

Aging and temporal discrimination in auditory sequences^{a)}

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This study examined age-related changes in temporal sensitivity to increments in the inter-onset intervals (IOI) of successive components in tonal sequences. Temporal discrimination was examined using reference stimulus patterns consisting of five 50-ms, 4000-Hz components with equal tonal IOIs selected from the range 100–600 ms. Discrimination was examined in separate conditions by measuring the relative difference limen (DL) for increments of tonal IOI in comparison sequences. In some conditions, comparison sequences featured equal increments of all tonal IOIs to examine listener sensitivity to uniform changes of sequence rate, or tempo. Other conditions measured the DL for increments of a single target IOI within otherwise uniform-rate comparison sequences. For these measurements, the single target IOI was either fixed in sequence location, or randomized in location across listening trials. Listeners in the study included four groups of young and elderly adults with and without high-frequency hearing loss. The results for all listeners showed the relative DL for rate discrimination to decrease from a maximum at the 100-ms IOI to a smaller stable value across the range of longer sequence IOI. All listeners also exhibited larger relative DLs for discrimination of single target intervals compared to rate discrimination for equivalent reference IOI values. Older listeners showed poorer performance than younger listeners in all conditions, with the largest age differences observed for discrimination of brief single intervals that were varied randomly in sequence location. None of the results revealed significant effects of hearing loss on performance of younger and older listeners. © 2001 Acoustical Society of America. [DOI: 10.1121/1.1371760]

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I. INTRODUCTION

This paper describes experiments that compared the ability of younger and older listeners to discriminate changes in the timing of successive events within auditory sequences. For many years, research on cognitive aging has provided evidence that elderly persons exhibit a generalized decline in the rate of information processing, with factors such as stimulus complexity and task demands having an important influence on performance (Meyerson *et al.*, 1990; Cerella, 1990; Salthouse, 1991). The contribution of sensory and perceptual influences on the cognitive tasks is not usually considered, and has only recently become an area of enhanced investigation. For example, it is generally known that high-frequency sensorineural hearing loss is a primary consequence of aging that can interact with temporal processing deficits to influence speech recognition in older listeners. This is particularly evident in experiments that utilize rapid or time-compressed speech stimuli, where both hearing loss and listener age independently influence recognition performance (e.g., Gordon-Salant and Fitzgibbons, 1993; Wingfield, 1996). Other studies report that older listeners have difficulty in processing the temporal order of nonspeech stimuli presented in sequential auditory patterns (Trainor and

Trehub, 1989; Humes and Christopherson, 1991; Fitzgibbons and Gordon-Salant, 1998). The source of age effects observed with sequential patterns, speech or nonspeech, is not clearly understood, but may be related to a loss of sensitivity to changes in sequential component durations or the timing structure of the pattern as a whole.

Evidence providing support for the existence of age-related changes in temporal sensitivity comes primarily from psychophysical data. Some of it relates to measures of the minimum detectable duration of a temporal gap separating successive acoustic markers, either pairs of tone or noise bursts. Recent studies report that gap thresholds measured with elderly listeners are about twice the magnitude of those observed for younger listeners (Schneider *et al.*, 1994, 1998; Snell, 1997; Snell and Frisina, 2000). Stimulus factors also appear to be important, with other studies finding that age effects in gap detection are evident primarily for short duration stimuli (Schneider and Hamstra, 1999) or for gaps located near onsets and offsets of longer signals (He *et al.*, 1999). Other temporal sensitivity measures reveal that older listeners exhibit greater difficulty than younger listeners in discriminating changes in the duration of simple noise or tone bursts, or silent intervals separating a pair of stimulus markers (Abel *et al.*, 1990; Fitzgibbons and Gordon-Salant, 1994). These duration discrimination results were reported to be largely independent of sensorineural hearing loss, indicating that cochlear mechanisms are not the principal source of the age-related differences in temporal sensitivity. Alterna-

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tively, Schneider and Pichora-Fuller (2000) suggest that diminished performance on tasks such as gap detection and duration discrimination may be linked in part to an age-related loss of synchrony in the neural firing response to stimulus markers, as suggested by findings from evoked-response studies on aging conducted with gerbils (Hellstrom and Schmiedt, 1990; Boettcher *et al.*, 1993, 1996).

In a recent experiment (Fitzgibbons and Gordon-Salant, 1995) we extended the study of aging and temporal processing to more complex stimulus patterns that featured tonal sequences with varying degrees of spectral complexity. The study compared difference limens (DLs) for changes in the duration of a single tonal component of the stimulus pattern to those measured for the same component presented in isolation. The older listeners in the study exhibited large reductions in discrimination ability for target stimuli embedded within the sequences, whereas younger listeners produced duration DLs that were about the same for the embedded and isolated target stimuli. Additionally, the discrimination performance of younger listeners was relatively unaffected by variations of spectral complexity within stimulus patterns, or the uncertainty introduced by randomization of sequence location for the embedded target component. There were some indications from the experiment suggesting that younger listeners were able to resolve changes in the duration of embedded pattern components, regardless of location, simply by attending to changes in the overall rhythm or tempo of the stimulus sequence. By contrast, older listeners appeared to be less sensitive to overall changes in pattern tempo, and their performance was diminished significantly by variations of spectral complexity and randomization of target location within sequences.

The present study is designed to examine more directly the hypothesis that elderly listeners exhibit diminished sensitivity to changes in the rhythm and timing pattern within tonal sequences. The perceived rhythmic characteristics of sequential patterns can be influenced by a large number of stimulus factors including variation in component frequency and intensity, as well as durations and interval spacings among successive events (Hirsh *et al.*, 1990). To minimize some of this complexity, the present investigation is restricted in scope to the examination of listener sensitivity to changes in the time intervals separating successive onsets of tones within sequences. The stimulus patterns included sequences of brief tone bursts of equal frequency, intensity, and duration.

Stimulus patterns of this type have been utilized in a number of earlier investigations of temporal processing, both in musical and psychoacoustic research. For example, Hirsh *et al.* (1990) studied temporal sensitivity in young listeners using sequences of tones equally separated in time (isochronous sequences). The stimuli were six or ten 20-ms 1000-Hz tones separated equally by silent intervals to produce uniform toner inter-onset intervals (IOIs) corresponding to different sequence presentation rates. Using these as reference patterns in discrimination trials, Hirsh *et al.* examined listener sensitivity to displacement of a tonal component within sequences introduced by the lengthening of a single IOI. The measured DLs for tonal displacement, expressed as a per-

centage of the reference IOI, were observed to be about the same as expected for discrimination of IOI changes between a pair of tones presented in isolation, that is about 10% for reference intervals of at least 100 ms or so. Additionally, the sequence location of the imposed interval change seemed to have little influence on discrimination performance for all but the fastest sequence presentation rates.

Whereas Hirsh *et al.* reported similar discrimination results for single intervals and sequences, other results indicate that temporal sensitivity for sequences is more acute than that observed for simple stimuli. Drake and Botte (1993) used a large set of isochronous sequences featuring 50-ms 440-Hz tones uniformly separated by silent intervals to produce a range of presentation rates for sequence lengths of 2–7 tones. In this experiment, sequence tempo discrimination was examined by measuring the DL for IOI changes when all sequence intervals were covaried equally and simultaneously to effect a uniform change of presentation rate. Their results, also reported as relative DLs for sequence IOI, showed a similar trend for all sequences with discrimination being fairly stable for reference IOIs in the range of about 200–800 ms, and poorer for shorter and longer reference IOI values. Of particular interest was the observation that for a given value of sequence IOI, discrimination improved progressively as the number of intervals in a sequence increased from two to six. For example, with a reference IOI of 400 ms, the relative DL was observed to decrease from about 6% for a two-tone sequence to about 2% for a seven-tone sequence. Drake and Botte suggested that this outcome might be attributed to a multiple-look mechanism that listeners use to enhance their temporal sensitivity for regularly spaced intervals in a sequential context.

Less is known about the consequences of aging as it pertains to temporal processing of extended sequential patterns. From the available evidence reported for simple sounds, it is anticipated that older listeners would be disadvantaged in their sensitivity to temporal spacings within a tonal sequence. This would be the case particularly for rapid presentation rates where any effects of reduced speed of processing, or perhaps loss of neural synchrony, would be expected to be most evident. The present study examines some potential age effects by assessing the ability of younger and older listeners to discriminate changes of presentation rate in tonal sequences. The study also examines the magnitude of age-related differences in temporal sensitivity for multiple versus single changes of interval spacing within stimulus sequences. Towards this goal, the DLs for rate discrimination are compared to those for single-interval discrimination under conditions of both low and high experimental certainty regarding sequence location of a target interval. Additionally, because hearing loss is prevalent among many older listeners, another purpose of the experiments is to examine the independent and interactive effects of age and hearing loss in each discrimination condition. This is accomplished by testing groups of listeners who were matched according to age and degree of hearing loss. All testing was restricted to a high-frequency region that coincided with a region of threshold elevation in those listeners with hearing loss.

TABLE I. Mean audiometric thresholds in the test ear (from 0.25–8.0 kHz, in dB HL *re*: ANSI, 1996), word recognition scores (Northwestern University Auditory Test No. 6) and ages of the four listener groups. Standard deviations are included in parentheses.

Group	Age	Audiometric thresholds						Word recognition % Correct
		0.25 kHz	0.5 kHz	1.0 kHz	2.0 kHz	4.0 kHz	8.0 kHz	
Young, norm hrg	25.3 (4.6)	5.3 (4.0)	3.7 (4.0)	5.3 (3.5)	3.7 (4.4)	5.0 (5.3)	5.3 (5.8)	97.6 (2.9)
Elderly, norm hrg	67.6 (2.0)	9.6 (4.3)	6.5 (3.1)	6.1 (3.0)	7.3 (6.0)	13.4 (5.5)	26.5 (11.3)	97.8 (2.6)
Young, hrg loss	30.3 (10.8)	23.0 (17.0)	29.0 (20.5)	37.5 (21.2)	41.5 (18.9)	51.0 (14.1)	54.0 (17.1)	92.0 (5.3)
Elderly, hrg loss	70.7 (2.6)	20.3 (7.9)	22.7 (11.0)	26.3 (13.4)	39.7 (12.7)	58.0 (7.5)	72.7 (7.0)	89.3 (6.0)

II. METHODS

A. Subjects

A total of 52 listeners participated in the experiments. These included a group of 15 younger listeners (18–40 years of age) with normal hearing (YNH: pure tone thresholds from 250–4000 Hz between 0 and 15 dB HL, *re*: ANSI, 1996), a group of 13 older listeners (65–76 years of age) with normal hearing (ONH), a group of 10 younger listeners with hearing loss (YHL: sloping, mild-to-moderate sensorineural hearing losses), and a group of 14 older listeners with hearing loss (OHL: sloping, mild-to-moderate sensorineural hearing losses). Additional audiometric criteria for participant selection were monosyllabic word recognition scores $\geq 80\%$ (Northwestern University Auditory Test No. 6) and normal acoustic immittance results (i.e., normal tympanograms, acoustic reflex thresholds elicited within the 90th percentile range for normal hearing or cochlear hearing loss, and negative acoustic reflex adaptation). Table I presents the mean ages, audiometric thresholds, and word recognition scores of the four listener groups. The etiology of hearing loss for listeners in the YHL group included heredity and noise exposure. The etiology of hearing loss for listeners in the OHL group was assumed to be presbycusis, based on an absence of a significant otologic history and gradual onset and progression of hearing loss during the sixth and seventh decade of life. Additionally, all listeners passed a screening test of cognitive function (Pfeiffer, 1975). Students at the University of Maryland were recruited to serve as participants in the YNH group. Clients of the University of Maryland Hearing Clinic and their family members were invited by letter to participate in the other three listener groups. All listeners were paid for their participation in the experiments.

B. Stimuli

All tonal sequences for the experiments were generated using an inverse fast-Fourier-transform (FFT) procedure with a digital signal processing board (Tucker–Davis Technologies, AP2) 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, 90dB/oct). Stimulus sequences were constructed with five 4000-Hz tone bursts separated in time by equal-duration silent intervals. Each tone burst in a sequence had a fixed duration of 50 ms that included 5-ms cosine-squared rise/fall envelopes, with all tone and silent-interval durations specified between zero-voltage points on the electrical wave forms. Within these isochronous sequences, the silent inter-

vals between tones were adjusted to establish the desired sequence inter-onset interval (IOI), an interval that includes both the tone and silent interval. Adjustments of sequence IOI also produced shifts in overall sequence duration. For some conditions of the experiment, tone sequences with equal IOI values of 100, 200, 400, and 600 ms were created to serve as the reference stimuli for examining rate discrimination. For these conditions, the comparison sequences used in discrimination trials were the same as the reference sequences except that all sequence IOIs were lengthened equally by increasing the inter-tone silent intervals, and co-varied to determine the duration DL for increments of sequence IOI. In other discrimination conditions, a DL was measured for changes in the duration of a single IOI within an otherwise isochronous sequence. The reference stimuli used for these measures were the isochronous sequences with uniform IOIs of either 100 ms or 600 ms, representing the fastest and slowest rates for the tonal patterns, respectively. The comparison sequences were the same as the reference sequences except one tonal IOI was longer than the others and was varied to measure a duration DL. For these single-interval conditions, some stimulus patterns featured minimal uncertainty in which the single variable IOI always preceded the third tone of the sequence, and was known to the listener. Other single-interval measures were collected for sequences featuring greater stimulus uncertainty in which the single variable IOI occurred in random fashion preceding the 2nd, 3rd, or 4th sequence tone across listening trials, with the selection of these particular intervals being arbitrary. The variation of single IOIs was accomplished while preserving other sequence IOIs at their original values, thus increasing overall sequence duration.

C. Procedures

The measurement of DLs for the tonal inter-onset intervals was obtained using an adaptive three-interval, two-alternative forced-choice discrimination procedure. Each discrimination trial contained three observation intervals spaced 750 ms apart. The first listening interval of each trial contained a sample of the reference stimulus sequence, with the second and third intervals containing samples of the reference and comparison sequence in either order selected randomly across listening trials. Measurements of sequence rate discrimination were collected for each of four reference IOI values of 100, 200, 400, and 600 ms. For each of these conditions, the reference and comparison stimulus sequences of a listening trial differed only by the duration of the tonal IOIs, which were always longer in the comparison sequence.

Measurements of single-interval discrimination were also collected in four conditions, for reference IOI values of 100 ms and 600 ms, each tested under two degrees of stimulus certainty regarding target-interval location. For single-interval conditions, the reference and comparison sequences of a listening trial were the same, except for a single longer target IOI in the comparison sequence. This single target interval in the comparison sequence was either fixed or randomized in sequence location, respectively, across listening trials in the minimal and maximal uncertainty conditions. 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 for all duration DLs were obtained using an adaptive rule for varying comparison sequence 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 of 1.4 times reference value, and a step size for IOI changes 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 the remaining even-numbered reversals. An average of six threshold estimates was used to calculate a final DL for IOI with each listener in each condition. Prior to data collection, each listener received 2–3 hours of practice for sequence discrimination, with all listeners showing performance stability after 3–4 trial blocks in each condition.

The listeners were tested individually in a sound-treated booth. The eight discrimination conditions (rate discrimination at four reference IOI values, and four single-interval measures) were tested in a different order for each listener. Stimulus levels were 85–90 dB SPL in order to provide adequate audibility and produce minimum sensation levels of 25–30 dB at 4000 Hz for the listeners with hearing loss. Testing was monaural through an insert earphone (Etymotic ER-3A) that was calibrated in a 2-cm³ coupler (B&K, DB 0138). All listening was conducted in 2-hour sessions over the course of several weeks. Total test time (not including practice) varied across listeners, but averaged about 8 hours.

III. RESULTS

For the purpose of analysis and comparison with previous findings, all duration DLs collected in the experiment were converted to relative values expressed as a percentage of sequence IOI, the interval representing the reciprocal of sequence rate for each of the reference stimulus patterns. Results from the sequence rate discrimination conditions are shown in Fig. 1, which displays the mean relative DLs in percent as a function of sequence IOI for each of the four listener groups, with vertical bars in the figure representing the positive standard error of the mean. Performance variability among the older listeners was equivalent to that of the younger listeners for 100-ms IOI, but was about twice that of

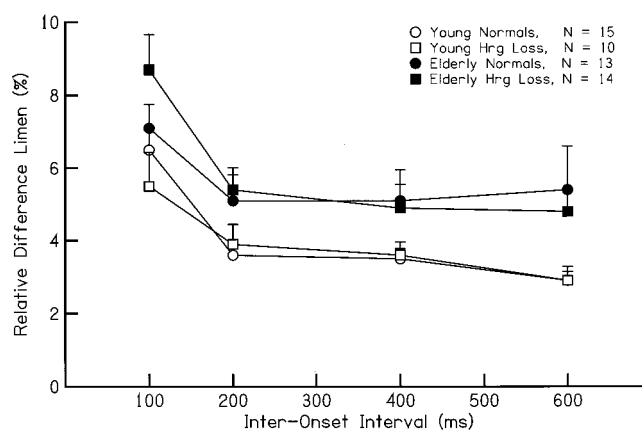


FIG. 1. Mean relative difference limen (DL) in percent as a function of sequence inter-onset interval (IOI) in ms (100 ms, 200 ms, 400 ms, and 600 ms); all conditions involved uniform changes in inter-onset interval. Vertical bars represent the positive standard error of the mean. The four listener groups are Young Normals (young adult listeners with normal hearing, $M = 15$), Young Hrg Loss (young adult listeners with mild-to-moderate sensorineural loss, $N = 10$), Elderly Normal (elderly listeners with normal hearing, $N = 13$), and Elderly Hrg Loss (elderly listeners with mild-to-moderate sensorineural hearing loss, $N = 14$).

the younger listeners across the range of longer IOI values. Among younger listeners, most of the performance variability was attributed to listeners with hearing loss. Among older listeners the reverse was true, with the normal-hearing listeners showing greater variability than those with hearing loss. The mean relative and absolute DL values (in parentheses) for younger listeners (collapsed across hearing loss groups) for IOIs of 100, 200, 400, and 600 ms were 6% (6 ms), 3.8% (7.6 ms), 3.5% (14.1 ms), and 2.9% (17.5 ms), respectively. Corresponding average values for the older listeners for the same IOIs were 7.9% (7.9 ms), 5.3% (10.5 ms), 5.0% (20 ms), and 5.1% (30.6 ms). Thus, younger and older listeners exhibited a similar trend in average threshold values across the IOIs examined here.

An analysis of variance (ANOVA) was performed on the individual data for relative DLs using a split-plot factorial design with two between-subjects factors (age and hearing status) and one within-subjects factor (sequence IOI). Results of the analysis revealed significant main effects of sequence IOI [$F(3,48) = 36.85$, $p < 0.01$] and listener age [$F(1,48) = 10.75$, $p < 0.01$] with no significant interaction effects. Multiple comparison testing (Scheffé) revealed that the effect of IOI was primarily attributed to the larger DL values for the 100-ms IOI, with no significant differences observed across conditions of longer IOIs ($p < 0.05$). The performance of the older listeners was significantly poorer than that of younger listeners across the range of sequence IOIs. None of the data analyses revealed systematic or significant influences of hearing loss within the groups of older and younger listeners.

A second analysis compared the relative DLs measured for the single-interval discrimination condition with the corresponding DLs measured for rate discrimination with the same reference sequence IOI. These results are displayed in Figs. 2 and 3, respectively, for the reference sequence IOIs of 100 ms and 600 ms. Each figure shows the mean relative

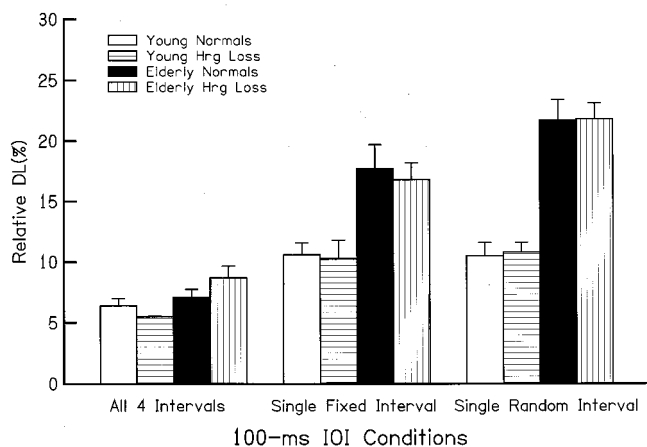


FIG. 2. Mean relative DL in percent for each listener group in stimulus sequence conditions with 100-ms IOI. The three conditions are uniform increments in all four intervals (All 4 Intervals), single increments in one fixed-location interval (Single Fixed Interval), and single increments in one random-location interval (Single Random Interval). Vertical bars represent the standard error of the mean. The four groups are the same as those described for Fig. 1.

DL for each listener group for a single interval that was either fixed (Single Fixed Interval) or randomized (Single Random Interval) in sequence location, together with the corresponding rate discrimination DL from Fig. 1 measured with covariation of all sequence intervals (All 4 Intervals). Error bars in the figures represent standard errors of the mean. Each figure shows that relative DLs for the single-interval conditions were larger than corresponding values for the four-interval conditions, with DLs of the older listeners being larger than DLs of the younger listeners. Additionally, relative DLs for 100-ms IOIs are larger than corresponding values for 600-ms IOIs, reflecting the same trend seen for the rate-discrimination results of Fig. 1. For the younger listeners, mean single-interval relative and absolute values (in parentheses) of DLs for the fixed- and random-location conditions, respectively, were 10.5% (10.5 ms) and 10.7% (10.7 ms) for 100-ms IOIs, and 4.3% (26.1 ms), and 3.9% (23.2 ms) for 600-ms IOIs. Corresponding mean single-interval DLs for the older listeners were 17.3% (17.3 ms) and 21.8%

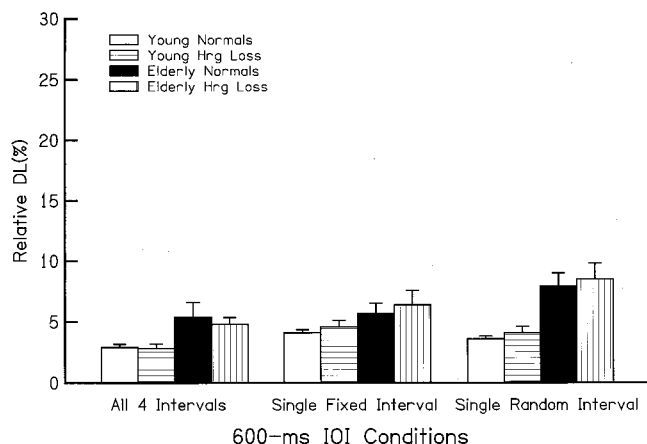


FIG. 3. Same as for Fig. 2, but for a 600-ms IOI.

(21.8 ms) for 100-ms IOIs, and 6.1% (36.4 ms) and 8.3% (49.2 ms) for 600-ms IOIs.

Separate ANOVAs were conducted with the individual relative DLs for the 100-ms and 600-ms IOI conditions shown in Figs. 2 and 3, each using a split-plot factorial design with two between-subjects factors, age, and hearing status, and one within-subjects factor, stimulus condition. Each analysis revealed significant main effects of age [$F(1,47) > 10.0$, $p < 0.01$], IOI condition [$F(2,94) > 17.6$, $p < 0.01$], and an age by condition interaction [$F(2,94) > 9.6$, $p < 0.01$], with no significant effect of hearing loss. Analysis of simple effects in these data revealed that relative DLs of the older listeners were significantly larger than those of the younger listeners ($p < 0.01$) in each condition for both IOIs. Additionally, all listeners produced significantly smaller relative DLs for the four-interval conditions compared to the single-interval conditions. However, for single intervals, younger listeners performed about the same for the fixed- and random-location conditions, whereas older listeners showed significantly larger DLs for the random-location versus fixed-location conditions ($p < 0.01$).

IV. DISCUSSION

The experiments compared the abilities of younger and older listeners to discriminate changes in the timing between successive components within simple tone sequences. In some conditions, listeners were asked to respond to uniform changes in tonal onset intervals that altered the presentation rate, or tempo, of the sequential stimulus patterns. In other conditions, listeners responded to changes in the magnitude of a single sequence interval that produced a localized disruption of timing within the tonal patterns. The results showed that listeners' sensitivity to changes of temporal intervals depends on both the magnitude and number of sequence intervals that are subjected to change. The results also indicated that older listeners were less sensitive than younger listeners to both single and multiple changes of sequence intervals. The magnitude of age-related performance deficits also differed for conditions featuring single and multiple timing cues.

A. Younger listeners

Results for the single-interval conditions revealed that younger listeners were able to discriminate interval changes with a degree of accuracy that was as good as, or better than, results reported in several earlier studies of duration discrimination for simple stimuli presented in isolation. Collective results from these earlier investigations indicate that, for a broad range of reference durations for filled and unfilled stimulus intervals (about 200–2000 ms), listeners can reliably discriminate duration increments exceeding 10–20 % of the reference interval, with larger values seen for much briefer reference intervals (Creelman, 1962; Small and Campbell, 1962; Abel, 1972; Divenyi and Danner, 1977; Allen, 1979). Younger listeners of the present study produced mean relative DLs of 4.3% and 10.5%, respectively, for single IOI intervals of 600 ms and 100 ms that were presented in a fixed mid-sequence location. By comparison, for a sequence IOI of 100 ms Hirsh *et al.* (1990) reported a

relative DL of 11.6% for single-interval discrimination, and Drake and Botte (1993) measured a relative DL for a single 600-ms IOI of about 5.4%. These values agree closely with the present single-interval estimates collected using stimulus patterns quite similar to those of the earlier studies. The single-interval DL estimates of the present investigation are smaller than those reported in our earlier study of duration discrimination for an embedded target tone or silent gap in tonal stimulus sequences (Fitzgibbons and Gordon-Salant, 1995). These earlier results, however, were collected using stimulus patterns that featured a high degree of spectral complexity, a factor that can exert a strong influence on discrimination performance. Despite the stimulus differences, the present results, like those of our earlier study, revealed that single-interval discrimination performance of the younger listeners was largely unaffected by stimulus uncertainty introduced by randomization of sequence location for the target interval. This outcome suggests that the younger listeners are able to attend to the timing characteristics of the pattern as whole, rather than attempting to focus on changes of a specific target interval.

The measurements for rate discrimination were collected by varying all sequence intervals by an equivalent amount at each of the four sequence presentation rates. As mentioned previously, the average performance of the younger listeners, as displayed in Fig. 1, revealed that the relative DL decreased from a maximum value for the 100-ms IOI to a smaller fairly stable value for each of the longer sequence IOIs tested. Additionally, the relative DLs for rate discrimination are smaller than those measured for single-interval discrimination for the same reference IOI. It could be argued that observed differences in DLs for rate and single-interval discrimination were a consequence of listeners attending to changes in overall sequence duration to perform the discrimination tasks. In this event, however, we would expect an equivalent increment in overall sequence duration at discrimination threshold, whether the sequence increment resulted from the lengthening of single or multiple sequence IOIs. Results show this not to be case. Sequence durations for the reference tonal patterns ranged from 450 ms with 100-ms IOI to 2450 ms for 600-ms IOI. For younger listeners, increases in duration for the 450-ms sequence at discrimination threshold were 10.4 ms for increments of a single interval and 24 ms for increments of multiple intervals (i.e., four times absolute DL of 6 ms). Corresponding duration increases for the 2450-ms reference pattern were 26.1 ms for a single-interval increment and 70 ms for multiple-interval increments. These differences indicate that it is unlikely that overall stimulus duration was a useful cue for sequence discrimination. Drake and Botte (1993) also provided convincing evidence that interval discrimination by their listeners was not based on changes of overall sequence duration. Additionally, the close agreement between the present single-interval DLs and those reported by Hirsh *et al.* (1990) is apparent despite differences in procedure wherein Hirsh *et al.* lengthened a single sequence IOI by tonal displacement without consequent changes in overall sequence duration.

Results for the rate discrimination measurements in the

present investigation display the same trends seen in the tempo discrimination data reported by Drake and Botte across a similar range of sequence IOIs. One characteristic of rate discrimination thresholds is the apparent constancy of the observed relative DLs across the range of longer IOIs from about 200–600 ms, a range corresponding to sequence durations of 850–2450 ms for tonal patterns of the present study. Thus it appears that a relatively constant Weber ratio for duration discrimination seen in the earlier studies with simple isolated sounds also extends to more complex sequential patterns, at least within the range of durations examined here. The Hirsh *et al.* experiments did not specifically measure rate discrimination, although the collective findings from that investigation suggested that discrimination of a repeated sequence interval would be about the same as that measured for a single interval. However, the present rate-discrimination data support those of Drake and Botte in showing that temporal sensitivity for changes of multiple intervals is more acute than that observed for single intervals, presented as either isolated targets or as an embedded component of an extended sequence. For example, in the present results for younger listeners the relative DLs for sequence rate at IOIs of 100 ms and 600 ms are smaller by 4.5% and 1.5%, respectively, than the corresponding DL values for single-interval discrimination.

Drake and Botte postulated a multiple-look hypothesis to account for the better temporal sensitivity seen for multiple- versus single-interval discrimination. This hypothesis argues that for an isochronous sequence, multiple repetitions of the same interval leads to a strengthening of memory trace for the reference interval and thus greater sensitivity to temporal deviations. In their examination of the hypothesis, Drake and Botte predicted that, for independent observations of each sequence interval, the absolute DL for sequences with a given number (N) of intervals should be equal to that measured for a single interval divided by the square root of N . Similar predictions, that are derived from the logic of signal-detection theory (Green and Swets, 1966), were examined earlier by Hafter and Dye (1983) to account for listeners' ability to lateralize click sequences that varied in duration and size of the inter-click interval. In applying the multiple-look model to the temporal discrimination data, Drake and Botte found approximate agreement between observed and predicted DLs for IOI, at least for a limited range of IOI and sequence length. For stimulus sequences with four intervals, as used in the present experiment, a multiple-look strategy would predict absolute DLs for rate discrimination to be about half those measured for a single interval. Inspection of the data for the younger listeners reveals that the observed differences between DLs for rate and single-interval discrimination are sizeable, but not quite as large as predicted. It should be noted, however, that our single-interval DLs were also measured within a sequential context that itself included multiple repetitions of the reference IOI. Thus, it is possible that the single-interval DLs measured here reflect better discrimination performance than would be expected for a pair of tones presented in isolation. We suspect this to be the case because some of our earlier measures (Fitzgibbons and Gordon-Salant, 1995) for duration discrimi-

nation with isolated stimuli produced larger relative DLs (about 20%) for single intervals than observed here for single intervals within sequences. Nevertheless, it is clear from the present results that multiple repetition of the same sequence interval leads to improve temporal sensitivity.

B. Older listeners

The older listeners exhibited reduced ability to discriminate temporal intervals. Additionally, like the younger groups of listeners, hearing loss among the older listeners was shown to have little influence on discrimination performance. For older listeners, the mean relative DLs for the fixed-location single intervals were 17.3% and 6.1%, respectively, for baseline IOIs of 100 ms and 600 ms. Each of these values is significantly larger than corresponding values measured for the younger listeners, with the absolute magnitude of the age-related difference being greatest for the 100-ms IOI. Unlike the younger listeners, the older listeners were significantly affected by the procedure of randomizing the sequence location of the single target interval that was subjected to variation in duration. For example, relative to their performance with fixed target locations, the relative DLs of older listeners increased by 4.5% and 2.1%, respectively, with randomization of the 100-ms and 600-ms target intervals. It is conceivable that the target randomization effects simply reflect differences in temporal sensitivity as a function of sequence location of the target interval, a possibility that was not specifically examined in the experiments. However, a sequence-location effect would necessarily apply to elderly listeners only, as the young listeners were largely unaffected by target randomization, and no sequence location effects for single intervals were observed in the discrimination experiments conducted by Hirsh *et al.* (1990). Thus, it seems reasonable to assume that the influence of target randomization on the performance of the older listeners was primarily a consequence of stimulus uncertainty. These age-related performance decrements associated with target randomization are similar to those observed earlier with the spectrally complex tonal patterns that produced larger temporal DLs (Fitzgibbons and Gordon-Salant, 1995).

The older listeners also exhibited less sensitivity than the younger listeners for rate discrimination, although the shifts in performance as a function of sequence IOI tended to parallel those observed with the younger listeners. For the older listeners, mean relative DLs for rate discrimination shifted from a value of about 8% for the 100-ms IOI to a relatively stable value of 5.1% across longer IOIs, where the Weber ratio was also fairly constant for younger listeners. For rate discrimination, the magnitude of the age-related decrement was reasonably uniform in degree across the range of sequence IOI that was examined.

Explanations for the age-related differences observed in temporal discrimination performance are not straightforward. On the basis of previous accounts of an age-related slowing in auditory processing, it was anticipated that the largest deficits among older listeners in the present experiments would be evident for the shorter temporal intervals associated with the fast sequence presentation rates. The rate discrimination results did not show a substantially larger age-

related deficit at the fastest sequence rate. However, it was apparent that the greatest age-related deviations from the performance of younger listeners were associated with the shortest reference interval (100-ms IOI) when presented as a single target interval. Thus the degree of improvement in temporal sensitivity from single-interval to multiple-interval discrimination was greatest among elderly listeners, but only for the brief reference intervals. This could imply more efficient utilization of a multiple-look strategy among elderly listeners, but this was not evident in the results for the slower stimulus rates featuring longer IOI values. Alternatively, an age-related loss of neural synchrony (Schneider and Pichora-Fuller, 2000) that is required to mark successive tonal onsets might be expected to impact discrimination of brief intervals more so than much longer reference intervals. As such, multiple repetition of the same brief stimulus interval might be expected to enhance the neural coding of stimulus onsets in the same manner as signal averaging reveals a robust onset response characteristically seen in the post-stimulus-time histograms of single VIII N. fibers (Kiang *et al.*, 1965). One outcome of this clearly defined onset marking would be to improve sensitivity to duration cues.

The results of the experiments provide additional evidence for age-related temporal processing deficits that are unrelated to the presence of sensorineural hearing loss. It is possible that a central timing mechanism is inherently involved for listening tasks requiring a judgment about stimulus duration, as postulated for some time in a theoretical model developed initially by Creelman (1962), and subsequently modified by Abel (1972) and Divenyi and Danner (1977). The theoretical accounts for duration discrimination postulate a central counter that essentially sums neural firings produced during the extent of stimulation, with a larger count resulting for the longer of two signals. Other elements of the model include a memory factor for the neural pulse count, and a factor indicating the degree of precision in marking of stimulus onsets and offsets. Earlier studies have demonstrated the utility of the model in describing the general trends and level of performance exhibited in a large body of discrimination data collected from young, trained listeners.

Consideration of the model components can provide a useful framework for examining possible sources of the age-related performance differences observed in the present investigation. A first consideration involves the possibility that age effects in duration discrimination are partially the result of reduced precision in marking signal onset/offset boundaries. For younger listeners, precision in marking signal boundaries is a factor that is primarily influenced by signal level, and Divenyi and Danner (1977) showed that levels of about 25 dB SL are sufficient to minimize uncertainty in registering signal onsets. This requirement was met in the present experiment for all listeners except three in the elderly hearing-loss group, who had thresholds of 65 dB HL at 4 kHz and may have listened at sensation levels below 25 dB. However, the discrimination performance of these three listeners was better than that of several others in the same elderly group of listeners. Another factor that could influence the coding of signal boundaries in elderly listeners is a loss

of synchrony in the neural response to stimulation, as suggested previously by Schneider and Pichora-Fuller (2000). However, the primary effects of this factor would be expected for the discrimination of brief intervals, with progressively less influence at longer reference durations, as noted by Divenyi and Danner. The present results did show the largest age-related deficit for single-interval discrimination of the shortest reference IOI of 100 ms, but for rate discrimination the age differences were similar in degree for all reference IOIs. Thus, there is no consistent trend in the present results indicating that lack of precision of the coding of stimulus boundaries was a primary source of age-related deficits. Of course, the shortest 100-ms reference interval of the current study may have been too long to observe any strong effects related to a loss of neural synchrony, a possibility that we are currently investigating by examining discrimination within a range of briefer reference intervals.

Other components of the Creelman model that could undergo changes with aging include the central counting mechanism itself, or the memory for accumulated counts that is required to compare durations of two or more signals in a discrimination task. For example, the density of neural pulses feeding a central counter may be diminished simply as a consequence of a reduction in the number of neural fibers with aging (Willott, 1990). In this event, longer increments of signal duration would be required for discrimination by elderly listeners compared to younger listeners. This factor could account for the uniform deficit with aging observed across the range of reference IOIs. Alternatively, a difference in memory for the clock count between younger and older listeners for accumulated pulse counts could also produce age-related differences in discrimination performance. In this case, an age-related memory deficit should produce more exaggerated performance differences between younger and older subjects at the longer reference intervals. The rate discrimination data shown in Fig. 1 do not provide strong evidence in support of this hypothesis. However, the larger variability observed for the elderly listeners across the range of longer reference IOIs suggest that the memory factor could have contributed to performance deficits in some of the elderly listeners. Additional testing with longer reference intervals than employed in the present study may show stronger influences of memory differences between younger and older listeners.

Finally, the observed age-related performance differences with single intervals for fixed- and random-location targets implicate a cognitive factor that deteriorates with aging but remains robust in younger listeners. Possible sources of this cognitive factor are auditory attention, auditory search capacity, or working memory capacity. However, the fact that a similar pattern of age-related performance deficits was observed at the 100-ms IOI and the 600-ms IOI argues somewhat against working memory as the likely candidate of the cognitive factor. These considerations of the model components suggest a number of factors that can be investigated independently in subsequent studies of aging and temporal processing: accuracy of marking of stimulus onsets, number of observation intervals, memory load, and the consequences of cognitive demands in specific discrimination tasks.

C. Summary

The experiments measured the ability of younger and older listeners with and without hearing loss to discriminate changes in the temporal intervals separating components of simple tonal sequences. Sequence rate discrimination was assessed by varying the inter-onset intervals of all tonal components in a uniform manner at each of four reference sequence rates. The relative DLs observed for rate discrimination for all listeners were larger for fast sequence rates, and smaller but equivalent at the slower rates tested. The rate DLs for the older listeners were larger than DLs of the younger listeners at each sequence rate. Temporal DLs were also measured for changes of a single sequence interval that was either fixed or randomized in sequence location in separate test conditions. For all listeners, the temporal DLs for single-interval changes were larger than corresponding DLs for multiple-interval changes. The older listeners also produced larger single-interval DLs than younger listeners, particularly for short reference intervals. The performance of the young listeners was unaffected by randomization of target interval location, whereas older listeners exhibited large performance decrements with target randomization. None of the results revealed a significant influence of sensorineural hearing loss. Collectively, the results indicate age-related differences in sensitivity to both localized and overall changes in the timing of components within sequential tone patterns.

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