Temporal processing in the aging auditory system

Anne Strouse,[a] Daniel H. Ashmead, Ralph N. Ohde, and D. Wesley Grantham
Division of Hearing and Speech Sciences, Vanderbilt University School of Medicine, Nashville, Tennessee 37232

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Measures of monaural temporal processing and binaural sensitivity were obtained from 12 young (mean age=26.1 years) and 12 elderly (mean age=70.9 years) adults with clinically normal hearing (pure-tone thresholds ≤20 dB HL from 250 to 6000 Hz). Monaural temporal processing was measured by gap detection thresholds. Binaural sensitivity was measured by interaural time difference (ITD) thresholds. Gap and ITD thresholds were obtained at three sound levels (4, 8, or 16 dB above individual threshold). Subjects were also tested on two measures of speech perception, a masking level difference (MLD) task, and a syllable identification/discrimination task that included phonemes varying in voice onset time (VOT). Elderly listeners displayed poorer monaural temporal analysis (higher gap detection thresholds) and poorer binaural processing (higher ITD thresholds) at all sound levels. There were significant interactions between age and sound level, indicating that the age difference was larger at lower stimulus levels. Gap detection performance was found to correlate significantly with performance on the ITD task for young, but not elderly adult listeners. Elderly listeners also performed more poorly than younger listeners on both speech measures; however, there was no significant correlation between psychoacoustic and speech measures of temporal processing. Findings suggest that age-related factors other than peripheral hearing loss contribute to temporal processing deficits of elderly listeners. [S0001-4966(98)05210-2]

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INTRODUCTION

One of the factors identified in psychoacoustic experiments as contributing to poor speech perception is the reduced temporal resolving power of the auditory system (Dreschler and Plomp, 1985; Ginzel *et al.*, 1982; Price and Simon, 1984; Schneider, 1997; Tyler *et al.*, 1982). Processing of temporal information may occur via monaural and/or binaural inputs. Monaural processing refers to what happens to the signal arriving at a single ear (although this normally occurs in parallel for the signals at both ears). Binaural processing refers to the analysis of the *differences* between signals arriving at the two ears. They operate at different time scales (a few milliseconds for monaural resolution versus small fractions of a millisecond for binaural resolution), and monaural temporal processing is more involved in following a speech signal whereas binaural processing contributes to separating the signal from competing sounds. Consequently, monaural and binaural aspects of temporal resolution may each contribute uniquely to speech perception.

A. Monaural temporal processing

The most common way of investigating monaural temporal processing is by means of gap detection, defined as the ability to detect a brief period of silence between two test signals. Numerous studies have reported that listeners with hearing loss have larger gap detection thresholds (Buus and Florentine, 1985; Glasberg and Moore, 1989; Irwin and McAuley, 1987; Moore and Glasberg, 1988; Moore *et al.*, 1989; Tyler *et al.*, 1982). Because most elderly listeners have some degree of hearing loss, it is important to determine whether changes in temporal processing occur independent of peripheral hearing loss.

Several studies have attempted to control for the confounding effect of age-related hearing loss on gap detection thresholds (Moore *et al.*, 1992; Schneider *et al.*, 1994; Snell, 1997). Moore *et al.* (1992) measured thresholds for the detection of temporal gaps in sinusoidal signals as a function of frequency in elderly hearing-impaired subjects and elderly subjects with ''near-normal'' hearing (audiometric thresholds ≤25 dB HL from 250 to 2000 Hz). Results were compared to previous data collected from young normally hearing subjects (Moore *et al.*, 1993), revealing that elderly subjects with near-normal hearing had higher gap detection thresholds than young subjects. Moore *et al.* (1992) attributed this result to the inclusion in the elderly group of some individuals who had large gap detection thresholds. Nevertheless, when they compared gap thresholds in elderly subjects with near-normal hearing to those with hearing impairment, they found no difference between the two groups. Schneider *et al.* (1994) reached a similar conclusion. In this study, thresholds for detecting a gap between two Gaussian modulated 2000-Hz tones were measured in young and elderly listeners with pure-tone thresholds ≤25 dB HL from 250 to 3000 Hz. Gap detection thresholds were longer and more variable for elderly listeners than for young listeners. Snell (1997) more rigorously controlled for high-frequency hearing loss in elderly subjects, measuring gap detection thresholds for noise-burst stimuli in young and elderly listeners with pure-tone thresholds ≤20 dB HL from 250 to 4000

[a]Current address: VA Medical Center, Audiology Service (126), Mountain Home, TN 37684. Electronic mail: anne.strouse@med.va.gov

Hz. Again, gap thresholds were significantly larger in elderly subjects. Thus the studies agree in that all found some elderly individuals who exhibited losses in temporal resolution that were unrelated to degree of hearing loss. Therefore it is reasonable to consider factors other than peripheral hearing loss that could account for age-related differences in monaural temporal resolution.

Whether gap detection ability is important for accurate perception of speech remains questionable. It is widely accepted that many speech events that are critical for speech perception are of short duration (Dorman *et al.*, 1979; Pickett and Decker, 1960; Repp *et al.*, 1978). For example, gap detection ability has been linked to a listener's ability to process time events related to distinctions in speech between voiced-voiceless cognates and various manners of syllable transition (DeFillippo and Snell, 1986). It has also been demonstrated that in adverse listening situations, segment duration may be an especially important cue to phonetic identity (Wardrip-Fruin, 1982). The relationship between gap detection and speech perception has been widely studied using multivariate correlation analyses. Several investigations reveal significant correlations between gap detection and speech recognition ability even when audiometric threshold is factored out (Dreschler and Plomp, 1985; Glasberg and Moore, 1989; Tyler *et al.*, 1982; Tyler and Summerfield, 1980). Reduced gap detection ability has been associated with poorer performance on speech in noise tests and discrimination of syllables varying in duration of voice onset time (VOT) (Dreshler and Plomp, 1985; Tyler *et al.*, 1982). Thus it is conceivable that perceptual problems with short duration stimuli such as those observed in temporal gap experiments may partially underlie the communication problems of the elderly. Other studies, however, find no significant correlation between these factors (Divenyi and Haupt, 1997; Festen and Plomp, 1983; Lutman and Clark, 1986; van Rooij and Plomp, 1990). Thus the relationship between gap detection and speech perception has not been firmly established.

The perception of temporal differences in speech can be measured directly by examining categorical perception of temporal aspects of speech such as duration of formant transitions, duration of frication, or differences in VOT. VOT, defined as the temporal interval between the burst or release of a stop consonant and the onset of periodic vibration of the vocal cords, is one of the major parameters distinguishing voiced and voiceless consonants (Lisker and Abramson, 1970). Several investigators have used categorical perception to study temporal factors in speech perception. Some have reported that neither age nor mild-to-moderate hearing impairment affect a listener's ability to make phonetic judgments based on temporal stimulus properties (Dorman *et al.*, 1985; Tyler *et al.*, 1982). On the other hand, Godfrey and Millay (1978) found that about half of their sample of hearing-impaired listeners were unable to identify stimuli which varied in the duration of formant transitions. Price and Simon (1984) found that older listeners (who had good hearing for their age, but higher pure-tone thresholds than younger listeners) required longer silence durations to report hearing differences in stop consonants. Age-related difficulties in identification have also been reported for stimuli in which vowel duration, voice onset time, and fricative noise duration were manipulated (Ginzel *et al.*, 1982).

B. Binaural temporal processing

Older adults with peripheral hearing loss show reduced performance on such binaural tasks as the masking-level difference (Findlay and Schuchman, 1976; Olsen *et al.*, 1976), interaural time discrimination (Herman *et al.*, 1977; Kirikae, 1969; Matzker and Springborn, 1958), and the precedence effect (Cranford *et al.*, 1990). However, little age-related change in binaural processing has been reported by other researchers (Kelly-Ballweber and Dobie, 1984; Palva and Jokinen, 1970).

Much of the psychoacoustic literature directed toward the effects of aging on binaural processing has focused on sensitivity to interaural time differences (ITD) (Herman *et al.*, 1977; Kirikae, 1969; Matzker and Springborn, 1958). These studies have varied widely in method, age groups tested, and stimuli, however, a consistent finding has been that younger adults have lower thresholds for ITDs than older adults. Little attempt was made, however, to control for the effects of hearing loss on ITD thresholds despite use of experimental stimuli containing higher-frequency spectra such as clicks and wideband noise.

Herman *et al.* (1977) recognized the possible confounding effects of high-frequency hearing loss on ITD thresholds and thus attempted to control for such an effect by testing individuals with normal pure-tone thresholds below 2000 Hz. Although all subjects in this study had normal hearing below 2000 Hz, older subjects had substantially greater hearing loss than young subjects at higher frequencies. Pure-tone loss in the elderly group increased from 4.38 dB at 2000 Hz to 44.38 dB at 4000 Hz, while loss for young subjects increased from -4.0 dB at 2000 Hz to only 1.56 dB at 4000 Hz. Thus it is not clear whether the reported age-related loss in the ability to lateralize the source of a sound on the basis of interaural time delay observed in elderly individuals was caused by aging, *per se*, or by the high-frequency peripheral hearing loss. Hearing loss in younger individuals has been shown to adversely affect binaural abilities (Durlach *et al.*, 1981; Hausler *et al.*, 1983).

To the extent that there are age-related changes in binaural processing, older people might be expected to have problems in situations where binaural hearing is useful, such as sound localization and comprehending speech in noisy settings. Although age-related changes in speech perception have not been tightly linked to binaural processing deficits, older adults tend to do worse than younger adults at various dichotic listening tasks (Kelly-Ballweber and Dobie, 1984; Martin and Cranford, 1991; Roush, 1985).

A common measure of binaural processing for speech is the masking level difference (MLD). The MLD is a phenomenon resulting in improved binaural hearing sensitivity when a phase reversal is imposed on either a primary signal or its masking noise. Several theories have been proposed to account for this phenomenon, but all are based on binaural analysis of interaural differences in time and intensity for dichotically presented stimuli (Moore, 1982). Several studies have indicated that elderly subjects have reduced MLDs compared to younger subjects (Findlay and Schuchman, 1976; Tillman *et al.*, 1973; Warren *et al.*, 1978). In a recent investigation, Grose *et al.* (1994) compared MLDs for speech in a group of elderly listeners with normal hearing through 2000 Hz to those obtained from a group of young normal-hearing listeners. Results again showed that elderly subjects performed more poorly than the young listeners. Although these findings may be due, in part, to age differences, peripheral hearing loss in the older subjects may have accounted for their smaller MLDs compared with those of the young normal-hearing groups, since it has been established that presence of peripheral hearing loss significantly reduces the MLD (Jerger *et al.*, 1984). Nonetheless, several studies have examined the MLD, accounting for peripheral effects, and have found statistically significant differences between young and elderly subjects, suggesting further decline in binaural processing with advancing age (Olsen *et al.*, 1976; Pichora-Fuller and Schneider, 1991).

To determine whether losses in temporal resolution are attributed to age-related factors other than sensorineural hearing loss, temporal resolution must be measured in an elderly population with good hearing sensitivity. Findings of previous studies may have been confounded by age-related hearing loss since high-frequency audiometric thresholds were not included in selection criteria of older subjects with normal hearing. For the present investigation, we were in a unique position in that elderly subjects available for study had audiometric thresholds $\leqslant$20 dB HL from 250 to 6000 Hz. By more rigorously controlling for degree of peripheral hearing loss over a wider range of audiometric frequencies, any changes in temporal processing ability could be more strongly attributed to factors associated with aging. Thus for the present sample, if temporal processing is normal as long as hearing is normal, regardless of age, this would mean that reported decreases in temporal processing ability in older listeners are primarily the result of reduced hearing sensitivity. On the other hand, if temporal processing is ''abnormal'' in older subjects even when hearing is better than 20 dB HL, this would imply that there exist age-induced alterations in auditory structures and/or processes which are not detected by conventional pure-tone measures.

I. METHOD

A. Subjects

Two groups of subjects were tested, 12 normally hearing young adults, aged 20–30 years (mean=26.1, range 22–30) and 12 normally hearing elderly adults aged 65–75 years (mean=70.9, range 66–75). The groups were matched for gender (ten female and two male subjects) and hearing sensitivity. Normal hearing was defined as 20 dB HL or better pure-tone thresholds for the frequencies 250–6000 Hz bilaterally. At 8000 Hz, close matching of young and elderly subjects could not be achieved despite extensive audiometric screening of potential subjects. Regarding the interpretation of ''normal hearing,'' some researchers have used published age-relative norms, whereas others have selected subjects who meet criteria established for young adults. We used the latter approach, based on evidence that reduced temporal processing ability is associated with hearing impairment, independent of age (Florentine and Buus, 1984; Moore and Glasberg, 1988; Moore *et al.*, 1989). The present study included older subjects with pure-tone thresholds as close as possible to those of a control group of young subjects, to help ensure that any resulting age differences would not be attributable to peripheral hearing loss, although this means that the older subjects had better hearing than is normal for their age. The mean pure-tone audiometric thresholds (in dB HL *re:* ANSI, 1969) for each group are shown in Table I. Hearing thresholds for all subjects were symmetrical (interaural differences $\leqslant$10 dB at each frequency), with no conductive component. There was no significant difference in pure-tone thresholds between groups at any frequency. In an analysis of variance there were no significant main effects or interactions involving age [$F(1,22)=3.72$; $p=0.07$], ear [$F(1,22)=0.93$; $p=0.34$], or tone frequency [$F(1,22)=0.30$; $p=0.143$].

TABLE I. Mean audiometric thresholds (dB HL) and standard deviations (dB) for young and elderly listeners.

	Frequency (kHz)						
	0.25	0.5	1	2	3	4	6
Young subjects ($N=12$)							
Mean—Right ear	7.9	7.5	7.9	8.3	10.4	11.2	13.8
	(4.9)	(4.5)	(3.9)	(4.4)	(3.9)	(4.3)	(4.3)
Mean—Left ear	7.1	5.0	5.8	8.8	9.6	12.9	13.3
	(4.9)	(5.2)	(4.2)	(2.3)	(2.6)	(2.6)	(3.9)
Elderly subjects ($N=12$)							
Mean—Right ear	9.6	10.8	10.0	10.4	12.5	14.1	15.8
	(2.6)	(3.6)	(6.0)	(5.8)	(3.9)	(3.6)	(5.1)
Mean—Left ear	7.1	5.8	7.1	10.4	11.6	14.6	16.3
	(3.9)	(3.6)	(3.3)	(3.9)	(4.4)	(3.9)	(4.8)

B. Procedures

Four tasks were presented to each subject. Monaural temporal processing was measured using a gap detection paradigm. Binaural sensitivity was measured by interaural time difference (ITD) thresholds. Data were collected from the two groups at three different presentation levels (4, 8, and 16 dB), defined with respect to each individual's threshold for detecting the test stimulus. Low presentation levels were chosen based on evidence that the temporal resolution of the auditory system has been found to worsen somewhat at low sound levels for all types of stimuli (Gregory, 1974). Thresholds for the detection of a temporal gap in a noise stimulus increase when the level per critical band is less than 40 to 50 dB above the absolute threshold (Buus and Florentine, 1985; Fitzgibbons, 1983; Shailer and Moore, 1983). Further evidence is consistent with a worsening of temporal resolution at low sound levels. For example, the rate of recovery from forward masking decreases as the sensation level of the masker is reduced (Jesteadt *et al.*, 1982; Moore and Glasberg, 1983). The ability to detect amplitude modulation at various modulation rates worsens at low sound levels, again indicating reduced temporal resolution at low levels (Bacon and Viemeister, 1985). Although no published data are available, researchers have examined age differences in sensitivity to interaural time differences as a function of sound level (Ashmead *et al.*, unpublished data). They tested young and older adults, obtaining ITD thresholds at each of three overall sound levels (8, 16, and 30 dB SL relative to individual detection thresholds). Findings revealed that the difference between age groups was greater at low stimulus levels.

Each subject was also evaluated on two measures of speech perception. One of these was the masking level difference (MLD), which examined the ability to utilize binaural cues including interaural temporal differences to recognize speech. The second test was a syllable identification task that included phonemes varying in voice onset time (VOT). All testing took place in a double-walled sound booth using TDH49P headphones, where subjects were seated in front of a computer. The computer monitor provided visual feedback during testing and subject responses were entered on the computer keyboard (with the exception of the responses for the MLD task, which were repeated aloud). The order of presentation for the four tasks was randomized across subjects. Subjects were tested in three sessions, each lasting 1–1.5 h, and were paid for their participation.

C. Gap detection

1. Stimuli

Stimuli for the gap detection task were computer-generated 1000-Hz sinusoidal signals presented in a continuous background noise with a spectral notch at the frequency of the sinusoid. Signals were generated using a Dell XPSP90 laboratory computer and Tucker-Davis Technologies (TDT) Psychoacoustic System, with 16-bit digital-to-analog (D/A) converters, a 10-kHz sampling rate (low-pass filtered at 4 kHz to prevent aliasing), and a rise–fall time of 5 ms. The overall duration of each observation interval was 200 ms. To determine the duration of the signal on either side of the gap, the gap duration was subtracted from 200 ms and the result divided by two. The duration of the signal preceding and following the gap was then rounded to the nearest ms. The gap started with the signal at a positive-going zero crossing and ended with the phase needed for a given gap duration.

The 1000-Hz signal was presented in a continuous background noise, with a sharp notch at the signal frequency, designed to mask the spectral splatter associated with the abrupt gating of the gap. The noise masker was a 65 dB SPL (22-dB spectrum level) Gaussian noise with a notch arithmetically centered at the frequency of the test signal (fc); the width of the notch was 0.4fc at the 3-dB down points. The depth of the notch was 37 dB. The noise was recorded on digital audio tape (DAT), and played back through a Panasonic SV3700 DAT deck that led to a programmable attenuator. The signal and noise were combined in a weighted signal mixer and passed through a headphone buffer to the TDH49P headphones.

2. Procedure

Gap detection thresholds were measured using an adaptive two-interval forced choice (2IFC) procedure. On each trial, two 200-ms signals were presented, separated by 1000 ms. One of the two sounds was the ‘‘signal’’ (containing the gap); the other sound was the ‘‘standard’’ (no gap). The order, either signal-standard or standard-signal, was chosen randomly with equal probability. Following stimulus presentation, the subject chose the interval that contained the signal by pressing the appropriate button on the computer keyboard. Gap duration on the first trial was 50 ms so that the stimulus gap was easily detectable. On subsequent trials, gap duration was increased by a factor of $\sqrt{2}$, then rounded to the nearest ms after each incorrect response and decreased by a factor of $\sqrt{2}$ after every two successive correct responses. This two-down, one-up algorithm estimates the 71% point on the psychometric function (Levitt, 1971). In order to ensure that subjects remained attentive to the appropriate cue, gap duration was increased to the starting level of 50 ms following four incorrect responses and remained at 50 ms until the subject responded correctly. Following a correct response, testing was resumed at the gap duration being evaluated before the jump to 50 ms occurred. Trials measured at 50 ms were not considered in gap threshold calculations. Testing continued until ten reversals occurred and gap threshold was estimated as the geometric mean of the gap durations at the last eight reversals.

Before testing began, a practice run was administered at a level of 30 dB relative to the masked threshold for a 1000-Hz continuous tone[1] to ensure that subjects were familiar with the task. Following the practice run, each subject contributed three gap threshold estimates at levels of 4, 8, and 16 dB relative to masked threshold.

Stimuli were presented monaurally to the ear with the least pure-tone threshold loss. If there was no difference between ears, the test ear was chosen randomly. The order of presentation level was randomized across subjects. The mean of the three gap threshold estimates obtained at each intensity level was taken as the gap threshold value.

D. Interaural time differences (ITD)

1. Stimuli

Stimuli for the ITD task were 400-ms-long trains of 40 rectangular clicks, each click lasting 50 μs with an interclick interval of 10 ms. Signals were generated using the same equipment as for the gap detection task, but with a 200-kHz sampling rate. Interaural time differences were implemented by delivering the signal to one ear by an integer multiple of the sampling period (5 μs).

2. Procedure

Thresholds for interaural time differences were measured using an adaptive 2IFC procedure. On each trial, two successive 400-ms click trains were presented. The first click train was presented with a 0-μs ITD, thus presented to both ears simultaneously. For the second click train in the series, the desired ITD was created by offsetting the clicks to the two channels in 5-μs intervals. Thus the auditory impression was of a sound image that occurred first at midline and then to the side (left or right, depending on the trial). The ear receiving the delayed click train was chosen randomly with equal probability. Following stimulus presentation, the subject indicated whether the sound image was perceived to the left or to the right by pressing the appropriate button on the computer keyboard. The ITD on the first trial was 100 μs. On subsequent trials, step size was 20 μs through the first reversal and 5 μs thereafter. In order to encourage subjects to remain attentive to the appropriate cue, ITD duration was increased to a level of 400 μs following four incorrect responses and remained at 400 μs until the subject responded correctly. Following a correct response, testing was resumed at the ITD being evaluated before the increase occurred. Trials measured at 400 μs were not considered in ITD threshold calculations. Testing continued until ten reversals occurred and ITD threshold was estimated as the geometric mean of the ITD from the last eight reversals.

Initially, a practice run was administered at a level of 30 dB relative to the binaural click threshold.[2] During testing, each subject contributed three ITD threshold estimates at levels of 4, 8, and 16 dB relative to binaural click detection threshold. The order of the presentation level was randomized across subjects. The mean of the three ITD threshold estimates obtained at each intensity level was taken as the ITD threshold value.

E. Voice onset time (VOT)

1. Stimuli

VOT was examined by creating a sound continuum which varied in the duration of VOT in small steps. A continuum of consonant–vowel (CV) syllables ranging from /ba/ to /pa/ was created using the Computerized Speech Research Environment (CSRE) cascade/parallel synthesis program modeled after Klatt (1980) (AVAAZ Innovations, Inc., 1994) and a laboratory computer. Acoustically, the stimuli differed only in VOT. VOT ranged from 0 to 60 ms in 10-ms steps, creating a continuum of seven stimuli. A /ba/ syllable with a duration of 300 ms was synthesized at a sampling rate of 20 kHz. Fundamental frequency ($F0$) contour began at 103 Hz and rose to 125 Hz over the duration of the syllable. During a 40-ms transition period, the three lowest formant onset frequencies moved until they reached appropriate steady-state values (Blumstein and Stevens, 1980). For generation of the six additional members of the continuum, VOT variations were accomplished by altering the onset of voicing and the duration of aspiration in 10-ms steps following the initial burst.

2. Procedure

Listeners identified and discriminated the /ba/–/pa/ continuum. Stimuli for both tasks were presented to the subject's better ear at an individually determined most comfortable loudness level. Subjects listened to conversational speech through headphones and adjusted the level of the speech using the computer keyboard to their preferred listening level. Because young and elderly subjects had similar hearing sensitivity, presentation levels did not vary significantly between groups [$F(1,23)=0.362$; $p>0.05$]. Presentation levels ranged from 68 to 86 dB SPL.

For the identification task, subjects initially responded to the series of seven stimuli representing the ordered continuum from /ba/ to /pa/. This set was then repeated to familiarize the listener with the range of stimuli involved. Following familiarization, stimuli were presented randomly. A set of ten stimulus blocks (70 trials) was used to generate identification functions. Data were collected using a single-interval forced-choice paradigm. After presentation of each stimulus, subjects identified the initial consonant of each syllable as either /b/ or /p/.

The discrimination task involved one-step and two-step presentations of a pair of stimuli in an AX (same–different) format. The stimulus pairs contained either two identical stimuli (i.e., ''catch'' trials), or two stimuli which differed in VOT. In the one-step condition, pairs of CV stimuli that differed by 10-ms VOT were presented, resulting in six pairs of experimental trials. Pairs were each presented 20 times, in random order, with 500-ms interstimulus intervals. Intermixed with the 120 experimental trials were 120 catch trials. The 240 stimuli were arranged in 20 blocks, each containing 12 randomized stimulus pairs. In the two-step condition, pairs of experimental stimuli that differed by 20-ms VOT were presented, resulting in five pairs which were each presented 20 times. Intermixed with the 100 experimental trials were 100 catch trials. The 200 stimuli were arranged in 20 blocks, each containing ten randomized stimulus pairs. After presentation of each stimulus pair in both one- and two-step tasks, the subject indicated whether the stimuli were the ''same'' or ''different.''

F. Masking level difference (MLD)

1. Stimuli

The MLD was measured using speech as the stimulus and was determined by presenting a continuous speech noise binaurally and in-phase (N_0), then determining the speech reception threshold when the binaural speech signal was presented interaurally in-phase (S_0) and interaurally out-of-phase 180° (S_π). The threshold difference (in decibels) between the two masking conditions (S_0N_0 minus $S_\pi N_0$) defined the MLD.

Both the speech signal and masker were presented through a standard two-channel clinical audiometer (GSI-10) which has a network allowing phase reversal of either the noise or test signal. The stimuli for the speech MLD were the 36 spondaic words of the CID W-1 list. The spondaic words, and their associated calibration tone, were presented using a compact disc recording (Department of Veterans Affairs, 1991) played on a JVC XL-V161 compact disc player routed through the audiometer. The recording consisted of two randomizations of the CID W-1 word list for a total of 72 spondaic words separated by 4-s interstimulus intervals. The masker for the speech MLD was a broadband noise with equal energy per Hz from 250 to 1000 Hz with 12 dB/oct rolloff from 1000 to 6000 Hz. During the experiment, the masker was presented continuously at an overall level of 65 dB SPL. Presentation levels of both the speech signal and

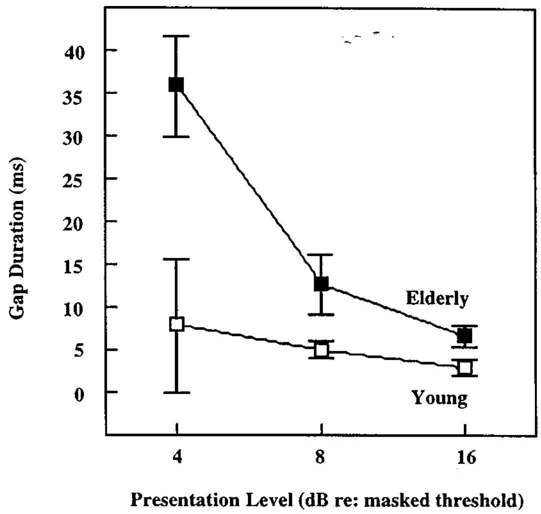

FIG. 1. Mean gap detection thresholds for young and elderly adult listeners at the 4-, 8-, and 16-dB sound levels presented relative to individual masked thresholds. Error bars indicate ± standard error.

masker were verified using sound level measurements (Larson-Davis Laboratories, model 800B).

2. Procedure

To familiarize listeners with the test materials, a written list of the CID W-1 spondaic words was provided for subjects to read before testing began. Each listener was then presented with a randomization of the stimuli at a comfortable listening level in the absence of masking noise. To obtain the MLD, threshold was determined for spondee words in the diotic (S_0N_0) and dichotic ($S_\pi N_0$) conditions in the presence of a continuous masking noise. To determine threshold, a one-up, one-down adaptive procedure was used. The first word of each test sequence was presented at 85 dB SPL, representing a level that was 20 dB greater than the level of the continuous noise masker. The subject reported aloud the perceived word. Following each correct response, the level of the speech was attenuated in 5-dB steps until an incorrect response was recorded. Thereafter, the level of the signal was decreased in 2-dB steps following a correct response and increased in 2-dB steps following an incorrect response. Testing continued until ten reversals occurred, and the mean of the final eight reversal levels was taken as an estimate of threshold. Once thresholds for both diotic and dichotic conditions were obtained, the dB difference between the two conditions was recorded as the speech MLD.

II. RESULTS AND DISCUSSION

Results of the present study indicated significant age differences on measures of gap detection, ITD thresholds, slope of the VOT identification function, discrimination of VOT cues, and MLD thresholds. Thus elderly subjects performed more poorly than their younger counterparts on these tasks, even though all subjects had normal-hearing sensitivity.

A. Gap detection

Figure 1 shows mean gap detection thresholds obtained at the 4-, 8-, and 16-dB sound levels (relative to individual masked thresholds). Data were examined using an analysis of variance (ANOVA) with sound level as the within-subjects factor and age group as the between-subjects factor. Results indicated significant effects of age group [$F(1,22) = 23.57$; $p < 0.0001$], sound level [$F(2,44) = 27.13$, $p < 0.0001$], and the interaction of age group and sound level [$F(2,44) = 14.05$, $p < 0.0001$]. As shown in Fig. 1, the difference in performance between young and elderly adults was especially large at very low sound levels. Performance was significantly different between age groups at all three sound levels (4 dB: [$F(1,22) = 14.49$, $p < 0.001$]; 8 dB: [$F(1,22) = 6.71$, $p < 0.05$]; 16 dB: [$F(1,22) = 21.45$, $p < 0.0001$]).

To further assess the relationship between gap detection performance and signal level, a linear regression line was fit for each individual subject (linear fits were used as they proved as good as linear plus quadratic fits during regression analysis), and slopes were averaged across subjects within each group. The mean slope values based on individual best-fit linear regression lines were significantly [$F(1,22) = 15.33$, $p < 0.001$] different for young adults (-0.44) as compared to those for the elderly group (-2.45).

Present findings are in agreement with earlier studies using sinusoidal stimuli which reported larger gap detection thresholds in elderly listeners with minimal hearing loss (Moore *et al.*, 1992; Schneider *et al.*, 1994). In fact, gap detection thresholds for young and elderly adult subjects measured at the highest presentation level in the present study (2.8 and 6.7 ms for young and elderly subjects, respectively) are quite similar to those reported by Schneider *et al.* (1994) (young = 3.8 ms; elderly = 6.2 ms) using suprathreshold stimuli. Collectively, findings of Moore *et al.* (1992), Schneider *et al.* (1994), and the present investigation are similar in that each identified some elderly individuals who exhibited deficits in temporal processing that were unrelated to hearing loss. Snell (1997) also observed larger thresholds for detection of gaps using noise-burst stimuli for elderly subjects with audiometric thresholds similar to those obtained for the present study.

Previous studies reported temporal processing ability as measured by the ability to detect gaps in sinusoids at relatively high sound levels. Moore *et al.* (1992) obtained gap detection thresholds at 25, 40, 55, 70, or 80 dB SPL and subjects were tested only at levels for which the signal was clearly audible. Schneider *et al.* (1994) evaluated three young control subjects at 10, 20, 40, and 60 dB SL, but elderly listeners were evaluated at a single high-intensity signal level. Thus the only information reported regarding performance of elderly subjects on gap detection tasks was measured well above audiometric threshold.

Schneider *et al.* (1994) did not find an effect of level on gap detection thresholds over most of the range of levels tested in their three young control subjects (with the exception of 10 dB SL). Therefore they concluded that it was not likely that the poorer gap detection performance of the older subjects was due to the effect of sensation level. Their use of Gaussian-enveloped tones minimized the likelihood that spectral differences contributed to the ability to detect temporal gaps. They showed that spectral differences within notched noise were much larger for gaps in continuous noise (used in the present study) than for gaps between two

Gaussian-enveloped tones. Thus it is possible that the increase in gap detection thresholds at lower presentation levels may have been influenced by spectral differences. Since all subjects in the present study had hearing within normal limits, however, we would expect the contribution of spectral cues, if any, to have a similar effect on gap threshold for all listeners regardless of age. Thus the large differences between groups at low sensation levels cannot be entirely explained by spectral cues. It is possible that the effect of level is only apparent closer to audiometric threshold, as even two of three young control subjects in the Schneider *et al.* (1994) study had elevated gap detection thresholds at the 10-dB sensation level (compared to the 20-, 40-, and 60-dB levels in the same study). Since stimulus levels in the present study were defined with respect to individual thresholds, and since the groups had comparable pure-tone thresholds, the age differences cannot be attributed to overall hearing sensitivity. Rather, results suggest that there is a general tendency for decreased performance on the gap detection task at low sound levels.

B. Voice onset time

Figure 2 shows mean identification functions for the /ba/–/pa/ syllable series. All listeners in both groups identified two clear phoneme categories. Phoneme intercept values (phonetic boundaries) along the identification functions were determined for each subject by performing a linear regression across *z*-transformed identification scores for stimuli on the continuum. The mean phonetic boundary for the young adult group was 27 ms, which is in agreement with previous findings for normal-hearing young adults (Lisker and Abramson, 1970; Tyler *et al.,* 1982). For the elderly adult group, the mean phonetic boundary was 32 ms. ANOVA on the data revealed that there was no significant difference in mean phonetic boundary between young and elderly listeners [$F(1,22)=2.41$, $p>0.05$], indicating that the two groups used a similar criterion for identifying VOT. The mean slope of the boundary was also determined for each subject using linear regression. The mean slope value was -1.41 for the young adult group and -0.93 for the elderly adult group. This identification slope for the younger group was significantly steeper than that of the elderly group [$F(1,22)=4.30$, $p<0.05$].

In Fig. 3, the open symbols show mean one-step and two-step discrimination functions for the /ba/–/pa/ continuum from each subject group. Predicted discrimination functions (shown by filled symbols) were derived from the identification responses using the procedures described in Pollack and Pisoni (1971), which are based on the assumption that subjects rely on phonetic labels in the discrimination task (Liberman *et al.,* 1967). The peak of the predicted curve depends on the position and slope of the phoneme boundary in the identification function. Predicted scores were calculated for each subject using the following formula:

$$P_{c(a,b)}=0.5[(1-P_{a1})^2+(1-P_{b2})^2]+P_{a1}P_{b2},$$

where $P_{c(a,b)}$ = predicted percent correct for any pair of stimuli along a continuum. P_{a1} = probability that the first stimulus in the pair is identified as a member of a given phoneme category. P_{b2} = probability that the first stimulus in the pair is identified as a member of another phoneme category. The phonetic model is based on the assumption that sounds are coded as one phoneme or another. Thus this model indicates the classical categorical perception phenomenon. That is, sounds that are of different categories should be discriminable whereas sounds in the same category should not be discriminable. When both stimuli involved in a comparison come from one phoneme category, the predicted percent correct discrimination scores are near chance (50%). When the pair of stimuli come from two different phoneme categories, the predicted score is greater than chance, with the magnitude of the score dependent on consistency of the identification performance.

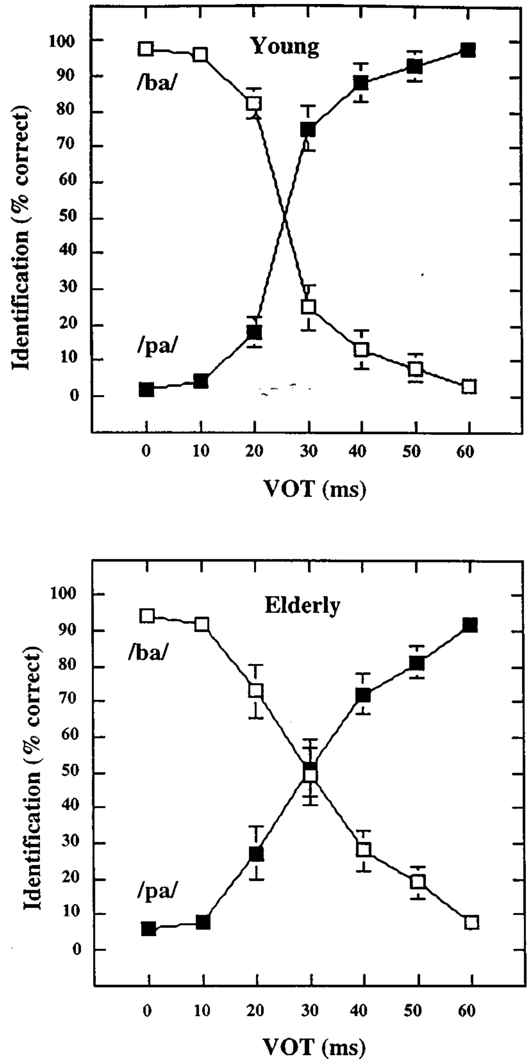

FIG. 2. Mean identification functions including standard error values for young and elderly listeners for the seven-step /bɑ/–/pɑ/ continuum.

Figure 3 (top) displays mean one-step discrimination scores for young and elderly adult listeners. Data were examined using an ANOVA with score type (obtained versus predicted) and stimulus pair as within-subjects factors and age group as the between-subjects factor. Results revealed a significant effect of age group [$F(1,22)=23.1$, $p<0.0001$], stimulus pair [$F(5,110=12.76$, $p<0.0001$], and a significant interaction between score type and stimulus pair [F(5,110

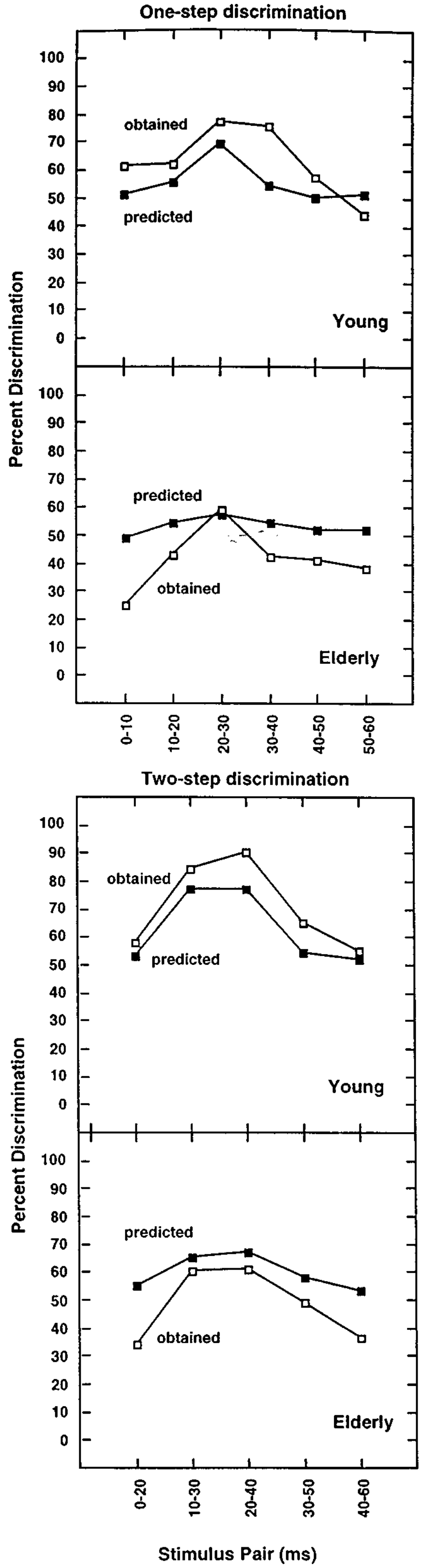

FIG. 3. Mean discrimination scores for the one- and two-step discrimination conditions for young and elderly adult listeners.

$=3.8$, $p<0.01$]. There was a significant interaction between age group and score type [$F(1,22)=17.15$, $p<0.0001$], indicating that the relationship between obtained and predicted scores differed between groups. All listeners exhibited improved discrimination performance at or near the phoneme boundary. An obvious difference is that obtained scores were higher than predicted scores for young adult subjects but not for the elderly subjects. As observed by others (Stevens *et al.*, 1969; Sharf *et al.*, 1988), actual discrimination performance for the young adult group exceeded that predicted by identification data on the one-step discrimination function. For elderly listeners, discrimination performance was poorer than predicted by identification data. To interpret the interaction effect of age group×score type, the simple main effect of age group at each of the two conditions was assessed. Comparisons revealed a significant difference between groups for both predicted and obtained scores at the $p<0.01$ level.

Figure 3 (bottom) shows two-step discrimination scores for young and elderly adult listeners. There was a significant effect of age group [$F(1,22)=16.12$, $p<0.001$], stimulus pair [$F(4,88)=24.36$; $p<0.0001$], and a significant interaction between score type and stimulus pair [$F(4,88)=2.73$, $p<0.05$]. The interaction between age group and score type was also significant [$F(1,22)=12.94$, $p<0.01$]. All listeners exhibited improved discrimination performance at or near the phoneme boundary. Actual discrimination performance for the young group exceeded that predicted by identification data for all stimulus pairs. For the elderly group, although performance increased near the phoneme boundary, overall discrimination ability was lower than predicted values for all stimulus pairs. *Post hoc* comparisons using simple effects testing revealed a significant difference between groups for both predicted and obtained scores ($p<0.01$).

Results of the present study indicate that elderly listeners have reduced sensitivity to differences in VOT as compared to younger listeners. Identification performance revealed a more gradually sloping phonetic boundary, indicating that elderly subjects were less able to clearly distinguish phoneme boundary categories. Discrimination data revealed that actual performance on both one-step and two-step discrimination tasks followed a similar pattern as predicted scores for both groups; the percent correct discrimination scores increased at areas near the phoneme boundary. Actual percentage scores of elderly listeners, however, were lower than what was predicted based on identification data, again indicating decreased ability to distinguish the temporal cue of VOT. The fact that young and old listeners performed differently as a function of predicted and observed discrimination indicates that the categorical model performed differently for these populations. It is likely that the difference in the populations relates to their ability to use auditory cues. Young adults appear to utilize temporal auditory cues within sound categories as evidenced by higher obtained than predicted scores. Older adults are limited in this auditory ability as reflected in poorer obtained than predicted scores across stimulus pairs. This may also indicate that the younger subjects might have been using acoustic as well as phonetic information in forming their discrimination judgments. In the future, one way to assess the auditory component would be to examine predicted functions using the dual-coding model that includes both an auditory and phonetic component (Fujisaki and Kawashima, 1970).

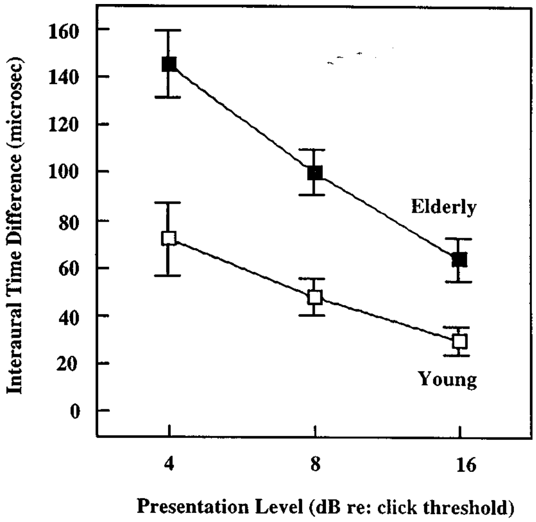

FIG. 4. Mean ITD thresholds for young and elderly adult listeners at the 4-, 8-, and 16-dB sound levels presented relative to individual detection thresholds. Error bars indicate ± standard error.

C. Interaural time differences

Figure 4 shows mean ITD thresholds for young and elderly adults at the 4-, 8-, and 16-dB sound levels. As in the gap experiment, the ITD thresholds of younger adults were lower than those of older adults at all presentation levels. Data were examined using an ANOVA with sound level as the within-subjects factor and age group as the between-subjects factor. Results indicated significant effects of age group [$F(1,22)=19.06$, $p<0.0001$], sound level [$F(2,44)=97.9$, $p<0.0001$], and the interaction of age group and sound level [$F(2,44)=9.52$, $p<0.0001$]. Performance was significantly different between groups at the 16 dB [$F(1,22)=9.18$, $p<0.0001$], 8 dB [$F(1,22)=16.98$, $p<0.0001$], and 4 dB [$F(1,22)=22.59$, $p<0.0001$] sound levels. The mean slope values based on individual best-fit linear regression lines were significantly [$F(1,22)=24.22$, $p<0.01$] different for young adults (−3.55) as compared to those for the elderly group (−6.78). Results for young adult listeners are in agreement with previous findings reporting increased thresholds for detecting interaural phase differences at low sensation levels (Zwislocki and Feldman, 1956).

Previous studies have examined the effects of aging on binaural hearing by measuring sensitivity to ITDs (Herman *et al.*, 1977; Kirikae, 1969; Matzker and Springborn, 1958), however, little attempt was made in these studies to adequately control for the effects of hearing loss on ITD thresholds despite the use of experimental stimuli containing higher-frequency spectra such as clicks and wideband noise. The present data for elderly subjects with normal-hearing sensitivity demonstrate a clear age-related loss in the ability to lateralize the source of a sound on the basis of an interaural time delay. Similar to findings of Herman *et al.* (1977), data revealed that older listeners required approximately twice the interaural time delay as young listeners for the same level of performance. The interaction of age and sound level indicated that a decrease in stimulus level had a more deleterious effect on ITD discrimination in the elderly group than in the younger group.

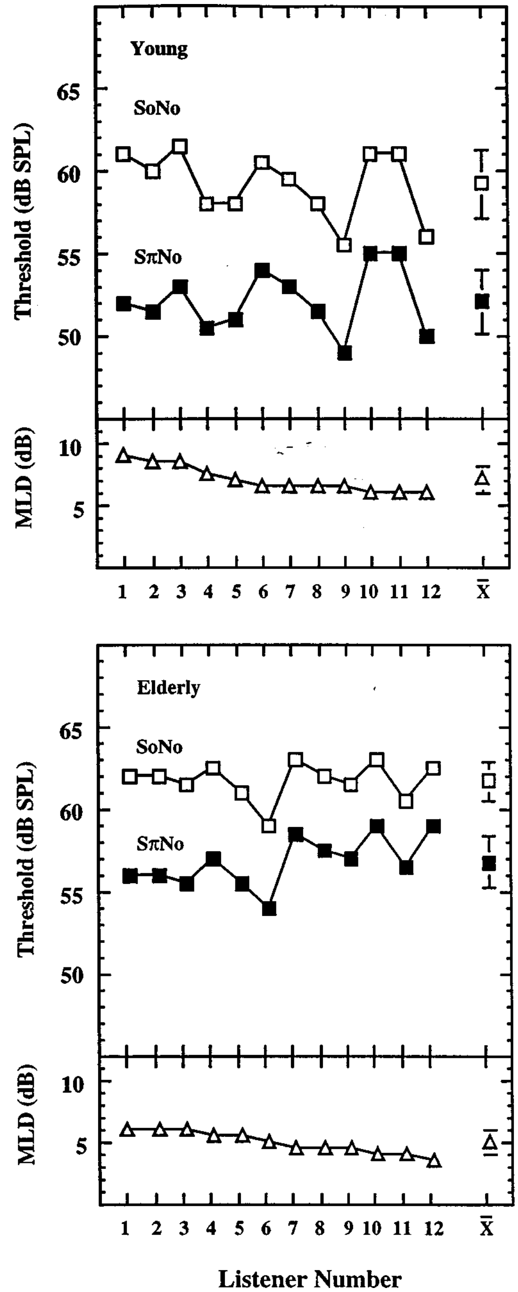

FIG. 5. Individual and group mean speech thresholds for S_0N_0 and $S_\pi N_0$ for young and elderly listeners. Individual listeners are ordered by magnitude of masking level difference, within each age group.

D. Masking level difference

The mean MLD was 7.0 dB for the young listeners, which is consistent with previous MLD studies using similar stimuli (Grose *et al.*, 1994; Wilson *et al.*, 1982). The elderly group had a mean MLD of 4.9 dB. This age difference was significant, as shown by a t test [$t(22)=5.31$, $p<0.0001$].

Individual thresholds for the S_0N_0 and $S_\pi N_0$ conditions are displayed in the two panels of Fig. 5 for young and elderly listeners. Pichora-Fuller and Schneider (1991, 1992) using pure-tone stimuli, and Grose *et al.* (1994) using speech stimuli, found that elderly listeners with normal hearing sen-

TABLE II. Correlation coefficients between psychoacoustic and speech measures of temporal processing for young adult subjects.

		GAP(4)	GAP(8)	GAP(16)	GAP(slope)	ITD(4)	ITD(8)	ITD(16)	ITD(slope)	VOT1	VOT2	MLD
Gap Detection	GAP(4)	--------	.856**	.077	.988**	.843**	.838**	.620*	.886**	-.148	.121	-.090
	GAP(8)		--------	.373	.799*	.721*	.805*	.705*	.655*	.021	-.076	-.215
	GAP(16)			--------	-.075	.190	.370	.469	.006	.345	.284	-.448
	GAP(slope)				--------	.816**	.781*	.551	.886**	-.202	-.164	-.029
Interaural Time Discrimination	ITD(4)					--------	.921**	.886**	.962**	-.229	-.178	-.346
	ITD(8)						--------	.873**	.853**	-.116	-.137	-.222
	ITD(16)							--------	.726*	.011	-.044	-.423
	ITD(slope)								--------	-.345	-.237	-.264
Voice Onset Time	VOT1									--------	.697*	.145
	VOT2										--------	.005
Masking Level Difference	MLD											-------

*p<0.05, **p<0.001

sitivity from 250 to 2000 Hz, exhibited an elevation in $S_\pi N_0$ thresholds but not S_0N_0 thresholds as compared to younger listeners. Present data show differences between the young and elderly groups for both S_0N_0 and $S_\pi N_0$ conditions. This was assessed using an ANOVA with signal condition (S_0N_0 vs $S_\pi N_0$) as the within-subjects factor and age group as the between-subjects factor. Results revealed significant effects of age [$F(1,22)=29.66$, $p<0.0001$] and signal condition [$F(1,22)=892.67$, $p<0.0001$], as well as a significant interaction [$F(1,22)=28.19$, $p<0.0001$]. Unlike past studies, S_0N_0 thresholds were more variable in the young group as compared to the elderly group. Nonetheless, intersubject variability of both groups was relatively small ($S_0N_0=2.0$ and 1.1 standard deviations; $S_\pi N_0=1.9$ and 1.5 standard deviations, for young and elderly groups, respectively). To interpret the interaction effect, the simple main effect of age group at each of the two conditions was assessed. In contrast to previously reported findings, analysis revealed that the two groups differed significantly for both the S_0N_0 condition at the $p<0.0001$ level and for the $S_\pi N_0$ condition at the $p<0.001$ level. Although both were statistically significant, differences in threshold between groups were greater in the $S_\pi N_0$ (4.6 dB) than in the S_0N_0 (2.5 dB) condition.

Previous research has reported age-related deficits in binaural processing reflected by reduced MLDs in elderly listeners (Grose *et al.*, 1994; Pichora-Fuller and Schneider, 1991; Tillman *et al.*, 1973; Warren *et al.*, 1978). Findings may have been due, in part, to age differences, although peripheral hearing loss in the older subjects may have accounted for their smaller MLDs since the presence of peripheral hearing loss significantly reduces the MLD (Jerger *et al.*, 1984). Present data support that binaural release from masking declines significantly as a function of advancing age, independent of peripheral hearing loss.

E. Correlations among measures

There was no significant correlation between the experimental measures and individual pure-tone thresholds or age for either subject group. Pearson *r* correlation coefficients were calculated to examine the relationships among experimental measures. The correlation analysis used the following variables: GAP(4), GAP(8), GAP(16), GAP(slope), ITD(4), ITD(8), ITD(16), ITD(slope) (representing mean gap and ITD thresholds at each presentation level and mean slope values for both tasks), MLD, VOT(slope), VOT1 and VOT2 (representing the slope of the identification function and percent identification scores at the phoneme boundary for one- and two-step discrimination tasks). For the following discussion we refer to the gap detection and ITD thresholds as ''psychoacoustic measures'' and the VOT scores and MLDs as ''speech measures.'' The correlation matrices for young and elderly adult subjects are presented in Tables II and III, respectively.

For young adult subjects, the slope measures of ITD and gap functions were strongly correlated. A significant relationship was found between GAP(4) measures across all ITD variables. The same finding was observed between GAP(8) measures and all ITD variables. No significant correlations were found for the GAP(16) condition and ITD variables. ITD(16) scores had lower correlations with the gap tasks than the ITD(4) and ITD(8) scores. Taken together, these patterns suggest that when trying to identify individual differences across tasks, it may be best to challenge the auditory system by working at low sound levels. When only suprathreshold levels are used, individual differences may be difficult to find. For elderly subjects, ITD thresholds were negatively and significantly correlated with gap detection thresholds at lower sound levels, however, this relationship was only of moderate statistical significance. There was no sig-

TABLE III. Correlation coefficients between psychoacoustic and speech measures of temporal processing for elderly adult subjects.

		GAP(4)	GAP(8)	GAP(16)	GAP(slope)	ITD(4)	ITD(8)	ITD(16)	ITD(slope)	VOT1	VOT2	MLD
Gap Detection	GAP(4)	--------	.460	.028	.984**	-.598*	-.575*	-.508	-.175	.226	.017	.060
	GAP(8)		--------	.155	.427	-.624*	-.464	-.308	-.430	-.106	-.322	.194
	GAP(16)			--------	-.153	-.244	-.115	-.155	-.130	.329	.346	-.148
	GAP(slope)				--------	-.547	-.781	-.475	-.149	.284	.079	.086
Interaural Time Discrimination	ITD(4)					--------	.926**	.643*	.524	-.253	-.004	-.019
	ITD(8)						--------	.790*	.269	-.467	-.157	.013
	ITD(16)							--------	-.316	-.602*	-.280	-.154
	ITD(slope)								--------	.356	.311	.148
Voice Onset Time	VOT1									--------	.822**	.088
	VOT2										-------	.423
Masking Level Difference	MLD											-------

*p<0.05, **p<0.001

nificant correlation between the slopes of ITD and gap functions for the elderly adult group. Overall, correlations between gap and ITD thresholds did not show a strong or consistent relationship for elderly subjects.

The relationship between speech measures was also examined. There were no significant correlations between MLD and VOT measures for either age group, indicating that performance on the MLD task was independent of performance on the VOT tasks.

Finally, there were no significant correlations observed between psychoacoustic and speech measures for young adult listeners. For elderly adult listeners, ITD thresholds obtained at 16 dB were moderately correlated with performance on the one-step discrimination task ($r=-0.602$). No other significant correlations were observed, however, suggesting an incidental relationship.

III. GENERAL DISCUSSION

A. Aging and monaural temporal processing

In the limited amount of research available on monaural temporal processing ability in elderly listeners, results have been mixed, and interpretation has been complicated by the presence of peripheral hearing loss in the elderly samples. Present data for normally hearing elderly listeners demonstrate a clear deficit in the ability of elderly subjects to process temporal information, as measured by detection of temporal gaps. Results are in agreement with recent studies by Moore *et al.* (1992), Schneider *et al.* (1994), and Snell (1997) who reported larger gap detection thresholds in elderly listeners with minimal hearing loss. Additional studies measuring gap discrimination thresholds and duration discrimination thresholds support that there is an age-related deficit in monaural temporal processing that is independent of hearing loss (Abel *et al.*, 1990; Fitzgibbons and Gordon-Salant, 1994; Trainor and Trehub, 1989).

A similar result was observed for monaural temporal processing of speech stimuli, as measured by sensitivity to changes in VOT. Elderly subjects were less able to clearly distinguish phoneme categories and were less accurate at discriminating speech stimuli which differed in VOT duration. Findings suggest that elderly listeners may be at a functional disadvantage in the perception of temporal changes in the acoustic waveform that comprise everyday conversational speech.

The question of whether deficits in temporal processing ability contribute to speech perception difficulties is an area of considerable controversy. Reduced temporal processing has been linked to some speech perception errors made by hearing-impaired listeners (Erber, 1972; Price and Simon, 1984; Tyler *et al.*, 1982), and similar errors have been demonstrated by normal-hearing listeners as a consequence of changes in temporal relations among signal components (Klatt, 1975; Schouten, 1980). In relation to gap detection, several investigations have revealed significant correlations between gap detection thresholds and speech recognition ability, even when audiometric threshold is factored out (Dreschler and Plomp, 1985; Glasberg and Moore, 1989; Tyler *et al.*, 1982). Taken together, these results suggest that poorer speech perception might be related, in part, to abnormal temporal processing. Despite this evidence, auditory temporal processing measures have not consistently proven to be strong predictors of speech perception performance in elderly listeners (Festen and Plomp, 1983; Lutman and Clark, 1986; vanRooij and Plomp, 1990). Results of the present investigation support this latter finding.

As Dorman *et al.* (1985) have suggested based on previous research, observed differences between young and elderly listeners on psychoacoustic measures, although statistically significant, may be small when compared to the magnitude of the differences in acoustic segment duration which signal phonetic contrasts in normal speech. In the case of gap detection, there is no doubt that silent intervals in continuous speech can have linguistic importance. For example, introduction of a period of silence between the [s] and [l] in the word ''slit'' results in the perception of the word ''split'' (Bastian *et al.*, 1961; Marcus, 1978). Relative duration of the silent interval is also important. One of the cues to voicing in intervocalic stops (e.g., rapid–rabid) is the duration of closure for the stop consonant (Lisker, 1957). The question, therefore, may not be whether periods of silence are linguistically important but, rather, whether gap detection thresholds are so elevated in elderly listeners that these silent periods are poorly perceived. For example, in speech, when a silent interval signals the presence of a stop consonant in a cluster, that interval is on the order of 80 ms or longer, while the absence of a stop is signaled by intervals of less than 20 ms (Dorman *et al.*, 1985). The distinction between ''slit'' and ''split'' is evoked with a pause of at least 30–45 ms. Relative to the present data, the poorest gap detection threshold measured at the loudest presentation level among elderly listeners was approximately 15 ms, and most elderly listeners exhibited even better resolution at this sound level. Therefore linguistically relevant silent periods in speech should be easily perceived by these listeners if the signal-to-noise (S/N) ratio is adequate. However, at near-threshold levels, gap detection thresholds for elderly listeners ranged from 6 to 60 ms (as compared to the 4–15-ms range for young adult listeners), suggesting that the magnitude of the loss in some elderly listeners may be such that speech perception is adversely affected.

It may also be the case that the failure to find a significant correlation indicates that the mechanisms underlying detection of temporal gaps are somehow different from mechanisms underlying the ability to distinguish temporal characteristics of speech. Although a complete discussion is beyond the scope of this paper, there is evidence that speech stimuli are perceived and processed in a different way from nonspeech stimuli. The evidence derives from studies of categorical perception, the phenomenon that speech sounds can be discriminated only when they are identified as being linguistically different (Liberman *et al.*, 1967); from studies of cerebral asymmetry, which indicate that certain parts of the brain are specialized for dealing with speech (Broadbent and Gregory, 1964; Kimura, 1964); and from the speech–nonspeech dichotomy, which shows that when a listener is presented with speechlike sounds there is a perceptual dichotomy in that the sounds are either perceived as speech or they are not (House *et al.*, 1962; Stevens and House, 1972). Thus it appears that the perception of speech sounds may be fundamentally different from that of nonspeech stimuli, which could account for the lack of significant correlation observed between measures of monaural temporal processing in the present study. Finally, significant correlations might have been found if a similar presentation level was used for both psychoacoustic and speech perception measures or if different tasks had been used.

Despite the lack of observed correlations and potential differences in the underlying processes involved in temporal processing of speech and nonspeech stimuli, results of the present investigation still suggest an age-related decline in monaural temporal processing of elderly listeners for both speech and nonspeech stimuli, even when peripheral hearing sensitivity is considered clinically normal. Importantly, these deficits are likely to be exaggerated in listeners with hearing loss.

B. Aging and binaural processing

The present data demonstrate a clear age-related loss in the ability to lateralize the source of a sound on the basis of an interaural time delay, replicating results first reported by Matzker and Springborn in the late 1950s. Similar to findings of Herman *et al.* (1977), the present data revealed that older listeners required approximately twice the interaural time delay as young listeners for the same level of performance.

To examine how decreased sensitivity to interaural time differences might contribute to speech perception difficulties, binaural processing for speech was measured using the MLD. Because binaural processing is acutely sensitive to interaural time differences, any loss of temporal resolution in the nervous system would be expected to reduce the size of the MLD (Durlach, 1972). It was found that elderly listeners performed more poorly than young listeners, primarily for the $S_\pi N_0$ condition, contributing to a 2-dB age effect on the MLD. This supports ITD findings that the elderly have a reduced ability to process interaural time cues, even when they have normal hearing. The MLD difference, while not large numerically, is important because it represents another way in which the effects of age probably reduce hearing efficiency in complex listening situations. It has been demonstrated that a loss of 1 dB S/N ratio may result in as much as a 20% reduction in speech intelligibility (Plomp, 1986). Thus a loss of 2 dB S/N ratio could result in considerable difficulty in everyday listening. Furthermore, it should be remembered that while the experimental group in this study was composed of elderly individuals, they did not manifest clinical symptoms of hearing impairment. The deficits which they showed in binaural signal processing are likely to be exaggerated in listeners with significant hearing loss.

Since ITD and MLD thresholds both measure aspects of binaural processing of auditory stimuli, it was hypothesized that performance on the ITD task may be related to the ability to use directional cues to perceive speech in noise as measured by the MLD. Correlations between mean ITD threshold and mean MLD scores for subjects in the present study, however, did not reach statistical significance. This lack of significant correlation between the two measures is consistent with findings of Warren *et al.* (1978) using similar binaural measures. The failure to find a significant correlation is perhaps not surprising since the mechanisms involved in binaural signal analysis are complex. As previously suggested, results indicate that the binaural mechanisms underlying discrimination of interaural time differences are likely different from those of binaural processing for speech. Again, significant correlations might have been found if a similar presentation level was used for both psychoacoustic and speech perception measures or if different tasks had been used.

Although no significant correlations between measures of binaural processing were found, present findings do indicate an age-related decline in binaural processing of temporal information in both speech and nonspeech stimuli. The reduced ability of elderly listeners to utilize interaural time cues has implications for tasks involving lateralization or localization. More importantly, the introduction of binaural, dichotic time cues has been shown to significantly improve the detection and perception of speech signals, especially in a background of noise. Although some of this ability arises from monaural cues such as frequency, timing, or syntax of the source, binaural cues improve the range of situations in which effective communication is possible. If the aging auditory system fails to preserve these cues, older adults may be at a functional disadvantage in the perception of speech in any situation where surrounding auditory space is noisy.

C. Relationships between psychoacoustic measures

Previous research has shown that temporal resolution worsens at low sound levels (Ashmead *et al.*, unpublished data; Buus and Florentine, 1985; Shailer and Moore, 1983; Viemeister, 1979). Present results revealed a significant interaction between age and sound level, indicating that at a given stimulus level older adults performed more poorly than younger adults, and this age difference increased as the overall stimulus level decreased. This interaction between age and signal level was found consistently across gap detection and ITD tasks. Thus the temporal resolution of elderly listeners was more adversely affected by low stimulus level, even when level was specified relative to individual thresholds. The contribution of spectral cues to the ability to detect temporal gaps as reported by Schneider *et al.* (1994), however, cannot be ruled out.

Correlations between the slopes of ITD and gap detection functions showed a highly significant positive relationship for young adult subjects, suggesting that changes in performance as a function of signal level were comparable across monaural and binaural types of processing. For elderly subjects, however, there was no significant correlation between the slope of the ITD function and that of the gap detection function. This result indicates that although there was a significant interaction of age and signal level across tasks, changes in performance as a function of signal level for elderly listeners were not consistent across measures. Thus the relationship between ITD and gap detection thresholds was quite different for young versus elderly subjects, indicating processing difficulties of the aging auditory system at low sound levels that are not attributable to a single, simple factor such as temporal resolution loss in the auditory periphery. Rather, the two types of temporal processing measured in this study may be affected differently by the aging process. It is likely that central factors play a role as well, especially with regard to ITD discrimination (vonWedel *et al.*, 1991; Yin and Chan, 1988). It also may be the case that binaural performance on the ITD task may have been affected by differences in monaural performance between ears on the gap detection task. Results for gap detection in the present study were obtained for one ear of each subject. Schneider *et al.* (1994) found that in older listeners, there were sometimes large differences in gap detection thresholds within the same subject between the two ears. Thus the fact that a significant correlation was found between gap detection and ITD performance in young but not older subjects may be because there are only small interaural differences in the gap detection thresholds of young listeners but larger differences may occur in older listeners.

IV. CONCLUSION

The results of this study support an age-related decrease in temporal processing ability. Elderly listeners had higher thresholds versus younger listeners on gap detection and ITD tasks, were less able to benefit from binaural release from masking, and were less accurate in discriminating changes in voice onset time. Importantly, these findings were observed in elderly listeners with no clinical symptoms of hearing loss. Findings support the following conclusions:

(1) Elderly persons with excellent hearing sensitivity nonetheless perform worse than younger persons on measures of temporal resolution and speech perception. It should be noted that although strict criteria were used to select subjects for the present study, future studies could apply more stringent criteria to ensure that elderly subjects have auditory peripheries that match those of young subjects.

(2) On measures of monaural and binaural processing of temporal information, elderly persons are more adversely affected than younger persons by having to listen at very low sound levels, even when those sound levels are defined with respect to individual thresholds.

(3) For younger persons, monaural performance (of one ear) and binaural performance were related when testing was performed at low sound levels (suggesting that the auditory system must be challenged in order to see individual differences), but for elderly persons there appeared to be no relation between measures of temporal resolution (perhaps suggesting unique effects of aging on specific auditory abilities).

(4) There is no evidence that individual differences in speech perception can be accounted for by temporal resolution abilities. This result is based on a limited number of subjects and a limited range of tasks.

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[1]To obtain masked thresholds for the gap detection task, each subject was presented with a 75 dB SPL continuous 1000-Hz pure tone. Using the computer keyboard, the subject manually attenuated the level of the tone until it was just barely audible in the noise background (descending series). A second threshold was measured using an ascending series, where the tone was initially presented at 0 dB SPL and the subject again adjusted the level of the tone until it was judged as barely audible. A third threshold was measured with the initial amount of attenuation adjusted to match the individual subject's threshold based on the first two threshold approximations, and the subject manually adjusted the level of the tone for a third time to a level just barely audible in the noise background. The mean of the three estimates was considered threshold. Masked tone thresholds ranged from 43 to 51 (mean=47.1) dB SPL for the young adult group and from 43 to

50 (mean=47.3) dB SPL for the elderly group. Masked gap detection thresholds for the 1000-Hz tone did not differ significantly between groups [$F(1,23)=0.073$, $p>0.05$].

[2]To obtain binaural click detection thresholds for the ITD task, each subject was presented with a 70 dB SPL continuous click train. A method of adjustment was used to determine individual thresholds, identical to that used in the gap detection task. Click thresholds ranged from 14 to 26 (mean=20.3) dB SPL for young adult listeners and from 18 to 28 (mean =23.3) dB SPL for the elderly group. Click thresholds did not differ significantly between groups [$F(1,23)=2.30$, $p>0.05$].

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