younger listeners with comparable hearing sensitivity in two of the three conditions featuring multiple degradations (the time-compressed speech + noise condition and the time-compressed + reverberant speech condition). Among listeners with normal hearing, elderly listeners also performed more poorly than the younger listeners in the time-compressed speech condition presented in quiet. This pattern of results is consistent with earlier findings that age effects appear in mildly difficult conditions for listeners with normal hearing but appear only in more degraded conditions for listeners with hearing loss (Gordon-Salant & Fitzgibbons, 1995). The previous study also showed that age effects were exaggerated in all conditions involving time compression of speech, a finding that is replicated in the present investigation. Time-compression techniques increase the rate of speech without producing spectral distortion. Thus, the current results support the notion that an older person's ability to decode excessively rapid fluctuations in the temporal waveform may be limited. This may be one manifestation of a global slowing of processing associated with the aging process, as described by numerous researchers (Birren, Woods, & Williams, 1980; Salthouse, 1980; Stine, Wingfield, & Poon, 1986; Wingfield, Poon, Lombardi, & Lowe, 1985).

The observed age effects are somewhat different from those reported by other investigators. Harris and Reitz (1985) and Helfer and Wilber (1990) reported that elderly listeners with normal hearing showed poorer recognition performance than younger listeners with normal hearing for reverberant speech presented in noise. Numerous methodological differences exist between these previous studies and the current study, including the type of stimuli, the type of noise, and the mode of presentation (binaural vs. monaural). The most important methodological differences, however, are the hearing sensitivity differences between the younger and older "normally hearing" groups, coupled with a speech presentation level of 40 or 50 dB SL re SRT employed in the earlier studies. These presentation levels may not have been sufficient to sample the maximum recognition ability of the elderly listeners with minimal hearing losses (Kamm, Morgan, & Dirks, 1983).

Hearing loss affected listener performance. Listeners with hearing loss revealed lower recognition performance than listeners with normal hearing in the undistorted speech condition presented in quiet. In addition, the effect of hearing impairment was significant in the time-compressed speech condition in quiet and the undistorted speech condition in noise, despite the fact that analyses of covariance were used to remove systematic differences in recognition of undistorted speech in quiet for listeners with and without hearing loss. These findings underscore the major influence of hearing loss on speech recognition tasks and the need to

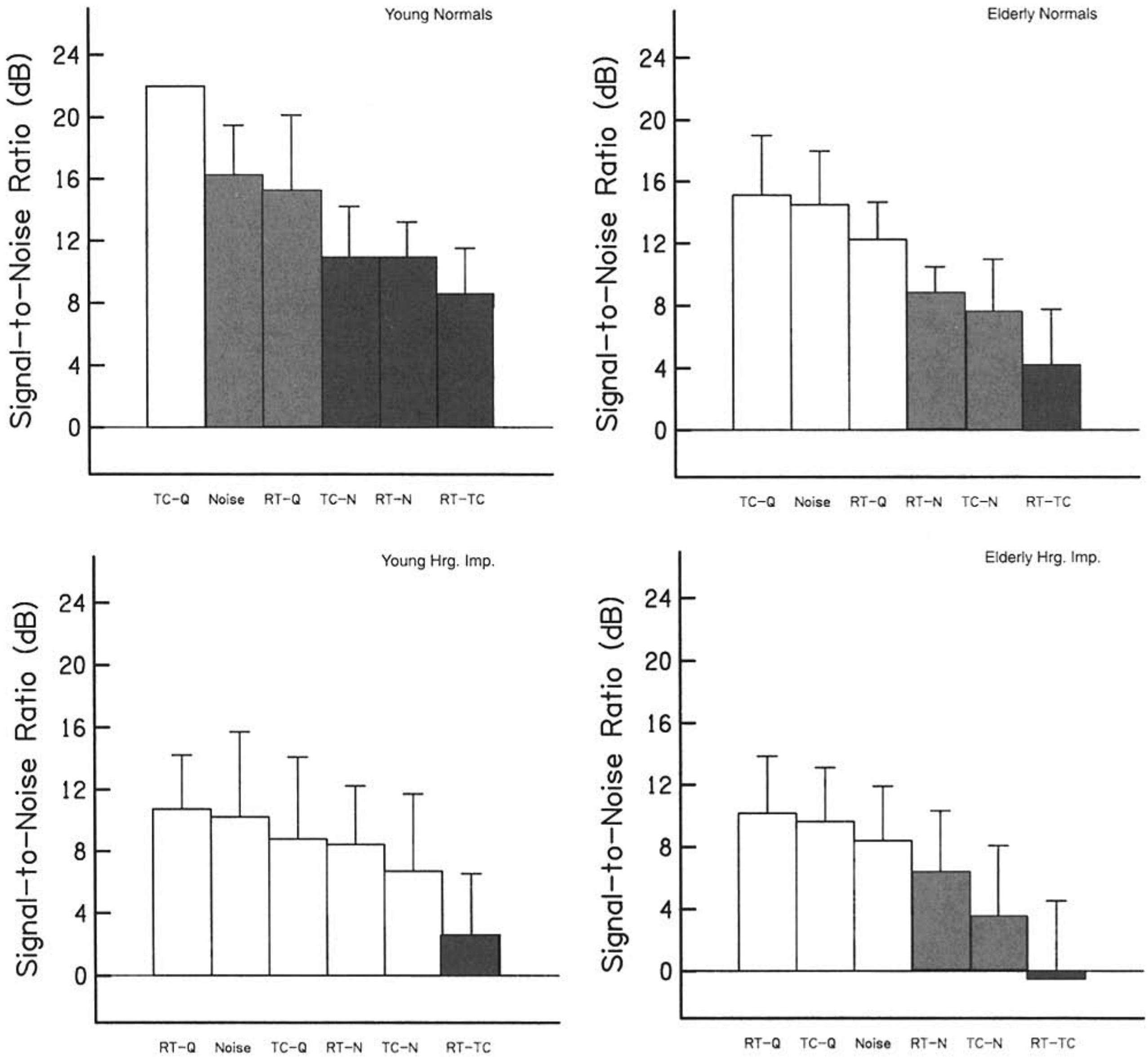

FIGURE 3. Mean equivalent SNRs for each of the four groups across the six degraded listening conditions.

separate the independent contribution of hearing loss from the contribution of age on these measures.

The equivalent SNR metric permitted a comparison of the relative difficulty of the different forms of speech degradation. Figure 3 clearly shows that the single forms of speech degradation were easiest for all groups, whereas the condition combining time compression and reverberation was the most difficult for all groups. The conditions in which the distorted speech signals were presented in noise were moderately difficult for all groups. Thus, the various single forms of speech degradation (noise, time compression, and reverberation) produced roughly equivalent scores for three of the four groups. This outcome confirmed that the specific degrees of distortion selected for each distortion type did produce approximately the same level of performance within a listener group, as intended. Nevertheless, the combination of time-compressed speech with reverberation produced deficits for all groups that exceeded those for the combination of either of these types of distorted speech with noise. The exact reason for this finding is unknown, but the net effect of combining time compression and reverberation may be to create unusual temporal or spectral masking of the brief speech cues that occur in the rapid sequence of time-compressed speech.

The severe deterioration in speech recognition performance with various combinations of distorted speech has also been reported by Harris (1960). Listeners with normal hearing were evaluated in a variety of *combined* distortion conditions (as opposed to *single* distortion conditions) that included reverberation, interruption, fast speech, nasal speech, and "eating" speech. Harris recommended that a battery of distortions both singly and in pairs should be presented to the client with hearing loss in order to assess accurately the extent of the person's communication difficulty in everyday listening situations. The results of the present study confirm the value of this approach, because it appears that especially for the elderly participants evaluated performance in the combined degradation conditions was considerably poorer than performance in the single forms of degradation.

The principal finding of this investigation was that age effects do occur on speech recognition tasks featuring multiple forms of stimulus degradation in listeners with normal hearing and mild-to-moderate sloping sensorineural hearing loss. This is particularly evident when the stimulus distortion involves some form of time compression of speech. The findings show reductions in equivalent SNR, reflecting poorer recognition performance, that become exaggerated in elderly listeners for multiple forms of stimulus distortion. To the extent that the equivalent SNR metric reflects internal stimulus state, it appears that elderly listeners operate with a reduced functional SNR in listening conditions that feature multiple degradations of the speech signal. Recognition of time-compressed speech also appears to be particularly difficult for elderly listeners, which suggests that an age-related slowing affects perceptual processing on these speech recognition tasks.

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