Profile of Auditory Temporal Processing in Older Listeners

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This investigation examined age-related performance differences on a range of speech and nonspeech measures involving temporal manipulation of acoustic signals and variation of stimulus complexity. The goal was to identify a subset of temporally mediated measures that effectively distinguishes the performance patterns of younger and older listeners, with and without hearing loss. The nonspeech measures included duration discrimination for simple tones and gaps, duration discrimination for tones and gaps embedded within complex sequences, and discrimination of temporal order. The speech measures were undistorted speech, time-compressed speech, reverberant speech, and combined time-compressed + reverberant speech. All speech measures were presented both in quiet and in noise. Strong age effects were observed for the nonspeech measures, particularly in the more complex stimulus conditions. Additionally, age effects were observed for all time-compressed speech conditions and some reverberant speech conditions, in both quiet and noise. Effects of hearing loss were observed also for the speech measures only. Discriminant function analysis derived a formula, based on a subset of these measures, for classifying individuals according to temporal performance consistent with age and hearing loss categories. The most important measures to accomplish this goal involved conditions featuring temporal manipulations of complex speech and nonspeech signals.

KEY WORDS: aging, temporal processing, speech perception, psychoacoustics, hearing loss

A decade ago, the Committee on Hearing, Bioacoustics, and Biomechanics (CHABA) published a seminal report on speech understanding and aging (CHABA, 1988). Among its recommendations for future research, the Committee suggested that a high priority for research is an investigation of the interaction of central and peripheral mechanisms required for speech understanding and how these factors, both individually and in combination, vary with age. Since that time, a considerable research base has emerged, examining factors that contribute to the speech understanding problems of older people. In addition to the obvious attenuation problems of peripheral hearing loss, one factor that appears to be compromised in older people is auditory temporal processing (e.g., Divenyi & Haupt, 1997; Fitzgibbons & Gordon-Salant, 1995, 1998; Humes & Christoperson, 1991). Strong evidence for auditory temporal processing problems in older people derives from a wide range of speech perception experiments and psychoacoustic experiments, particularly those manipulating the complexity of the signal (e.g., Fitzgibbons & Gordon-Salant, 1995; Gordon-Salant & Fitzgibbons, 1995).

One type of evidence to support the notion of an auditory temporal processing deficit comes from speech recognition experiments using temporally degraded speech. Rapid speech, in the form of natural alterations

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in speaking rate or through time-compression, has long been known to be difficult for older listeners to perceive (Bergman et al., 1976; Blumenfeld, Bergman, & Milner, 1969; Konkle, Beasley, & Bess, 1977; Letowski & Poch, 1995, 1996; Schmitt & McCroskey, 1981; Sticht & Gray, 1969; Vaughan & Letowski, 1997; Wingfield, Poon, Lombardi, & Lowe, 1985). The age effect has been shown for stimuli varying in speech rate (Gordon-Salant & Fitzgibbons, 1993; Konkle et al., 1977; Letowski & Poch, 1996; Vaughan & Letowski, 1997; Wingfield et al., 1985), type of speech material (Vaughan & Letowski, 1997; Wingfield et al.,1985), and discard interval (Letowski & Poch, 1995, 1996). The most sizeable age effects are observed for sentence-length stimuli with minimal syntactic and contextual cues presented at speech rates of twice the normal speech rate, or faster (Gordon-Salant & Fitzgibbons, 1993; Wingfield et al., 1985). One hypothesis to explain the older listener's difficulty in recalling speech stimuli of increasing rate is that there is an age-related decline in the rate of information processing (Salthouse, 1985).

Another form of temporal waveform distortion, reverberant speech, is also sensitive to age-related processing differences (Divenyi & Haupt, 1997; Gordon-Salant & Fitzgibbons, 1993; Helfer & Wilber, 1990; Nabelek & Robinson, 1982). Older listeners show poorer recognition of reverberant speech compared to younger listeners over a range of reverberation times and speech materials (Gordon-Salant & Fitzgibbons, 1993; Harris & Reitz, 1985; Helfer & Wilber, 1990; Nabelek & Robinson, 1982). Although the presence of hearing loss has a considerable effect on a listener's ability to recognize temporally distorted speech (both time-compressed and reverberant speech), a listener's age has a significant, independent, and additive effect to the attenuation imposed by hearing loss (Gordon-Salant & Fitzgibbons, 1993). Moreover, older listeners with normal hearing exhibit poorer performance than younger listeners with normal hearing on these temporally degraded speech measures (Gordon-Salant & Fitzgibbons, 1993). The convergent findings of a robust age effect for recognition of both rapid speech and reverberant speech suggest that older listeners have difficulty following the rapidly changing acoustic elements in a speech sequence, which is revealed when those rapidly changing acoustic elements are impoverished by the imposed temporal distortions. The effect of hearing loss indicates that peripheral mechanisms influence the processing of temporally altered speech cues; the independent age effect additionally implicates deficits in perceptual processing mechanisms beyond the auditory periphery.

Older listeners are also at a disadvantage, compared to younger listeners, for recognizing speech signals featuring multiple forms of distortion when at least one form of distortion includes temporally distorted speech. Indeed, age effects become exaggerated in more complex conditions of multiple speech distortions; such conditions are thought to challenge more central, perceptual processing capabilities (Gordon-Salant & Fitzgibbons, 1995; Harris & Reitz, 1985) because the listener must extract the target signal and ignore irrelevant information. Time compression of speech, when combined with other forms of distortion, appears to produce more prominent age effects than reverberant speech (Gordon-Salant & Fitzgibbons, 1995). This finding in particular is consistent with the hypothesis that older listeners have deficits in following rapid alterations in the speech waveform.

Supporting evidence for diminished temporal processing among older listeners also comes from psychophysical measures collected with nonspeech stimuli. Some of the investigations used simple tonal or noise signals and reported age-related difficulties for tasks such as temporal gap resolution (Schneider, Pichora-Fuller, Kowalchuk, & Lamb, 1994; Snell, 1997) or duration discrimination (Abel, Krever, & Alberti, 1990; Fitzgibbons & Gordon-Salant, 1994). Other studies used more complex stimuli or increased task demands and revealed pronounced differences in temporal processing abilities between younger and older listeners. Thus, age-related difficulties with duration discrimination can be exaggerated if a simple target stimulus is embedded within a sequence of sounds that features varying degrees of stimulus complexity (Fitzgibbons & Gordon-Salant, 1995). Additionally, older listeners tend to have difficulty with auditory sequencing tasks that require discrimination or recognition of stimulus temporal order within serial patterns (Fitzgibbons & Gordon-Salant, 1998; Humes & Christopherson, 1991; Trainor & Trehub, 1989). Unlike speech recognition data, results for many of the psychoacoustic temporal processing tasks show little or no influence of peripheral hearing loss in the older listeners. This outcome, in conjunction with the observed prominent effects of stimulus complexity and task demands, indicates the likelihood of age-related dysfunction at central, perceptual stages of auditory processing.

While congruent findings from different kinds of experimental paradigms have emerged for an auditory temporal processing deficit, a single study has yet to examine older listeners' performance on a range of temporal processing measures, speech and nonspeech, to specify which measures are most sensitive to effects of auditory aging. There are several potential merits for examining older listeners' performance on an array of auditory temporal processing measures. First, measures that reveal the most prominent age-related deficits can be adapted for clinical use to identify older individuals who might require auditory training for temporal cues (e.g., Merzenich et al., 1996) or who might benefit from signal processing devices aimed at enhancing temporal cues (e.g., Nejime, Aritsuka, Imamura, Ifukube, & Matsushima, 1996; Picheny, Durlach, & Braida, 1985). Second, examination of older listeners' performance on a range of simple and complex listening tasks could serve to identify age-related profiles of temporal processing that reveal relative influences of peripheral, central, and cognitive processing capabilities. There are three interrelated purposes of the present study: (1) to examine older and younger listeners' performance on a series of temporally based speech and nonspeech tests that have proven effective in revealing age-related performance differences in previous stages of our investigation (Fitzgibbons & Gordon-Salant, 1994, 1995, 1998; Gordon-Salant & Fitzgibbons, 1993, 1995), (2) to select a subset of these measures that are most effective in discriminating listeners on the basis of age and hearing status, and (3) to analyze individual performance of listeners on these tasks to determine the adequacy of the selected temporal processing measures for accurately classifying listeners into respective groups.

Method

Participants

The basic experimental paradigm evaluates and compares the performance of younger and older listeners with normal hearing and with hearing loss, in order to clarify the contributions of hearing loss and age to the performance measures. As a consequence, there were four groups of participants, each comprising 10 individuals. The "young normal" group included individuals, aged 18–40 years, with pure tone thresholds within the normal range (≤15 dB HL, re: ANSI, 1996, from 250–4000 Hz). The "older normal" group included individuals, aged 65–76 years, with hearing sensitivity within this same normal range. The "young hearing loss" group was comprised of listeners (18–40 years) with mild-to-moderate, sloping sensorineural hearing losses. Finally, the "older hearing loss" group included older listeners (65–76 years) with mild-to-moderate, sloping sensorineural hearing losses. Pairs of listeners from the two hearing loss groups were matched on the basis of pure tone thresholds across the audiometric frequency range (±10 dB). Additional audiometric criteria for all participants were good-to-excellent monosyllabic word recognition scores (>80%) in quiet, normal tympanograms (normal shape, pressure peak, peak admittance, equivalent volume), acoustic reflexes elicited within the 90th percentile range re: the pure-tone threshold at 500, 1000, and 2000 Hz (Silman & Gelfand, 1981), and the absence of acoustic reflex adaptation. These criteria ensured that the participants had normal middle ear function and, in the case of participants with hearing loss, a primarily cochlear lesion site. There were no systematic differences in results of screening measures for the younger and older listeners.

Participants were all native speakers of English with at least a high school education. Additionally, participants were in good general health, possessed sufficient motor skills to respond to the stimuli in a timely manner, and passed a basic screening test for cognitive awareness (Pfeiffer, 1975). None of the listeners participated in previous stages of the investigation.

Speech Materials and Procedures

The basic speech materials were the 25 low-probability sentences from each of the eight lists of the Revised Speech Perception in Noise Test (LP–SPIN; Bilger, Nuetzel, Rabinowitz, & Rzeckzkowski, 1984). These stimuli were digitized onto a laboratory computer at a 10-kHz sampling rate (Gateway 2000 486 computer) and processed through various algorithms to create the temporal distortions. (For complete descriptions of the processing algorithms, see Gordon-Salant & Fitzgibbons, 1993.) Six forms of temporal manipulations were implemented with all of the sentences: no modification (undistorted), time compression with 50% time compression ratio (TCR), time compression with 60% TCR, reverberation with 0.4-s reverberation time (RT), reverberation with 0.6-s RT, and combined time compression (40% TCR) and reverberation (0.3-s RT). The distortion conditions selected were those that showed the most prominent age-related differences in previous stages of investigation using single forms of temporal manipulation (Gordon-Salant & Fitzgibbons, 1993) and combined forms of temporal and noise manipulation (Gordon-Salant & Fitzgibbons, 1995). Following the digital processing to create these various temporal distortions, the stimuli were equated in RMS level, converted to analog form (10-kHz rate), low-pass filtered (5-kHz nominal cutoff, 104 dB/octave attenuation rate), and recorded onto one channel of digital-audio tape (DAT; SONY PCM-2500A). Each stimulus sentence was preceded by a carrier phrase ("Number x"). The interstimulus interval was 8 s. The 12-talker babble from the R–SPIN materials served as a noise background and was recorded directly onto the second channel of the DAT, without any signal modifications.

There were 12 speech conditions, corresponding to each of the six forms of temporal distortions presented both in quiet and in noise. The baseline condition consisted of the undistorted LP–SPIN sentences presented in quiet. Five conditions featured a single form of distortion: undistorted speech in noise, time-compressed speech at 50% TCR in quiet, time-compressed speech at 60% TCR in quiet, reverberant speech at 0.4-s RT, and reverberant speech at 0.6-s RT. Another five conditions included two forms of distortion: time-compressed speech in noise (50% TCR and 60% TCR), reverberant speech in noise (0.4-s RT and 0.6-s RT), and time-compressed + reverberant speech in quiet (40% TCR + 0.3-s RT). One condition combined three forms of distortion and consisted of time-compressed + reverberant speech presented in noise (40% TCR + 0.3-s RT + noise).

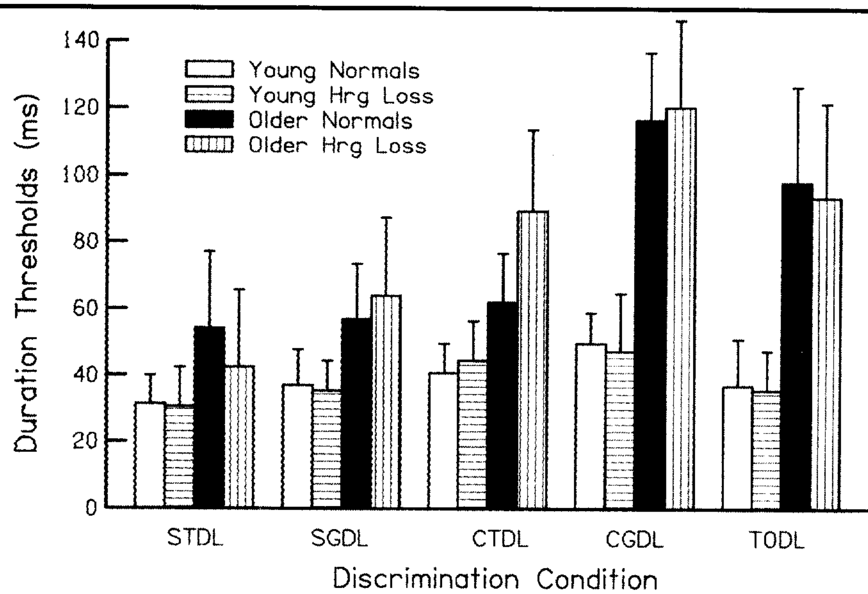
The 12 test conditions were preceded by presentation of an audiotape that included several samples of each form of speech stimulus. This tape was intended to familiarize the listeners with the various stimulus distortions and the response procedures. During formal testing, there was random assignment of test list to test condition, and each of the conditions was presented in random order across participants. The speech stimuli and noise were played from separate channels of the DAT, amplified (Crown D-75), attenuated (Hewlett-Packard 350D), mixed (Colbourn audio-mixer amplifier, S82-24), and delivered to a single insert earphone (Etymotic ER-3A). The test ear was the right ear, for listeners with normal hearing, and, for listeners with hearing loss, it was the ear with better word recognition. The stimulus presentation level was 90 dB SPL. For the quiet conditions, the noise channel was disconnected. For the noise conditions, the signal-to-noise ratio was +12 dB. This signal-to-noise ratio was selected on the basis of previous observations (Gordon-Salant & Fitzgibbons, 1995) that this level likely would avoid floor and ceiling effects across the range of distortion conditions for the four listener groups. The listener's task was to write the last word of each sentence presented. All testing was conducted in a double-walled sound attenuating chamber.

Psychoacoustic Measures

The psychophysical testing included five selected conditions that revealed consistent age-related performance differences in the earlier investigations using simple and complex stimuli, including sequential stimuli (Fitzgibbons & Gordon-Salant, 1995, 1998). Each condition examined listeners' sensitivity to changes in stimulus duration for tonal signals at or near 4000 Hz, a region of maximum sensitivity loss for the listeners with hearing impairment. All tonal stimuli for the discrimination experiments were generated using inverse fast Fourier transform (FFT) procedures with a digital signal processing board (Tucker-Davis Technologies, AP2) and a 16-bit digital-to-analog (D/A) converter (Tucker-Davis Technologies, DD1, 20-kHz sampling rate) that was followed by low-pass filtering (Frequency Devices 901F; 6-kHz cutoff, 90 dB/octave). Two of the conditions used simple stimuli and served as baseline measures. One of the conditions (simple tonal difference limen, STDL) measured the difference limen (DL) for increments in the duration of a 4-kHz tone burst of 250-ms standard duration (5-ms rise/fall times). The other condition (simple gap discrimination difference limen, SGDL) measured the duration DL for a silent interval, or gap, of 250 ms that was inserted between two successive 4-kHz tone bursts, each 250 ms in duration. Other conditions examined duration discrimination within the context of sentence-length complex stimuli that consisted of sequences of five temporally contiguous 250-ms pure tones (5-ms rise/fall times), with frequencies that spanned a one-third octave range centered geometrically about 4000 Hz. With these stimuli, one condition (complex tonal difference limen, CTDL) measured the duration DL for a 4-kHz tone burst that served as the embedded target component within each tonal sequence. For another condition, complex gap difference limen (CGDL), the duration DL was measured for a 250-ms temporal gap inserted within tone sequences; the gap was created by replacing the 4-kHz component by a silent interval of equal duration. The final condition assessed listeners' ability to discriminate differences in the temporal ordering of tones within a sequence. The stimuli for this condition, temporal order difference limen (TODL), were sequences of three temporally contiguous tones of equal duration (1-ms rise/fall times) that also spanned a one-third octave region centered at 4000 Hz. For this condition, a threshold was measured by simultaneously varying the duration of all tones in a sequence to determine the minimum component durations that permitted accurate discrimination of differences in tonal temporal order.

The duration thresholds for each of the discrimination conditions were measured using a three-interval, cued, two-alternative, force-choice procedure with an adaptive rule for duration changes that converged on a discrimination performance level of 70.7% correct (Levitt, 1971). Each discrimination trial included three listening intervals, with a standard stimulus always presented first, followed by a random ordering of the standard and comparison stimuli in the second and third intervals. The listener's response was simply to select which interval, two or three, sounded different from the first, regardless of the discrimination condition or stimulus type. For the baseline conditions, STDL and SGDL, the standard and comparison stimuli differed only by the duration of the 4-kHz tone or gap, respectively. Similarly, for the duration DLs measured with tonal sequences in the CTDL and CGDL conditions, the standard and comparison sequences of a listening trial differed only by the duration of the embedded target component, tone or gap, respectively. Additionally, for each of these complex conditions, the location of the embedded target component, tone or gap, was made to vary randomly among the second, third, or fourth sequence component locations across trials in a listening block. For temporal-order discrimination limen (TODL)

Figure 1. Mean duration thresholds and standard deviations of the four listener groups in the five non-speech discrimination conditions. (STDL = simple tonal difference limen; SGDL = simple gap difference limen; CTDL = complex tonal difference limen; CGDL = complex gap difference limen; TODL = temporal order difference limen.)



the standard and comparison stimulus sequences of a given trial were equal in duration but featured different permutations of tone order that changed randomly across listening trials.

Each discrimination condition was run in 50-trial listening blocks with a threshold estimate for each block calculated as an average of the final 10 reversal point stimulus values. Each listener was practiced on 6–8 trial blocks for each condition prior to data collection. Final thresholds for each condition were based on an average of four trial-block estimates for each listener. As with the speech measures, the stimuli were presented monaurally to the designated test ear through an insert earphone (Etymotic ER-3A). Presentation level was 85 dB SPL for all conditions. The order of the five psychoacoustic measures was randomized across subjects. Additionally, half of the participants were tested with the psychoacoustic measures first; the other half were tested with the speech measures first. All of the testing was conducted at the Hearing Science Laboratory at the University of Maryland. The same testing procedures were applied for all listener groups. The entire procedure was completed in approximately 12 hours, scheduled in two-hour sessions. Participants were given frequent breaks during testing to minimize fatigue.

Results

The first level of analysis entailed comparing the group means separately for the psychoacoustic measures and the speech measures. Figure 1 presents the mean discrimination thresholds (DLs) and standard deviations of the four participant groups for the five psychoacoustic measures. Four of these conditions involved duration discrimination for 250-ms tones or gaps presented as isolated targets or embedded as components of tonal sequences. The mean DLs for these four conditions are converted to Weber fractions (DL/250) and displayed in Table 1 for each group of listeners. Individual threshold data for all five conditions were submitted for a repeated measures analysis of variance (ANOVA) with two between-subjects factors (age, hearing status) and one within-subjects factor (condition). Because of the multiple comparisons evaluated, an alpha level of .01 was chosen for results to be considered significant. The ANOVA showed significant main effects

Table 1. Average group Weber ratios (DL/250) for the duration discrimination conditions.

	Condition			
	STDL	**SGDL**	**CTDL**	**CGDL**
Young normals	.13	.15	.16	.20
Young hearing loss	.12	.14	.18	.19
Older normals	.22	.23	.25	.47
Older hearing loss	.17	.26	.36	.48

Note. STDL = simple tonal difference limen. SGDL = simple gap difference limen. CTDL = complex tonal difference limen. CGDL = complex gap difference limen.

of condition [$F(4, 144) = 43.14, p < .01$] and age [$F(1, 36) = 131.76, p < .01$], and a significant interaction between condition and age [$F(4, 144) = 19.63, p < .01$]. The effect of hearing status was not significant [$F(1, 36) = .306, p > .01$]. Similarly, none of the interactions involving the hearing status effect was significant ($p > .01$). Simple main-effects analysis of the Condition × Age interaction showed that the effect of age was significant for all conditions ($p < .01$), but the magnitude of the age effect was substantially greater in the conditions that used complex tone sequences than in the conditions that used simple tone or gap stimuli. Both younger and older listeners had more difficulty on the discrimination tasks involving complex sequences than on the corresponding baseline conditions with simple stimuli. In all conditions, the age effect reflected poorer discrimination performance of the older participants compared to the younger participants.

Correct identification scores on the speech measures were analyzed separately for the conditions presented in quiet and noise. The mean percent correct identification scores (and standard deviations) in the quiet conditions for the four subject groups are shown in Figure 2; scores in the noise conditions are shown in Figure 3. Prior to conducting the statistical analyses, the percent correct scores were transformed using the arcsine transformation, which is recommended when the distribution of scores has a binomial form and the means and variances are proportional (Kirk, 1995). Results of the repeated measures ANOVA for the speech scores obtained in quiet revealed significant main effects of age [$F(1, 36) = 6.36, p < .01$], hearing status [$F(1, 36) = 21.34, p < .01$], and condition [$F(5, 180) = 138.37, p < .01$]. There were also significant interactions between condition and age [$F(5, 180) = 3.92, p < .01$] and condition and hearing status [$F(5, 180) = 3.20, p < .01$]. Simple main-effects analysis of the Condition × Age interaction, of particular interest in this report, is attributed to the absence of age effects for two conditions: undistorted speech and reverberant speech at 0.4-s RT ($p > .01$). Age effects in the remaining conditions reflected poorer performance by the older listeners compared to the younger listeners.

The ANOVA conducted on the correct identification scores obtained in the noise conditions showed significant main effects of age [$F(1, 36) = 7.87, p < .01$], hearing status [$F(1, 36) = 12.71, p < .01$], and condition [$F(5, 180) = 131.26, p < .01$]. None of the interactions between these main effects was significant ($p > .01$). Older listeners performed more poorly than younger listeners in all noise conditions. In addition, listeners with hearing loss performed more poorly than listeners with normal hearing.

The second approach to data analysis was to identify a selected set of the speech and nonspeech measures that most effectively distinguishes the temporal processing

Figure 2. Mean percent correct recognition scores (and standard deviations) of the four listener groups in the six speech conditions presented in quiet. (Und = undistorted speech; TC50 = time-compressed speech with 50% TCR; TC60 = time-compressed speech with 60% TCR; RT.4 = reverberant speech with 0.4-s RT; RT.6 = reverberant speech with 0.6-s RT; TC40+RT.3 = time- compressed speech with 40% TCR combined with reverberant speech with 0.3-s RT.)

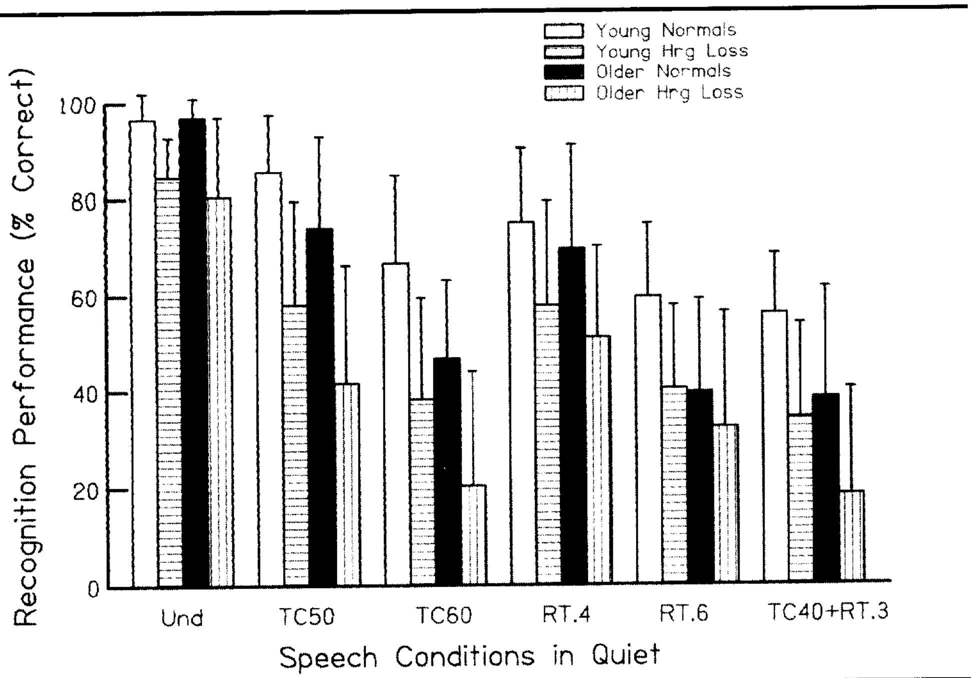
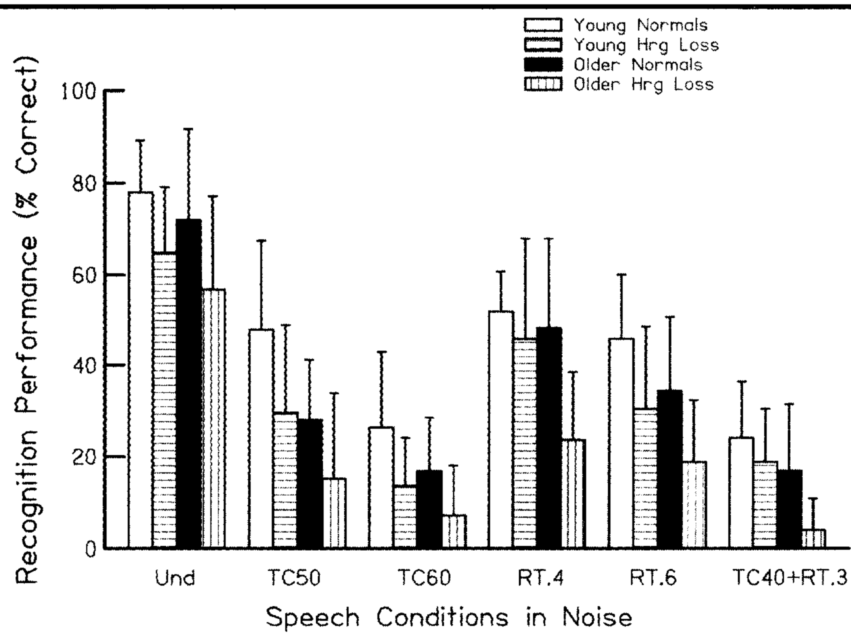


Figure 3. Mean percent correct recognition scores (and standard deviations) of the four listener groups in the six speech conditions presented in noise. (Und = undistorted speech; TC50 = time-compressed speech with 50% TCR; TC60 = time-compressed speech with 60% TCR; RT.4 = reverberant speech with 0.4-s RT; RT.6 = reverberant speech with 0.6-s RT; TC40+RT.3 = time-compressed speech with 40% TCR combined with reverberant speech with 0.3-s RT.)



performance of the four participant groups. Discriminant function analysis is a multivariate analysis technique that attempts to differentiate groups of persons on the basis of measures obtained from the same set of variables (Bennett & Bowers, 1976). The discriminant function consists of a set of weights, one for each variable, that maximizes the differences in performance for each group. Discriminant function scores for each group are calculated by multiplying the means of each variable by their corresponding weights and summing these products. The significance of the discriminant function indicates whether or not the discriminant function derived in this manner can significantly distinguish between the groups. In addition, the error rate for accurate classification of individuals into a particular group can be determined by calculating the individual's discriminant function score and assigning that individual to a group on the basis of a predetermined performance cutoff for group membership.

An initial discriminant function analysis was conducted for all of the variables entered simultaneously into the equation, as recommended by Lachin and Schachter (1976), using SPSS 7.5 for Windows. Three canonical discriminant functions were derived that were significant, accounting for 100% of the cumulative variance. However, an examination of the weights for each variable indicated that many of the weights were low and did not contribute significantly to the discriminant function. According to Bennett and Bowers (1976), variables should be eliminated whose weights do not appear important in discriminating between the groups. Subsequently, efforts were made to minimize the number of variables to derive a more informative set of discriminant functions.

Several strategies were employed for reducing the full set of variables. First, because the weights and their corresponding variables can only be interpreted when the correlation between variables is not high, variables were removed if they were highly intercorrelated (>.7; Bennett & Bowers, 1976). Second, variables that did not contribute significantly to the initial discriminant function were removed. Third, variables were removed on the basis of minimizing the increase in the conditional risk—probability of misclassification (McKay, 1976; McLachlan, 1976). The final reduced set of variables consisted of four speech measures (undistorted speech in quiet, time-compressed speech at 50% TCR in noise, reverberant + time-compressed speech in quiet, and reverberant + time-compressed speech in noise) and four psychoacoustic measures (simple gap DL, complex tone DL, complex gap DL, and temporal order DL).

The final discriminant analysis derived three canonical discriminant functions; Wilks's lambda test of significance confirmed that these three functions were significant ($\Lambda(24) = .042$, $p < .01$). The weights (standardized canonical discriminant function coefficients) for each function associated with each variable are shown in Table 2. The corresponding structure matrix, shown in

Table 3, indicates the pooled within-groups correlations between discriminating variables and standardized canonical discriminant functions. An examination of this structure matrix for the three canonical discriminant functions indicates that the first function (accounting for 86.6% of the variance) is associated with performance on two psychoacoustic measures: complex gap DL and temporal order DL. The second discriminant function accounts for an additional 10.9% of the variance in performance scores and is attributed to performance on three speech recognition measures (undistorted speech in quiet, combined time-compressed + reverberant speech in quiet and in noise) and one psychoacoustic measure (complex tone DL). The third discriminant function was associated exclusively with recognition of time-compressed speech (TCR = 50%) in noise, and accounted for an additional 2.5% of the variance in performance.

Each individual's score on each discriminant function was calculated by multiplying each standardized canonical discriminant function coefficient by the individual's performance on each of the eight associated measures, and summing these products. The mean scores for each group on the two discriminant functions that accounted for the majority of the variance are shown in Figure 4. It is clear from the figure that the first discriminant function separates the two younger groups from the two older groups, whereas the second function separates the two groups with hearing loss from the two groups with normal hearing.

The discriminant analysis also derived casewise statistics indicating the accuracy of the classification of participants on the basis of individual discriminant function scores. An overall correct classification rate of 90% was observed. Errors in classification involved predicting group membership in the hearing loss groups for 2 individuals with normal hearing (1 young participant and 1 older participant), and in the normal hearing groups for 2 individuals with hearing loss (1 young participant and 1 older participant). There were no errors in classification on the basis of age. It should be noted that the classification accuracy (90%) with the reduced set of measures was identical to that obtained with the full set of measures.

Table 2. Standardized canonical discriminant function coefficients.

	Function		
	1	2	3
Complex-gap DL	1.02	.30	−.54
Tone-order DL	.72	−.07	.03
TC50—noise	.16	−.04	.51
Complex-tone DL	−.23	−.77	1.13
TC40+RT.3—quiet	−.15	.11	.48
TC40+RT.3—noise	−.08	.18	−.25
Und speech—quiet	.29	.68	.43
Simple-tone DL	.14	.54	.17

Table 3. Structure matrix of the canonical discriminant function coefficients.

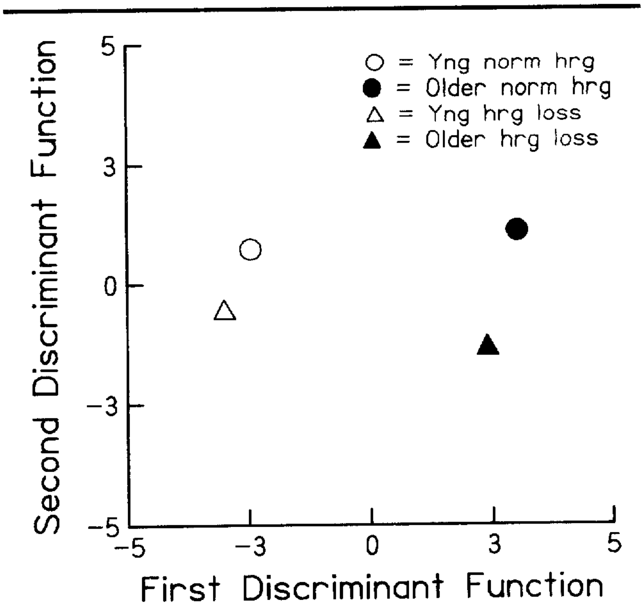
	Function		
	1	2	3
Complex-gap DL	.66*	−.24	.05
Temporal-order DL	.49*	−.07	−.11
Simple-gap DL	.27*	−.20	.18
Und speech—quiet	−.00	.75*	.25
Complex-tone DL	.36	−.70*	.39
TC40+RT.3—quiet	−.13	.55*	.41
TC40+RT.3—noise	−.16	.47*	−.06
TC50—noise	−.16	.45	.47*

Note. Variables are ordered by absolute size of correlation within function. *largest absolute correlation between each variable and any discriminant function.

Discussion

One purpose of this study was to examine independent and interactive effects of age and hearing loss on a range of temporally based speech and nonspeech measures in the same group of listeners. Although previous stages of our investigation have demonstrated strong age effects on individual speech and psychoacoustic temporal tasks, none of the previous investigations evaluated the same listeners with a set of the most age-sensitive temporal measures.

Figure 4. Discriminant function means of the four groups on the first two canonical discriminant functions.



Psychoacoustic Measures

The psychoacoustic testing revealed consistent age-related performance differences on each measure of temporal sensitivity. For the four duration-discrimination conditions, the observed Weber fractions displayed in Table 1 generally reflect a better absolute performance level than observed previously (Fitzgibbons & Gordon-Salant, 1995), but reveal similar trends across conditions and listener groups. Although gap discrimination was generally more difficult than tone discrimination for most listeners, no significant differences between tones and gaps for the isolated targets (STDL and SGDL) emerged from the data analysis either for younger or older listener groups. For these isolated targets, performance of the younger listeners agrees closely with corresponding estimates reported by others for various stimulus types of similar reference duration (Abel, 1972; Creelman, 1962; Small & Campbell, 1962). For the embedded targets (CTDL and CGDL), young listeners showed a significant performance decrement, but the absolute magnitude of the DL shifts from simple to complex conditions were not substantial for many of these listeners.

Discrimination performance of the older listeners was also similar for isolated tones and gaps with a mean Weber fraction of .22 for the two conditions, a value that was significantly elevated relative to that for the younger listeners. Additionally, most of the older listeners exhibited substantial performance decrements for discrimination of tones and gaps embedded within sequences. These latter results show the sizeable influence of stimulus complexity on the performance of the older listeners, with gap DLs being significantly larger than tone DLs for these listeners with the complex stimulus conditions. The final task, temporal order discrimination, also proved to be quite difficult for the older listeners. Results for this condition showed older listeners requiring sequence component durations almost three times longer than younger listeners (95.6 ms vs. 35.0 ms) in order to discern temporal order differences within three-tone patterns. The magnitude of age-related difficulty for temporal-order perception is comparable to that reported previously (Fitzgibbons & Gordon-Salant, 1998; Trainor & Trehub, 1989).

The diminished performance of the older listeners on the psychoacoustic measures is probably related to the nature of the tasks selected for study. For example, the perceptual processing of stimulus duration and stimulus temporal order is generally believed to be a function of the central auditory system (Creelman, 1962; Divenyi & Hirsh, 1974). This central mediation is also thought to be the primary locus of age-related dysfunction and slowed information processing (e.g., Salthouse, 1985). Additionally, central factors are believed to underlie the strong influences of stimulus complexity and uncertainty observed with basic auditory discrimination tasks (Watson & Foyle, 1985). Finally, the negligible peripheral effects of hearing loss observed for the present tasks provide further support for the contention of age-related dysfunction in temporal processing that is central in origin.

Speech Measures

Age-related deficits were observed for some, but not all, speech recognition tasks. Older participants exhibited poorer performance than younger participants on all conditions involving time compression of speech, as well as for speech conditions that included a background of noise. The age effect was observed also for the more severe speech reverberation condition (0.6-s RT), but not for the more mild reverberation condition (0.4-s RT). In addition, younger and older listeners exhibited comparable performance scores for recognition of undistorted speech presented in quiet. The statistical analyses did not reveal any interactions between age and hearing loss; thus, these age effects can be viewed as independent of effects attributed to peripheral hearing loss.

The finding of age-related problems for recognition of time-compressed speech, independent of attenuation imposed by hearing loss, agrees with previous reports (Gordon-Salant & Fitzgibbons, 1993, 1995). The robust nature of the age effect with time-compressed speech strongly indicates that aging imposes a limitation on the ability to process rapid speech segments. The findings for reverberant speech were not quite as strong: older people did not show exaggerated difficulty understanding mildly reverberant speech (0.4-s RT in quiet), but did show reduced scores relative to the younger listeners in more degraded conditions (0.6-s RT in quiet, 0.4-s RT in noise, 0.6-s RT in noise). This general performance pattern was observed also in a previous study (Gordon-Salant & Fitzgibbons, 1995). Two different types of processing limitations may be governing the deficits shown by older listeners for these two forms of temporally distorted speech. Time compression removes brief epochs of the speech signal, rendering the overall signal less redundant and the rapid acoustic cues for consonant identification even more transient. The limited time window available for perceiving these transitory acoustic events and labeling the brief acoustic trace may overburden the older person's temporal resolving power and capacity for processing sequential information. As suggested by the psychoacoustics data, these temporal processing limitations are believed to be central in nature. Thus, the older person's difficulty in recognizing time-compressed speech is most likely associated with deterioration of central timing mechanisms. For reverberant speech, modulation characteristics of the signal are altered together with an extension of its durational charcteristics beyond the time it is presented. These effects are comparable to a masking of the speech signal by itself with a time delay. Thus, this form of temporal speech distortion may represent more of a temporal masking phenomenon than a speed of processing limitation. Temporal masking in older listeners with normal hearing and with hearing loss has not been examined systematically, but investigation of this ability may be useful for deriving a better understanding of the older listener's difficulties in understanding the more degraded forms of reverberant speech.

Performance Profiles of Speech and Psychoacoustic Measures

The second and third purposes of this study were to identify a subset of the speech and nonspeech measures that most effectively distinguishes the performance of the listeners on the basis of age and hearing status, and to examine individual performance patterns (profiles) of the younger and older listeners.

The discriminant function analysis was conducted to serve these purposes. The results of the analysis indicate that a small set of speech and nonspeech measures can be used to separate the performance patterns of the current groups of listeners with a reasonably high level of accuracy. The measures that maximally separated the groups were those derived in the first canonical function, complex gap DL and temporal order DL. These two measures most effectively distinguished the performances of the younger and older groups. However, because of negligible hearing loss effects in the psychoacoustic data, these two measures could not differentiate the performance patterns of listeners with normal hearing and hearing loss. The second canonical discriminant function included one speech recognition measure (undistorted speech in quiet) and two additional speech recognition measures (combined time-compressed + reverberant speech in quiet and noise), which separated the groups primarily on the basis of hearing loss. The third canonical discriminant function identified only the time-compressed speech (50% TCR) in noise measure as contributing further to the variance accounted for. This measure by itself appears to be sensitive to a combination of the effects of hearing loss and age.

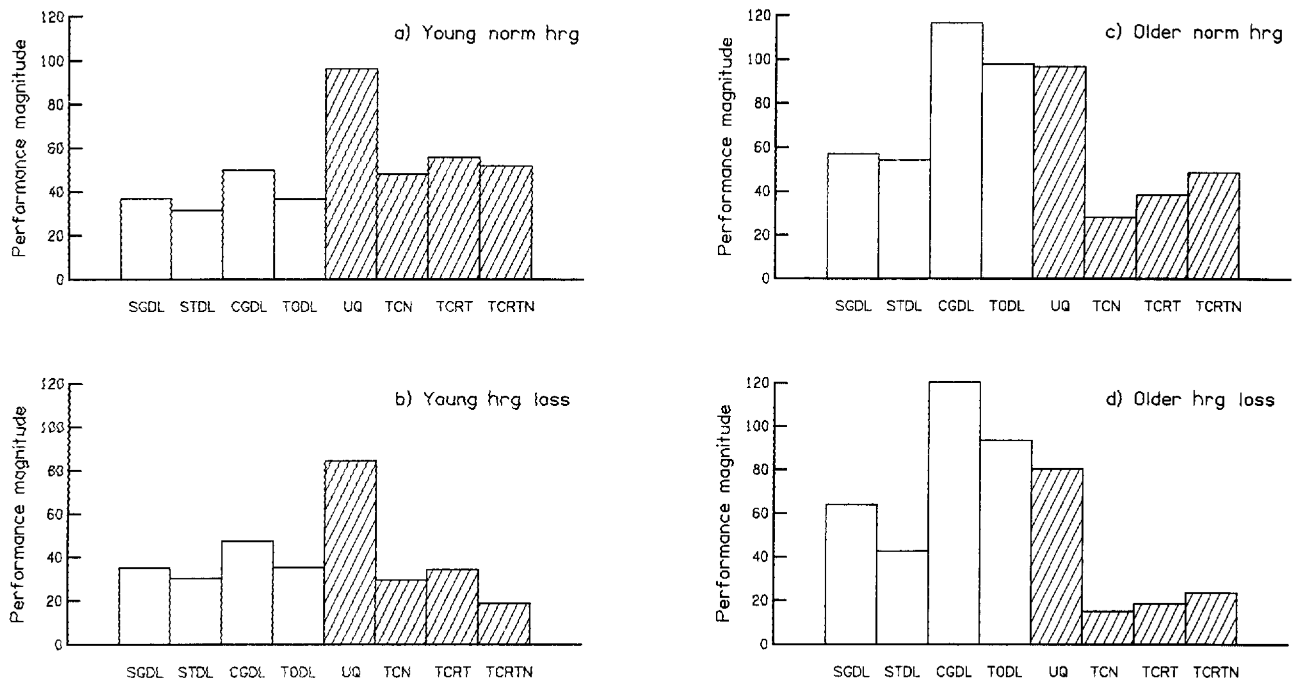
The discriminant function analysis therefore shows that a combination of both speech and nonspeech measures are necessary for accurately profiling listeners on the basis of age and hearing loss. The selected speech and nonspeech measures used in this analysis were not highly intercorrelated, and, therefore, each contributed independently to the performance variance seen across listeners. Additionally, this finding suggests that a single measure cannot accurately capture the range of deficits in auditory temporal processing that can be observed in older people with normal hearing and with hearing loss.

As noted in the introduction to this article, the purpose of using a subset of speech and nonspeech temporally based measures is to begin to identify temporal processing patterns that are characteristic of each of these four groups. Sample performance profiles of participants in the four groups are shown in Figure 5, based on mean performance data for the eight measures of interest. One application of such group profiles and the corresponding discriminant functions is that they can serve as a "normative reference" to which the profile of an individual belonging to one of these groups can be compared. For example, an older listener with hearing loss who exhibits a performance pattern comparable to that of the younger group with hearing loss is predicted to experience less difficulty with temporal processing in complex stimulus situations than most older people.

Examination of the classification accuracy of the discriminant functions derived in the present analysis indicates that 90% of the 40 listeners were accurately classified into age and hearing loss groups on the basis of performance on the temporal processing measures. The only errors in classification related to errors of hearing status and not age. It should be noted that, in general, the apparent error rate, or proportion of cases in the original sample that are misclassified (in this case, 10%), usually decreases as sample size increases (McLaughlin, 1980). The current sample size was limited to 40 participants, in part because of the large number of observations required for each individual and the cumulative length of the procedures. As discussed by McLaughlin (1980), the needed sample size varies considerably with the number of variables and the size of the squared distance between the populations. Although the present sample size adequately addresses these criteria, a larger sample size in relation to the number of variables would yield greater power and even more reliable results. Thus, future research could be directed toward replication of the present findings with a larger number of observers.

A related issue concerns the use of the original sample to determine the apparent error rate of the derived discriminant functions. Alternative procedures are the "jackknife" error rate, which is the proportion of misclassification derived from observations obtained on multiple occasions, or the "hold-out" error rate, which is a cross validation from a portion of the original sample withheld from the original discriminant function (McLaughlin, 1980). In the present study, there was not a sufficient number of participants to withhold a sample for cross validation purposes. Thus, while these preliminary data are encouraging, a stronger test of the accuracy of the derived discriminant functions would entail applying these functions to a new set of data obtained from different listeners.

Figure 5. Sample profiles of performance on the eight performance measures derived from the discriminant function analysis for younger listeners with normal hearing (Panel a), younger listeners with hearing loss (Panel b), older listeners. with normal hearing (Panel c), and older listeners with hearing loss (Panel d). Performance values should be interpreted as DLs in ms for the psychoacoustic measures (unfilled bars) and as recognition scores in percent correct for the speech measures (filled bars).



The present findings show that a combination of speech and nonspeech temporal measures can be used effectively to distinguish performance patterns of younger and older listeners, with and without hearing loss. The variation in performance in the different temporal processing measures is attributed to the relative importance of peripheral and central effects associated with the processing demands of the selected speech and nonspeech tasks.

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