Age-related differences in discrimination of an interval separating onsets of successive tone bursts as a function of interval duration

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The study measured listener sensitivity to increments in the inter-onset interval (IOI) separating pairs of successive 20-ms 4000-Hz tone pulses. A silent interval between the tone pulses was adjusted across conditions to create reference tonal IOI values of 25–600 ms. For each condition, a duration DL for increments of the tonal IOI was measured in listeners comprised of young normal-hearing adults and two groups of older adults with and without high-frequency hearing loss. Discrimination performance of all listeners was poorest for the shorter reference IOIs, and improved to stable levels for longer reference intervals exceeding about 200 ms. Temporal sensitivity of the young listeners was significantly better than that of the elderly listeners in each condition, with the largest age-related differences observed for the shortest reference interval. Age-related differences were also observed for duration DLs measured using single 4000-Hz tone bursts set to three reference durations in the range 50–200 ms. The tone DLs of all listeners were smaller than the corresponding tone-pair IOI DLs, particularly for the shorter reference stimulus durations. There were no significant performance differences observed between the older listeners with and without hearing loss for either discrimination task.
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I. INTRODUCTION

There is growing awareness among auditory researchers that aging is associated with a general decline in auditory temporal processing, one that appears to be largely independent of factors related to audiometric hearing loss. Observations of the age-related processing decline came from earlier studies revealing that older listeners had particular difficulty understanding speech that was temporally altered in some manner by rate alteration or reverberation (Bergman, 1980; Wingfield *et al.*, 1985; Gordon-Salant and Fitzgibbons, 1993; Vaughan and Letowski, 1997). The altered speech signals are acoustically complex, but feature a number of correlated changes in the temporal properties of the signals that are thought to underlie some of the processing difficulties among older adult listeners. Some of these changes influence the overall timing and prosodic characteristics of speech, while other changes occur at segmental levels and alter the relative durations of bursts, formant transitions, and silent intervals that can serve as acoustic cues to phoneme identity. The possibility that older listeners exhibit a decline in sensitivity for some of these speech temporal cues prompted an interest in studying the temporal processing abilities of older listeners using controlled samples of both speech and nonspeech sounds.

The predominant emphasis of investigation has involved use of psychophysical experiments to measure listeners' ability to detect or discriminate very brief time intervals inserted between successive stimulus markers, defined usually by pairs of tones or noise bursts. The measured detection thresholds for these temporal gaps in older listeners are observed in several studies to be larger than those measured in younger listeners (Schneider *et al.*, 1994; Snell, 1997; Strouse *et al.*, 1998). Additionally, some related findings indicate that discrimination thresholds for brief temporal gaps are elevated among older listeners (Grose *et al.*, 2006), while other findings indicate that gap discrimination difficulties among older listeners become more pronounced when measured using spectrally disparate stimulus markers consisting of either speech or nonspeech sounds (Lister *et al.*, 2002; Lister and Tarver, 2004; Pichora-Fuller *et al.*, 2006; Grose *et al.*, 2006). Other research findings indicate that the limitations in temporal gap resolution among older listeners are most apparent for shorter duration stimuli (Schneider and Hamstra, 1999), or for temporal gaps inserted near the onsets of longer signals (He *et al.*, 1999). Each of the studies concludes that the age effects observed for the detection or discrimination of brief temporal gaps are largely independent of factors associated with age-related changes in hearing sensitivity.

A smaller number of studies on aging and duration discrimination have been conducted using stimuli that span a longer range of reference durations, as defined by the extent of tone or noise signals, or an interval of silence inserted between a pair of acoustic signals. One such study by Abel *et al.* (1990) used filtered noise-burst stimuli and observed that older listeners exhibited diminished sensitivity to changes in the duration of relatively brief 20-ms reference signals, but not longer signals of 200-ms duration. Later, Fitzgibbons and

Gordon-Salant (1994) observed reduced abilities among older listeners to discriminate changes in the duration of either a 250-ms tone burst or a silent interval of equivalent duration inserted between a pair of 250-ms tonal markers. More recently, Grose *et al.* (2006) showed that age-related declines in temporal sensitivity are evident at earlier stages of aging than considered previously. This discrimination study found that older (65–83 years) and middle-aged (40–55 years) listeners exhibited similar and significantly poorer sensitivity than young listeners (18–27 years) to changes in the duration of an intertone silent interval, with the age effects observed for reference silent intervals of 0, 35, and 250 ms. Grose *et al.* also observed that age-related deficits in temporal sensitivity sometimes could be exacerbated by increases in task complexity, a result that was also observed in our earlier discrimination experiments conducted with multi-tone sequences that featured varying degrees of stimulus complexity and task demands (Fitzgibbons and Gordon-Salant, 1995, 2001). Each of the duration discrimination studies conducted with the longer reference stimuli, like those conducted with minimum-duration temporal gaps, reports that the observed age-related differences in discrimination performance are not significantly influenced by the presence or absence of hearing loss in some of older listeners.

One finding that emerges from several of the earlier experiments on aging and temporal discrimination concerns the relative importance of stimulus duration. That is, some studies report that the predominant age-related difficulties associated with temporal discriminations are restricted to the processing of relatively brief sounds. For example, Schneider and Hamstra (1999) reported that the largest age-related differences in temporal gap detection occur for stimulus durations less than about 250 ms. Gap detection results reported by Muchnik *et al.* (1985) and He *et al.* (1999) also support the conclusion that gap detection deficits among older listeners are more pronounced when signals bounding a temporal gap are short in duration. For experiments on duration discrimination, the influence of the reference stimulus duration is less clear, because most of the available discrimination results have come from testing with a small number of stimulus conditions. One notable exception is a study on aging and duration discrimination conducted by Bergeson *et al.* (2001), who tested groups of younger and older listeners using a 2-kHz tonal signal that was set to different reference durations within the broad range of 1.5–1000 ms. These results with the tonal stimuli revealed large discrimination deficits among older listeners for brief tones less than about 20–40 ms, but little or no age-related performance differences for tones of longer reference duration. These findings for duration discrimination, like some of those reported for temporal gap detection, suggest that the reduction in temporal sensitivity among older listeners is primarily associated with the processing of relatively brief stimuli.

Less is known about the manner in which the discrimination of silent intervals by older listeners is influenced by the magnitude of the reference interval. Collective evidence from earlier studies conducted with trained young listeners indicates that the Weber fraction associated with the discrimination of silent intervals bounded by pairs of stimulus markers becomes progressively larger as the duration of the reference interval is reduced systematically below about 100–200 ms (Abel, 1972b; Getty, 1975; Penner, 1976). Corresponding results for older listeners are currently restricted to a smaller sample of reference silent intervals (e.g., Grose *et al.*, 2006), and do not indicate that age-related declines in gap discrimination become disproportionately larger for shorter reference intervals, as appears to be the case for tonal stimuli (Bergeson *et al.*, 2001). However, there are some reasons to anticipate that older listeners might be particularly disadvantaged in discriminating changes in the duration of brief temporal intervals. For example, most theoretical accounts that are relevant to the processing of stimulus duration invoke the operation of central timing mechanisms that are thought to act as counters to sum neural firings during stimulation to code signal duration (e.g., Creelman, 1962; Abel, 1972b; Divenyi and Danner, 1977). These accounts also postulate a high degree of precision in the sensory coding of stimulus onsets and offsets in order to accurately mark stimulus boundaries. It would seem to follow that any age-related changes within the auditory system that degrade the sensory response to stimulus onsets and offsets could influence listeners' temporal discrimination performance.

These considerations prompted us to measure the abilities of younger and older listeners to discriminate changes in the interval separating the onsets of brief tone pulses over a range of reference durations. The tone pulses within stimulus pairs were created to have rapid onsets in order to emphasize the onset-to-onset interval as the relevant timing cue for the discrimination measures, as suggested also by Penner (1976) and Divenyi and Danner (1977). If aging of the auditory system is associated with impoverished coding of signal onsets, a loss in sensitivity for the onset-to-onset interval is expected for older listeners, particularly for brief intervals with closely spaced stimulus onsets. Some preliminary support for this hypothesis emerged from results of our earlier experiments (Fitzgibbons and Gordon-Salant, 2001) with multi-tone isochronous stimulus sequences in which older listeners exhibited diminished sensitivity to changes in sequence tempo, or rhythm, particularly for stimulus sequences that featured relatively short tonal onset-to-onset intervals (e.g., 100 ms). However, interpretation of the earlier tempo discrimination results for multi-tone sequences is complicated by the current lack of corresponding discrimination data for single stimulus intervals over an extended range of reference durations. The present experiments are designed to collect these measurements.

In addition to the main discrimination experiments conducted with the successive tone-pair stimuli, the experiment also included a smaller number of conditions that measured duration discrimination for a single tonal stimulus set to three reference durations in the range 50–200 ms. Initially, this range of durations was selected for its correspondence to a range of speech phoneme durations that we are currently investigating as temporal cues in distinguishing various word-pair contrasts such as *beat* versus *wheat*, which differ in initial consonant transition duration (approximately 50 ms), or *wheat* versus *weed*, which differ in vowel duration

TABLE I. Mean pure tone air conduction thresholds and standard deviations (in dB HL, *re*: ANSI, 2004) across frequency for the three listener groups.

	Pure tone frequency (Hz)					
	250	500	1000	2000	4000	8000
Younger normal hearing						
Mean	8.0	6.0	1.0	2.0	1.5	5.5
Standard deviation	5.9	5.7	5.6	6.7	5.8	5.5
Older normal hearing						
Mean	15.0	11.5	12.0	16.0	20.5	48.0
Standard deviation	7.1	5.3	6.7	8.1	4.6	21.8
Older hearing loss						
Mean	16.5	20.0	25.0	38.0	51.0	71.7
Standard deviation	7.8	10.3	11.0	11.4	6.6	9.0

(approximately 200 ms). Also, the discrimination measures for samples of shorter reference tone durations were collected because our initial observation of an age-related difference in tonal duration discrimination was restricted to a single longer tone of 250 ms (Fitzgibbons and Gordon-Salant, 1994). Moreover, the results collected with tonal stimuli can provide some needed comparison data for a range of reference stimulus durations that appeared to show little or no age-related performance differences in previous duration discrimination studies (Abel *et al.*, 1990; Bergeson *et al.*, 2001).

In all stimulus conditions of the experiment, discrimination performance was examined in groups of younger and older listeners. Testing in each condition was restricted to a high-frequency region, and the potential effects of hearing loss were examined by comparing discrimination performance between groups of older listeners with and without hearing loss in the frequency region of the test stimuli.

II. METHOD

A. Subjects

Listeners in the experiments included 30 subjects assigned to three groups of ten each according to age and hearing status. One group (younger normal hearing) included younger listeners ranging in age from 18 to 30 years (mean =21.4 years) with mean pure-tone thresholds ≤20 dB HL (*re*: ANSI, 2004) across the octave frequencies 250–8000 Hz. Another group (older normal hearing) included older listeners ranging in age from 67 to 78 years (mean =72.4 years) with normal mean pure-tone thresholds ≤20 dB HL from 250 to 4000 Hz. For these listeners, hearing loss varied in degree at 8000 Hz, exhibiting a mean value of 48 dB HL, with thresholds ≤35 dB HL for four of the listeners and thresholds ≥45 dB HL for six of the listeners. The third group included older listeners (older hearing loss) ranging in age from 67 to 78 years (M=73.0 years) with bilateral mild-to-moderate sloping high-frequency sensorineural hearing losses from 250 to 8000 Hz. These listeners had a negative history of otologic disease, noise exposure, and family history of hearing loss. The probable etiology of hearing loss in the older listeners was presbycusis. Table I presents the mean tone thresholds in dB HL for the test ears of the listeners in each group of subjects. Additional criteria for subject selection included monosyllabic word recognition scores in quiet ≥80% (Northwestern University Auditory Test No. 6), normal middle ear function as assessed by tympanometry, and acoustic reflex thresholds that were within the 90th percentile for a given pure tone threshold (Gelfand *et al.*, 1990). Also, the listeners were tested using transient-evoked otoacoustic emissions (TEOAEs). Click stimuli were presented at 80 dB peak-equivalent SPL using the ILO88 OAE system. Band reproducibility (percent) and band signal-to-noise ratio (SNR) were analyzed within frequency bands centered from 1 through 4 kHz. Criteria for the presence of TEOAEs was band reproducibility >70% and SNR >6 dB (Robinette and Glattke, 2007). All listeners with normal hearing (except one of the older normal-hearing listeners) demonstrated TEOAEs that met these criteria. None of the listeners in the older hearing loss group met the criteria to document the presence of TEOAEs. The absence of TEOAEs and the presence of acoustic reflex thresholds at expected levels confirmed a cochlear site of lesion in listeners with hearing loss. All listeners were in general good health, with no history of stroke or neurological impairment and possessed sufficient motor skills to provide responses using a computer keyboard. Additionally, all listeners passed a screening test for general cognitive awareness (Pfeiffer, 1977). The listeners had not participated previously as subjects in psychoacoustic experiments and were paid for their services in the study.

B. Stimuli

The tonal stimuli for the experiments were generated using an inverse fast Fourier transform (FFT) procedure with a digital signal processing board (Tucker-Davis Technologies, AP2) and 16-bit D/A converter (Tucker-Davis Technologies DD1, 20-kHz sampling rate) that was followed by low-pass filtering (Frequency Devices 901F, 6000-Hz cutoff, 90 dB/oct). All testing was conducted using a stimulus frequency that was selected to coincide with a spectral region of sensitivity loss in the listeners with hearing impairment. The tone-pair stimuli were constructed using 4000-Hz tone bursts separated in time by a silent interval. Each tone burst within a pair had a fixed duration of 20 ms that included 2.5-ms cosine-squared rise/fall envelopes, with all tone and silent-interval durations specified between zero-voltage points on the electrical waveforms. Within each stimulus pair, the silent interval between the tones was adjusted to establish the desired reference tonal inter-onset interval (IOI), an interval that included the duration of the leading tone burst and the intertone silent interval. Six discrimination conditions were evaluated with the stimulus tone pairs, using reference IOI values of 25, 50, 100, 200, 400, and 600 ms. For each condition, comparison tone pairs used for the discrimination trials were the same as the reference pairs, but featured a longer IOI that was varied across trials to measure a duration DL for increments of the IOI. Figure 1 displays a sample waveform for a tone pair featuring an IOI of 25 ms (panel a), along with the corresponding amplitude spectrum (panel b). Also shown in the figure is a waveform and corresponding amplitude spectrum for a tone pair with an IOI of 30 ms in panels

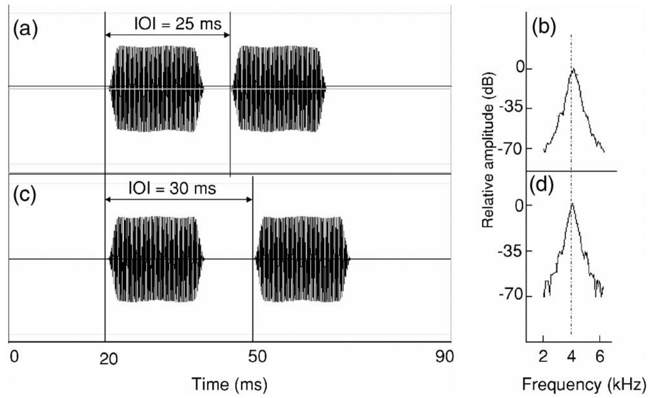

FIG. 1. Waveform and amplitude spectrum of tone-pair stimuli with IOI =25 ms [panels (a) and (b), respectively], and waveform and amplitude spectrum of tone-pair stimuli with IOI=30 ms [panels (c) and (d), respectively].

c and d, respectively. As the figure reveals, the amplitude spectra of the two tone-pair stimuli are approximately the same. For each tone-pair waveform, the spread of spectral energy in the 4-kHz region is determined primarily by the duration of the tonal markers, with the intertone silent interval affecting details of spectral side-band structure. Thus, with all stimulus pairs in the experiment having fixed tone-burst durations, changes in the tonal IOI do not alter the spectral spread of energy in a manner that is likely to serve as a reliable discrimination cue for listeners.

Three additional duration discrimination conditions were conducted using single 4000-Hz tone bursts set to reference durations of 50, 100, and 200 ms, values that included the 2.5-ms rise/fall envelopes described above. For each reference value, a similar duration DL for increments was measured by varying the duration of a comparison tone across a series of discrimination trials. For these tonal stimuli, increments in duration will produce a correlated narrowing of the spectral energy distribution, a result that could provide a potential spectral cue for listeners discriminating a change in stimulus duration. However, these potential spectral cues in tonal duration discrimination have been shown previously to influence listeners' discrimination performance only for very brief stimulus durations, less than 5–10 ms (Small and Campbell, 1962; Abel, 1972a). In the present experiment, all testing with the tonal stimuli was restricted to a range of longer reference durations, where spectral factors do not exert a significant influence on listeners' duration discrimination performance.

C. Procedure

For the stimulus tone pairs, the measurement of DLs for the tonal inter-onset interval was obtained using an adaptive three-interval, two-alternative forced-choice discrimination procedure. Each discrimination trial contained three observation intervals spaced 500 ms apart. The first listening interval of each trial contained a sample of the reference stimulus pair, with the second and third intervals containing samples of the reference and comparison stimulus pairs in either order selected randomly across listening trials. For each of the six IOI conditions, the reference and comparison tone pairs of a listening trial differed only by the duration of the intertone silent interval, which was always longer in the comparison stimulus pair. Listeners used a keyboard to respond to the comparison stimulus in the second or third observation interval of each trial. All listening intervals were marked by a visual display that also provided correct-interval feedback for each trial.

Estimates of the duration DLs were obtained using an adaptive rule for varying the comparison tonal IOI such that the IOI decreased in magnitude following two consecutive correct responses by the listener and increased in magnitude following each incorrect response. Threshold estimates derived by this adaptive rule corresponded to values associated with 70.7% correct discrimination (Levitt, 1971). Testing in each condition was conducted in 50-trial blocks with an IOI starting value 1.4 times the reference value, and a step size for IOI change that decreased logarithmically over trials to produce rapid convergence on threshold values. Following the first three reversals in direction of IOI change, a threshold estimate was calculated by averaging reversal-point IOI values associated with remaining even-numbered reversals. The same procedures were used to measure duration DLs for the simple tonal signals for each of the three reference duration values. For these measurements, the duration of the comparison tone on each listening trial was varied adaptively to measure the DL for a duration increment. An average of six threshold estimates was used to calculate a final DL for each listener in each discrimination condition. Prior to data collection, each listener received eight to ten practice blocks of trials in each condition, with each listener showing performance stability after three to five blocks of trials in each condition.

The listeners were tested individually in a sound-treated booth. The nine discrimination conditions (six reference tone-pair IOIs, and three reference durations for the single tone) were tested in a different randomly selected order for each listener. Stimulus levels were 85–90 dB SPL in order to provide adequate audibility for the older listeners with high-frequency hearing loss. Each of the older listeners participated in an audibility screening using a Bekesy tracking procedures to insure that stimulus audibility for the 20-ms tone bursts corresponded to minimum sensation levels of 25–30 dB at 4000 Hz. The stimuli were delivered to listeners through an insert earphone (Etymotic ER-3A) that was calibrated in a 2-cm^3 coupler (B & K, DB0138). Testing was monaural in the better ear of listeners with hearing loss, and in the preferred ear of listeners with normal hearing. Listening was conducted in 2-h sessions over the course of several weeks. Total test time (not including practice sessions) varied across listeners, but averaged 7–8 hours.

III. RESULTS

For the purpose of analysis and comparison of results across stimulus conditions, all duration DLs collected with tone-pair stimuli were converted to relative values expressed as a fraction of the reference tonal IOI (i.e., the Weber fraction). Table II displays these mean relative DLs for each reference IOI value for each of the younger and older listener

TABLE II. Mean relative difference limens (DLs) in each of the tonal IOI conditions for the three listener groups. Standard errors of the means are shown also.

	Tonal IOI (ms)					
	25	50	100	200	400	600
Younger normal hearing						
Mean	0.25	0.18	0.18	0.11	0.07	0.06
Standard error	0.02	0.02	0.02	0.01	0.01	0.01
Older normal hearing						
Mean	0.62	0.44	0.35	0.20	0.13	0.14
Standard error	0.04	0.02	0.02	0.02	0.01	0.01
Older hearing loss						
Mean	0.60	0.43	0.36	0.21	0.14	0.13
Standard error	0.05	0.02	0.02	0.01	0.01	0.01

groups, with the standard errors of the means also shown. Performance variability among listeners in each of the older groups was about double that of the younger listeners for the 25-ms IOI reference, but there was relatively little difference in performance variability among listener groups across the range of longer IOI reference values. An analysis of variance (ANOVA) was conducted on the individual relative DL values using a repeated-measures design with one within-subjects variable (reference IOI) and one between-subjects variable (listener group). Results of the analysis revealed significant main effects of the reference IOI $[F(5,135) = 176.83, p < 0.01]$ and listener group $[F(2,27) = 76.33, p < 0.01]$, and a significant interaction between IOI and listener group $[F(10,135) = 12.03, p < 0.01]$. *Posthoc* analysis of simple group effects in the data and subsequent multiple comparison tests (Scheffe) revealed that the performance of the younger listeners was significantly better than that of either group of older listeners ($p < 0.05$) for each IOI value, and there was no significant performance difference between the two groups of older listeners with normal hearing and with hearing loss at each IOI value. Additional *posthoc* analysis of simple IOI effects revealed that, for each listener group, discrimination thresholds did not vary significantly across the range of longer reference IOIs of 200–600 ms ($p > 0.05$). For the older listeners, thresholds increased progressively as the reference IOI decreased from 100 to 25 ms, with each relative DL in this range of shorter reference IOIs being significantly larger than those observed for the longer IOI reference intervals ($p < 0.01$, each comparison). Discrimination thresholds of the young listeners were also elevated for the shorter reference IOIs, but only the thresholds for the shortest 25-ms IOI proved to be significantly larger ($p < 0.01$) than thresholds measured for the longer IOIs in the 200–600-ms range.

Because audiometric hearing loss among the older listeners produced no significant effects in discrimination performance, results for the two older listener groups were subsequently collapsed and compared to those for the younger listeners. These results are displayed in Fig. 2, which shows the mean relative DLs in percent as a function of the tonal IOI(ms) for the younger and older listeners, with error bars in the figure representing standard errors of the means. Results in the figure reveal that the relative DLs of the younger and older listeners decrease from larger values for the shorter IOIs to smaller relatively stable values for the longer IOIs. For each of the reference IOIs, the mean relative DLs of the older listeners are larger than corresponding values of the young listeners, with the greatest age-related performance difference observed for the shortest tonal IOI.

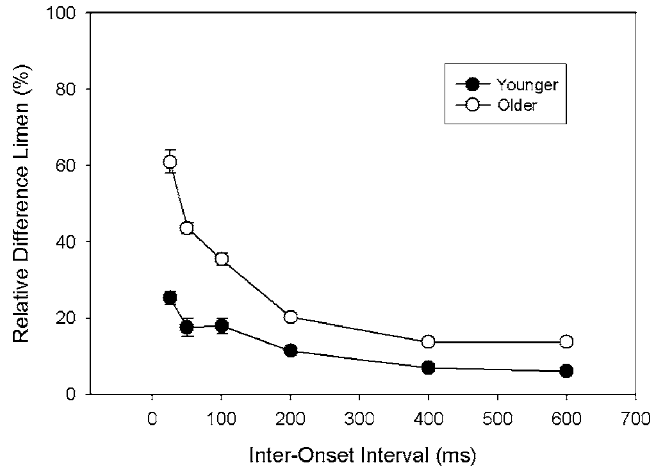

FIG. 2. Mean relative difference limens in percent as a function of the tonal inter-onset interval (ms) for the younger listeners (filled symbols) and older listeners with and without hearing loss (unfilled symbols). Error bars represent standard errors of the means.

The mean relative tone DLs measured for the three reference durations tested are shown in Table III for each group of listeners, with values representing standard errors of the means also displayed. For these tone discrimination results, a separate ANOVA was conducted on the individual relative tone DLs using a repeated-measures design with one within-subjects variable (reference tone duration) and one between-subjects factor (listener group). The analysis revealed significant main effects of reference duration $[F(2,54) = 24.8, p < 0.01]$ and listener group $[F(2,27) = 315.1, p < 0.01]$, with no significant interaction between the two variables. Multiple comparison testing (Scheffe) on group means revealed that the younger listeners performed significantly better than the older listeners for each reference tone duration ($p < 0.01$), with no significant performance differences observed between the two groups of older listeners with normal hearing

TABLE III. Mean relative difference limens (DLs) for each reference tone duration for the three listener groups. Standard errors of means are shown also.

	Reference duration (ms)		
	50	100	200
Younger normal hearing			
Mean	0.15	0.11	0.09
Standard error	0.01	0.01	0.01
Older normal hearing			
Mean	0.33	0.29	0.21
Standard error	0.02	0.02	0.01
Older hearing loss			
Mean	0.34	0.30	0.24
Standard error	0.02	0.02	0.01

TABLE IV. Results of stepwise multiple regression analyses conducted with each DL value in the various discrimination conditions serving as the criterion variable, and age, 4 kHz threshold, and 8 kHz threshold as predictor variables. R^2 entries indicate the variance accounted for (VAF) by the derived regression equations, with associated F values and significance levels. Significant predictor variables are indicated by *.

Criterion variable (DL)	R^2 VAF	F	Age	4 kHz threshold	8 kHz threshold
IOI 25 ms	68.4%	58.4, $p<0.01$	$t=2.6$, $p<0.01^*$	$t=0.6$, $p>0.05$	$t=0.2$, $p>0.05$
IOI 50 ms	76.6%	88.3, $p<0.01$	$t=9.4$, $p<0.01^*$	$t=0.5$, $p>0.05$	$t=0.9$, $p>0.05$
IOI 100 ms	58.8%	38.5, $p<0.01$	$t=6.2$, $p<0.01^*$	$t=-0.5$, $p>0.05$	$t=-0.4$, $p>0.05$
IOI 200 ms	47.7%	24.9, $p<0.01$	$t=5.0$, $p<0.01^*$	$t=-0.5$, $p>0.05$	$t=-1.3$, $p>0.05$
IOI 400 ms	53.6%	31.1, $p<0.01$	$t=5.6$, $p<0.01^*$	$t=-1.2$, $p>0.05$	$t=-1.1$, $p>0.05$
IOI 600 ms	76.5%	87.7, $p<0.01$	$t=9.4$, $p<0.01^*$	$t=1.0$, $p>0.05$	$t=0.3$, $p>0.05$
tone 50 ms	79.7%	106.2, $p<0.01$	$t=10.3$, $p<0.01^*$	$t=0.8$, $p>0.05$	$t=-0.1$, $p>0.05$
tone 100 ms	72.1%	69.8, $p<0.01$	$t=8.4$, $p<0.01^*$	$t=-1.3$, $p>0.05$	$t=0.1$, $p>0.05$
tone 200 ms	84.5%	147.6, $p<0.01$	$t=12.1$, $p<0.01^*$	$t=-2.2$, $p<0.05$	$t=-0.9$, $p>0.05$

and hearing loss. The main effect of reference duration was also analyzed using multiple comparison testing (Scheffe). The results showed that all listeners exhibited significantly larger DLs for the 50-ms tones than for the 200-ms tones ($p<0.01$). There were no significant differences in tone DLs between the 100 ms tone and either the 50- or 200-ms tones.

Subsequent multiple regression analyses were conducted on the discrimination results for the tone-pair stimuli and the single-tone stimulus conditions, to examine further the contributions of age and high-frequency hearing loss on the relative DL values. These analyses were motivated by the observation that the younger and older listeners with normal hearing appear to have different pure-tone thresholds, despite both groups satisfying the criterion of hearing within normal limits through 4 kHz. To that end, separate multiple regression analyses (stepwise method) were conducted on data from all 30 participants with the relative DL value in each condition serving as the criterion variable, and age, 4-kHz threshold, and 8-kHz threshold serving as the predictor variables. The results of these analyses are shown in Table IV. The table shows that the variance accounted for (R^2) by the regression equations ranged from 47.7% to 84.5%, and each was significant, across the different conditions. The results also show that the variable age was the primary significant predictor of the discrimination performance in each condition, whereas the listeners' detection thresholds at 4 and 8 kHz generally were not significant predictors of performance.

IV. DISCUSSION

The experiments were designed primarily to compare the abilities of younger and older listeners to discriminate changes in the duration of an interval separating the onsets of two brief tone bursts, for a range of shorter and longer reference intervals. Duration discrimination was also assessed for a smaller sample of reference durations using pure-tone stimuli. Results of the measurements indicated that auditory sensitivity to changes of stimulus duration depends on the age of listener, magnitude of the reference interval, and type of stimulus defining the reference interval.

A. Younger listeners

Results collected from the young adult listeners in the experiments exhibit trends that are similar in several ways to those reported in earlier studies. Several of the earlier studies on duration discrimination found that the Weber fraction remains fairly stable over a range of stimulus reference durations exceeding about 200 ms, but increases progressively as the reference duration is reduced within the range of shorter durations (Creelman, 1962; Small and Campbell, 1962; Abel, 1972a, b; Getty, 1975). In a similar manner, the results of our young listeners for tonal IOI discrimination showed only small variation in the relative DLs for reference IOI durations in the 200–600-ms range, and progressively larger values as the reference IOI is reduced. Other comparable studies that used tone-pair stimuli like those of the present experiments observed that young listeners could discriminate increments in tonal onset-to-onset intervals of about 6%–10%, with performance being fairly stable for reference intervals exceeding about 200 ms (e.g., Divenyi and Danner, 1977; Hirsh *et al.*, 1990; Drake and Botte, 1993). Young adult listeners in the present study produced relative DLs for increments of tonal IOI in the range of 6%–11% for the reference durations of 200 ms or longer, values that agree closely with the previously reported estimates.

The data collected from the younger listeners in the three duration discrimination conditions that used single tonal stimuli revealed mean relative DLs that shifted from about 9% to 14.5% as the reference tone duration decreased from 200 to 50 ms. This performance shift is similar in magnitude to that observed for the IOI DLs across the same range of reference durations, indicating that the two DL measures are closely related. This impression was confirmed with correlation analysis, which showed a high correlation between the IOI DLs and tone DLs at each of the three corresponding reference durations ($r>0.66$, $p<0.01$). The tone DLs of the younger listeners were somewhat smaller than the IOI DLs for corresponding reference durations of 50 and 100 ms, but the two DL measures were equivalent for the reference duration of 200 ms. These comparison results for the single-tone and tone-pair stimuli are similar in some respects to those reported in earlier duration discrimination studies in which tone DLs were compared to the DLs for silent intervals, or gaps, inserted between a pair of acoustic markers. Some of these earlier results indicated that duration DLs for single tones were consistently smaller than those for temporal gaps of equal reference duration (e.g., Abel, 1972a; Rammsayer and Lima, 1991), although our earlier discrimination measurements using longer 250-ms reference duration found that duration DLs for tones and gaps were approximately the same in younger listeners (Fitzgibbons and Gordon-Salant, 1994). However, it should be noted that straightforward comparisons between tone DLs and gap DLs in some of the earlier experiments are complicated by findings that show that gap discrimination thresholds can be influenced by parameters of the acoustic markers surrounding the gap, particularly the duration of the leading marker (Penner, 1976; Grose *et al.*, 2001, 2006). These marker duration effects are less relevant to the present comparison of DLs across stimulus types, as the tonal IOI is used as the reference interval for all tone-pair discrimination testing.

The discrimination measures collected for the tone-pair stimuli show essentially the same trends observed previously in our temporal discrimination experiment conducted using sequences of five brief tone bursts separated equally by silent intervals (Fitzgibbons and Gordon-Salant, 2001). Listeners in this earlier study were asked to discriminate small changes in sequence presentation rate that were implemented by simultaneous variation of the tone-burst IOIs at different baseline sequence rates. Results with the tone sequences, like those of the present experiments, revealed nearly equivalent rate discrimination performance for sequences having IOIs in the 200–600-ms range, with somewhat poorer temporal sensitivity seen for a fastest sequence rate featuring an IOI of 100 ms. However, results from the two studies differ in one important respect. That is, all relative DLs measured in the present experiment with the tone-pair stimuli are about twice the magnitude of those measured previously with the five-tone sequences, for corresponding values of the reference tonal inter-onset interval. These performance comparisons suggest that the repetition of a fixed stimulus interval in multi-tone sequences may lead to improved discrimination performance, and that the duration DLs measured here for single reference intervals might not reflect the absolute limits in listeners' temporal sensitivity for tonal IOI.

B. Older listeners

For the older listeners, the magnitude of the relative IOI DLs with the tone-pair stimuli was fairly stable across the range of longer reference durations 200–600 ms, and became progressively larger as the reference duration was reduced. Across the range of reference durations tested, the mean relative DL for increments of tonal IOI for the older listeners shifted from about 14% at the longer durations to about 61% at the shortest reference duration of 25 ms. For each reference tonal IOI, the discrimination performance of the older listeners was found to be poorer than that of the younger listeners. The size of the age-related performance difference was greatest at the shortest reference IOI duration, where the mean relative DL of the older listeners was observed to be about 2.5 times that of the younger listeners. The age-related differences were smaller for the longer IOI values of 100–600 ms, but the relative DLs of the older listeners were still about twice those of the younger listeners across this range of tonal IOI. The performance differences among listener groups are primarily attributed to age, rather than shifts in hearing sensitivity in the two older groups, as the multiple regression analysis revealed that age was the primary factor that accounted for most of the variance in the discrimination DLs.

For the single-tone discrimination conditions, the mean relative DLs of the older listeners shifted progressively from 22.5% to 33.5% across conditions of decreasing reference tone duration from 200 to 50 ms. These relative tone DLs were found to be significantly larger than those of the younger listeners at each corresponding reference duration. However, unlike the discrimination results for the tone-pair stimuli, there was no evidence indicating that the magnitude of the age-related difference in tone DLs was disproportionately larger for the shortest reference tone duration. This particular outcome may simply reflect the limited range of reference durations tested with the single-tone stimuli. Like the younger listeners, the older listeners exhibited smaller tone DLs compared to IOI DLs for the shorter reference durations of 50 and 100 ms, but not for the longer 200-ms reference duration. For the shortest comparable reference duration of 50 ms, the mean IOI DLs were larger than tone DLs by about 10% for the older listeners, and about 3% for the younger listeners. Thus, it appears that for this shorter reference duration, the older listeners, and to lesser extent, the younger listeners exhibit greater relative difficulty discriminating changes in a tonal onset-to-onset interval compared to an equivalent onset-to-offset interval that defines the duration of a single tone.

One purpose of the experiments was to extend the examination of aging and duration discrimination to a broader range of reference intervals than examined in most of the previous investigations. Additionally, a specific goal of the testing was to examine the hypothesis that discrimination difficulties among older listeners become more pronounced for shorter reference stimulus durations. Support for this hypothesis is found in the tone-pair discrimination data, which shows larger age-related performance differences for stimulus durations less than about 100 ms, and smaller stable discrimination differences for longer reference durations. Bergeson *et al.* (2001) also observed exaggerated age-related deficits in duration discrimination for their shorter duration tonal stimuli of less than 20 ms, but age effects in these data were reported to be negligible across a broad range of longer reference durations exceeding 40–80 ms. However, Bergeson *et al.* also reported a high degree of performance variability among their older listeners, a situation that obscures interpretation of possible age effects in some of their results collected with longer reference stimuli. For example, although Bergeson *et al.* do not examine the statistical significance of age effects in their data analysis, they do report that the mean relative DLs for duration increments in their older and younger listeners were 60% and 30%, respectively, for a reference tone duration of 200 ms. These mean DL values are much larger than corresponding estimates in the present study, but they show agreement with our findings in revealing that the mean discrimination thresholds of older listeners are about twice those of the younger listeners for the longer reference stimuli. This outcome describes the present discrimination results for our reference tonal stimulus of 200 ms, and each of the tone-pair conditions with IOIs in the range 100–600 ms.

Overall, the results of the experiments provide additional evidence for the existence of age-related temporal processing deficits that are largely independent of factors associated with audiometric hearing loss in older listeners. However, the sources of diminished temporal sensitivity among the older listeners remain unclear. It is possible that some aspects of the processing difficulties can be attributed to age-related changes in the central timing mechanisms that are thought to be implicated in discrimination tasks involving judgments about stimulus duration (e.g., Creelman, 1962). As discussed previously, the postulated timing mechanism is presumed to function as a counter that accumulates neural pulses during stimulation to code duration. However, the density of neural pulses feeding such a counter could become diminished simply as a consequence of an age-related reduction in the population of nerve fibers (Willott, 1990). In this case, longer stimulus increments would be required to discriminate duration differences by older listeners, compared to young listeners. This account would seem most applicable in explaining the smaller and relatively uniform discrimination deficits observed for the older listeners across the range of longer reference stimulus intervals examined in the present investigation.

The decrease in discrimination performance among older listeners observed for the tone-pair stimuli of relatively brief duration would seem to implicate a different process, perhaps one involved with the coding of signal onsets. For young listeners, the coding of stimulus boundaries is usually presumed to depend primarily on signal audibility, and Divenyi and Danner (1977) reported that levels of about 25 dB SL are sufficient to minimize uncertainty in registering signal onsets, a criterion that was satisfied in the present experiments for both younger and older listeners. However, in recent years, some investigators (e.g., Schneider and Pichora-Fuller, 2000) have pointed to physiological evidence from animal studies on aging indicating a possible age-related loss of synchrony in the nerve-fiber response patterns associated with stimulus onsets (e.g., Hellstrom and Schmiedt, 1990; Boettcher *et al.*, 1996). Other animal studies on aging in the neurosciences have observed age-related reductions in the number of subcortical neural units that are uniquely sensitive to brief time-separated auditory stimuli (Walton *et al.*, 1998; Frisina, 2001). These types of evidence point to a number of possible age-related changes within the auditory system that could influence accuracy in the timing of stimulus boundaries. In psychophysical experiments, any imprecision in the coding of signal onsets would be expected to influence temporal discriminations, particularly for signals of brief duration, or sequential stimuli with closely spaced onsets of the type used in the present experiments.

As mentioned earlier, many of the psychophysical studies on aging and auditory temporal processing were broadly motivated by a desire to learn if diminished temporal sensitivity was a principal source of the speech understanding difficulties demonstrated by many older listeners. For example, some of the earlier studies with older listeners applied correlation analysis techniques to their data and found significant relationships between speech recognition performance and specific psychophysical measures of temporal resolution, such as gap detection (Lutman, 1991) or gap duration discrimination (Gordon-Salant and Fitzgibbons, 1993). However, other investigators reported only weak correlations between measures of speech recognition and temporal sensitivity in their older listeners (Abel *et al.*, 1990; Humes, 1996). More recent investigations have addressed the issue by targeting specific temporal cues found in speech that are known to be used by listeners to distinguish phoneme categories. One such speech cue that is relevant to the present experiment is the brief silent interval found in spoken word samples containing unvoiced stop consonants (e.g., stay, stew, ditch), but which is absent in corresponding word-pair counterparts without the stop consonant (e.g., say, sue, dish). Two recent studies on aging reported that the magnitude of the silent interval at the perceptual boundary between word samples in a pair was significantly larger in older versus younger listeners (Gordon-Salant and Fitzgibbons, 2006; Grose *et al.*, 2006). These studies also collected discrimination measures for silent intervals and found that duration DLs among the older listeners were larger than those of the younger listeners. Additionally, the age-related difficulties in discriminating changes in the duration of brief tonal signals, as observed in the present experiments, are similar to some of our speech results, which show that older listeners required extended consonant glide transitions in order to distinguish word pairs such as *beat-wheat*. Thus, it appears that the age-related differences in the temporal discrimination, as observed in the earlier and present experiments, have relevance to speech processing as well.

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Abel, S. M. (**1972a**). “Duration discrimination of noise and tone bursts,” J. Acoust. Soc. Am. **51**, 1219–1223.

Abel, S. M. (**1972b**). “Discrimination of temporal gaps,” J. Acoust. Soc. Am. **52**, 519–524.

Abel, S. M., Krever, E. M., and Alberti, P. W. (**1990**). “Auditory detection, discrimination, and speech processing in ageing, noise-sensitive and hearing-impaired listeners,” Scand. Audiol. **19**, 43–54.

ANSI. (**2004**). ANSI S3.6-2004, “American National Standard Specification for Audiometers,” (American National Standards Institute, New York).

Bergeson, T. R., Schneider, B. A., and Hamstra, S. J. (**2001**). “Duration discrimination in younger and older adults,” Can. Acoust. **29**, 3–9.

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

Boettcher, F. A., Mills, J. H., Swerdloff, J. L., and Holley, B. L. (**1996**). “Auditory evoked potentials in aged gerbils: responses elicited by noises separated by a silent gap,” Hear. Res. **102**, 167–178.

Creelman, C. D. (**1962**). “Human discrimination of auditory duration,” J.

Acoust. Soc. Am. **34**, 582–593.
Divenyi, P. L., and Danner, W. F. (**1977**). "Discrimination of time intervals marked by brief acoustic pulses of various intensities and spectra," Percept. Psychophys. **21**, 125–142.
Drake, C., and Botte, M.-C. (**1993**). "Tempo sensitivity in auditory sequences: Evidence for a multiple-look model," Percept. Psychophys. **54**, 277–286.
Fitzgibbons, P. J., and Gordon-Salant, S. (**1994**). "Age effects on measures of auditory duration discrimination," J. Speech Hear. Res. **37**, 662–670.
Fitzgibbons, P. J., and Gordon-Salant, S. (**1995**). "Age effects on duration discrimination with simple and complex stimuli," J. Acoust. Soc. Am. **98**, 3140–3145.
Fitzgibbons, P. J., and Gordon-Salant, S. (**2001**). "Aging and temporal discrimination in auditory sequences," J. Acoust. Soc. Am. **109**, 2955–2963.
Frisina, R. D. (**2001**). "Subcortical neural coding mechanisms for auditory temporal processing," Hear. Res. **158**, 1–35.
Gelfand, S., Schwander, T., and Silman, S. (**1990**). "Acoustic reflex thresholds in normal and cochlear-impaired ears: Effect of no-response rates on 90th percentiles in a large sample," J. Speech Hear Disord. **55**, 198–205.
Getty, D. J. (**1975**). "Discrimination of short temporal intervals: A comparison of two models," Percept. Psychophys. **18**, 1–8.
Gordon-Salant, S., and Fitzgibbons, P. J. (**1993**). "Temporal factors and speech recognition performance in young and elderly listeners," J. Speech Hear. Res. **36**, 1276–1285.
Gordon-Salant, S., and Fitzgibbons, P. J. (**2006**). "Age-related differences in identification and discrimination of temporal cues in speech segments," J. Acoust. Soc. Am. **119**, 2455–2466.
Grose, J. H., Hall, J. W., and Buss, E. (**2001**). "Gap duration discrimination in listeners with cochlear hearing loss: effects of gap and marker duration, frequency separation, and mode of presentation," J. Assoc. Res. Otolaryngol. **2**, 388–398.
Grose, J. H., Hall, J. W., and Buss, E. (**2006**). "Temporal processing deficits in the presenescent auditory system," J. Acoust. Soc. Am. **119**, 2305–2315.
He, N.-J., Horwitz, A. R., Dubno, J. R., and Mills, J. H. (**1999**). "Psychometric functions for gap detection in noise measured from young and aged subjects," J. Acoust. Soc. Am. **106**, 966–978.
Hellstrom, L. L., and Schmiedt, R. A. (**1990**). "Compound action potential input/output functions in young and quiet-aged gerbils," Hear. Res. **50**, 163–174.
Hirsh, I. J., Monahan, C. B., Grant, K. W., and Singh, P. G. (**1990**). "Studies in auditory timing: I. Simple patterns," Percept. Psychophys. **47**, 215–226.
Humes, L. E. (**1996**). "Speech understanding in the elderly," J. Am. Acad. Audiol **7**, 161–167.
Levitt, H. (**1971**). "Transformed up-down methods in psychoacoustics," J. Acoust. Soc. Am. **49**, 467–477.
Lister, J., Besing, J., and Koehnke, J. (**2002**). "Effects of age and frequency disparity on gap discrimination," J. Acoust. Soc. Am. **111**, 2793–2800.
Lister, J., and Tarver, K. (**2004**). "Effects of age on silent gap discrimination in synthetic speech stimuli," J. Speech Lang. Hear. Res. **47**, 257–268.
Lutman, M. E. (**1991**). "Degradations in frequency and temporal resolution with age and their impact on speech identification," Acta Oto-Laryngol., Suppl. **476**, 120–126.
Muchnik, C., Hildescheimer, M., Rubinstein, M., Sadeh, M., Shegter, Y., and Shibolet, B. (**1985**). "Minimal time interval in auditory temporal resolution," J. Aud Res. **25**, 239–246.
Penner, M. J. (**1976**). "The effect of marker variability on the discrimination of temporal intervals," Percept. Psychophys. **19**, 466–469.
Pfeiffer, E. (**1977**). "A short portable mental status questionnaire for the assessment of organic brain deficit in elderly patients," J. Am. Geriatr. Soc. **23**, 433–441.
Pichora-Fuller, M. K., Schneider, B. A., Benson, N. J., Hamstra, S. J., and Storzer, E. (**2006**). "Effect of age on detection of gaps in speech and nonspeech markers varying in duration and spectral complexity," J. Acoust. Soc. Am. **119**, 1143–1154.
Rammsayer, T. H., and Lima, S. D. (**1991**). "Duration discrimination of filled and empty auditory intervals: cognitive and perceptual factors," Percept. Psychophys. **50**, 565–574.
Robinette, M. S., and Glattke, T. J. (**2007**). *Otoacoustic Emissions: Clinical Applications* (Thieme, New York).
Schneider, B. A., Pichora-Fuller, M. K., Kowalchuk, D., and Lamb, M. (**1994**). "Gap detection and the precedence effect in young and old adults," J. Acoust. Soc. Am. **95**, 980–991.
Schneider, B. A., and Hamstra, S. J. (**1999**). "Gap detection thresholds as a function of tonal duration for younger and older listeners," J. Acoust. Soc. Am. **106**, 371–380.
Schneider, B. A., and Pichora-Fuller, M. K. (**2000**). "Implications of perceptual deterioration for cognitive aging research," in *The Handbook of Aging and Cognition*, 2nd ed., edited by F. I. Craik and T. A. Salthouse (Erlbaum, Mahwah, NJ), pp. 155–219.
Small, A. M., and Campbell, R. A. (**1962**). "Temporal differential sensitivity for auditory stimuli," Am. J. Psychol. **75**, 401–410.
Snell, K. B. (**1997**). "Age-related changes in temporal gap detection," J. Acoust. Soc. Am. **101**, 2214–2220.
Strouse, A., Ashmead, D. H., Ohde, R. N., and Grantham, D. W. (**1998**). "Temporal processing in the aging auditory system," J. Acoust. Soc. Am. **104**, 2385–2399.
Vaughan, N., and Letowski, T. (**1997**). "Effects of age, speech rate, and type of test on temporal auditory processing," J. Speech Lang. Hear. Res. **40**, 1192–1200.
Walton, J. P., Frisina, R. D., and O'Neill, W. E. (**1998**). "Age-related alteration in processing of temporal sound features in the auditory midbrain of the CBA mouse," J. Neurosci. **18**, 2764–2776.
Willott, J. F. (**1990**). *Aging and the Auditory System* (Singular, San Diego).
Wingfield, A., Poon, L. W., Lombardi, L., and Lowe, D. (**1985**). "Speed of processing normal aging: effects of speech rate, linguistic structure, and processing time," J. Gerontol. **40**, 579–585.