Age effects in discrimination of repeating sequence intervals

Peter J. Fitzgibbons[a)]
Department of Hearing, Speech, and Language Sciences, Gallaudet University, 800 Florida Avenue NE, Washington, D.C. 20002

Sandra Gordon-Salant
Department of Hearing and Speech Sciences, University of Maryland at College Park, 0100 Lefrak Hall, College Park, Maryland 20742

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The study measured listener sensitivity to increments in the inter-onset intervals (IOIs) of successive 20-ms 4000-Hz tone bursts in isochronous sequences. The stimulus sequences contained two-six tone bursts, separated equally by silent intervals, with tonal IOIs ranging from 25 to 100 ms. Difference limens (DLs) for increments of the tonal IOIs were measured to assess listener sensitivity to changes of sequence rate. Comparative DLs were also measured for increments of a single interval located within six-tone isochronous sequences with different tone rates. Listeners included younger normal-hearing adults and two groups of older adults with and without high-frequency sensorineural hearing loss. The results, expressed as Weber fractions (DL/IOI), revealed that discrimination improved as the sequence tone rate decreased and the number of tonal components increased. Discrimination of a single sequence interval also improved as the number of sequence components increased from two to six but only for brief intervals and fast sequence rates. Discrimination performance of the older listeners with and without hearing loss was equivalent and significantly poorer than that of the younger listeners. The discrimination results are examined and discussed within the context of multiple-look mechanisms and possible age-related differences in the sensory coding of signal onsets. © *2011 Acoustical Society of America*. [DOI: 10.1121/1.3533728]

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I. INTRODUCTION

Investigations of aging and audition find a number of disparities in the processing abilities of younger and older listeners. Many of the processing differences reflect an age-related loss in temporal sensitivity, as evidenced by the observations of older listeners' elevated temporal gap-detection thresholds with simple sounds (Schneider and Hamstra, 1999; Snell, 1997; Strouse *et al.*, 1998), and decreased sensitivity to changes in stimulus durations (Abel *et al.*, 1990; Fitzgibbons and Gordon-Salant, 1995; Grose *et al.*, 2006). Corresponding findings from evoked-response recordings in humans and single-unit brainstem measures in laboratory animals also indicate age-related reductions in temporal sensitivity (Boettcher *et al.*, 1996; Walton *et al.*, 1998). Additionally, it is observed that many older listeners have difficulty in processing more complex stimulus sequences, especially speech sentences that are degraded by noise or altered in the time domain. These difficulties are most evident for accelerated speech, as might be produced by time compression of the stimulus waveform (Wingfield *et al.*, 1985; Gordon-Salant and Fitzgibbons, 1993). The rate-altered speech sequences feature a number of temporal modifications, some of which affect overall timing and prosodic characteristics and others reduce specific segmental durations that are cues for phoneme recognition. These various timing changes indicate the importance of examining age-related differences in temporal sensitivity using both simple sounds and more complex auditory sequences.

Some comparative evidence shows that certain measures of temporal sensitivity collected from older listeners can be quite different for simple sounds vs sounds presented within sequential patterns. One study (Fitzgibbons and Gordon-Salant, 1995) compared measures of duration discrimination for simple tone bursts presented in isolation to corresponding measures for the same tone bursts embedded as target components within multi-tone sequences. For this earlier study, the largest age-related performance differences were observed for tonal targets embedded within sequences, for which discrimination performance of older listeners was observed to be much poorer than that measured for the isolated tonal targets. By contrast, younger listeners in the same study exhibited only small differences in discrimination for the isolated and embedded target tones. Presently, little is known about the specific underlying sources of the large temporal discrimination differences exhibited by older adults for simple vs complex stimuli. However, it has been demonstrated that various non-auditory factors related to degree of stimulus spectral complexity, or listener uncertainty regarding sequential target locations, can influence several measures of listener discrimination performance with multi-component stimulus sequences (Watson *et al.*, 1975). The relative effects of these factors on temporal discrimination performance of older listeners are not clear.

Other discrimination results collected with multi-tone sequences reveal that temporal discrimination performance can sometimes be better than observed for simple isolated

[a)]Author to whom correspondence should be addressed. Electronic mail: peter.fitzgibbons@gallaudet.edu

signals (Fitzgibbons and Gordon-Salant, 2001). This earlier discrimination study minimized stimulus complexity by using sequences of five identical tone bursts separated equally by silent intervals with magnitudes set to establish a desired sequence presentation rate. These isochronous tone sequences were then used to assess the abilities of younger and older listeners to discriminate changes in the sequence presentation rate, or tempo, a task that required listeners to attend to the entire stimulus sequence rather than a single embedded target component. Rate discrimination with these sequences was assessed using procedures common to other discrimination experiments conducted with isochronous tone sequences (Hirsh *et al.*, 1990; Drake and Botte, 1993; Friberg and Sundberg, 1995; Miller and McAuley, 2005); that is, difference limens (DLs) were measured for uniform increments of the sequence inter-tone intervals and subsequently expressed as relative DL values referenced to the tonal inter-onset interval (IOI), the interval representing the reciprocal of sequence presentation rate. Fitzgibbons and Gordon-Salant (2001) found that older listeners were less sensitive to changes in sequence rate than younger listeners, a result that was observed for baseline sequence IOIs ranging from 100 to 600 ms. In addition to the observed age-related rate discrimination differences, the results also revealed a general level of temporal sensitivity for the isochronous sequences that was considerably better than expected on the basis of discrimination estimates previously reported for a single interval bounded by a pair of stimulus markers (e.g., Abel, 1972; Divenyi and Danner, 1977; Hirsh *et al.*, 1990). The better degree of sensitivity observed for temporal intervals within the multi-tone sequences was evident for both the younger and older listeners.

The temporal discrimination results collected with tone sequences indicate that the repetition of an interval within an isochronous sequence leads to improved discrimination performance relative to that observed for a single stimulus interval. For example, Drake and Botte (1993) tested a small group of young listeners with isochronous tone sequences and reported mean relative DLs for the tonal IOIs that decreased from about 6%, for sequences with a single interval, to about 3%, for sequences with six intervals. These shifts in discrimination performance prompt questions about possible sources of the enhanced temporal sensitivity observed for multi-component sequences and whether the processing mechanisms involved operate in a similar manner for younger and older listeners. It seems reasonable to expect that successive repetitions of an interval within an isochronous sequence would lead to a strengthening of the memory trace for the interval in all listeners. The improved memory trace could then serve as a reference to enhance listener sensitivity to small temporal deviations, thereby reducing the magnitude of the measured duration DL. As envisioned, the processing of successive intervals is generally consistent with predictions from statistical decision theory as it relates to listeners' accumulation of information from multiple observations of a stimulus (Green and Swets, 1988; see also Viemeister and Wakefield, 1991). A multiple-looks account for interval discrimination essentially predicts that listener sensitivity to a temporal interval will improve by the square root of the number (N) of interval repetitions within a sequence. Assumptions underlying the predictions are that each interval within an isochronous sequence is an independent observation and that listeners are able to optimally integrate the information gleaned from each interval. For younger listeners, Drake and Botte (1993) and Miller and McAuley (2005) determined that the multiple-look model was useful in predicting some of their interval discrimination data, but the accuracy of predictions was restricted to a limited range of isochronous sequence presentation rates.

For older listeners, the influence of interval repetition within sequences on temporal discrimination performance is unknown. However, there are reasons to expect that older listeners may respond differently to repetition of an interval than is hypothesized for younger listeners. One reason relates to the role of signal onsets in defining the boundaries of a stimulus temporal interval (e.g., a silent interval between a pair of stimulus markers). That is, psychophysical evidence indicates that the onset of a stimulus marker is more salient than its offset as a timing cue in interval discrimination tasks (Penner, 1975; Divenyi and Danner, 1977). Additionally, it appears that the sensory coding of signal onsets may be diminished in older listeners. This follows from the physiological and behavioral data collected from animals and humans indicating that aging is associated with a loss of synchrony in neural responses to stimulus onsets (Hellstrom and Schmiedt, 1990; Boettcher *et al.*, 1996; Schneider, 1997; Schneider and Pichora-Fuller, 2000; Frisina *et al.*, 2001). Any loss of precision in the sensory coding of signal onsets would be expected to diminish listeners' temporal discrimination accuracy, especially for a brief interval defined by closely spaced stimulus onsets. However, for older listeners, the multiple repetitions of an interval in isochronous stimulus sequences could lead to enhanced coding of stimulus onsets (relative to a single interval) in the same manner as signal averaging produces a more robust onset response in the post-stimulus-time histograms of VIII nerve fibers (Kiang *et al.*, 1962). In this case, the relative influence of interval repetition on temporal discrimination performance could actually prove to be greater among older listeners compared to younger listeners, who presumably exhibit no deficit in the coding of signal onsets.

These possibilities prompted the present investigation examining the temporal discrimination abilities of younger and older listeners with isochronous tone sequences. The stimulus sequences incorporated different numbers of equally spaced tonal components in order to measure changes in discrimination performance as a function of the number of sequence components. Additionally, sequence presentation rate was varied across stimulus conditions in order to examine potential interaction effects between the number and magnitude of the sequence intervals on listeners' discrimination performance. The focus of all measurements was restricted to relatively rapid sequence rates, with brief sequence intervals, as these conditions were expected to produce the greatest age-related discrimination differences and thus the largest effects of interval repetition. Additionally, while the prevalence of hearing loss among older listeners is well established, the effects of cochlear damage

TABLE I. Mean pure tone thresholds (and standard deviations) for the three listener groups, from 250 to 4000 Hz, in dB HL.

	Frequency (Hz)				
	250	500	1000	2000	4000
Yng Norm	6.3 (4.4)	6.3 (3.9)	5.6 (5.3)	6.3 (5.8)	3.0 (4.9)
Older Norm	9.4 (6.6)	10.9 (5.5)	13.4 (6.2)	13.1 (7.3)	13.1 (8.5)
Older Hrg Imp	17.8 (8.0)	23.2 (11.0)	27.5 (15.0)	39.6 (13.5)	49.2 (9.5)

on the sensory coding of repetitive signal onsets are less certain. As a result, older listeners recruited for the present investigation included groups of individuals with and without sensorineural hearing loss in the spectral region of the stimulus sequences.

II. METHOD

A. Participants

A total of 43 adults participated in the experiments. These individuals were assigned to three groups based on age and hearing status. Two of the three groups had normal hearing, defined as pure tone thresholds ≤20 dB hearing loss (HL) from 250 to 4000 Hz (re: ANSI, 2004). The young normal-hearing group (Yng Norm, $N = 15$) included individuals aged 18–25 yr (mean = 20.2 yr) and the older normal-hearing group (Older Norm, $N = 13$) included listeners aged 65–76 yr (mean = 69.5 yr). The third group, older hearing impaired (Older Hrg Imp, $N = 15$) included adults aged 65–80 yr (mean = 71.8 yr) with bilateral mild-to-moderate sloping high-frequency sensorineural hearing losses from 250 to 4000 Hz. Table I displays the mean pure tone thresholds in dB HL in the 250–4000 Hz frequency range for each of the three listener groups. The listeners had a negative history of otologic disease, noise exposure, and family history of hearing loss. The probable etiology of hearing loss in these older listeners was presbycusis.

Additional criteria for subject selection included monosyllabic word recognition scores in quiet exceeding 80% (Northwestern University Auditory Test No. 6, Tillman and Carhart, 1966). The participants also exhibited tympanograms with peak admittance, pressure peaks, tympanometric width, and equivalent volume within normal values for adults (Roup *et al.*, 1998) and acoustic reflex thresholds that were within the 90th percentile for a given pure tone threshold (Gelfand *et al.*, 1990). These criteria were established to ensure that listeners with hearing loss had primarily a cochlear site of lesion, and that all listeners had normally functioning middle ear systems. The 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). Many of the listeners reported some degree of childhood exposure to musical instruments, but none received formal musical training as adults or currently practiced as musicians. The listeners had not participated previously as subjects in listening 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 procedure with a digital signal processing board [Tucker-Davis Technologies, AP2 (TDT, Alachua, FL)] and a 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/oc (Frequency Devices, Inc., Ottawa, IL)]. All testing was conducted using stimulus sequences that featured minimal spectral complexity and a fixed tonal frequency, selected to coincide with a region of moderate hearing loss in the older listeners with hearing impairment. The isochronous sequences were constructed using tone bursts that were separated equally in time by silent intervals. Each tone burst within a sequence had a frequency of 4000 Hz and 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. In different conditions, the stimulus sequences differed in length, defined by the number of tonal components, and were constructed with two, four, or six tone bursts, to establish sequences with one, three, or five inter-tone intervals, respectively [see Fig. 1(a) for an illustration]. For each sequence length, the silent interval between successive tone bursts was set to values of 5, 30, or 80 ms in different sequence rate conditions. These silent-interval values produced, respectively, reference tonal IOIs of 25, 50, or 100 ms for the sequences, thus producing nine sequence conditions for discrimination testing (3 sequence lengths × 3 sequence IOIs). For each of the nine sequence conditions, comparison sequences used during discrimination trials were constructed to be the same as the reference sequences, except that all tonal IOIs in the comparison sequences were longer [see Fig. 1(b)]. Tonal IOIs in the comparison sequences were lengthened equally by increasing the inter-tone silent intervals, which were then co-varied adaptively across listening trials to determine a duration DL for the silent-interval increments; tone burst durations within sequences remained fixed.

In addition to the above nine discrimination conditions, measurements were also collected to assess listener

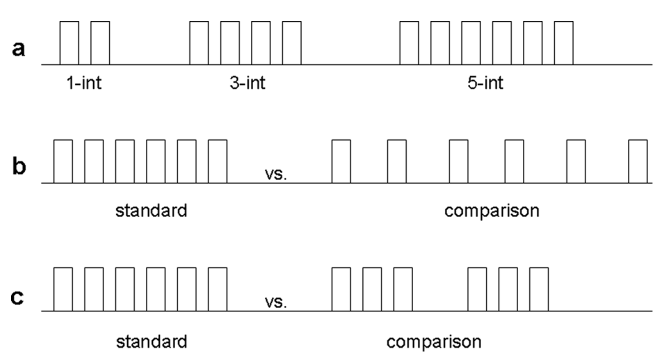

FIG. 1. Schematic diagrams of the tone sequences. (a) The three isochronous sequence lengths featuring one, three, and five inter-tone intervals. (b) Samples of standard and comparison six-tone sequences presented in a typical listening trial for sequence rate discrimination. (c) Trial samples for standard and comparison sequences used in the single-interval discrimination task.

sensitivity to increments of a single targeted inter-tone silent interval embedded within an isochronous sequence of six tone bursts. The reference six-tone sequences used for these single target-interval DL measurements featured uniform tonal IOIs of 25 or 100 ms, representing the fastest and slowest of the reference sequence rates tested. For these conditions, comparison sequences were the same as the references, except the single target interval in the comparison sequence was longer than the others, and varied adaptively to measure a duration DL [see Fig. 1(c)]. The single target interval was fixed in sequence location between the third and fourth tonal components to minimize listener uncertainty, and its duration was varied while preserving the other sequence inter-tone intervals at their original reference values. The purpose of these DL measurements for the single target interval within the six-tone sequences was to provide comparisons to the DLs measured with the two-tone sequences featuring a single inter-tone interval. Earlier discrimination studies reported that listeners generally exhibit similar degrees of sensitivity to changes in the duration of a temporal interval, whether the interval is presented in isolation (i.e., between two tonal markers) or embedded within an extended sequence of isochronous intervals (Hirsh *et al.*, 1990; Drake and Botte, 1993). However, these earlier experiments were conducted primarily with well-trained younger listeners using stimulus sequences that generally featured slower presentation rates than utilized in the present experiments. As a result, it is not clear that the findings of those earlier studies would be observed for older listeners or for the rapid sequences of the present experiments. Additionally, if interval repetition within a sequence serves to enhance listener sensitivity to changes of overall sequence tempo, then such repetition might be expected also to enhance sensitivity to changes in a single localized sequence interval. For older listeners, the anticipated changes in temporal sensitivity associated with interval repetition were expected to be greater than that observed for younger listeners, particularly for stimulus sequences with the fastest presentation rates.

C. Procedure

The measurement of all DLs for the inter-tone intervals was obtained using an adaptive three-interval two-alternative forced-choice procedure. Each discrimination trial contained three observation intervals spaced 750 ms apart. The first interval of each trial contained a sample of the reference tone sequence, with the second and third intervals containing samples of the reference and comparison sequences in either order selected randomly across listening trials. Discrimination measurements with the isochronous sequences were collected for each of the three sequence lengths (two, four, or six tone bursts), each tested with the reference sequence IOI values of 25, 50, and 100 ms. For each of these nine sequence conditions, the reference and comparison sequences of a listening trial differed only by the durations of the inter-tone silent intervals, which were always longer in the comparisons sequences. The additional discrimination measures for the single target silent interval within the six-tone sequences were collected for two reference sequence IOI values of 25 and 100 ms. For these single target-interval measurements, the reference and comparison sequences of a listening trial were also the same, except for the single inter-tone silent interval in the comparison sequence, which was longer. For all discrimination trials, listeners used a keyboard to respond to the comparison sequence in the second or third observation interval of each listening trial. Each observation interval of a trial was marked by a visual display that also provided correct-response feedback for the trial.

Estimates of the silent-interval DLs in each condition were obtained using an adaptive rule for varying interval values in the comparison sequences. For the conditions involving rate discrimination, all inter-tone silent intervals in the comparison sequences were co-varied equally across trials. The adaptive rule stipulated that interval values in the comparison sequence decreased in magnitude following two consecutive correct responses by the listener and increased in magnitude following each incorrect response. Threshold estimates derived with 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 a starting value of the silent intervals 1.4 times the reference value and a step size for interval changes that decreased logarithmically over trials to produce rapid convergence on threshold values. Following the first three reversals in the direction of interval change, a threshold estimate was calculated by averaging the reversal-point interval values associated with the remaining even-numbered reversals. An average of three threshold estimates was used to derive a final DL for each discrimination condition. Prior to data collection, each listener received 2–3 h of practice for sequence discrimination, with all listeners showing performance stability after three–four trial blocks in each condition.

The listeners were tested individually in a sound-treated booth. The discrimination conditions were tested in a different order for each listener. Sequence stimulus levels were 85 dB sound pressure level (SPL) in order to provide adequate signal audibility for the listeners. Stimulus audibility for the listeners with hearing loss was screened via threshold assessment to insure that tone bursts of the sequences were received at minimum sensations levels of 25–30 dB for each listener. Testing was monaural through an insert earphone [Etymotic ER-3A (Etymotic Research, Inc., Elk Grove Village, IL)] that was calibrated in a 2-cm^3 coupler [B&K DB0138 (Bruel & Kjaer, Inc., Norcross, GA)]. All listening was conducted in 2-h sessions over the course of several weeks. Total test time varied across listeners but averaged about 6 h. Listeners were given frequent breaks as needed. The experimental protocol was approved by the Institutional Review Board of the University of Maryland.

III. RESULTS

Results for each listener group for the nine conditions involving sequence rate discrimination are shown in Fig. 2, which displays the mean DLs for the reference inter-tone silent intervals as a function of the number of intervals associated with each sequence length; vertical error bars represent standard errors (SEs) of the means. For clarity, results

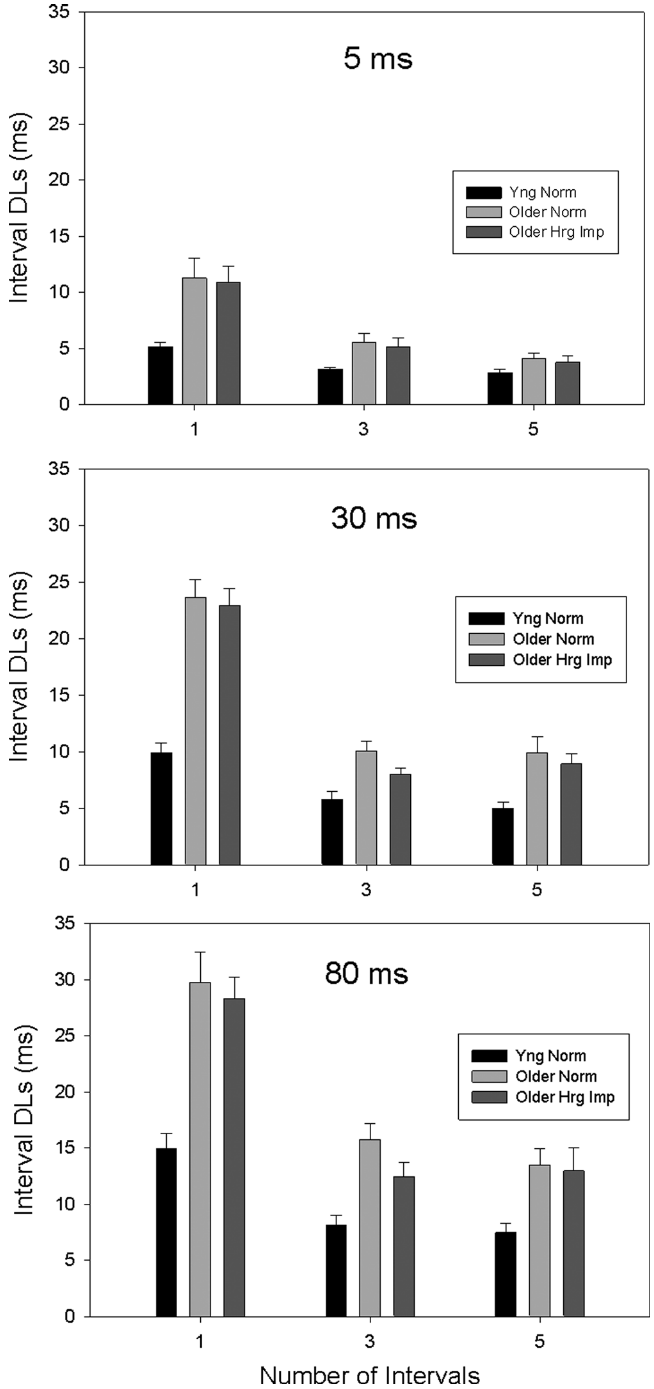

FIG. 2. Mean absolute DLs as a function of the number of sequence intervals for each listener group. Separate panels of the figure show results for each value of the reference sequence inter-tone silent interval. Error bars reflect 1 SE of the mean.

for each of the reference silent intervals associated with the three sequence rate conditions are shown in the separate panels of the figure. The DLs in Fig. 2 were also converted to relative values referenced to the sequence tonal IOI (i.e., Weber fraction); these relative IOI DLs provide data that are directly comparable to those reported in previous discrimination experiments conducted with isochronous tone sequences. The mean relative IOI DLs are displayed in Fig. 3 for each listener group and number of sequence intervals, with separate figure panels showing results for the reference tonal IOIs of the three sequence rate conditions. An analysis of variance (ANOVA) was conducted on the individual relative IOI DL values using a repeated-measures design with two within-subjects variables (reference sequence IOI and sequence length) and one between-subjects variable (listener group). Results of the analysis revealed significant main effects of the reference IOI [$F(2, 80) = 27.2$, $p < 0.01$], sequence length [$F(2, 80) = 209.3$, $p < 0.01$], and listener group [$F(2, 40) = 20.7$, $p < 0.01$]. There were also significant two-way interactions between sequence length and listener

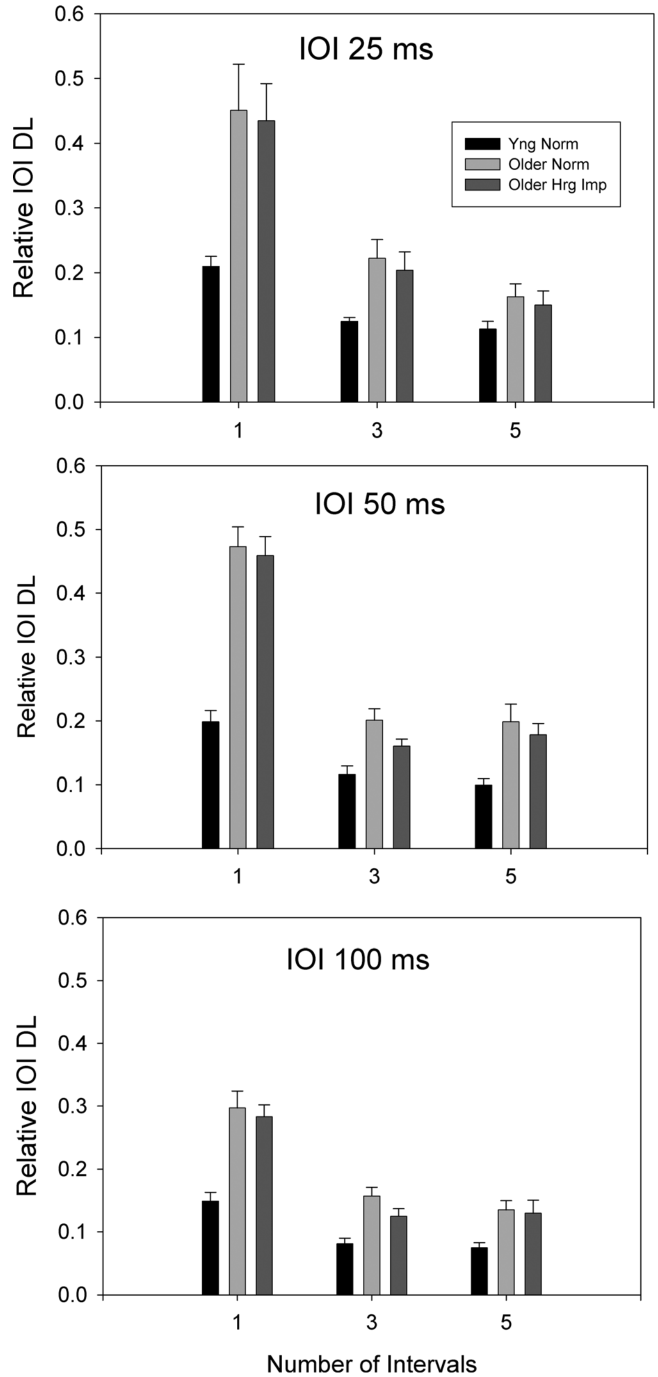

FIG. 3. Mean relative IOI DLs as a function of the number of sequence intervals for each listener group. Separate panels of the figure show results for each reference sequence IOI. Error bars reflect 1 SE of the mean.

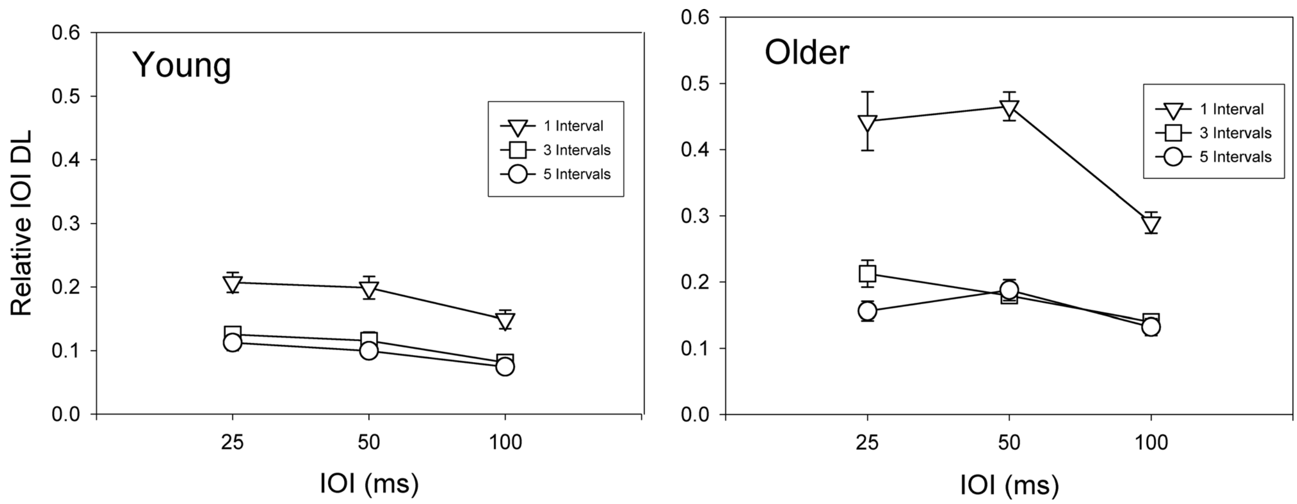

FIG. 4. Mean relative IOI DL as a function of the reference IOI for each number of sequence intervals. The leftmost figure panel shows results for the younger listeners, and the rightmost panel shows results for the older listeners, with data collapsed across hearing-loss groups. Error bars reflect 1 SE of the mean.

group [$F(4, 80) = 15.9$, $p < 0.01$] and between reference IOI and sequence length [$F(4, 160) = 7.03$, $p < 0.01$].

For the interaction between listener group and sequence length, *post hoc* analysis of simple main effects and multiple comparison tests (Scheffe) revealed that the relative DLs of the younger listeners were significantly smaller than those of the older listeners for each sequence length ($p < 0.05$), with the greatest age-related differences apparent for the two-tone sequences with one inter-tone interval. No significant differences in the relative DLs of the two older listener groups were evident for any of the sequence conditions. Additionally, for each listener group, relative DLs for the sequences with one interval were significantly larger than relative DLs for three-interval and five-interval sequences ($p < 0.01$).

For the interaction between the reference IOI and sequence length, *post hoc* analysis of simple effects and multiple comparison tests (Scheffe) revealed that the relative DLs for reference IOIs of 100 ms were significantly smaller than those measured for the two shorter reference IOI values for each sequence length ($p < 0.01$). Also, for each reference IOI value, there was a significant decrease in the relative DLs between sequences with one interval and three intervals ($p < 0.01$) but not between three-interval and five-interval sequences. One exception was for the sequences with reference IOIs of 25 ms, where the relative DLs also decreased significantly as the number of sequence intervals increased from three to five ($p < 0.01$).

These interaction effects in the data are displayed separately for the two listener age groups in Fig. 4, which shows the mean relative IOI DLs as a function of the reference sequence IOI values for each number of inter-tone intervals associated with the different sequence lengths. Separate panels of the figure show the results for the younger listeners (leftmost panel) and the older listeners (rightmost panel), with the data for the two older listener groups collapsed following observation of negligible effects of hearing loss in the discrimination measures. Both panels of the figure show the largest relative DL values for two-tone sequences with one interval, with this condition also producing the greatest differences in discrimination performance between the younger and older listener groups for each value of the reference IOI. With one exception, each panel of the figure reveals relatively small performance differences between four-tone sequences with three intervals and the six-tone sequences with five intervals. The exception occurs for 25-ms IOI, where the relative DLs of the older listeners are smaller for the sequences with five intervals compared to those with three intervals. By comparison, differences in the relative DLs of the younger listeners with the 25-ms IOIs for the sequences with three intervals and five intervals were relatively small.

Discrimination DLs for the single target intervals embedded within the context of six-tone isochronous sequences were measured for the two reference sequence IOI values of 25 and 100 ms. These DLs were compared to those measured for the same two reference IOIs collected with the two-tone sequences. The relevant DLs are shown in Table II, which presents the mean relative IOI DLs for the single target interval in the two-tone and six-tone sequences for each group of listeners. Also shown in Table II are the corresponding mean absolute DLs (milliseconds) associated with each of the mean IOI DLs. ANOVA was conducted on the individual

TABLE II. Mean relative IOI DLs and SEs for each listener group for single reference target IOIs of 25 and 100 ms in the two-tone and six-tone sequences. Values in parentheses are corresponding mean absolute DLs.

	25 ms IOI-ms		100 ms IOI	
	Two-tone	Six-tone	Two-tone	Six-tone
Yng Norm				
Mean	0.21 (5.3)	0.15 (3.7)	0.15 (15.0)	0.16 (16.0)
SE	0.02	0.01	0.01	0.01
Older Norm				
Mean	0.45 (11.3)	0.35 (8.8)	0.30 (30.0)	0.29 (29.0)
SE	0.07	0.03	0.03	0.02
Older Hrg Imp				
Mean	0.44 (11.0)	0.32 (8.0)	0.28 (28.0)	0.27 (27.0)
SE	0.06	0.02	0.02	0.03

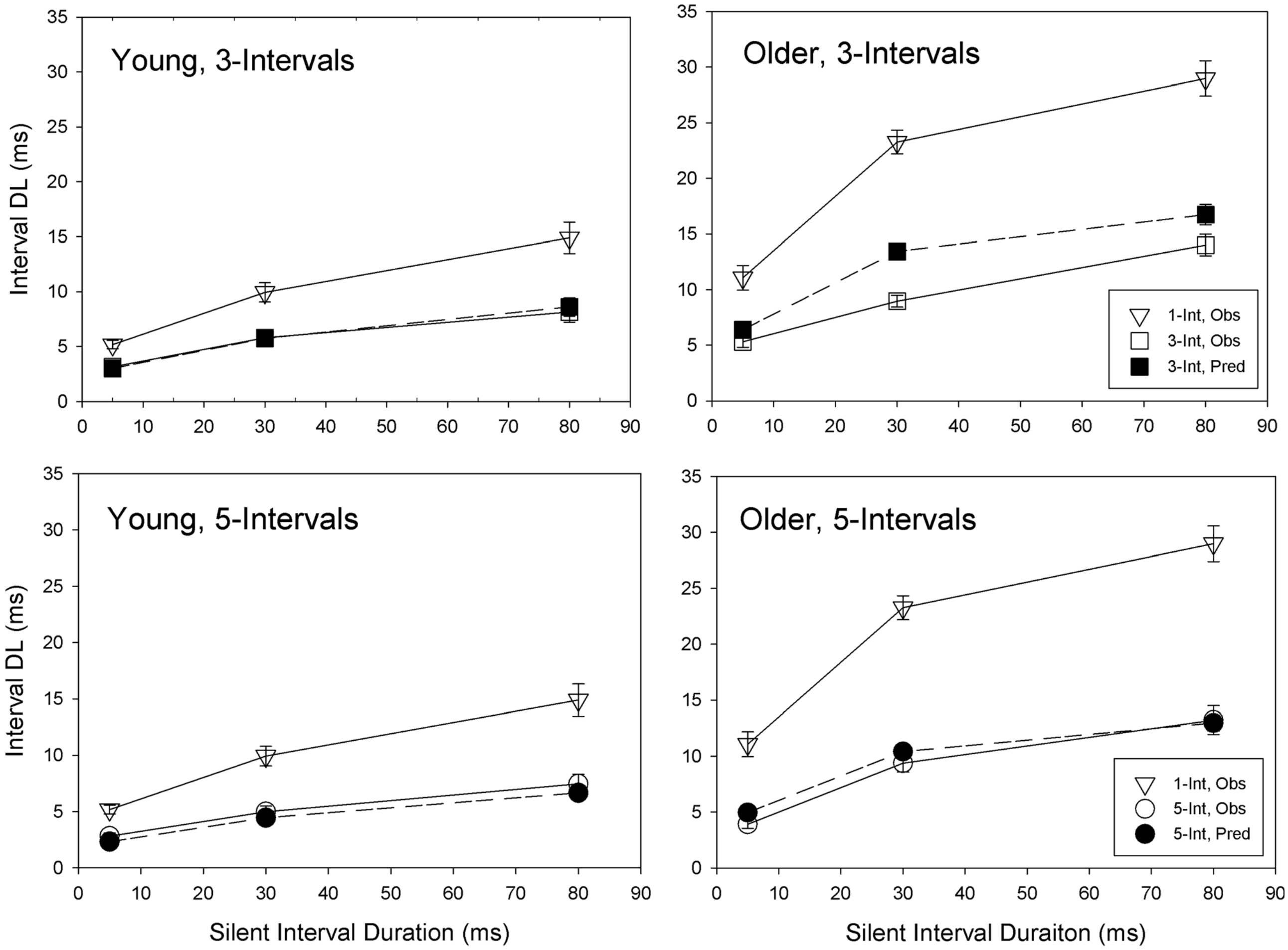

FIG. 5. Mean silent-interval DLs and a function of the sequence silent interval duration for the young (leftmost panels) and older (rightmost panels) listeners. Figure panels at the top show DLs for the single- and three-interval sequences, while the bottom panels show DLs for the single- and five-interval sequences. In each figure panel, open symbols represent observed DLs, and closed symbols represent DLs predicted by the multiple-look hypothesis.

relative IOI DLs using a repeated-measures design with two within-subjects variables (reference IOI and sequence length) and one between-subjects variable (listener group). Results of the analysis revealed significant main effects of listener group [$F(2,40) = 19.5$, $p < 0.01$], reference IOI [$F(1,40) = 20.9$, $p < 0.01$], and sequence length [$F(1, 40) = 8.9$, $p < 0.01$]; there was also a significant interaction between reference IOI and sequence length [$F(1, 40) = 10.6$, $p < 0.01$]. For the interaction, *post hoc* analysis of simple effects and multiple comparison testing (Scheffe) revealed that the relative IOI DLs were significantly smaller for the six-tone sequences compared to the two-tone sequences for the shorter 25-ms IOI reference ($p < 0.01$) but not for the longer 100-ms IOI reference. Discrimination performance of the two older listener groups was equivalent, with each being significantly poorer than that of the younger listeners for each sequence length ($p < 0.01$).

Another examination of the data compared the discrimination performance predicted by the multiple-look hypothesis with the observed results collected in the conditions involving sequence rate discrimination. As stated previously, the multiple-looks account for interval discrimination predicts that listener sensitivity for a given interval should improve by the square root of the number (N) of repetitions of the interval within a stimulus sequence. Consequently, the absolute DLs shown in Fig. 2 for the sequences with one interval were divided by the square root of N to calculate the predicted DLs for the sequences with three and five intervals. The results are shown in Fig. 5, which displays the mean DLs as a function of the reference interval magnitude for each sequence rate and number of stimulus sequence intervals. The leftmost figure panels show results for the younger listeners, while rightmost panels show combined results of the two older listener groups. Each panel of the figure replicates the observed DLs for the sequences with a single interval, together with the observed and predicted DLs for sequences with three intervals (top panels) and five intervals (bottom panels). As the figure shows, the observed and predicted DLs of the younger listeners for sequences with three and five intervals were equivalent; paired-samples analysis (t-tests) found no significant differences between observed and predicted DLs for the sequences with three and five intervals for any of the reference inter-tone silent intervals ($p > 0.05$, all comparisons). For the older listeners, the observed DLs were smaller than the predicted values in all but one of the comparison conditions (five 80-ms intervals), with the largest differences evident for the sequences with three intervals. In the paired-samples analysis, the magnitude of the differences between the observed and predicted DLs was found to be significant ($p < 0.05$) for the three-interval sequences with reference silent intervals of 30 and 80 ms and for the five-interval sequences with reference intervals of 5 ms.

IV. DISCUSSION

The experiments were designed to compare the abilities of younger and older listeners to discriminate changes in the duration of time intervals separating successive tone bursts in a sequence. Of particular interest to the investigation was an examination of the changes in listener sensitivity for a stimulus interval that was repeated within a stimulus sequence. Toward this purpose, the stimuli selected included isochronous sequences of brief tone bursts, with the sequences featuring different numbers of tonal components and interval separations to vary the tonal presentation rate. Results of the discrimination measurements indicated that listener sensitivity to changes in the duration of the sequence intervals depends on the number and magnitude of the intervals within the sequences and the age of the listener. However, differences in hearing sensitivity among older listeners had no systematic influence on discrimination performance. Testing was conducted at a single high frequency and fixed stimulus levels in decibels SPL, a situation that necessarily produced some variation in audibility across listeners in terms of decibels sensation level. Despite these variations, stimulus audibility for the listeners with hearing loss did not prove to be an important factor in limiting the discrimination performance of older listeners. This outcome is consistent with other reported findings indicating an absence of hearing-loss effects in temporal discrimination experiments that used a variety of stimulus types and testing levels that exceeded about 25–30 dB sensation level (Fitzgibbons and Gordon-Salant, 1995; Grose *et al*., 2001; Lister *et al*., 2002).

A. Younger listeners

Studies of duration discrimination have been conducted in the past using a variety of tonal and noise signals or silent intervals bounded by pairs of acoustic markers (Creelman, 1962; Small and Campbell, 1962; Abel, 1972; Getty, 1975; Penner, 1976). The performance measures, usually expressed in terms of the Weber fraction, differ somewhat across the studies but are generally found to be relatively constant across a fairly large range of longer stimulus durations exceeding about 100–200 ms. Each of the earlier studies also reports that discrimination performance tends to deteriorate (Weber fraction increases) rapidly for durations less than about 100 ms. This latter trend is evident in the DLs displayed in Fig. 2 for the young listeners with the two-tone sequences featuring a single inter-tone interval. These DLs, if converted to Weber fractions relative to the inter-tone silent interval, have values of about 0.19, 0.33, and 1.03, respectively, for the reference inter-tone intervals of 80, 30, and 5 ms. These results reveal similar trends and Weber fractions reported by Abel (1972) and Penner (1976) for interval discrimination, although exact DL comparisons are complicated by differences in stimulus attributes and reference intervals tested across studies.

Another problem that limits direct comparisons of silent-interval DLs across studies concerns the influence of stimulus parameters associated with the acoustic markers that are used to define the boundaries of an interval. Particularly, both Abel (1972) and Penner (1976) observed that the duration of the marker preceding a stimulus interval can have an important influence on discrimination performance, an effect that is also addressed in the more recent gap discrimination experiments of Grose *et al*. (2001, 2006). These stimulus marker effects led Penner (1976) to conclude that listeners appear to rely on the onset to onset interval of acoustic markers, rather than the marker offset to onset, in discriminating the duration of brief temporal intervals. Subsequently, Divenyi and Danner (1977) showed that, if the marker IOI is used as the reference interval, then Weber fractions for much of the earlier interval discrimination data, including those of Abel (1972), compute to a value of almost exactly 0.2 for a broad range of marker IOIs from 25 to 320 ms. The relative IOI DLs of the younger listeners in the present experiments (Fig. 3) also have values of about 0.2 for the single intervals of the two-tone sequences with reference IOIs of 25 and 50 ms, and a value of 0.15 for the sequence IOI of 100 ms.

The present results for the younger listeners also reveal that if an interval is repeated in an isochronous sequence then listener sensitivity to the interval improves. The relative DLs of the younger listeners exhibited a significant decrease as the number of sequence intervals increased from one to three, with a much smaller decrease in DLs observed between sequences with three and five intervals. Comparable data reported in the literature are limited, as most previous discrimination experiments conducted with younger listeners have used isochronous sequences with slower presentation rates than tested in the present experiments. However, two of the earlier studies did include a sequence condition featuring reference tonal IOIs of 100 ms and reported relative IOI DLs of about 5% for seven-tone sequences (Drake and Botte, 1993) and about 6% for five-tone sequences (Fitzgibbons and Gordon-Salant, 2001). These values are comparable in magnitude to the mean relative IOI DLs of about 7% measured in the present experiments for the young listeners using the same reference 100-ms IOI with the six-tone sequences. It is worth noting that the two earlier experiments used 50-ms tone bursts in their sequences and produced results similar to those of the present study collected using sequences comprised of 20-ms tone bursts for the same reference IOI. This similarity provides further support for the suggestion of Penner (1976) that listeners utilize the tonal IOI, rather than inter-tone silent interval, as the relevant timing cue in discriminating temporal intervals separating successive acoustic signals.

Some of the results collected from the young listeners reveal that the effects of interval repetition on discrimination performance do not generalize uniformly to the task of discriminating changes to a single target interval embedded within an isochronous sequence. For this task, the results displayed in Table II reveal that the influence of interval repetition within the longer six-tone sequences was to enhance discrimination of the brief 25-ms target interval but not the longer 100-ms interval. This outcome for the longer 100-ms target interval was somewhat unexpected, given the clear effects of interval repetition observed for the same interval in the sequence rate-discrimination task. For the single-interval task, listeners may have adopted a strategy of focusing solely on the known sequence location containing the target interval, thus diminishing the effects of repetition in the non-target sequence intervals. This strategy may have been easier to implement for the slower sequences with the 100-ms IOIs, than for the fast sequences with the brief 25-ms IOIs, where interval repetition effects on discrimination were evident. Stated differently, the brief 25-ms IOIs may have produced a strong perceptual grouping of sequence intervals in the listeners, wherein it was easier to detect a disruption of isochrony than in slower sequences with less pronounced perceptual groupings. This argument is analogous to that reported for pitch-based stream segregation phenomena described by Bregman (1990). However, the data presently available for discrimination of single intervals within extended sequences are insufficient to draw general conclusions. Also, there is some evidence indicating that the location of a target interval within sequences may influence discrimination performance (Hirsh *et al.*, 1990). These effects need to be explored in greater detail.

B. Older listeners

The discrimination performance of the older listeners was observed to be significantly poorer than that of the younger listeners in each of the stimulus conditions, as shown in the DLs in Figs. 2 and 3. For the single interval in the two-tone sequences, the relative IOI DLs of the older listeners shifted from 29% to about 45% as the reference IOI decreased from 100 to 25 ms. These DLs are at least twice the magnitude of the corresponding relative IOI DL values for the younger listeners, with the largest age-related performance differences observed for the shorter 25- and 50-ms reference IOIs. As mentioned previously, differences in discrimination between the older groups of listeners with and without hearing loss were negligible, indicating that sensitivity loss in these listeners had little effect on duration discrimination. This outcome generally agrees with some earlier observations indicating that sensorineural hearing loss does not systematically affect duration discrimination for clearly audible stimuli (e.g., Abel *et al.*, 1990; Grose *et al.*, 2001, 2006).

The effects of interval repetition on sequence rate discrimination were significant in the older listeners. As Fig. 4 shows, the relative DLs for the single interval of the two-tone sequences decreased substantially for sequences with multiple interval repetitions. Performance differences associated with the two sequence conditions featuring multiple intervals are generally small, except for those with the brief 25-ms IOIs, where the relative IOI DLs of the older listeners decreased from 21.4% to 15.7%, respectively, as the number of sequence intervals increased from three to five. This outcome was less evident for the younger listeners, who showed essentially equivalent discrimination performance for sequences with three and five intervals with each of the three reference sequence IOI values. Relative to younger listeners, the older listeners also showed a greater influence of interval repetition on discrimination performance, particularly for the two shorter sequence IOIs of 25 and 50 ms. For these shorter reference IOIs, the relative DLs of the older listeners observed for the single interval of the two-tone sequences decreased by a factor of 2.5–3.0 for the longer sequences with three and five intervals. For the 100-ms IOI, the relative DLs of the older listeners for sequences with a single vs multiple intervals differed by a factor of about 2, a ratio similar to that observed for the younger listeners.

Also, as Table II shows, the mean relative IOI DLs (in percent) of the older listeners for the single embedded target interval of 100 ms was about the same for the two-tone sequences (about 29%) and the six-tone sequences (28%). This equivalency in discrimination performance for the embedded 100-ms target interval in the two-tone and six-tone sequences was observed also for the younger listeners, although the general level of discrimination performance among the older listeners was considerably poorer than that of the younger listeners. However, for the shorter 25-ms target interval, the IOI DLs of the older listeners were smaller by about 11% for the six-tone vs the two-tone sequences, compared to a smaller corresponding performance shift of about 6% observed for the younger listeners. These differing performance shifts between the two-tone and six-tone sequence conditions, for the brief 25-ms targets, could be interpreted as indicating a greater influence of interval repetition on older compared to younger listeners. However, these interval repetition effects were not apparent for discrimination results with the 100-ms target interval, an outcome observed for both younger and older listeners. Reasons for this absence of interval repetition effects with the longer single target interval are not clear at present. Additionally, these data collected for single target intervals embedded within sequences are presently quite limited in scope; additional measurements for target intervals of different magnitudes and sequence locations are needed for better understanding of interval repetition effects in this discrimination task. However, for the present data, the performance trends observed for the single targets within the two-tone and six-tone sequences suggest that on some level the processing of synchrony with tone sequences may operate in a similar manner for younger and older listeners.

C. Processing considerations

The results indicate that both younger and older listeners exhibit better temporal sensitivity in discriminating sequences of a repeating interval compared to a single sample of the interval. Similar observations have been reported previously for sequence discrimination data collected by Drake and Botte (1993) from small groups of young trained listeners. Those investigators used a large set of isochronous sequences that differed in length (two–seven tone bursts) and presentation rate (tonal IOIs from 100 to 1500 ms). Discrimination of changes in sequence rate in this earlier study was assessed in the same manner as in the present experiments by measuring duration DLs for the sequential tonal IOIs. Drake and Botte postulated a multiple-look hypothesis to account for their observations of better discrimination performance for their sequences with multiple repetitions of a given sequence interval. As stated previously, the multiple-look hypothesis derives from the detection theory of Green and Swets (1988) and essentially predicts that, for independent observations of each isochronous sequence interval, the DL for sequences with a given number (N) of intervals should be equal to that for a single interval divided by the square root of N. In their analysis of the multiple-look hypothesis, Drake and Botte found approximate agreement between their observed and predicted DLs, for some sequence IOIs (700–800 ms), but not others; observed DLs were found to be smaller than predicted for the faster sequences (100–600 ms IOIs) and larger than predicted for the slowest sequences (900–1500 ms IOIs). These results led Drake and Botte to conclude that the multiple-look mechanism operates only for a limited range of sequence rates. Miller and McAuley (2005) also reported that the multiple-look hypothesis provided a reasonably accurate account of their observed IOI DLs measured with four-tone isochronous sequences. However, the experiments of Miller and McAuley were not designed to examine a range of sequence presentation rates, hence their multiple-look predictions applied primarily to results collected for a single sequence IOI of 500 ms.

In the present study, the stimulus sequence intervals were generally shorter in duration than those tested in the previous experiments of Drake and Botte (1993) and Miller and McAuley (2005). For the present discrimination measures, multiple-look transformations of the DLs for the younger and older listeners produced some interesting comparisons. First, for the younger listeners, the predicted DLs for the inter-tone silent intervals proved to be quite close to the observed values, as shown in Fig. 5. This was the case for sequences with three intervals and five intervals, for each of the three reference inter-tone intervals of 5, 30, and 80 ms. For these data, the average magnitude of the differences in DLs between observed and predicted values was 0.4 ms, with the observed DLs being slightly larger (but not significantly different) than the predicted values in five of six possible comparisons. By contrast, the observed discrimination DLs of the older listeners were uniformly smaller than the predicted values in five of six comparisons associated with three-interval and five-interval sequences for each reference inter-tone interval. However, as Fig. 5 shows for the older listeners, the differences in DL magnitudes between observed and predicted values were much larger for the three-interval sequences than the five-interval sequences. This outcome suggests that, for older listeners, the relative accuracy of the multiple-look model could vary with the number of interval repetitions within a stimulus sequence. Overall, the results for younger listeners indicate that the benefit of interval repetition on discrimination performance can be explained largely by an ability to optimally integrate information about an interval from each of several independent samples of the interval within the isochronous sequences. For older listeners, the benefit of interval repetition on discrimination performance appears to exceed that of the younger listeners, suggesting that other processing factors may influence their temporal sensitivity for repeated intervals.

As mentioned previously, one potential processing factor that could influence the discrimination performance of older listeners relates to the accuracy of coding stimulus onsets. That is, most theoretical accounts of duration discrimination postulate the operation of a central counting mechanism, one that essentially sums neural firings produced during stimulation, with a larger count resulting for the longer of two signals (Creelman, 1962; Abel, 1972; Divenyi and Danner, 1977). One element of this counter model is a factor related to the coding of signal onsets, which is primarily related to signal audibility and assumed to be accurate in younger listeners for signal levels exceeding about 25 dB sensation level (Divenyi and Danner, 1977). However, for older listeners, even with sufficient signal audibility, the marking of signal onsets may be compromised by a loss of synchrony in the neural response to stimulus onsets (Schneider and Pichora-Fuller, 2000; Frisina *et al.*, 2001). This diminished neural response could be expected to influence listeners' interval discrimination, especially for brief intervals marked by closely spaced stimulus onsets, similar to those tested in the present experiments. Diminished coding of stimulus onsets might contribute to the relatively large age-related discrimination differences observed for the simple two-tone sequences with a single brief inter-tone silent interval. Additionally, for a repeating stimulus interval, the relatively large change observed in temporal sensitivity could be due, in part, to an increase in the precision of signal onset coding. This could happen as a result of an averaging of neural responses to the onsets of the successive tone bursts within an isochronous stimulus sequence. These arguments seem plausible, although confirmation of the presumed underlying processes requires more information about the neural responses to signal onsets in the aging auditory system.

D. Summary

The experiments measured the ability of listeners to discriminate changes in the time intervals separating the onsets of tone bursts in isochronous sequences. All listeners demonstrated improved temporal sensitivity for sequences with multiple repetitions of an interval compared to sequences with a single interval. The improved discrimination performance observed for a repeating temporal interval suggests that listeners are able to extract information from each interval in a manner that is largely predictable from statistical decision theory underlying the multiple-look hypothesis. The relative effects of interval repetition on discrimination performance are greater in older listeners compared to younger listeners. Across stimulus sequence conditions, discrimination of older listeners, with or without sensorineural hearing loss, was observed to be significantly poorer than that of younger listeners. An age-related loss of precision in the neural coding of signal onsets is suggested as a possible factor contributing to the discrimination performance of older listeners. The results also show that the magnitude of the age-related deficits in temporal sensitivity depends on the length and presentation rate of the stimulus sequence. This outcome provides additional evidence for the conclusion that performance measures collected with simple stimuli do not necessarily generalize to listening conditions with extended stimulus patterns.

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