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Hearing loss and aging: New research findings and clinical implications

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Abstract—This review provides an overview of recent research that addressed hearing loss and auditory processing problems among elderly people. It focuses on research from the University of Maryland on problems in auditory temporal processing by elderly listeners as assessed in speech perception experiments using temporally altered signals and in psychoacoustic experiments of duration and rhythm discrimination for simple and complex signals. Some recent studies of perceived hearing disability are also reviewed. The clinical implications of the research findings are discussed in relation to hearing aid performance and use by elderly people as well as potential signal processing strategies that may prove to be beneficial for this population.

Key words: age-related hearing loss, aging, auditory temporal processing, aural rehabilitation, hearing aids, hearing disability, presbycusis, reverberant speech, signal processing, speech perception, time-compressed speech.

INTRODUCTION

Hearing loss is the third most common chronic condition reported by elderly people [1]. The estimated prevalence of significant hearing impairment among people over the age of 65 is approximately 40 to 45 percent and among people over the age of 70 exceeds 83 percent [2]. Despite the widespread occurrence of significant hearing loss in the elderly population, only about 20 percent of elderly individuals with significant hearing impairment obtain hearing aids [3]. Moreover, about 30 percent of hearing aid owners are dissatisfied with their instruments [4], and approximately 16 percent of hearing aid owners report never using their hearing aids [5]. This article will review recent research findings on auditory performance among elderly listeners (those over 65 years) that might help explain the limited use of hearing aids by this population. Emerging trends in hearing aid technology and rehabilitative techniques will also be presented that may alleviate some of the auditory difficulties experienced by senior citizens.

AUDITORY THRESHOLDS

Hearing sensitivity declines gradually and progressively with aging. A study of the normal progression of hearing thresholds across the adult life span (ages 20 to 90+) was conducted by the Baltimore Longitudinal Study on Aging of the National Institute on Aging [6]. The changes in hearing sensitivity among 1,097 otologically normal men and women who had no history or evidence of noise exposure were examined over a 30-year period in the men and a 17-year period in the women. **Figure 1** shows the longitudinal hearing threshold changes in the men and women across the adult age span, for five audiometric

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Abbreviations: DL = difference limen, FCC = Federal Communications Commission, FM = frequency modulation, IOI = interonset interval, SNR = signal-to-noise ratio, SPL = sound pressure level, WPM = words per minute.

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frequencies. The data indicate that the decline in hearing sensitivity accelerates above age 20 to 30 in men, and above age 50 in women. At most ages and frequencies, the amount of longitudinal change in hearing level over 10 years is more than twice as fast for the men than the women.

Cross-sectional data of average hearing thresholds in large populations of unscreened elderly adults have been reported for the Framingham Heart Cohort Study [7] and the Beaver Dam, Wisconsin, Epidemiology of Hearing Loss Study [2] and are generally quite consistent. **Figure 2** presents the data reported for the Beaver Dam Study, based on measured thresholds of 3,753 adults. The average hearing thresholds of men are typically poorer than those of women in the high frequencies, with men exhibiting a sharply sloping hearing loss in the moderately severe range in the high frequencies, and the women exhibiting a more gradual sloping hearing loss in the moderate range in the high frequencies [2,7]. A high proportion of participants in the Framingham study reported significant histories of noise exposure, otologic disease, and ototoxicity [7]; thus the source of the hearing impairment among unscreened populations is not associated exclusively with aging.

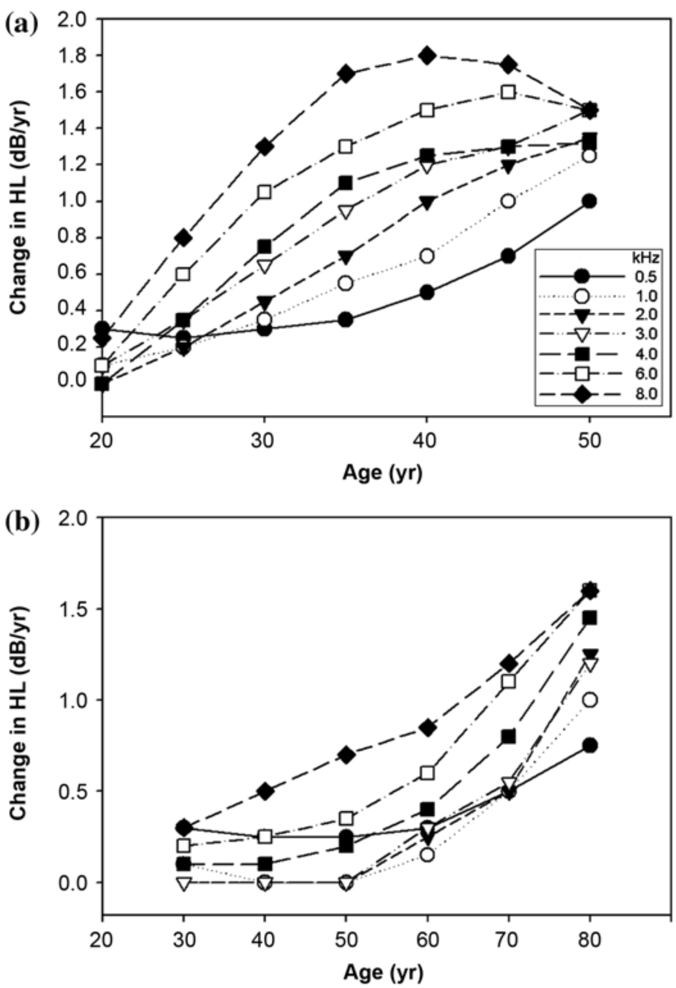

Figure 1.
Average 10-year longitudinal changes in pure-tone hearing level (HL) thresholds across frequency for **(a)** men and **(b)** women, from Baltimore Longitudinal Study on Aging. *Source:* Pearson JD, Morrell CH, Gordon-Salant S, Brant LJ, Metter EJ, Klein LL, Fozard JL. Gender differences in a longitudinal study of age-associated hearing loss. J Acoust Soc Am. 1995;97:1196–1205.

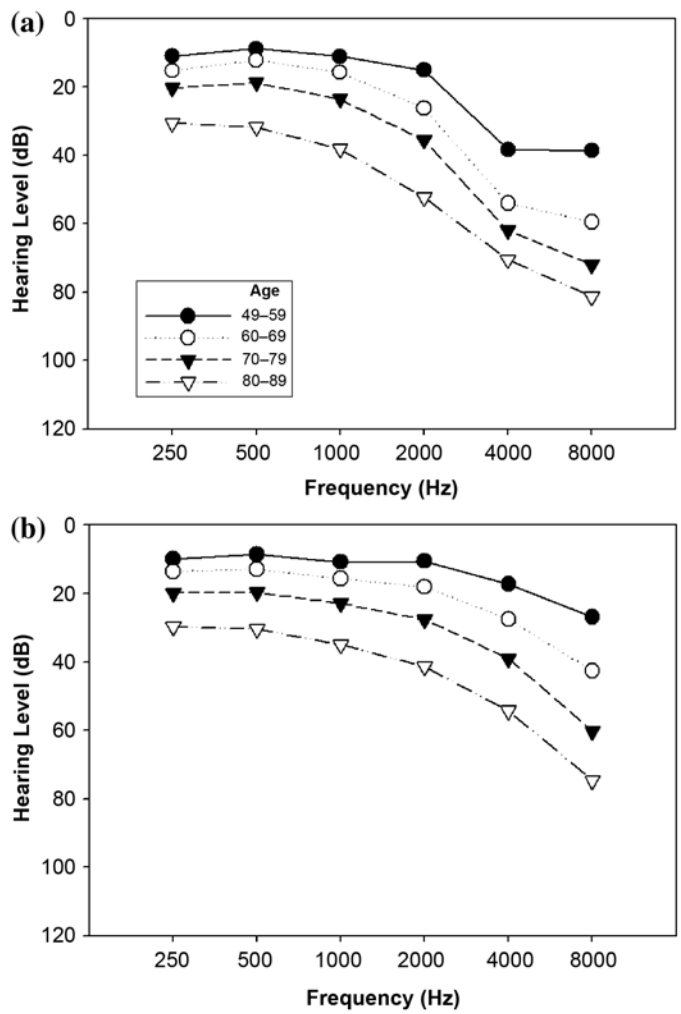

Figure 2.
Mean pure-tone air conduction thresholds for **(a)** men and **(b)** women in four age groups, from Beaver Dam Wisconsin, Epidemiology of Hearing Loss Study. *Source:* Cruickshanks KJ, Wiley TL, Tweed TS, Klein BE, Klein R, Mares-Perlman JA, Nondahl DM. Prevalence of hearing loss in older adults in Beaver Dam, Wisconsin. The Epidemiology of Hearing Loss Study. Am J Epidem. 1998;148:879–86.

SPEECH-UNDERSTANDING PERFORMANCE

Perhaps the most important consequence of the decline in hearing sensitivity with aging is difficulty understanding speech. Articulation Index theory predicts that recognition of average conversational speech (60 dB sound pressure level [SPL]) will be reduced among people with age-related hearing loss (presbycusis) as a result of the limited audibility of high-frequency acoustic cues [8]. However, elderly people usually do not experience problems understanding speech in ideal listening conditions that include quiet environments and familiar talkers, as long as the speech level permits audibility of high-frequency information [9].

Difficulties arise when elderly listeners must follow conversational speech in adverse listening conditions, including noise and reverberation. The research evidence supporting age-related deficits for speech recognition in noise is mixed, however, and appears to depend on a number of stimulus variables, including the audibility of the speech signal, the type of speech signal (words vs. sentences), the type of noise background (steady-state, modulated noise, or speech), the signal-to-noise ratio (SNR), and subject variables, including efforts to equate the hearing thresholds between younger and older groups. The **Table** presents results of recent investigations that examined age-related differences in speech-recognition performance in noise [10–15]. A comparison of these results suggests that if the speech signal is presented at a relatively high level (70–90 dB SPL) to elderly listeners with normal hearing or mild or moderate hearing losses and if the SNR is adjusted to approximate a 50 percent correct score (i.e., near 0 dB SNR), then significant age-related deficits often are observed [10–14], but not always [15]. Additionally, the specific age, gender, and hearing loss characteristics of the study samples influence observed results. For example, Dubno et al. reported that speech-recognition performance of elderly males declined significantly with age after adjusting for average hearing thresholds [16], but no significant changes were found in speech recognition with age for females in the same age range (55–84 years). In contrast, data from a large cohort of adults (48–92 years) in the Beaver Dam Epidemiology of Hearing Loss Study show significant age effects in word recognition scores in competing messages for both men and women, but performance is consistently poorer in men than in women at all age groups and hearing loss categories [14].

Another variable that has received considerable attention in recent literature is age-related differences in the masking release afforded by a modulated noise masker compared with a steady-state noise masker. Young listeners with normal hearing exhibit better recognition performance in temporally modulated noise compared with steady-state noise, suggesting that they can take advantage of “windows” in the noise at moments when the SNR is relatively high [17]. Several reports indicate that elderly listeners can benefit from temporal interruptions in noise to improve speech-recognition scores compared with steady-state noise conditions, but the magnitude of the temporal masking release is smaller than that observed in young listeners [13,17–18]. Other reports suggest that the reduction in temporal masking release is due primarily to the presence of hearing loss and not to age [15]. Nevertheless, the overall findings across studies suggest that elderly listeners with hearing loss are less able to use temporal fluctuations in noise than young listeners with normal hearing—a result that may partially explain the inordinate difficulty elderly listeners experience in daily situations with a background of multiple talkers.

Reverberant environments are notably difficult for elderly listeners. Reverberation is the prolongation of sound in an enclosed room and is quantified as the time, in seconds, for a signal to decay 60 dB below its steady-state value after termination. Large rooms with high ceilings and walls composed of glass (windows or mirrors) are characterized by long reverberation times. Reverberation has a smoothing effect on the waveform of the signal, thus creating a distortion of the temporal waveform [19]. Elderly listeners with normal hearing, minimal hearing loss, or significant hearing loss perform poorer than young listeners with comparable hearing sensitivity in reverberation across a range of reverberation times [20–22]. **Figure 3** shows recognition performance of young adult and elderly listeners with normal hearing and mild-to-moderate hearing loss in four reverberation time conditions. The age-related deficit is exacerbated in conditions that combine reverberation and noise [11,20,23]. These findings indicate that poor room acoustics that include both noise and reverberation are particularly adverse for communication by elderly people [24].

The characteristics of the talker, particularly the rate of speech production, can affect the speech-recognition task for elderly individuals. Normal conversational speech is spoken at a rate of 200 to 275 words per minute (WPM) [25]. Using a mechanical manipulation of speech

Table.
Findings from six studies evaluating age effects on speech-recognition measures in noise.

Reference	Subject Groups	Speech Stimuli	Noise Type	Signal Level (dB SPL)	SNR (dB)	Results of Age Effects
Dubno et al. [1]	Young normal hearing Young hearing impaired Elderly normal hearing Elderly hearing impaired	R-SPIN (high and low context)	Speech babble	56.0 72.0 88.0	Adaptive to 50% correct	Observed in all conditions
Gordon-Salant & Fitzgibbons [2]	Young normal hearing Young hearing impaired Elderly normal hearing Elderly hearing impaired	R-SPIN (low context)	Speech babble	90.0	–8, 0, 8, 16, 24	Observed at 0 dB SNR only
Studebaker et al. [3]	Ages 20–89 with normal hearing through 2 kHz	NU-6 (band-passed)	Speech spectrum	70.7	2.5	Observed above age 70
Stuart & Phillips [4]	Young normal hearing Elderly near-normal hearing Elderly hearing impaired	NU-6	Steady state and interrupted	30.0 (SRT)	–20, –15, –10, 0, 5, 10	Observed for steady state and interrupted noise
Wiley et al. [5]	Ages 18–34, 48–92; normal hearing, mild hearing loss, marked hearing loss	NU-6	Single talker	36.0 (threshold at 2 kHz)	8	Observed for all hearing categories
Souza & Turner [6]	Young normal hearing Young hearing impaired Elderly hearing impaired	NU-6 (with high-pass noise)	Speech spectrum: modulated and unmodulated, speech babble	80.0	5	None observed

1. Dubno JR, Dirks DE, Morgan DE. Effects of age and mild hearing loss on speech recognition in noise. J Acoust Soc Am. 1984;76:87–96.
2. Gordon-Salant S, Fitzgibbons PJ. Comparing recognition of distorted speech using an equivalent signal-to-noise ratio index. J Speech Hear Res. 1995;38:706–13.
3. Studebaker GA, Sherbecoe RL, McDaniel DM, Gray GA. Age-related changes in monosyllabic word recognition performance when audibility is held constant. J Am Acad Audiol. 1997;8:150–62.
4. Stuart A, Phillips DP. Word recognition in continuous and interrupted broadband noise by young normal-hearing, older normal–hearing, and presbyacusic listeners. Ear Hear. 1996;17:478–89.
5. Wiley TL, Cruickshanks KJ, Nondahl DM, Tweed TS, Klein R, Klein BK. Aging and word recognition in competing message. J Am Acad Audiol. 1998;9:191–98.
6. Souza PE, Turner CW. Masking of speech in young and elderly listeners with hearing loss. J Speech Hear Res. 1994;37:665–61.

SNR = signal-to-noise ratio, R-SPIN = Revised Speech Perception in Noise test, SPL = sound pressure level, SRT = speech-recognition threshold, NU-6 = Northwestern University Test No. 6.

rate, Wingfield and his colleagues showed that elderly listeners' recognition of five- and eight-word speech signals declined with increments in speech rate [25] up to 420 WPM, with young listeners exhibiting little change in performance as speech rate increased. The age-related deficits were more prominent for recognition of speech signals with reduced contextual information (i.e., speech phrases and random word strings) than for recognition of everyday sentences. The results are interpreted as reflecting a slowing of perceptual processing that accompanies the aging process [26–27].

Time compression is a method to simulate rapid speech rates and is currently accomplished with computer algorithms that sample the spoken message, remove a proportion of quasiperiodic pitch periods in the speech sample, and concatenate the remainder of the acoustic signal. Spectral information, including voice pitch, is preserved in the time-compressed signal. The time-compression ratio describes the percentage of reduction in the overall duration of the compressed speech signal relative to the original signal. Thus, a signal that is 60 percent time-compressed has a duration that is 60 percent less than that of the original

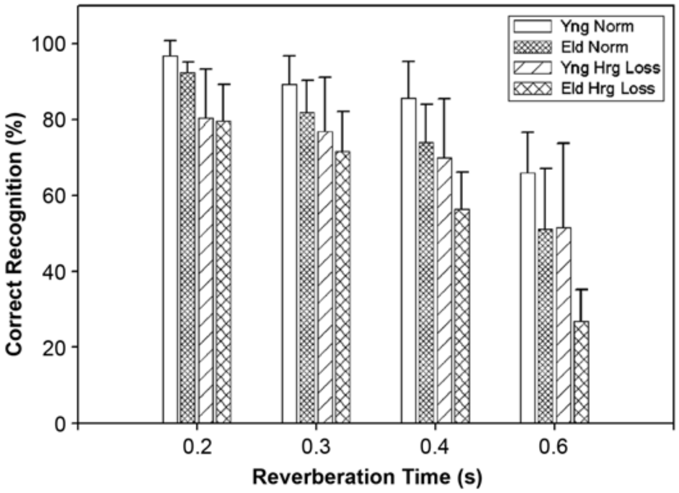

Figure 3.
Average recognition scores of low probability Speech Perception in Noise test sentences (final word) at four reverberation times by four adult listener groups: young listeners with normal hearing (Yng Norm), elderly listeners with normal hearing (Eld Norm), young listeners with mild-to-moderate sensorineural hearing loss (Yng Hrg Loss), and elderly listeners with mild-to-moderate sensorineural hearing loss (Eld Hrg Loss). Error bars are standard deviations. *Source:* (redrawn) Gordon-Salant S, Fitzgibbons PJ. Temporal factors and speech recognition performance in young and elderly listeners. J Speech Hear Res. 1993;36:1276–85.

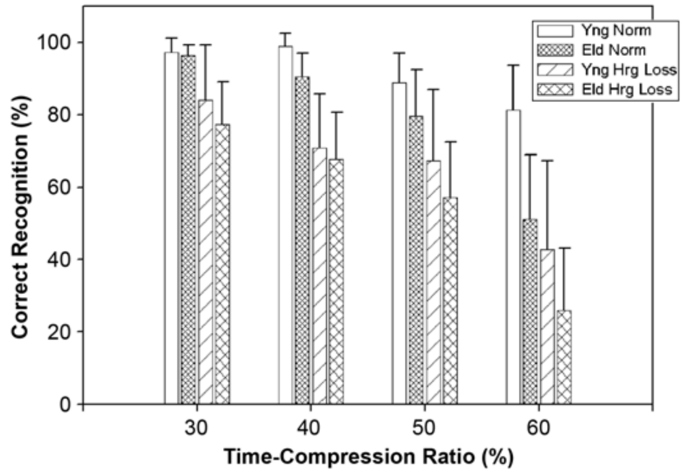

Figure 4.
Average recognition scores of low probability Speech Perception in Noise test sentences (final word) at four time-compression ratios by four adult listener groups: young listeners with normal hearing (Yng Norm), elderly listeners with normal hearing (Eld Norm), young listeners with mild-to-moderate sensorineural hearing loss (Yng Hrg Loss), and elderly listeners with mild-to-moderate sensorineural hearing loss (Eld Hrg Loss). Error bars are standard deviations. *Source:* (redrawn) Gordon-Salant S, Fitzgibbons PJ. Temporal factors and speech recognition performance in young and elderly listeners. J Speech Hear Res. 1993;36:1276–85.

signal. As shown in **Figure 4**, elderly listeners with normal hearing and with mild-to-moderate hearing impairment exhibit significantly poorer speech-recognition scores than young listeners with comparable hearing sensitivity across a range of time-compression ratios (30%–60%), at high signal presentation levels in quiet conditions [22,28–30]. Additionally, age-related deficits for time-compressed speech are larger in noise conditions than in quiet conditions [11,31].

A recent investigation sought to determine if the age-related performance deficits for time-compressed speech were attributed primarily to a reduction in overall processing time or to a reduction in specific acoustic cues for speech [32]. Stimuli were sentence-length materials presented at a normal rate and four speeded speech rates created by time-compression methods, including uniform time compression of the entire utterance, selected time compression of consonant phonemes, selected time compression of vowel phonemes, and selected time compression of pauses. Some of the results are shown in **Figure 5** and indicate that elderly listeners exhibited significantly poorer performance than young listeners in all time-compression conditions except selected time compression of pauses. Moreover, time compression of consonants accounted for considerably more of the variance in recognition of uniformly time-compressed speech than any of the other forms of selective time compression. These results support the notion that elderly listeners' difficulty in recognizing rapid speech is attributed largely to their difficulty resolving the brief, impoverished consonants in time-compressed speech. A follow-up study investigated the magnitude of age effects observed with increments in the proportion of the speech signal that was time-compressed and the location of the time-compressed phrase in the sentence [33]. **Figure 6** presents the findings for the young and elderly listeners of this study, with data collapsed across hearing loss groups because the hearing loss effect was not involved in any interactions. Elderly listeners showed similar performance to young listeners in the normal-rate condition, but poorer recognition performance than young listeners in all time-compressed speech conditions, indicating that even if a single phrase of a sentence is time-compressed, elderly listeners are at a disadvantage. The elderly listeners showed progressively poorer performance with increments in the

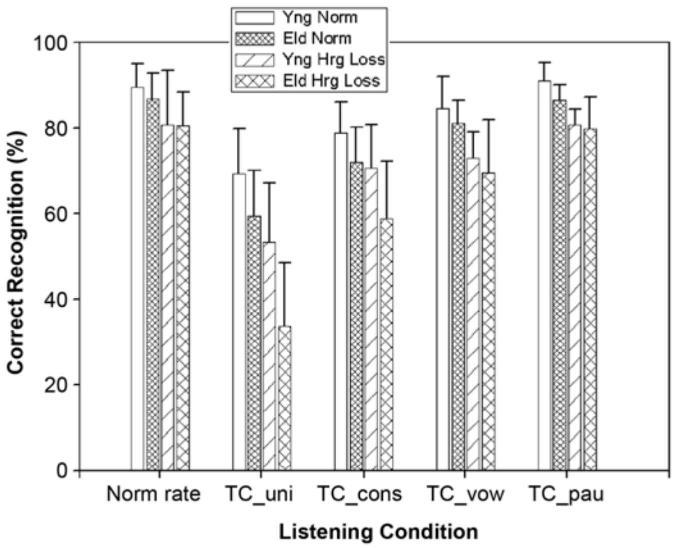

Figure 5.
Mean recognition scores obtained by young adult and elderly listeners with normal hearing (Yng and Eld Norm) and with hearing loss (Yng and Eld Hrg Loss) for sentence-length phrases presented at normal speech rate and with four forms of time compression (TC): uniform TC (TC_uni), selective TC of consonants (TC_cons), selective TC of vowels (TC_vow), and selective TC of pauses (TC_pau). Error bars are standard deviations. *Source:* (redrawn) Gordon-Salant S, Fitzgibbons PJ. Sources of age-related recognition difficulty for time-compressed speech. J Speech Lang Hearing Res. 2001;44:709–19.

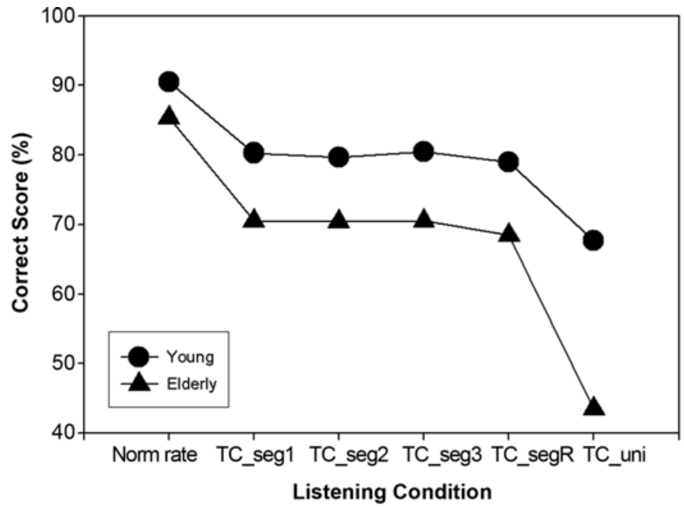

Figure 6.
Average recognition scores of young adult and elderly listeners (collapsed across hearing loss groups) for sentence-length phrases presented in six speech rate conditions: normal (Norm) rate, time compression (TC) of segment 1 (TC_seg1), TC of segment 2 (TC_seg2), TC of segment 3 (TC_seg3), TC of a single random segment (TC_segR), and uniform TC of entire utterance (TC_uni). *Source:* Gordon-Salant S, Fitzgibbons PJ. Effects of stimulus and noise rate variability on speech perception by younger and older adults. J Acoust Soc Am. 2004;115:1808–17.

proportion of the speech signal that was time-compressed. Because of the overall age effect, these findings suggest that slowed processing time with aging influences recognition of time-compressed speech. Together, these two recent studies suggest that elderly listeners with hearing loss experience difficulty understanding fast speech because of at least two factors: (1) a decline in rapid information processing associated with a generalized slowing and (2) an inability to process extremely brief acoustic consonant information.

Another talker characteristic that appears to affect speech understanding by elderly listeners is the presence of a talker's accent. Nonnative speakers of English may alter the duration or intensity of specific consonant and vowel phonemes [34–36], vary the stress of syllables in a spoken utterance [37], or modify the overall prosody of the message [37]. Each of these alterations represents a distortion of the spoken message and potentially can be challenging for elderly listeners to perceive. At least one study has compared the recognition performance of young and elderly native speakers of English for speech produced by nonnative speakers of English. The results showed that elderly listeners' recognition scores were poorer than those of young listeners for accented words and sentences, but the magnitude of these age-related differences was associated with the strength of the speaker's accent [38]. The changing demographics in the United States, with a dramatic increase in the number of immigrants and a concomitant increase in the number of nonnative speakers of English, suggest that understanding of accented English will become a real challenge for elderly people in future years.

The preceding discussion underscores the problems that elderly people experience when the signal is degraded acoustically in some manner, suggesting that "bottom-up" processing of an impoverished signal is compromised with age. Evidence also suggests that cognitive decline with aging influences speech understanding. Advanced age is accompanied by reductions in working memory capacity [39]; an inhibition deficit that permits distracting information to affect attention, memory, or processing [40]; and a generalized slowing of perceptual processing [41]. All of these senescent changes potentially limit accurate reception of a spoken message in complex listening tasks. Elderly listeners demonstrate poorer recall of target words at unfavorable SNRs than young listeners and remember fewer words to recall on a memory task in these adverse listening conditions compared with more favorable conditions [42]. The length of the recall task also affects elderly listeners detrimentally when the speech stimuli have few semantic contextual cues, but not when multiple contextual cues exist to aid recognition [43]. Compared with young listeners, elderly listeners are also at a disadvantage, on tasks featuring talker variability, including the use of multiple target speakers and multiple speaking rates [44]. Thus, elderly people appear to be less adaptable to alterations in the speaker's characteristics, a phenomenon known as "perceptual normalization." This certainly could affect speech understanding in everyday situations that involve multiple talkers with varying dialects, vocal characteristics, speech clarity, and speaking rates.

Some research has been directed at techniques that might improve elderly listeners' performance. For example, one aspect of language processing that appears to be preserved with aging is the lexical system and its semantic associations [45]. Studies have shown that elderly listeners with and without hearing impairment are able to take advantage of a few contextual cues in a message to achieve nearly perfect speech-recognition scores, despite challenging listening conditions with noise, altered timing, and an added memory load [42–43].

Figure 7 shows sentence recognition performance data of young and elderly listeners with normal hearing and with hearing loss in multitalker babble (SNR = +16 dB), with a slowed presentation rate, as implemented with increments in silent intervals between words (i.e., interword intervals). This method of slowing was detrimental for most listeners when understanding low-context sentences (**Figure 7(a)**), perhaps because of the added memory load or disruption of natural prosody with this technique. Nevertheless, providing contextual cues dramatically improved performance for young and elderly listeners in this challenging speech task, as illustrated in **Figure 7(b)**.

Another potentially beneficial technique is to expand the overall duration of the speech signal through time expansion. A preliminary investigation has shown that increasing the duration of consonant phonemes by 100 percent in sentence-length speech materials, produced at a rapid rate, significantly improved elderly listeners' speech-recognition scores [46]. As shown in **Figure 8**, the magnitude of this improvement for elderly listeners is about 24 to 30 percent. This same signal processing applied to natural-rate speech had no effect on performance, suggesting that altering consonant duration does not distort the spoken message in a manner that decreases intelligibility. This type of selective time expansion of consonants, coupled with a corresponding time compression of vowels to achieve equivalent overall word duration pre- and postprocessing, may improve speech-recognition performance in the auditory mode while retaining an approximate temporal match between the auditory and visual signal for face-to-face communication.

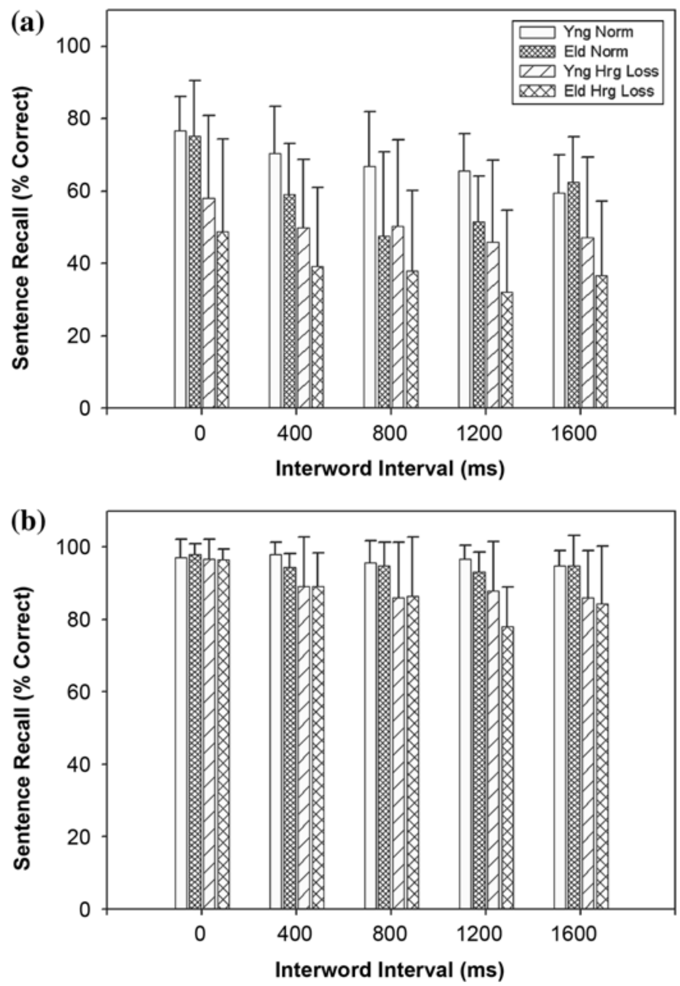

Figure 7.
Sentence recall scores of **(a)** low-context and **(b)** high-context sentences (of Speech Perception in Noise test) obtained by young adult listeners with normal hearing (Yng Norm) and with hearing loss (Yng Hrg Loss), and elderly listeners with normal hearing (Eld Norm) and with hearing loss (Eld Hrg Loss), as a function of interword interval and contextual cues. Stimuli were presented in a babble background. Error bars are standard deviations. *Source:* Gordon-Salant S, Fitzgibbons PJ. Selected cognitive factors and speech recognition performance among young and elderly listeners. J Speech Lang Hear Res. 1997;40:423–31.

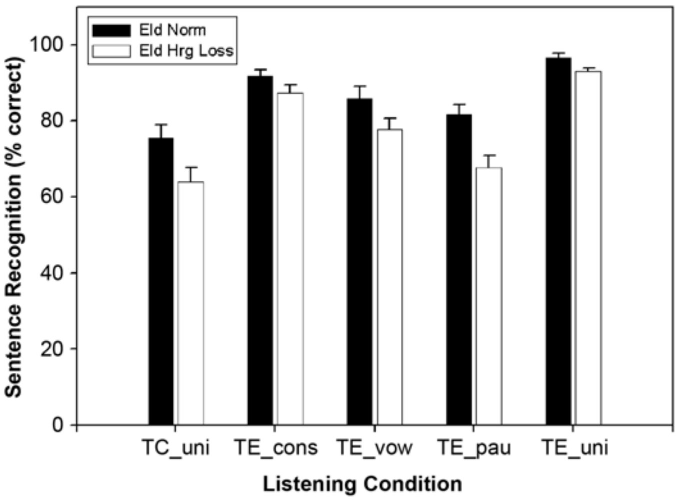

Figure 8.
Mean recognition scores for Speech Perception in Noise test sentences (low context) by elderly listeners with normal hearing (Eld Norm) and with hearing loss (Eld Hrg Loss) in five temporally altered listening conditions: uniform time compression throughout sentence (TC_uni), time expansion (TE) of consonants imposed on fast speech (TE_cons), TE of vowels imposed on fast speech (TE_vow), TE of pauses imposed on fast speech (TE_pau), and uniform TE imposed on fast speech (TE_uni). Error bars are standard deviations. *Source:* Gordon-Salant S, Fitzgibbons PJ. Effects of age and hearing on recognition of time-expanded sentence-length stimuli. Midwinter Meeting at the Association for Research in Otolaryngology; 2004; Daytona Beach, Florida. Mt. Royal (NJ): Association for Research in Otolaryngology; 2004.

AUDITORY TEMPORAL PROCESSING

The observed deficit that elderly people exhibit in understanding fast speech has led to the hypothesis that the ability to process rapid acoustic information may deteriorate with aging [47–48]. A comprehensive examination of temporal processing deficits using speech signals is limited because the listener's knowledge of the language has a substantial influence on performance, as noted earlier. Researchers have turned to psychoacoustic measures of auditory temporal processing with simple tonal signals that permit better control of the spectral content of the acoustic stimulus and precise manipulation of the duration parameters of interest. Elderly listeners are generally expected to have difficulty on measures that mimic some temporal aspects of rapid speech. Thus, the stimuli of interest are isolated or sequential stimuli that vary primarily in duration or presentation rate.

One basic question is, Do elderly people have difficulty processing changes in stimulus duration for stimuli presented in isolation and for stimuli embedded in a sequence? A related issue is the extent to which possible age effects interact with loss of hearing sensitivity on these measures. Some psychophysical evidence demonstrates that measured thresholds for detecting brief temporal gaps between successive tone or noise bursts are diminished with aging. Elderly listeners show gap thresholds that are about twice the magnitude of those reported for young listeners [49–51]. Additional evidence is derived from duration discrimination experiments in which tonal reference stimuli are comparable in duration with monosyllabic words (250 ms). Young listeners generally require increments in stimulus duration that are about 15 percent of the reference duration of a single isolated tone for accurate discrimination, whereas elderly listeners require about a 25 percent duration increment [47]. The age-related deficit increases substantially when the identical target stimuli are embedded in a sequence of contiguous tones, although young listeners exhibit comparable discrimination of stimuli in sequences and in isolation [52], as shown in **Figure 9**. Thus, increasing the complexity of the target stimulus increases the difficulty of the duration discrimination task for elderly listeners but not for young listeners. Effects of hearing loss are not observed consistently on these duration discrimination tasks for clearly audible signals.

The difficulty in processing changes in the duration of a component stimulus embedded in a tonal sequence may be related to a decreased sensitivity to the overall rhythm of a stimulus sequence. Rhythm discrimination can be assessed in a task that varies the silent intervals between component stimuli; in turn, this manipulation alters the overall presentation rate. A relatively simple paradigm is to present a sequence of brief tones of equal frequency separated equally by silent intervals; the resulting sequence with uniform tonal interonset intervals (IOIs) corresponds to a particular sequence presentation rate. A faster presentation rate would correspond to a sequence with briefer IOIs, and a slower presentation rate would correspond to a sequence with longer IOIs. In the psychoacoustic discrimination paradigm reported here, the comparison stimuli for listener judgments feature simultaneous covariation of the tonal IOI to measure the relative difference limen (DL) for changes of tonal IOI corresponding to a slowing of the sequence rate. In one study, reference sequences were composed of five 50 ms component tones of 1 kHz, with baseline IOIs varying from 100 to 600 ms [53]. As shown in **Figure 10**, relative

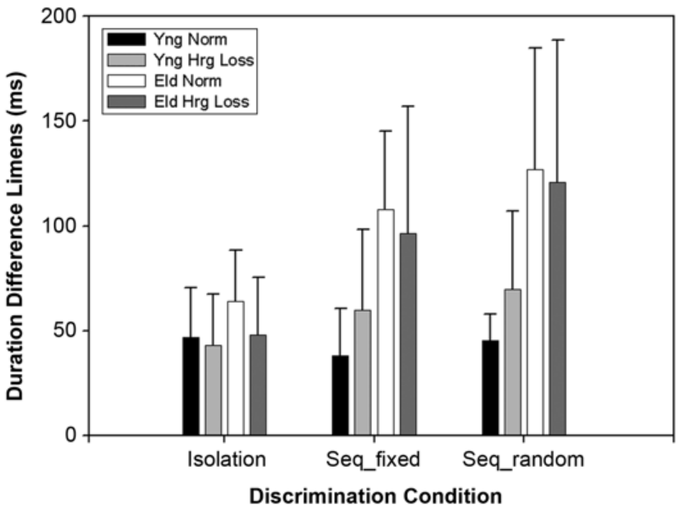

Figure 9.
Duration discrimination for 250 ms tones presented in isolation, a fixed target location in a sequence (Seq_fixed), and a random target location in a sequence (Seq_random) by young adult (Yng Norm) and elderly listeners with normal hearing (Eld Norm) and by young adult and elderly listeners with mild-to-moderate sensorineural hearing loss (Yng Hrg Loss and Eld Hrg Loss). Error bars are standard deviations. *Source:* Fitzgibbons PJ, Gordon-Salant S. Age effects on duration discrimination with simple and complex stimuli. J Acoust Soc Am. 1995;98:3140–45.

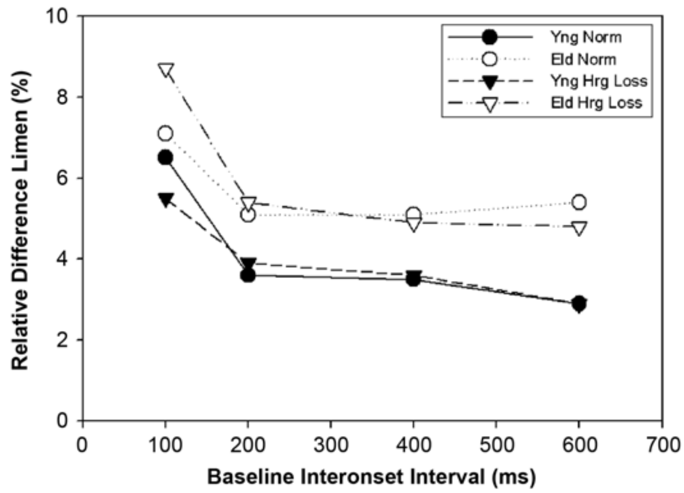

Figure 10.
Relative difference limens, in percent, as a function of tonal interonset interval obtained from young adult (Yng Norm) and elderly (Eld Norm) listeners with normal hearing and with hearing loss (Yng Hrg Loss and Eld Hrg Loss). *Source:* Fitzgibbons PJ, Gordon-Salant S. Aging and temporal discrimination in auditory sequences. J Acoust Soc Am. 2001;109:2955–63.

DLs are higher for short baseline IOIs of 100 ms and DLs are constant and smaller for baseline IOIs of 200 ms and above for all listener groups [53]. Age effects are observed on the rhythm, or tempo, discrimination task for these uniform sequences at all baseline IOIs ranging from 100 to 600 ms. The magnitude of these age effects is greater with increments in a single target IOI compared with uniform increments across the sequence [53]. A follow-up study examined discrimination of tonal sequence rate in sequences that more closely approximate speech signals by varying temporal, spectral, or combined temporal and spectral complexity [54]. The findings indicated that the processing of sequences with variable timing was more difficult for all listeners than the processing of sequences with variable spectral markers. As shown in **Figure 11**, elderly listeners exhibited larger relative DLs than young listeners for discrimination of all sequences, but the greatest age-related effects were observed for stimuli with variable timing [54]. The spectral complexity of the sequences appeared to have little effect on performance of both young and elderly listeners. These results suggest that another source of the elderly listener's difficulty in accurately recognizing rapid speech is a significant deficit in processing the temporal characteristics of complex sequential stimuli. The findings also indicate that irregular disruptions in overall sequence rhythm are particularly challenging for elderly listeners and may underlie some of the problems in processing accented English that is characterized by altered prosody.

PERCEIVED HEARING DISABILITY

The range of performance difficulties that elderly people exhibit on complex listening tasks suggests that these individuals are likely to experience a considerable impact of the hearing loss and related deficits on daily communication function. The term "disability" refers to the effect of an impairment on a person's capacity to meet personal, social, or occupational demands [55]. Although hearing impairment, coupled with some of the perceptual and cognitive effects of aging, limits an elderly person's ability to communicate effectively in social or work settings, the extent to which an individual recognizes this disability may influence his or her motivation to seek assistance through amplification or aural rehabilitation. Age-related differences are observed on measures of perceived hearing disability. For example, compared

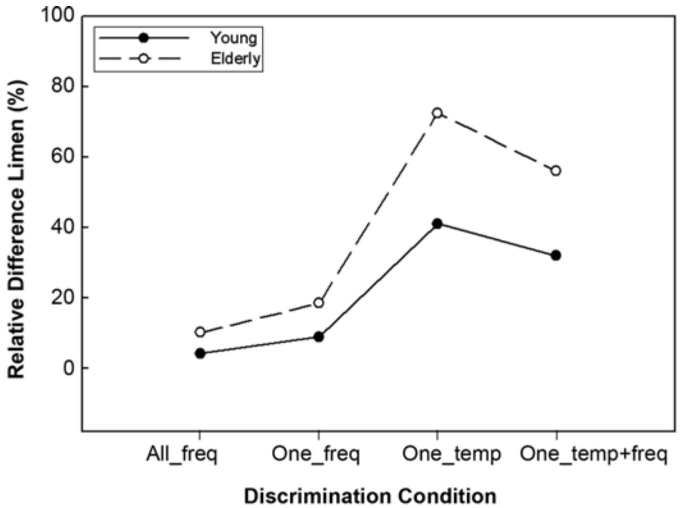

Figure 11.
Relative difference limens, in percent, for tonal interonset interval (IOI) measured in young and elderly listeners (collapsed across hearing loss groups) in four tonal sequence conditions: all IOIs covaried simultaneously in sequences with variable frequencies (All_freq), a single IOI varied in sequences with variable frequencies (One_freq), a single IOI varied in fixed frequency sequences with variable timing (One_temp), and a single IOI varied in sequences with variable timing and variable tone frequencies (One_temp+freq). *Source:* Fitzgibbons PJ, Gordon-Salant S. Age effects on discrimination of timing in auditory sequences. J Acoust Soc Am. 2004;116:1126–34.

with young adults with similar hearing sensitivity, elderly adults (65–76 years) with mild-to-moderate hearing losses report less social and emotional impact of hearing impairment on their daily lives [56], fewer communication problems, and less demand for communication [57]. In a large-scale study of 2,150 adults in Japan, Uchida and his colleagues found significant age differences in self-perceived hearing problems [58]. Elderly subjects (60–79 years) reported less hearing disability than middle-aged subjects (40–59 years). These analogous findings in studies conducted in the United States and Japan underscore the universality of this phenomenon. Some possible reasons for the apparent under-reporting of hearing disability among elderly people with hearing loss are the gradual onset and progressive nature of presbycusis that produce subtle changes in communication function over time, or fewer communication demands on elderly people in retirement.

Elderly men and women react differently to hearing impairment. Overall, middle-aged and elderly men report less hearing disability than women in the same age range [58], although as noted earlier, men generally have poorer hearing sensitivity than women of the same age. Garstecki and Erler specifically examined gender differences in self-perceived hearing disability among 301 women and men aged 65 and older [59] to identify possible sensory, physical, and social differences between men and women that could influence the impact of the hearing impairment. Demographic differences between the groups included age and marital status. Participants responded to items on the Communication Profile for the Hearing Impaired [60], which samples opinions about the importance of effective communication, the respondent’s typical communication environment, communication strategies employed, and personal adjustment to hearing loss. In general, women were more concerned than men with communicating effectively in social situations, perhaps because most women were widowed and relied more on social interactions outside of the family. The men were more likely to deny experiencing negative reactions to their hearing loss when compared with women who reported feelings of stress associated with their hearing loss. Men and women also tended to rely on different communication strategies to accommodate their hearing loss. In particular, the women relied on nonverbal communication strategies, such as preferential seating and paying attention to the speaker’s face, to a greater extent than the men. This preference for nonverbal strategies is less likely to call attention to the individual’s hearing loss. Thus, many of the differences in hearing disability reported by elderly men and women are probably related to differing sociodemographic variables and personality attributes. All the reports on hearing disability among elderly people suggest that some aspects of denial of the hearing loss, especially in men, could contribute to the relatively low rate of seeking and acquiring amplification.

TREATMENT

The principal treatment for age-related hearing loss at present is with suitable amplification that provides appropriate gain at selective frequencies, compression of high-level signals, and attenuation of background noise through adaptive filtering and directional microphones. The current generation of hearing aids provides acoustic cues across the frequency range for most elderly people with age-related hearing loss and produces significant improvements in speech recognition in quiet, ideal listening environments [61–62]. Benefits in speech understanding in noise are reported for elderly people with the use of linear hearing aid circuits featuring output compression [61] and wide dynamic-range-compression hearing aids [62]. Older people's use of amplification also has been shown to reduce the perceived impact of the hearing loss in daily communication, as measured with the Hearing Handicap Inventory for the Elderly [63–65]. A recent meta-analysis of 36 consumer surveys of hearing aid satisfaction and benefit showed that 31 percent of hearing aid consumers (average age of 69) report benefit from their hearing aids in noise and 76 percent report overall benefit with their hearing aids [4]. Moreover, the results indicate that satisfaction is considerably higher for more technologically advanced instruments. Specifically, hearing aid users report greater satisfaction with directional and omnidirectional, programmable hearing aids (81% and 72% satisfaction, respectively) than for nonprogrammable hearing aids (58% satisfaction).

Despite the documented benefit of amplification for elderly, hearing-impaired individuals, market trends show that only about 20 percent of this population purchase hearing aids [3]. The reasons for this low rate of hearing aid use are likely to be complex and may vary between those individuals who never inquire about a hearing aid, those who seek to obtain hearing healthcare but do not choose to follow a recommendation to purchase a hearing aid, and those who acquire a hearing aid but do not use it regularly. Factors reported by elderly people who do not adhere to recommendations to purchase a hearing aid are cost and a relatively low value placed on effective communication [66]. Some of these individuals also have low self-esteem, depression, and a low locus of self-control. In addition to these factors, denial of the hearing loss, stigma, and low perceived benefit of amplification by some people may contribute to their reticence to seek assistance with a hearing loss. However, a substantial group of elderly people remains who purchase hearing aids but rarely use them. Consumers report the top reason for not wearing hearing aids is poor benefit, particularly in noise, restaurants, and large groups [5]. The rejection of hearing aid use by this group appears to be associated, at least in part, with the inordinate difficulties that elderly listeners experience in the realistic, degraded listening situations described earlier in this article (pages 11–14). The current generation of hearing aids, by themselves, will not reduce the deleterious effects of reverberation, rapid speech, or a background of multiple talkers. Moreover, hearing aids will not reduce the impact of excessive cognitive demands of a particular listening task, which may include a considerable memory load, alternating talkers, and minimal contextual cues. Hearing aids may also provide limited benefit for individuals with extensive damage to high-frequency regions of the cochlea [67–68] or throughout the cochlea as evidenced by severe-to-profound sensorineural hearing loss [69].

Recent technological developments provide solutions to many of these seemingly intractable problems. Assistive listening devices, including frequency modulation (FM) systems and infrared systems, improve speech understanding in rooms characterized by long reverberation times and poor SNRs. Miniature FM receivers can now be built into a behind-the-ear hearing aid, and with the use of a hand-held transmitter, a personal FM system is available as an option on an individual's own hearing aid, making this technology more portable and easier to use than ever before. Boothroyd reported that eight elderly listeners with hearing impairment achieved similar phoneme recognition scores in noise with an FM system compared with scores in quiet with amplification provided by a hearing aid [70]. However, these elderly subjects tended to report less subjective benefit from the FM system than young subjects in the investigation. In another study, 18 elderly veterans with severe hearing loss reported improvement with the use of an FM system for hearing at a distance and for hearing conversations with groups in noise [71]. Careful counseling and instruction appear to be crucial factors in maximizing the benefit of FM technology for this population.

Closed captioning is an assistive technology designed to provide access to television and other video broadcasts for persons with hearing disabilities. A text display of the audio portion of the program is superimposed on the video at a rate of approximately 141 WPM [72]. The Federal Communications Commission (FCC) has required that all analog television sets with screens 13 inches and larger sold in the United States after 1993 contain the circuitry that decodes and displays closed captioning. This FCC requirement has also been applied to digital televisions since 2002. Closed captioning eliminates the problems in hearing and understanding speech that may be produced by variable talkers, fast talkers, and heavily accented speakers. It also eliminates problems associated with a poor SNR in the broadcast or because of poor acoustics in the viewing room. The application of closed captioning has expanded recently to movie theaters. Rear window technology, developed by the National Center for Accessible Media at WGBH in Boston, provides closed captioning through a small Plexiglas screen that can be mounted at any seat in the theater [73]. Although closed captioning was developed initially for use by deaf people, it undoubtedly improves reception of television programs and theater movies for elderly people with hearing loss. To date, however, virtually no research has been conducted to verify the benefit and use of closed captioning among elderly hearing-impaired adults.

Cochlear implants are another treatment option and have been shown to be quite beneficial for elderly people (>60 years) with severe and profound acquired hearing losses. Elderly people show better speech-recognition performance in quiet with their cochlear implants than their preimplant performance [74–75]. They also report satisfaction with their cochlear implants [76]. While some reports indicate that elderly people achieve the same speech-recognition scores as younger people with cochlear implants [77], these same reports also indicate that elderly cochlear implant users have a slower learning curve. Other studies indicate that people over the age of 70 with cochlear implants, on average, obtain lower speech-recognition scores than younger people [78]. These observations are not surprising, because cochlear implants convey speech information using high pulse rates of stimulation, and aging appears to be accompanied by limits in processing information presented at a rapid rate.

Future technological developments in digital hearing aids are likely to employ signal processing strategies that alter the speech signal in some manner to make it more intelligible for elderly people. One promising strategy is to increase the duration of selected segments of the speech signal, as discussed in a previous section (page 15) of this article. In particular, the technique of selective time expansion of consonants has proven to be quite beneficial to young and elderly listeners alike when the original speech stimulus is presented at a fast rate [46]. A portable device has been developed in Japan that slows the speed of speech in real time using time-scale modification of speech segments above a certain power level (i.e., vowels, fricatives) [79]. The device, which features user-selected speech rates, was developed for elderly people who have difficulty processing the rapid speech rates inherent in radio broadcasting. Preliminary reports indicate that elderly listeners show improvement for sentence recognition, but not word recognition, using this device [79].

CONCLUSIONS

Hearing loss among elderly citizens is a prevalent problem that affects their ability to understand speech in quiet, noise, and reverberation. Elderly people also experience difficulty understanding rapid speech, heavily accented English, and speech with few contextual cues and/or added memory demands. Multiple sources are thought to contribute to the communication deficits of elderly people, including hearing loss, cognitive decline, and slowed temporal processing. Processing brief changes in stimulus duration and presentation rate for signals embedded in sequences are notably difficult for elderly people, which suggests that auditory temporal processing deficits may relate to the observed problems in understanding rapid speech and accented English. Hearing aids provide benefit for elderly people in hearing and understanding conversational speech in quiet and some noise conditions, and they reduce the communication disability imposed by hearing impairment. Nevertheless, most elderly people with hearing loss do not choose to use amplification, because of an array of complex psychological and social factors. Moreover, a substantial number of elderly people who obtain hearing aids do not use them consistently, undoubtedly because hearing aids do not alleviate the communication difficulties that elderly people experience in many degraded listening situations. The research findings suggest that the older person's problems in processing rapid acoustic information and information with disruption in prosody may be important to address in the next generation of signal processing hearing aids. Assistive listening devices and new advances in digital signal processing hold great promise to improve speech reception for elderly listeners in some of these difficult communication situations. However, extensive counseling is necessary for elderly people to set realistic expectations of the value and use of new technology and ultimately to reap the benefits that new devices may provide.

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