Age effects on discrimination of timing in auditory sequences

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The experiments examined age-related changes in temporal sensitivity to increments in the interonset intervals (IOI) of components in tonal sequences. Discrimination was examined using reference sequences consisting of five 50-ms tones separated by silent intervals; tone frequencies were either fixed at 4 kHz or varied within a 2–4-kHz range to produce spectrally complex patterns. The tonal IOIs within the reference sequences were either equal (200 or 600 ms) or varied individually with an average value of 200 or 600 ms to produce temporally complex patterns. The difference limen (DL) for increments of IOI was measured. Comparison sequences featured either equal increments in all tonal IOIs or increments in a single target IOI, with the sequential location of the target changing randomly across trials. Four groups of younger and older adults with and without sensorineural hearing loss participated. Results indicated that DLs for uniform changes of sequence rate were smaller than DLs for single target intervals, with the largest DLs observed for single targets embedded within temporally complex sequences. Older listeners performed more poorly than younger listeners in all conditions, but the largest age-related differences were observed for temporally complex stimulus conditions. No systematic effects of hearing loss were observed. © *2004 Acoustical Society of America.* [DOI: 10.1121/1.1765192]

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I. INTRODUCTION

This paper describes results of some experiments that examined the ability of younger and older listeners to discriminate changes in the temporal characteristics of auditory sequences. The specific experiments are part of a larger project designed to explore the hypothesis that aging is accompanied by a general decline in auditory temporal processing that can affect listeners perception of both speech and nonspeech sequential sounds. Speech recognition studies have shown consistently that elderly listeners have difficulty understanding stimuli that have been time altered in some manner. This observation is most evident for listening tasks that utilize sentence-length speech samples presented at rapid presentation rates, produced either by fast talkers or time-compression techniques applied to speech waveforms (Wingfield *et al.*, 1985; Gordon-Salant and Fitzgibbons, 1993, 2001; Tun, 1998). By comparison to younger listeners, the diminished recognition performance exhibited by many elderly listeners with rapid speech can be quite pronounced. These speech results provide some general auditory support for a class of cognitive theories which stipulate that aging is accompanied by a generalized slowing of information processing for events throughout the nervous system (Birren, 1965; Salthouse, 1991).

Despite the prevalence of experimental observations, the specific sources of the speech understanding problems among elderly listeners are less certain. Part of the problem relates to the inherent temporal and spectral complexity of the speech signal itself. Additionally, a number of other factors, including the prevalence of sensorineural hearing loss among older listeners, as well as complex effects of speech semantic and syntactic factors, can each exert a significant influence on speech processing. However, in terms of acoustical changes, rapid speech is primarily characterized by a relative reduction in the duration of some or all of the component phoneme and pause intervals, together with consequent changes to overall speech tempo and rhythm. Therefore, it seems reasonable to assume that any loss of sensitivity to these component duration changes, or sequence timing characteristics, could be important factors underlying the age-related difficulties observed with rapid speech.

Additionally, psychophysical evidence lends some support to the conclusion that aging does appear to be a factor that contributes to diminished auditory temporal sensitivity. Some of the evidence relates to measured thresholds for the detection of brief temporal gaps between successive acoustic markers, either pairs of simple tone or noise bursts. Most of the gap thresholds measured for elderly listeners are reported to be about twice the magnitude of those observed for younger listeners (Schneider *et al.*, 1994, 1998; Snell, 1997). Older listeners are also observed to have difficulty discriminating changes in the duration of simple tones and noise bursts, or reference intervals defined by a silent interval inserted between a pair of acoustic markers (Abel *et al.*, 1990; Fitzgibbons and Gordon-Salant, 1994; Lister *et al.*, 2000; Grose *et al.*, 2001). Generally, the age-related deficits observed for duration discrimination are also found to be largely independent of sensorineural hearing loss, indicating that cochlear mechanisms are not the likely source of reduced temporal sensitivity among the elderly listeners.

Other evidence also indicates that measures of temporal

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sensitivity collected with simple stimuli do not always generalize to listening conditions that feature more complex extended sequences of sounds. For example, in one study (Fitzgibbons and Gordon-Salant, 1995), we compared the ability of younger and older listeners to discriminate duration changes for a simple tone presented in isolation and the same tone embedded as one component of a five-tone contiguous sequence that approximated the length of a simple spoken sentence. One notable finding of the study was that younger listeners were able to discriminate duration changes in the embedded target tone with about the same accuracy as they demonstrated for the target tone presented in isolation. However, this was not the case for older listeners. These listeners showed significant reductions in discrimination performance for tones within a sequential context versus the same targets presented in isolation. The performance of these older listeners was also reduced considerably if the sequence location of the embedded target tone changed randomly across a series of listening trials. By comparison, younger listeners were largely unaffected by uncertainty regarding sequential location of a target tone. These results indicate that relatively small age- related effects measured for simple isolated stimuli may become pronounced when examined within a more complex sequential stimulus context.

One possible explanation for the age effects seen with the sequential stimuli is that younger listeners are able to utilize overall timing cues related to changes of sequential rhythm or tempo to perform the duration discrimination tasks. By comparison, older listeners may not, or can not, process these overall timing cues as effectively. Recently, we conducted an initial investigation of this hypothesis by directly comparing the ability of younger and older listeners to discriminate changes in sequence tempo within relatively simple tonal patterns (Fitzgibbons and Gordon-Salant, 2001). The stimulus sequences consisted of five brief tones of equal frequency separated equally by silent intervals to create sequences with uniform tonal interonset intervals (IOIs) that corresponded to a given presentation rate. For each of several reference sequence rates, the intertone silent intervals were co-varied simultaneously in order to measure the relative DL for changes of tonal IOI corresponding to a slowing of the sequence rate. The results indicated that young listeners are generally quite sensitive to changes of sequence rate, with the relative DLs for IOI changes being about 3% over a broad range of presentation rates. The same results also revealed significant age-related performance differences, with the older listeners observed to be consistently less sensitive to changes of sequence rate than younger listeners. Additionally, the performance of older listeners was notably poor for discriminating localized changes in sequence timing, changes that were examined in some conditions by alterations of a single tonal interval within the otherwise equal-interval patterns. While the age differences in performance were evident across a range of stimulus sequence rates, many of the elderly listeners exhibited the greatest difficulty in tracking timing changes at the faster stimulus rates.

These results with simple tonal patterns suggest that older listeners may have specific problems processing the timing pattern within auditory sequences. However, the extent to which the results collected with the fixed-frequency uniform sequences is useful towards understanding the processing of more complex temporal patterns is unclear. We know, for example, that even simple sequences of speech sounds feature considerable spectral complexity as well as variation of timing within patterns. These stimulus factors may contribute to the speech recognition problems that are evident for many older listeners. Therefore, the focus of the present investigation is to examine the manner in which stimulus temporal and spectral complexity interact with the listeners age to influence sequential processing of nonspeech stimulus patterns. Additionally, because diminished speed of processing is hypothesized to be a consequence of aging, we anticipate that the specific effects of spectral and temporal stimulus factors will vary with sequence presentation rate. Finally, hearing loss is a well-established consequence of aging, one that is known to influence listeners' processing of both speech and non-speech sounds in a number of listening tasks (Dubno and Schaefer, 1992; Dubno and Ahlstrom, 1995). Thus, another purpose of the study is to examine the independent and interactive effects of listener age and hearing loss on all discrimination measures. This is accomplished by testing groups of younger and older listeners in the experiments who were matched by age and degree of sensorineural hearing loss.

II. METHODS

A. Subjects

Listeners in the study included 51 subjects assigned to four groups according to age and hearing status. One group included young normal-hearing subjects (YNH, $n=15$) ages 18–40 ($M=23.2$ years, s.d.$=5.3$) with pure-tone thresholds $\leqslant 15$ dB HL (*re*: ANSI, 1996) from 250 to 4000 Hz. Another group included young hearing-impaired listeners (YHI, $n=10$) of 18 to 40 years ($M=29.9$ years, s.d.$=10.2$) with mild-to-moderate sloping high-frequency sensorineural hearing losses of hereditary or unknown etiologies. A third group of subjects included normal-hearing elderly listeners (ENH, $n=11$) of 65–76 years ($M=70.8$, s.d.$=5.2$) who met the same audiometric criteria as the YNH listeners. Lastly, an elderly group of listeners with hearing impairment (EHI, $n=15$) were 65–76 years ($M=70.5$, s.d.$=3.9$) and also had mild-to-moderate sloping sensorineural hearing losses. The young and elderly listeners with hearing loss exhibited bilateral impairment of equivalent degree ($\pm 5-10$ dB) and configuration across the range of audiometric test frequencies. These subjects had a negative history of otologic disease, noise exposure, and family history of hearing loss. The probable etiology of hearing loss in the older listeners was presbycusis. All testing in the study was monaural, and Table I presents the mean audiograms for test ears of the four listener groups.

Additional criteria for subject selection included monosyllabic word recognition scores exceeding 80%, normal tympanograms, and acoustic reflex thresholds for contralateral pure tone stimuli (500–2000 Hz) elicited at levels below the 90th percentile for individuals with comparable hearing thresholds (Silman and Gelfand, 1981). None of the listeners

TABLE I. Thresholds (dB HL) (*re*: ANSI, 1996) and standard deviations (shown in parentheses) for test ears of young normal hearing (Yng Norm Hrg), elderly normal hearing (Eld Norm Hrg), young hearing-impaired (Yng Hrg Imp), and elderly hearing-impaired (Eld Hrg Imp) listeners for octave frequencies from 250 through 4000 Hz.

	Frequency (Hz)									
	250		500		1000		2000		4000	
Yng Norm Hrg	5.7	(4.6)	1.7	(3.1)	2.0	(3.2)	2.0	(5.6)	2.3	(5.3)
Eld Norm Hrg	12.7	(7.5)	7.7	(7.5)	7.3	(4.7)	5.45	(5.68)	11.82	(7.51)
Yng Hrg Imp	9.5	(17.4)	25.0	(19.7)	30.5	(18.6)	32.0	(17.5)	43.5	(14.9)
Eld Hrg Imp	19.0	(9.49)	19.3	(11.63)	25.3	(10.26)	36.0	(10.89)	50.67	(8.84)

had participated previously in listening experiments and each was paid for their services as subjects. Older listeners also passed a brief screening test for general cognitive awareness [the Mini-Mental Status Questionnaire (Pfeiffer, 1975)].

B. Stimuli

All stimulus 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 (DD1, 20-kHz sampling rate) that was followed by low-pass filtering (Frequency Devices 901F, 6000-Hz cutoff, 90 dB/oct). The sequences were constructed using five equal-duration tone bursts that were separated by silent intervals. Each tone burst of 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 in the electrical waveforms. For each sequence the silent intervals between tones were adjusted to establish a desired tonal interonset interval (IOI), an interval that included both the tone and silent interval durations. The stimulus sequences used as reference patterns for discrimination testing were designed to feature spectral complexity, temporal complexity, or a combination of spectral and temporal complexity. Spectrally complex sequences (F) featured variable tone frequencies with fixed tonal IOIs, while temporally complex patterns (T) featured variable tonal IOIs with fixed tone frequencies. Sequences with combined spectral and temporal complexity (FT) featured variable frequencies and variable IOI values.

The stimulus sequences were used in different test conditions that were designed to examine listeners ability to discriminate either uniform changes in sequence presentation rate or localized changes of timing within a sequence. Uniform changes in sequence rate were introduced by covariation of all sequence IOIs (ALL), whereas localized timing changes were effected by variation of a single sequence IOI value (ONE). The experiments included four discrimination conditions, each of which was conducted with reference sequences that were presented at a faster and slower rate. One of the conditions (F_ALL) used the spectrally complex sequences in which all IOI values were varied equally to examine discrimination of uniform changes of sequence rate. The individual tones within the reference patterns were 2000, 2500, 3000, 3500, and 4000 Hz. This octave range was selected to allow a degree of spectral variability within sequences, while also restricting testing to a region that coincided with that of greatest sensitivity loss in the listeners with hearing impairment. For these reference patterns, the ordering of the five tone frequencies within a sequence was randomized across listening trials, but the sequence IOIs were equal, with values of 200 ms for the faster-rate sequences and 600 ms for the slower-rate sequences. Another condition (F_ONE) used these same spectrally complex reference sequences at the faster and slower rates to measure discrimination of changes in one sequence IOI. The sequence location of the selected target interval, an IOI of either 200 ms or 600 ms, also shifted randomly across the four possible tonal IOIs within a sequence on each listening trial.

The other two conditions also assessed discrimination of a single sequence interval, using reference stimulus patterns that featured temporal complexity. One of these (T_ONE) used fixed-frequency stimulus sequences, with all tones set to 4000 Hz. The tonal IOIs in these reference sequences were nonuniform in magnitude, with fixed values in the faster-rate sequences of 100, 150, 200, and 350 ms, with the 200-ms IOI representing the average interval magnitude that always served as the target interval for discrimination testing. Corresponding IOI values for the slower-rate reference sequences were 400, 500, 600, and 900 ms, with the 600-ms IOI being the average value that served as the target interval for discrimination testing. The selection of IOI values for these faster and slower reference sequences was in part arbitrary, but was intended to include intervals shorter and longer than that of the 200 or 600-ms target interval. Additionally, the fixed IOI values in these temporally complex reference patterns were selected to preserve overall sequence durations to match those of the corresponding equal-interval reference sequences of the F_ALL and F_ONE conditions. These sequence durations were 850 and 2450 ms, respectively, for the faster and slower patterns, which were intended to grossly mimic the durations of rapidly and slowly spoken sentences. The final condition (FT_ONE) used these same temporally complex reference sequences, but with the addition of tone frequencies that differed in the same manner as described for the spectrally complex patterns. These sequences with both frequency and temporal complexity were also used to assess discrimination of a single target IOI with reference values 200 or 600 ms, respectively, in the faster and slower stimulus patterns. For both conditions that utilized the temporally complex stimulus patterns, the ordering of the four tonal IOI values changed randomly across a series of discrimination trials. As such, the sequence location of the 200-ms, or 600-ms, target IOI for discrimination testing also changed randomly across the four possible tone intervals of a sequence on each listening trial.

C. Procedures

The measurement of DLs for increments of 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. For all conditions, reference and comparison sequences of a given listening trial differed only by the duration of one or more IOI values, which were always longer in the comparison sequence. In all cases, the lengthening of IOIs in the comparison sequence was accomplished by incrementing one or more intertone silent intervals, with no change of tonal durations, thus extending overall duration of the comparison sequence. In the F_ALL condition, measurements of sequence rate discrimination were collected with the spectrally complex reference sequences which featured uniform IOI values of 200 or 600 ms for the faster and slower patterns, respectively. Adjustments of sequence rate in the comparison sequences were implemented by co-varying all sequence IOIs equally to produce a slowing of presentation rate. The sequential ordering of tone frequencies changed randomly across trials, but was always the same for the reference and comparison sequences of a given listening trial. These same reference sequences were also used for the single-interval discrimination condition, F_ONE. For this condition, only one IOI in the comparison sequence, designated as the target interval, was lengthened, with other sequence IOI values remaining fixed and equal to their original reference values, either 200 or 600 ms. Within the comparison sequence, the location of the target IOI changed randomly across the four sequence intervals on each listening trial; the ordering of tone frequencies did not change across listening intervals within a trial but did change randomly across trials. In a similar manner, discrimination of a single target IOI was assessed in the two conditions that featured temporally complex reference sequences, that is, T_ONE, with the fixed-frequency patterns, and FT_ONE, with the variable-frequency patterns. In each condition, the variable target interval in the comparison sequences had a reference duration of 200 or 600 ms, respectively, for the faster and slower reference sequences. Again, the ordering of sequence tone frequencies, IOI values, and sequence location of the target interval changed randomly across discrimination trials, but not across listening intervals of a given trial.

Estimates of all duration DLs in each condition were obtained using an adaptive rule for varying the target IOI value(s), such that the target decreased in magnitude following two consecutive correct responses by the listener and increased following each incorrect response. Threshold estimates derived by this adaptive rule corresponded to values associated with 70.7% correct discrimination (Levitt, 1971). Testing was conducted in 50-trial blocks with an IOI starting value of 1.4 times its reference value, and 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 four 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 h of practice for sequence discrimination, with all listeners showing performance stability after 3–4 trial blocks in each condition.

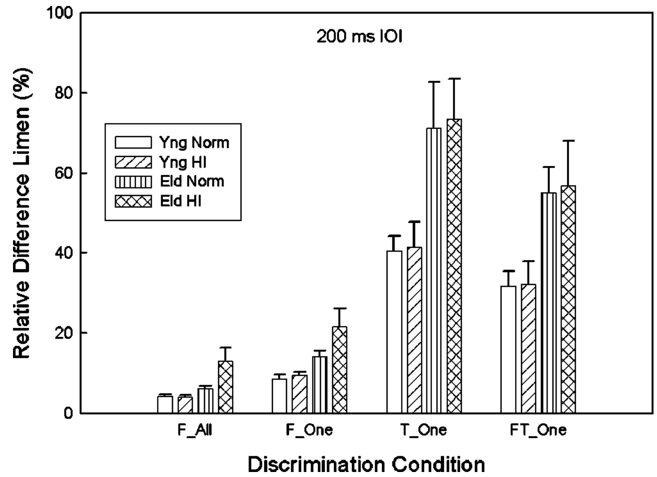

FIG. 1. Mean relative difference limen (DL) in percent for each listener group in the four stimulus sequence conditions with 200 ms as the reference tonal inter-onset interval (IOI). The four sequence conditions include equal increments of all IOIs in equal-interval patterns with variable frequencies (F_ALL), increments of a single IOI in equal-interval patterns with variable frequencies (F_ONE), increments of a single IOI in unequal-interval patterns with fixed frequencies (T_ONE), and increments of a single IOI in unequal-interval patterns with variable frequencies (FT_ONE). The four listener groups are young normal hearing (Yng Norm), young hearing-impaired (Yng HI), elderly normal hearing (Eld Norm), and elderly hearing-impaired (Eld HI). Error bars represent the standard error of the mean.

The listeners were tested individually in a sound-treated booth. The discrimination conditions were tested in a different random 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 in the 2000–4000-Hz region for the listeners with hearing loss. Testing was monaural in the listener's preferred ear using an insert earphone (Etymotic ER-3A) that was calibrated in a 2-cm^3 coupler (B&K, DB0138). All listening was conducted in 2-h sessions over the course of several weeks. Total test time (not including practice) varied across listeners, but averaged about 8 h.

III. RESULTS

For the purpose of analysis and comparison with previous findings, all duration DLs collected in the experiments were converted to relative values expressed as a percentage of the reference IOI value. Results of the four experimental conditions for each of the four listener groups are displayed in Fig. 1, for the conditions with faster-rate sequences (200-ms IOI targets), and Fig. 2, for the conditions with slower-rate sequences (600-ms IOI targets). Each of the figures displays the mean relative DLs for each condition and

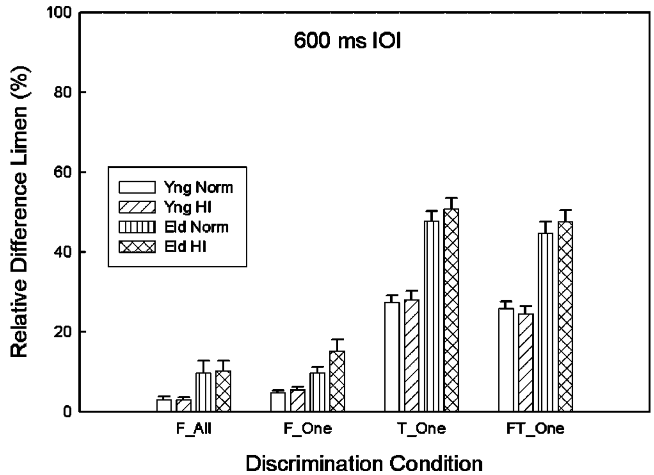

FIG. 2. Same as for Fig. 1, but for 600-ms reference IOIs.

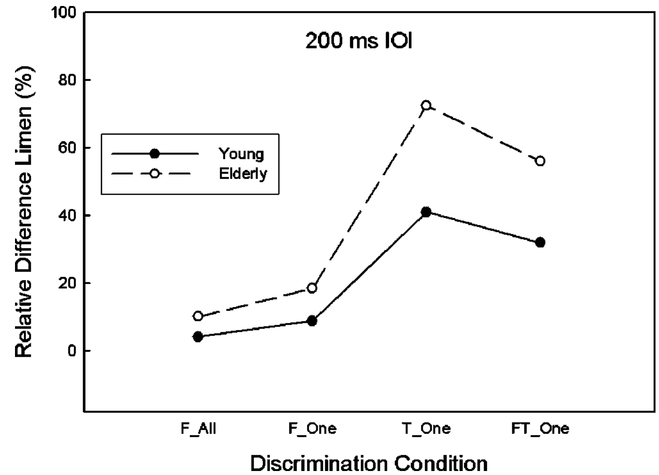

FIG. 3. Mean relative DLs in percent for 200-ms reference IOIs in the four sequence conditions for young and elderly listeners. The data are collapsed across the normal-hearing and hearing-impaired listener groups.

group of subjects, with vertical bars in the figures representing the standard error of the means. The relative DLs displayed in Fig. 1 are generally larger than those of Fig. 2, particularly for the three conditions that involved single-interval discrimination (F_ONE, T_ONE, FT_ONE). The F_ALL condition that involved discrimination of changes in sequence rate produced the smallest relative DLs, and these values were essentially equivalent for the sequences with the faster and slower reference rates. A separate analysis of variance (ANOVA) was conducted for the relative DLs shown in Figs. 1 and 2, using a split-plot factorial design with two between-subjects factors (age and hearing status) and one within-subjects factor (discrimination condition). Each analysis revealed significant main effects of listener age ($p < .001$), discrimination condition ($p < .001$), and significant interactions between age and condition ($p < 0.01$). The analyses revealed no significant effects of hearing loss across conditions, for either the faster or slower sequence presentation rates.

Simple main effects analysis and multiple comparison tests were subsequently conducted to examine sources of the age×condition interactions that were evident in the data collected for both the faster and slower stimulus sequences. To examine the interaction effects, the mean relative DLs for the two age groups (collapsed across hearing status) are shown in Fig. 3, for the four conditions with 200-ms target intervals, and Fig. 4, for the four conditions with the 600- ms targets. As each figure shows, the relative DLs for both listener age groups were smaller for the conditions featuring only sequence spectral complexity (F_ALL and F_ONE), and significantly larger for the conditions featuring sequence temporal complexity (T_ONE and FT_ONE), ($p < 0.01$). For both age groups, the mean performance differences were relatively small between the two conditions with spectral complexity (F_ALL and F_ONE), and were also not significantly different between the two conditions with temporal complexity (T_ONE and FT_ONE). The discrimination performance of the older listeners was poorer than that of the younger listeners in each of the four conditions, but the largest age-related performance differences were observed for the T_ONE and FT_ONE conditions at both sequence rates ($p < 0.01$).

IV. DISCUSSION

The experiments compared the abilities of younger and older listeners to discriminate changes in the timing between successive components of tonal sequences that featured spectral complexity, temporal complexity, or a combination of the two. In some conditions, listeners were asked to respond to uniform changes in all tonal interonset intervals that altered the presentation rate 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 number and magnitude of the temporal intervals that are subjected to change. Additionally, the spectral and temporal characteristics of the stimulus sequence can affect discrimination performance, with temporal complexity exerting the most pronounced effects. The results indicated that older listeners were less sensitive than younger listeners to changes of timing within the stimulus sequences.

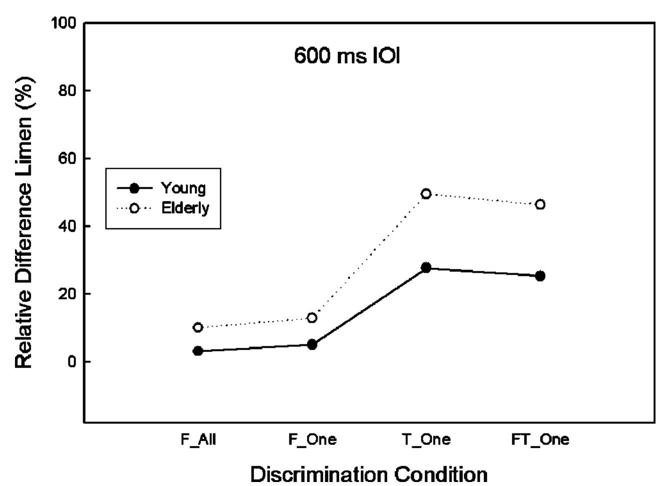

FIG. 4. Same as Fig. 3, but for 600-ms reference IOI values.

However, the magnitude of the age-related discrimination deficits varied across stimulus conditions, and depended largely upon the timing characteristics of the stimulus patterns.

A. Equal interval patterns

For the stimulus conditions that featured tonal IOIs of equal magnitude in the reference patterns (F_ALL and F_ONE), the younger listeners were able to discriminate interval changes with a relatively high degree of accuracy. The estimates of discrimination for overall changes of presentation rate with the equal-interval sequences revealed the best temporal sensitivity among the younger listeners. Thus, for the F_ALL condition, with all sequence IOIs co-varied equally, the relative DLs for rate change were 4.1% for the faster reference sequences and 3.1% for the slower sequences. The near equivalence of these DLs for rate discrimination with the faster and slower sequences agrees with earlier findings that were collected with fixed-frequency tone sequences that also featured uniform timing patterns (Drake and Botte, 1993; Fitzgibbons and Gordon-Salant, 2001). Collective findings from these earlier studies indicated that the relative DL for changes of sequence rate remains fairly constant over a broad range of reference tonal IOIs ranging from about 200 to 800 ms. This was not the case for the single-interval DLs, which generally reflected larger relative DL values for the shorter 200-ms interval compared to the longer 600-ms interval. For example, for the F_ONE condition that examined discrimination of a single embedded sequence interval, the younger listeners produced mean relative DLs of 8.9% and 5.2% for the target IOIs of 200 and 600 ms, respectively. These values are larger than the corresponding DLs for the F_ALL condition, indicating that localized changes of timing within sequences are more difficult to discern than uniform changes in presentation rate.

The discrimination performance of the older listeners with the equal-interval reference sequences was generally poorer than that of the younger listeners. For discrimination of sequence rate with the equal-interval patterns (F_ALL condition), the older listeners produced mean DLs of 9.6% for the faster sequences with 200-ms reference IOIs and 10.0% for the slower sequences with 600-ms IOIs. These values are larger than corresponding estimates for rate discrimination in the younger listeners. However, like the younger listeners, the mean DLs for rate discrimination among the older listeners were essentially equivalent for the faster and slower reference sequences, indicating a fairly constant Weber fraction for the two reference presentation rates. This outcome also agrees with observations from our previous experiment with fixed-frequency tone sequences (Fitzgibbons and Gordon-Salant, 2001), which revealed a relatively constant relative DL in elderly listeners for rate discrimination across a large range of reference sequence presentation rates.

For single-interval discrimination (F_ONE condition), the mean relative DLs of the older subjects was 17.9% and 12.4% for the 200- and 600-ms target IOIs, respectively. Each of these values is at least twice the corresponding DL values for the younger listeners. It should be noted, however, that the performance variability among the elderly listeners was sometimes large, especially among the DLs measured for the shorter 200-ms target interval. This outcome was primarily attributed to the poor discrimination performance of two elderly listeners, who produced abnormally large DLs for the 200-ms single target interval. However, even with the omission of the data for these two subjects, the mean relative DL for the elderly listeners was 14.6% for the 200-ms target, a value that remains considerably larger than that observed for the younger listeners.

B. Unequal interval patterns

The reference sequences with irregular timing featured unequal tonal intervals with an average value of 200 or 600 ms, values that served as the respective sequence targets for single-interval discrimination in the faster and slower reference sequences. For these temporally complex stimulus patterns, discrimination of changes in the single target interval proved to be difficult for both younger and older listeners, with performance being significantly poorer than that observed for the same target intervals embedded within the sequences with equal tone intervals. For the sequences with unequal intervals and fixed tone frequencies (T_ONE condition), the younger listeners produced mean relative DLs of 41.1% and 27.7% for the 200- and 600-ms single IOI targets, respectively. Similarly, for the same temporally complex sequences with variable tone frequencies (FT_ONE condition), the mean relative DLs of the younger listeners were 32.0% and 25.2% for the 200- and 600-ms single target intervals, respectively. For both conditions, discrimination performance among listeners was always poorer and more variable for the shorter 200-ms target than for the 600-ms target interval, a result that was also observed for the stimulus patterns with the equal tone intervals. Additionally, no significant differences in the discrimination performance of the younger listeners were observed between temporally complex sequence conditions that featured fixed-frequency and variable-frequency tonal patterns. Thus, the combined effects of spectral and temporal complexity in the stimulus sequences of the FT_ONE condition were about the same as those produced by temporal complexity alone with sequences of the T_ONE condition.

The older listeners exhibited pronounced difficulty discriminating changes in the target interval within the sequences with unequal timing. For the fixed-frequency patterns (T_ONE), these older listeners produced mean relative DLs of 72.4% and 49.3% for the 200- and 600-ms target IOIs, respectively. Corresponding mean DLs for the variable-frequency sequences (FT_ONE) were 56.0% and 46.2%, respectively, for the same 200- and 600-ms targets. These results also showed poorer and more variable discrimination performance for 200-ms targets relative to that for the longer 600-ms target intervals. This was particularly the case for the 200-ms targets in the T_ONE condition, in which two elderly listeners from each hearing status group exhibited abnormally poor discrimination. With the data from these subjects omitted, the mean DL value for the elderly listeners in the T_ONE condition with the 200-ms target interval would have shifted from 72.4% to 59.4%, a value equivalent to that for the FT_ONE condition for the elderly listeners. In either case, the DL values of the older listeners with the unequal-interval patterns were at least three times larger than their corresponding DLs measured for the same reference target intervals embedded within the stimulus patterns with equal intervals. The performance of the elderly listeners was also significantly poorer than that of the younger listeners in both the T_ONE and FT_ONE sequence conditions. However, like the younger listeners, the discrimination performance of the older listeners with the temporally complex sequences was not significantly different for the conditions with fixed-frequency and variable-frequency tonal patterns.

C. Stimulus complexity effects

The experiments were designed to examine some effects of temporal and spectral complexity on listeners ability to discriminate changes of timing within tonal stimulus sequences. The results indicate that the temporal complexity associated with the unequal sequence intervals produced substantial performance decrements, relative to that observed for the patterns with equal intervals. This outcome was evident for all listeners, but the magnitude of the effects was significantly larger among the elderly subjects. It was anticipated, on the basis of earlier reports, that the introduction of irregular timing to stimulus patterns could influence listeners ability to discriminate one or more embedded target intervals. Some of the earlier studies (Bharucha and Pryor, 1986; Hirsh *et al.*, 1990; Monahan and Hirsh, 1990; Drake and Botte, 1993) reported that even small deviations from regularity in the timing patterns of tonal sequences could produce decrements in listeners temporal discrimination performance. In the present investigation, the temporally complex stimulus sequences featured a substantial degree of irregularity in the timing patterns, with each tonal IOI differing across a relatively wide range of values. This dispersion of interval values within the stimulus sequences undoubtedly contributed to the listeners difficulty in discriminating incremental changes to any single embedded target interval. Additionally, the procedure of randomizing the ordering of the unequal tonal IOIs within sequences across listening trials, as well as randomizing the sequential location of the target interval, introduced a large degree of stimulus uncertainty that further complicated the discrimination task. In all likelihood, this degree of stimulus uncertainty with the complex sequences precluded listeners from developing a memory trace for timing patterns within the reference sequences that was sufficiently strong to discern small deviations in the magnitude of a particular target interval. This would necessarily be the case for stimuli that required substantial memory resources to encode the pattern of temporal intervals within reference sequences, a task that was perhaps more taxing for the older listeners. Without the aid of stimulus context, it seems likely that even the younger listeners had to adopt the less efficient strategy of attempting to isolate and focus on the specific target interval that was subjected to duration changes. In this event, we might expect that the DLs measured for single target intervals within the temporally complex tonal patterns would more closely approximate those values reported for corresponding target intervals that are measured in isolation.

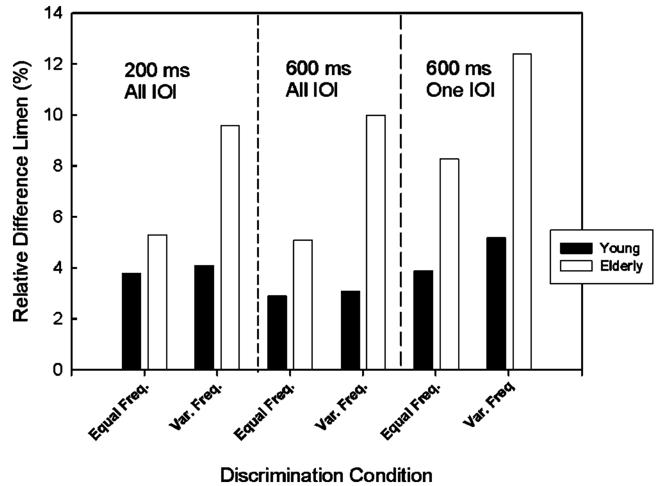

FIG. 5. Mean relative DLs in percent of young and elderly listeners for changes of IOI in three stimulus conditions with equal-interval tone sequences. The conditions include equal increments to all sequence IOIs with reference values of 200 ms (200 ms All IOI) or 600 ms (600 ms All IOI), and increments of a single 600 ms IOI (600 ms One IOI). The sequence tone frequencies were either fixed at 4 kHz (Equal Freq.), or variable in the 2–4-kHz range (Var. Freq.). The results are collapsed across normal-hearing and hearing-impaired listener groups. The DLs shown for Equal Freq. conditions are from Fitzgibbons and Gordon-Salant (2001).

Our results generally support this prediction, with the DLs of our younger listeners for both the 200- and 600-ms target intervals showing reasonably good agreement with the duration DLs reported previously for similar reference silent intervals bounded by a simple pair of stimulus markers presented in isolation (Abel, 1972b; Grose *et al.*, 2001).

The general equivalence of results observed for the T_ONE and FT_ONE single-interval discrimination conditions indicates that the effect of adding spectral complexity to the sequences with unequal intervals was minimal for both the younger and older listeners. This outcome was unexpected, primarily because we had previously observed substantial effects of sequential spectral variation on duration judgments in a different type of discrimination task. (Fitzgibbons and Gordon-Salant, 1995). However, the lack of spectral effects in the present results is most likely due to the high level of difficulty already associated with the temporally complex patterns, a situation that could have obscured observation of any potential additional spectral influences on temporal discrimination. We suspect this to be the case in part on the basis of a *post hoc* examination that compared the DLs measured here for the variable-frequency sequences with equal intervals (F_ALL and F_ONE conditions) to some corresponding results reported in our earlier study that utilized fixed-frequency tone sequences with the same uniform timing characteristics (Fitzgibbons and Gordon-Salant, 2001). Each of the studies examined groups of younger and older listeners that exhibited the same age and hearing characteristics. Some of these comparative data are displayed in Fig. 5, which shows the mean relative DLs of younger and older listeners for two corresponding conditions that measured discrimination of sequence rate changes, labeled All IOI for sequences with equal 200- or 600-ms tonal IOIs, and one condition that measured discrimination for a single sequence interval, labeled One IOI, for a 600-ms target interval. Results in the figure from the earlier study are labeled Equal Frequency (Equal Freq.), while those from the present investigation are labeled Variable Frequency (Var. Freq.) As the figure shows, the sequence rate discrimination performance (All IOI conditions) of the younger listeners was virtually the same for the equal-frequency and variable-frequency tone sequences, while the single-interval DLs for the 600-ms target were slightly larger for the variable- frequency sequences. Thus, the discrimination performance of the younger listeners was largely unaffected by the addition of spectral variability to the stimulus patterns with uniform timing. By comparison, the data of elderly listeners show large effects of spectral complexity, with the relative DLs for the variable-frequency sequences (both All IOI, and the One IOI conditions) being considerably larger than those for the corresponding equal-frequency sequences, and also larger than those of the younger listeners in each condition.

The above comparison of data indicates that the independent effects of sequential spectral complexity on temporal discrimination performance may be substantial, at least for older listeners, and sequences with uniform timing characteristics. This outcome, in conjunction with the strong effects of temporal complexity seen in the present results, suggests that both of these stimulus factors could contribute to the age-related processing difficulties commonly associated with time-altered speech. While the importance of spectral cues in speech understanding is well documented, the role of variable timing within and across speech utterances is less well understood. However, the present findings with nonspeech sounds indicate that the processing of sequences with variable timing is difficult for all listeners, but especially for older listeners and faster sequence presentation rates. Of course, in addition to ongoing variations in frequency and timing, sequences of spoken speech also exhibit substantial variation in component intensity, a factor that undoubtedly contributes to the significant effects of listener hearing loss observed in many of the speech recognition studies. In the present experiments with nonspeech sequences, all testing was restricted to spectral regions of hearing loss, but stimulus intensity was fixed at a relatively high level to insure signal audibility. As a result, no systematic effects of hearing loss among either the young or elderly listeners were observed in the discrimination measures. This outcome agrees with conclusions previously reported for studies that examined effects of hearing loss on duration discrimination tasks (Fitzgibbons and Gordon-Salant, 1995, 2001; Grose *et al.*, 2001). These hearing- loss results regarding duration discrimination provide indirect support for the contention that the processing of stimulus duration is primarily controlled by central timing mechanisms (Creelman, 1962; Abel, 1972a; Divenyi and Danner, 1977). Given sufficient stimulus audibility, the postulated timing mechanisms are unlikely to be affected by peripheral hearing loss, but may exhibit diminished function with aging.

D. Summary

The temporal discrimination results collected from the young and elderly listeners for the sequential stimulus patterns used in the investigation can be summarized as follows:

(1) For equally timed tonal sequences, all listeners generally show better sensitivity for uniform changes of sequence rate than they do for localized changes of timing in a single sequence interval.

(2) The relative DLs for uniform changes of sequence rate were equivalent for the faster and slower sequences, but discrimination performance was generally poorer for single intervals within the faster, compared to slower, sequences.

(3) Discrimination of temporal intervals within sequences with unequal timing is considerably more difficult than discrimination of corresponding intervals within equally timed sequences.

(4) Older listeners exhibit larger relative DLs than younger listeners for all stimulus sequences, but the largest age-related differences were observed for stimulus patterns with unequal timing.

(5) There were no significant effects of hearing loss observed in any of the discrimination conditions for younger and older listeners.

The present findings confirm some of our previous observations that elderly listeners have difficulty discriminating temporal differences in tonal sequences. Whereas our earlier results were collected with fixed-frequency stimulus sequences with equal timing, the current results pertain to spectrally and temporally complex patterns that were intended to mimic some characteristics inherent to sequential speech patterns. The collective evidence indicates that spectral complexity within sequences may exert an important influence on the temporal discrimination performance of older listeners. The discrimination of temporal deviations in stimulus patterns with variable timing structure is relatively difficult for all subjects, but especially for older listeners. The combination of results lends further support to the hypothesis that aging is associated with significant difficulty processing the temporal characteristics of complex sequential stimuli.

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