Effects of age and sequence presentation rate on temporal order recognition

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The experiments examined the ability of younger and older listeners to identify the temporal order of sounds presented in tonal sequences. The stimuli were three-tone sequences that spanned two-octave frequency range, and listeners identified random permutations of tone order using labels of relative pitch. Some of the sequences featured uniform timing characteristics, and the sequence duty cycle was varied across conditions to examine the relative influence of tonal durations and intertone interval on recognition performance across a range of sequence presentation rates. Other stimulus sequences featured nonuniform timing with unequal tone durations and intertone intervals. The listeners were groups of younger and older persons with or without hearing loss. Results indicated that temporal order recognition was influenced primarily by sequence presentation rate, independent of tonal duration, tonal interval spacing, or sequence timing characteristics. The performance of older listeners was poorer than younger listeners, but the age-related recognition differences were independent of sequence presentation rate. There were no consistent effects of hearing loss on temporal ordering performance.
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I. INTRODUCTION

This paper describes the results of an investigation that examined the abilities of younger and older listeners to correctly identify the presentation order of sound in simple stimulus sequences. The specific experiments are part of an ongoing project designed to explore the hypothesis that aging is accompanied by a gradual decline in auditory temporal processing that can influence listeners' perception of both speech and non-speech sequential sounds. Studies of speech recognition have consistently found that many elderly listeners have difficulty accurately perceiving sounds sequences that have been temporally modified in some manner. This is particularly evident for speech sequences delivered at rapid presentation rates, as might result from either fast talking or time compression techniques applied to speech wave forms (Wingfield *et al.*, 1985; Gordon-Salant and Fitzgibbons, 1993; Vaughan and Letowski, 1997; Tun, 1998). For rapid speech, the observed age-related decline in recognition performance is frequently offered as supporting evidence for a class of cognitive theories which postulate that aging is accompanied by a generalized slowing of information processing within the nervous system (Salthouse, 1996).

While the above studies report age-related difficulties in understanding rapid speech, the underlying sources of the problem are not easily identified. Study of the problem is complicated in part by the inherent spectral and temporal complexity of speech sounds, especially the speech sequences that characterize sentence-length stimuli. Additionally, factors related to the semantic and syntactic structure of speech sequences, and age-related changes in hearing sensitivity, can each exert a significant influence on the accuracy of speech processing among elderly listeners. However, in terms of acoustic modifications, one general characteristic of rapid speech is the shortened durations of some or all of the component phoneme segments and pause intervals, along with corresponding suprasegmental changes in overall sequence tempo and rhythm. Thus, any age-related reductions in sensitivity to either the segmental duration changes or the sequential timing characteristics could contribute to the diminished ability of older listeners to process rapid speech. Consideration of this possibility prompted us to examine age-related changes in temporal sensitivity using a combination of simple and complex nonspeech stimulus patterns that mimic some aspects of sentence-length speech sequences.

Currently, psychophysical measurements collected with relatively simple stimuli indicate that aging can be an important factor contributing to diminished temporal sensitivity. Some of the evidence refers to threshold measurements for the detection of brief temporal gaps inserted between successive acoustic markers, either pairs of non-speech or speech sounds. Generally, the gap thresholds measured for older listeners are found to be larger than those of younger listeners, with the age-related threshold differences being larger when measured with acoustic markers that feature spectral disparities (Schneider *et al.*, 1994, 1998; Snell, 1997; Lister *et al.*, 2002; Pichora-Fuller *et al.*, 2006). In other temporal sensitivity tasks, older listeners are observed to exhibit a reduced ability to discriminate changes in the duration of simple sounds, or silent intervals inserted between pairs of simple speech or nonspeech sounds (Abel *et al.*, 1990; Fitzgibbons and Gordon-Salant, 1995; Lister *et al.*, 2002; Grose *et al.*, 2001; Lister and Tarver, 2004). Also, the age-related difficulties observed for duration discrimination with simple stimuli appear to become more pronounced for tasks that utilize complex stimulus sequences. For example, in one such task, we presented sentence-length tone sequences and measured listeners' ability to discriminate changes in the duration of a single target sequence component, either a tone or an embedded silent interval (Fitzgibbons and Gordon-Salant, 1995). Younger listeners performed this task with relatively little difficulty, but older listeners exhibited discrimination performance that was substantially poorer than that measured previously for the same target component presented in isolation. In a related experiment with tone sequences (Fitzgibbons and Gordon-Salant, 2004), it was observed that older listeners exhibited a reduced ability to discriminate changes in the overall timing, or tempo, within multitone sequences. The diminished temporal sensitivity of older listeners with these stimulus patterns was most evident at faster sequence presentation rates, and for sequences that featured irregular timing characteristics.

These results of the different discrimination tasks with simple and complex stimulus patterns indicate that some aspects of auditory temporal processing may undergo changes with aging. However, results collected in temporal discrimination tasks may not be predictive of those observed in more difficult tasks, such as sequence recognition. For example, even with nonspeech stimuli the temporal thresholds associated with discrimination tasks and recognition tasks can be substantially different, as we observed in an earlier investigation of temporal order processing (Fitzgibbons and Gordon-Salant, 1998). This previous study used stimulus sequences consisting of three tonal components of equal duration presented contiguously, with sequence rate altered by covariation of the component durations. Different task conditions required listeners to discriminate random changes of tone order, and also to identify the random orders using labels of relative tone pitch (e.g., high, medium, low). Results for younger listeners in the study confirmed that the tone durations required for order discrimination were substantially shorter than those required for order identification. Presumably, the longer stimulus durations required for the order identification task reflect the added processing demands associated with the requirement to label each tonal component. Relative to the younger listeners, the older listeners in the study required much longer tonal durations to perform the order discrimination task. However, for order identification, the age-related performance differences were restricted primarily to sequence conditions with relatively rapid presentation rates, where the tone durations approached values required by the older listeners for order discrimination. Other investigations of sequential processing also report findings indicating that tasks involving temporal order judgments can be quite difficult for many elderly listeners (Trainor and Trehub, 1989; Humes and Christopherson, 1991).

It is noteworthy that the elderly listeners in our earlier study exhibited difficulty for temporal order recognition with faster sequence presentation rates, but not with slower sequence rates. This outcome suggests the existence of an age-related limitation in processing speed, rather than a general difficulty among elderly listeners in performing the task demands associated with component labeling, storing, and recalling of order information. However, other results reported by Trainor and Trehub (1989) point to a different conclusion. Their sequential ordering task required younger and older listeners to distinguish between two alternatives of a four-tone sequence that differed only by the temporal ordering of two tonal components. Older listeners in this study also exhibited impaired sequencing abilities, but the magnitude of the observed age effects appeared to be independent of stimulus presentation rate, or specific factors related to processing speed. Thus, the influence of sequence rate and the nature of the processing difficulty exhibited by elderly listeners on temporal ordering tasks remain unclear. The present investigation is undertaken to examine these issues by investigating the specific sequence factors that influence temporal order processing in younger and older listeners. Additional motivation for this investigation comes from the collective findings of earlier temporal order recognition studies, as reviewed in various reports (e.g., Divenyi and Hirsh, 1974; Pinheiro and Musiek, 1985; Trainor and Trehub, 1989). The earlier studies, conducted primarily with young listeners, indicate that temporal order recognition can be difficult, particularly for tasks that require the labeling of individual sequence items comprised of less familiar nonspeech sounds. However, one common finding from these studies was the observation indicating that the introduction of silent intervals between successive items in sequential stimulus patterns acted to enhance temporal order recognition (e.g., Aaronson *et al.*, 1971; Peters and Wood, 1973; Warren, 1974). The improved recognition performance associated with the presence of interitem silent intervals was generally attributed to the increased availability of processing time that listeners used to encode individual sequence items for later recall. Similar observations were made more recently by Wingfield *et al.* (1999), who reported that the insertion of interitem pause intervals within rapid speech sequences effectively enhanced recognition performance, particularly for older listeners.

Thus, it appears that stimulus manipulations which increase available processing time may be beneficial for listeners participating in sequence recognition tasks. Unfortunately, the concept of processing time is not well defined, and in terms of stimulus parameters, it could be associated with item durations, interitem temporal spacing, overall sequence presentation rate, or some combination of these factors. However, if slowed processing is associated with aging, then order recognition among elderly listeners should be affected by variations in sequence timing, or item durations, particularly under the time constraints associated with faster sequence presentation rates. The present experiments are designed to examine these potential stimulus effects on sequential processing by measuring order recognition in younger and older listeners using uniformly timed tonal sequences in which tone durations and intertone intervals are systematically varied across a range of sequence presentation rates. Other measurements are collected to determine if the effects of sequence presentation rate on temporal order recognition for uniformly timed tone sequences pertain as well to stimulus sequences with nonuniform tone intervals. These comparisons are of interest in part because some of our earlier observations (Fitzgibbons and Gordon-Salant, 2004) indicated larger age-related differences in discrimination performance for stimulus sequences with non-uniform timing characteristics compared to those with uniform timing. Additionally, the timing characteristics associated with many meaningful sound sequences, such as rapid speech, are inherently nonuniform. Last, for all testing, we investigated the possible interactive effects of listener age and sensorineural hearing loss on temporal order recognition performance. Toward this end, performance was compared across four groups of listeners, who were matched according to age and degree of hearing loss.

II. METHOD

A. Subjects

Listeners in the main experiments with uniform stimulus sequences included 46 subjects assigned to four groups according to age and hearing status. Six of these listeners (one to two per listener group) were unavailable for subsequent testing with the nonuniform stimulus sequences, leaving a total of 40 listeners participating in these conditions. For the main experiments, one group of listeners included younger normal-hearing subjects (Yng Norm, $n=13$) ages 19–40 ($M=24.2$ years) with mean pure-tone thresholds ≤ 20 dB HL (re: ANSI, 2004) from 250 to 4000 Hz. Another group included younger listeners with hearing loss (Yng Hrg Loss, $n=9$) ages 19–42 ($M=28.2$ years) with mild-to-moderate sloping high frequency sensorineural hearing losses of hereditary or unknown etiologies. A third group of listeners included normal-hearing elderly listeners (Eld Norm, $n=9$) of 65–76 years ($M=71.8$ years) with mean pure-tone thresholds ≤ 20 dB HL from 250 to 4000 Hz. Last, an elderly group of listeners with hearing loss (Eld Hrg Loss, $n=15$) age 65–79 ($M=73.1$ years) also had mild-to-moderate sloping high-frequency hearing losses. The young and elderly listeners with hearing loss exhibited bilateral impairment of equivalent degree 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. Table I presents the mean subject data, showing ages, group sizes, and audiograms for the test ears of the four listener groups. The table also shows entries for listener group sizes (in parentheses) associated with the test conditions using the non-uniform stimulus sequences.

Additional criteria for subject selection included monosyllabic word recognition scores exceeding 80%, normal middle ear function as assessed by tympanometry, and acoustic reflex thresholds that were within the 90th percentile for a given pure tone threshold (Gelfand *et al.*, 1990). All listeners were in general good health, with no history of stroke or neurological impairment and possessed sufficient motor skills to provide responses using a computer keyboard. Additionally, all listeners passed a screening test for general cognitive awareness (Pfeiffer, 1975). Most of the listeners reported some degree of childhood exposure to musical instruments, but none received formal musical training as adults, or currently practiced as musicians. The listeners had not participated previously as subjects in listening experiments and were paid for their services in the study.

TABLE I. Average pure tone air conduction thresholds and standard deviations (in decibels HL, re: ANSI, 2004) across frequency, average listener age, and number of subjects for the four groups. Values in parentheses reflect group sizes for conditions with nonuniform stimulus sequences.

	Pure tone frequency					Age	N
	250	500	1000	2000	4000		
Yng Norm							
mean	7.3	5.0	4.6	6.2	1.5	24.2	13(11)
s.d.	3.2	6.2	5.0	5.3	7.4		
Eld Norm							
mean	10.0	7.2	8.9	10.0	14.1	71.8	9(8)
s.d.	5.3	5.9	3.9	5.3	5.2		
Yng Hrg Loss							
mean	23.3	22.2	27.2	43.9	45.0	28.2	9(7)
s.d.	14.1	17.2	14.7	6.6	16.2		
Eld Hrg Loss							
Mean	16.3	19.0	26.3	38.7	54.3	73.07	15(14)
s.d.	6.8	7.6	11.0	7.2	7.7		

B. Stimuli

All stimuli for the experiments were sequences of three pure tones generated using inverse fast Fourier transform (FFT) procedures with a digital signal processing board (Tucker-Davis Technologies AP2) and a 16-bit digital-to-analog (D/A) converter (Tucker-Davis Technologies DD1, 20 kHz sampling rate) that was followed by low-pass filtering (Frequency Devices 901F; 6000 kHz cutoff, 90 dB/oct). The tone frequencies for all sequences spanned a two octave range for ease of labeling, and were arbitrarily designated as low (L), 500 Hz; medium (M) 1000 Hz; and high (H) 2000 Hz.

For the uniform sequences, the tones within each sequence were equal in duration with each component having a 1 ms cosine-squared rise/fall envelope. Within each sequence, the onset-to-onset intervals between successive tones (the interonset interval, or IOI) were also equal, but were set to different fixed values across four conditions of sequence presentation rate; the IOI values were 500, 350, 250, or 150 ms, respectively, for each of the four sequence rate conditions. For each sequence rate condition, the tonal IOI included a combination of tone segment and silent interval, with the percentage of IOI filled by tone (the duty cycle) having a fixed value of 25, 50, 75, or 100 % in four separate test conditions conducted for each of the four sequence IOI values.

The nonuniform stimulus sequences were designed to examine the same four sequence rate conditions tested with the uniform sequences. Within the nonuniform sequences, each tonal IOI was different, with two of the values set to be 40% larger than, and 40% smaller than, a third mean IOI value that was fixed at 500, 350, 250, or 150 ms, respectively, in each of four sequence rate conditions. Thus, for the nonuniform tone sequences, the mean IOI values were the same as those in the uniform sequences, for corresponding rate conditions. Additionally, within the nonuniform stimulus sequences, each tonal IOI was created to have a 50% duty cycle.

In total, there were 16 conditions with the uniform stimulus sequences, defined by the combination of four duty cycles tested at each of four sequence rates. There were four conditions with the nonuniform sequences, each associated with a different sequence rate but the same sequence duty cycle.

C. Procedures

The listening trials for the temporal order recognition task were single interval in which one stimulus sequence was presented with a tone order that was selected randomly from six possible permutations of the three tone frequencies. Using procedures of the earlier study (Fitzgibbons and Gordon-Salant, 1998) that were adapted from Divenyi and Hirsh (1974), listeners used labels of relative pitch to identify each sequence tone; that is, high (H), medium (M), and low (L), respectively, for the three tone frequencies of 2000, 1000, and 500 Hz. Listeners identified the stimulus sequence order for each recognition trial by keyboard response, selecting one of six keys (each labeled with a different sequence tone order: HML, HLM, MHL, MLH, LMH, LHM); a simple line drawing above each response key was also provided as a visual aid to depict the pitch-shift directions associated with each sequence ordering. The identification trials were listener paced, with a 3 s intertrial interval following each listener response; the stimulus presentation interval was also marked by a visual display on a computer monitor facing the listener. Percent-correct feedback was provided to listeners following each block of identification trials, but not for individual trials.

The 16 conditions with uniform sequences, comprising combinations of the four sequence duty cycles and four fixed IOI values, were tested in a different randomly determined order for each listener. Similarly, subsequent measurements collected for the four rate conditions with the nonuniform sequences were conducted using a different random order of the rate conditions for each listener. All testing was conducted using 50-trial blocks with duty cycle and sequence rate fixed within each block of listening trials. Prior to data collection, each listener was familiarized with the task and trained with the order identification task. Listeners practiced for 4–6 h in 2 h sessions that included 10–12 blocks of listening trials per session. The practice sessions included blocks of listening trials using relatively slow presentation rates with sequences featuring 1 s tonal durations. Listeners were required to demonstrate order recognition of at least 75% correct on three consecutive trial blocks with the practice sequences in order to participate in the experiments. The number of trial blocks required to achieve the performance criterion varied across individual listeners, but there was no systematic difference in the number of practice blocks required by younger and older listeners. Three listeners with normal hearing (two young, one elderly) could not perform the ordering task at criterion levels, and were excluded from further testing. For these listeners, the problem appeared to be related to difficulties in labeling tonal components according to relative pitch; similar problems were observed for a subset of listeners in our previous experiments (Fitzgibbons and Gordon-Salant, 1998). Listeners selected for the experiments were tested individually in a sound-attenuating booth, with all testing conducted monaurally via an insert earphone (Etymotic ER-3A) calibrated in a 2 cm^3 coupler (B&K DB0138). All stimuli were presented at 85 dB SPL, which corresponded to at least 30 dB sensation levels for the listeners with hearing loss. Testing was conducted in the better ear for listeners with hearing loss, and in the preferred ear for listeners with normal hearing. Excluding practice sessions, total time for data collection was about 12 h, scheduled in 2 h sessions over the course of 3–4 weeks.

III. RESULTS

A. Uniform sequences

The temporal order recognition performance of the listeners in the 16 conditions conducted with the uniformly timed stimulus sequences was initially analyzed to examine the specific effects of sequence duty cycle for each of the sequence IOI values. The individual percent-correct recognition scores for the blocks of listening trials in each condition were arcsine transformed and subjected to an analysis of variance (ANOVA) using a repeated measures design for the two within-subjects factors of duty cycle and IOI, and the between subject factors, age and hearing status. This initial analysis revealed a significant effect of sequence IOI [$F(3,126)=42.69, p<0.01$], but the effect of sequence duty cycle was not significant [$F(3,126)=0.33, p>0.05$], nor were any of the interaction effects involving duty cycle. Results that are representative of this outcome are displayed in the panels of Fig. 1, which show the mean percent correct scores for each group of listeners as a function of sequence IOI, with the parameter in the figure reflecting the sequence duty cycle. Each panel of the figure reveals that recognition performance improved progressively across increasing values of IOI, but results for each of the four duty cycles, ranging in value from 25 to 100 %, were virtually the same at each value of IOI for each of the listener groups.

Following evidence of negligible duty-cycle effects in the data, we collapsed the individual data across the four duty-cycle conditions for each of the IOI values for each group of listeners. These results are displayed in Fig. 2, which show the mean recognition performance of each listener group for each of the four sequence IOI values; error bars in the figure represent standard errors of the mean for each listener group. A repeated-measures ANOVA on the data of Fig. 2 was conducted using one within-subjects variable, IOI, and two between-subjects variables, age and hearing status. This analysis revealed significant main effects of sequence IOI [$F(3,540)=73.2, p<0.01$] and age [$F(1,180)=8.57, p<0.01$] with no other significant interactions involving IOI. There was no significant effect of hearing status [$F(1,180)=0.054, p>0.05$] or interaction between age and hearing status [$F(1,180)=3.21, p>0.05$] among the listener

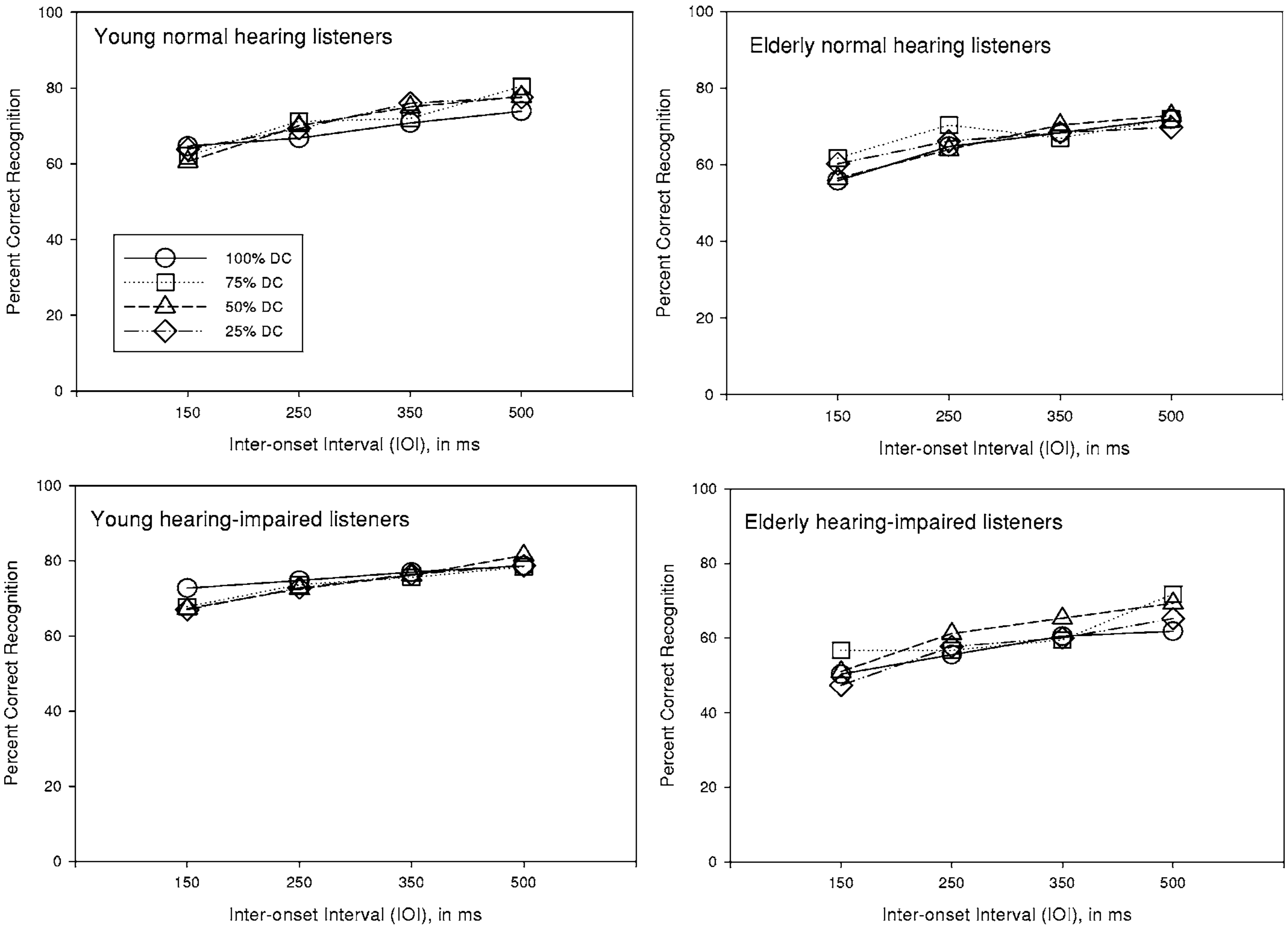

FIG. 1. Mean percent correct temporal order recognition scores for each group of listeners as a function of sequence interonset interval (IOI ms) for the uniform tone sequences. The parameter in the figure panels is the sequence duty cycle in percent.

groups. The main effect of IOI is reflected by the progressive improvement in recognition performance for each listener group with increasing values of sequence IOI. The main effect of age reflects the poorer performance of the older listeners relative to the young listeners. Each of these main effects is displayed more clearly in Fig. 3. This figure shows the mean recognition scores of the older and younger listeners, collapsed across hearing status, for each of the IOI con-

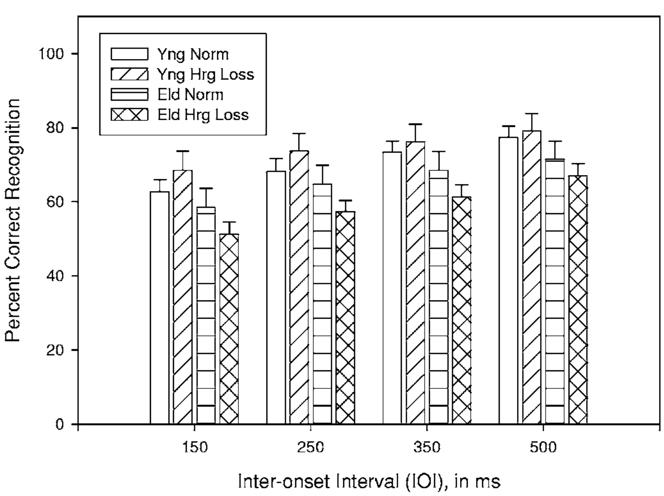

FIG. 2. Mean percent correct temporal order recognition scores for each listener group collapsed across duty cycle for each sequence IOI (ms) condition with the uniform tone sequences. Error bars show one standard error of the mean.

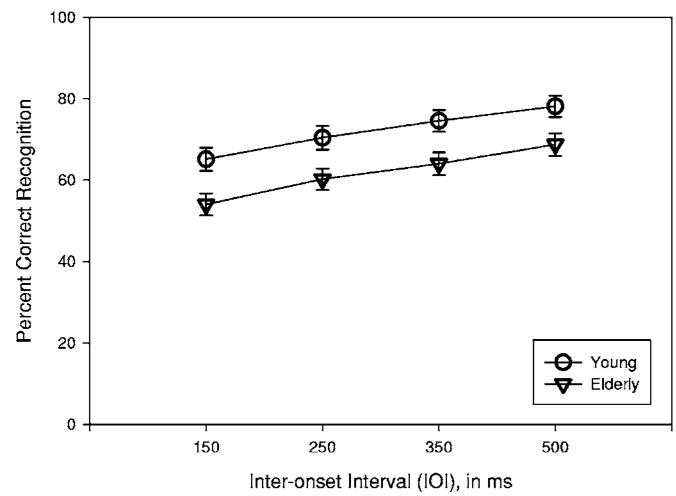

FIG. 3. Mean percent correct temporal order recognition scores for the younger and older listeners for each sequence IOI value (ms) with the uniform tone sequences. Error bars show one standard error of the mean.

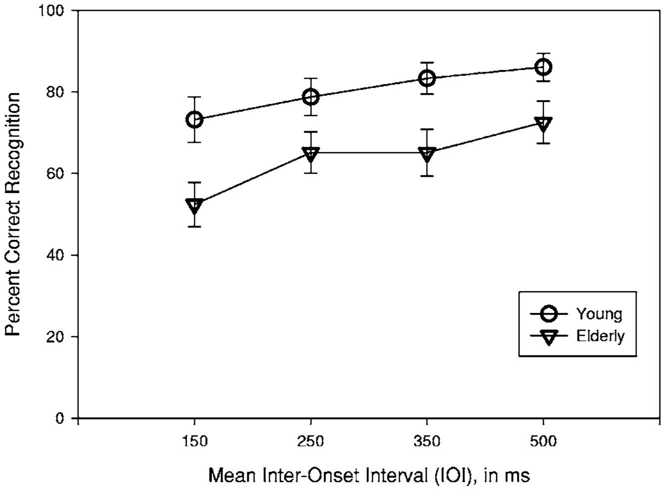

FIG. 4. Mean percent correct temporal order recognition scores for the younger and older listeners as a function of mean sequence IOI value (ms) for the nonuniform tone sequences. Error bars show one standard error of the mean.

ditions; vertical bars in the figure represent standard errors of the means. For each sequence IOI condition, the order recognition performance of the older listeners was poorer than that of the younger listeners.

B. Nonuniform sequences

The nonuniform stimulus sequences were used to examine the same four sequence rate conditions as measured with the uniform sequences. Individual IOIs within the nonuniform sequences differed, but the mean IOI values were the same as those of the uniform sequences for corresponding sequence rates. The percent-correct recognition data collected with these nonuniform sequences were also arcsine transformed and subjected to an ANOVA using a repeated-measures design with one within-subjects variable, mean IOI, and two between-subject variables, age and hearing status. Results of the analysis revealed significant main effects of IOI condition $[F(3,108)=24.3, p<0.01]$ and age $[F(1,36)=5.7, p<0.05]$, with no other significant interactions involving either of these two variables. Additionally, the effect of hearing status was not significant $[F(1,36)=0.025, p>0.05]$, nor was the interaction between age and hearing status $[F(1,36)=2.74, p>0.05]$ in these performance data. The significant effects from this analysis are displayed in Fig. 4, which shows the mean recognition performance, collapsed across hearing loss, as a function of average sequence IOI ms, for the groups of older and younger listeners; vertical bars in the figure represent standard errors of the means. The data for both groups of listeners reveal a progressive increase in recognition performance for increasing value of mean IOI. The mean performance of the older listeners was poorer than that of the younger listeners at each IOI value.

IV. DISCUSSION

A. Uniform sequences

The temporal ordering task with the three-tone sequences appeared to be difficult for many of the listeners, and none of the participants achieved perfect recognition performance for all of the sequence rates tested. For the uniform sequences, where IOI values are simply the reciprocal of sequence rate, the mean accuracy of order recognition for the younger listeners decreased progressively from about 78 to 66 % across sequence conditions of decreasing IOI values from 500 to 150 ms. This range of performance is substantially greater than chance level (16.7% correct for this six-choice task), indicating that, despite the perceived difficulty of labeling individual sequence tones, the listeners were capable of performing the ordering task. These results for the younger listeners were improved somewhat relative to those reported for younger listeners in our earlier temporal ordering study that used uniform contiguous three-tone sequences (Fitzgibbons and Gordon-Salant, 1998). Some degree of performance difference between the two studies was anticipated, because sequence tone frequencies in the previous investigation spanned a relatively narrow 1/3-octave range, whereas sequences in the present experiment featured a larger two-octave frequency range that was intended to facilitate the task of labeling individual tones according to relative pitch. Additional comparisons of the present results to those reported in other temporal ordering studies is hampered by the fact that performance measures in such tasks appear to depend on a large number of factors, including the number and type of components in sequences, and the response mode utilized in the order tasks. However, for ordering tasks like the present one, where listeners are required to name or attach labels to individual sequence items, component durations of 150–500 ms are frequently reported to be necessary for moderately trained listeners to achieve accurate ordering performance (Pinheiro and Musiek, 1985). Results collected from the younger listeners in the present study are consistent with this range of previous estimates.

The recognition performance of the older listeners with the uniform stimulus sequences shifted across changes of IOI value in a manner similar to that observed for the younger listeners. For these older listeners, mean performance levels decreased progressively from about 69 to 55 % across the range of decreasing IOI values from 500 to 150 ms. These performance levels were poorer than those of the younger listeners, but the magnitude of age-related deficit was fairly stable across the range of IOI values tested; that is, mean recognition performance of older listeners was about 10% poorer than that of younger listeners in each of the four sequence IOI conditions. The hearing status of listeners in the experiment did not prove to have a systematic influence on order recognition performance, and no significant interaction effects involving hearing loss and listener age emerged in the data analysis. However, there were performance trends in the individual group results that did appear to be related to hearing status. For example, inspection of Fig. 2 shows that among the younger listeners, the group with hearing loss performed somewhat better than those with normal hearing, while the opposite was true for the older listeners; that is, the group with normal hearing performed better than the group with hearing loss. These group differences related to hearing loss were relatively small, and most likely reflected individual differences in the ordering abilities of the subjects sampled for each listener group. Several of the listeners within the younger group of subjects with hearing loss were observed to be among the better performers in the ordering tasks. The absence of systematic effects of hearing loss in the data was not surprising given the relatively high stimulus presentation levels, in conjunction with the mild degrees of listener hearing loss in the two-octave frequency range of the tonal sequence components.

The age-related performance differences seen in the present data differ from those observed in our earlier experiments with uniform contiguous tone sequences. The earlier results revealed no significant age-related performance differences on order identification across a range of longer sequence IOI values exceeding 250 ms, but did show a significant age-related decline in performance for a faster sequence rate featuring an IOI value of 100 ms. The earlier results also showed a relatively high degree of performance variability within listener groups, a situation that hampered analysis of age effects for several of the sequence rate conditions. By comparison, performance variability within subject groups of the present study was smaller and relatively uniform, an outcome that can probably be attributed to the use of more frequency-disparate tone sequences that were easier for listeners to label. The earlier study also examined listeners with hearing loss using high-frequency tone sequences narrowly spaced about 4 kHz, a spectral region associated with the greatest degree of sensitivity loss in the subjects with hearing impairment. The earlier results, like those of the present study, showed no significant influence of hearing loss on the temporal order recognition task.

A primary purpose of the present study was to investigate the relative importance of tonal duration, intertone interval, and sequence rate on temporal order recognition. This goal was motivated, in part, to help clarify interpretation of earlier results collected with contiguous tone sequences, for which changes in tonal durations are accompanied by changes of sequence presentation rate. Additionally, it is of general theoretical interest to identify the stimulus parameters most closely associated with the processing time required by listeners to perform a temporal ordering task. As mentioned previously, various earlier investigations with temporal sequencing tasks reported that the insertion of silent intervals between successive items in a stimulus sequence could facilitate listeners' recall of temporal order. The facilitating effects of interitem silent intervals were presumed to reflect the increased availability of processing time that listeners used to encode and store item order information for later recall (Aaronson 1971; Warren, 1974; Pinheiro and Musiek, 1985). Of course, this reasoning also requires that component durations are sufficient for listeners to process enough sensory information to distinguish the individual sequence items. In the present experiments, we examined these effects of component duration and interitem silent intervals within the tone sequences by systematically manipulating the tonal duty cycle from 25 to 100 %, while holding sequence presentation rate constant. Contrary to expectations, the sequence duty cycle had no significant influence on listeners' temporal order recognition, for any of the sequence rates examined. It was anticipated that older listeners, in particular, might benefit the most from duty cycles that afforded relatively larger intertone intervals, especially for the faster sequence rates in which processing time is limited. At the fastest sequence rate tested, with tonal IOI of 150 ms, intertone silent intervals took on values ranging from 0 to 112.5 ms as the duty cycle changed from 100 to 25 % across conditions. Similarly, for this same IOI condition, tone durations decreased from 150 to 37.5 ms through the range of decreasing duty cycle values. Despite these changes in parameter values, the order recognition performance of the older listeners remained stable. For all test conditions with the uniform stimulus sequences, the results from each group of listeners indicated that sequence IOI is the only stimulus factor that influenced temporal order recognition. Recognition performance improved progressively as the tonal IOI increased, an outcome that was independent of tone duration, or intertone interval, within the range of values examined. Thus, for these sequences, the introduction of intertone silent intervals would benefit order recognition only if the silent intervals acted to increase the tonal IOI, and thus slow sequence presentation rate.

B. Nonuniform sequences

The results collected from the subset of listeners in conditions with the nonuniform stimulus sequences allow additional examination of the stimulus factors that influence temporal order recognition. Recall that the nonuniform sequences had different IOI values, but the same sequence presentation rates that characterized the uniform sequences. The mean order recognition measurements of the younger listeners with the nonuniform sequences showed systematic effects of mean IOI, with performance accuracy shifting progressively from about 87 to 74 % across decreasing values of mean IOI from 500 to 150 ms. These mean performance levels are somewhat better than those cited above for the younger listeners with the uniform sequences. However, much of the improvement in mean performance of the younger listeners can be attributed largely to the sample of participants within younger groups tested with the nonuniform sequences. That is, inspection of individual results indicated that the individual subjects who were unavailable for testing with the nonuniform conditions were among the poorer performers in the previous conditions with uniform sequences. This was particularly the case for the group of younger listeners with hearing loss, which showed the largest improvement in mean performance with the nonuniform sequences.

Results collected from the older listeners with the nonuniform sequences exhibited similar effects of sequence IOI as seen in results obtained from the younger listeners. For the older listeners, accuracy in recognition performance shifted from about 74 to 54 % across the range of decreasing mean IOI value for the nonuniform sequences. The older listener groups (each missing a single subject) produced equivalent mean recognition performance across the uniform and nonuniform sequences, for corresponding IOI conditions. Also, performance of these older listeners was consistently poorer than that of the younger listeners at each sequence IOI condition. The magnitude of the age-related performance difference was fairly stable across IOI conditions, with an average performance difference of 16.5%. The largest age-related performance difference occurred for the nonuniform sequence with the 150 ms mean IOI, but the magnitude of this difference was not sufficient to produce a significant interaction effect between listener age and mean IOI value in the data analysis.

The collective findings from measurements obtained with both the uniform and nonuniform stimulus sequences provide some additional insight about the role of stimulus and processing factors that influence temporal order recognition. If the stimulus sequence consists of equally timed events, as with the uniform tone sequences, then the time between successive component onsets appears to be the relevant processing interval for order recognition. We found no evidence to support the argument that component duration, or intercomponent silence, has an independent influence on tone order processing. Of course, it is possible that factors such as interitem spacing might have greater influence on the processing of longer stimulus sequences that contain a larger number of components than was evident for our three-tone stimulus patterns. Additionally, it is reasonable to assume that component durations need to be sufficient for item identification, with specific values perhaps depending on the complexity and number of the sequence items. For example, with speech sequences, changes in some segment durations (e.g., consonant sounds) are reported to impact recognition performance more than adjustments of other segment durations (e.g., vowel sounds) (Pickett, 1999). Also, accurate temporal order recognition of speech sequences comprised of vowel segments can be accomplished with shorter component durations than is required for sequences of unrelated nonspeech sounds (Pinheiro and Musiek, 1985).

The effects of tonal IOI seen in the performance measures collected with uniformly timed sequences tend to obscure possible independent effects of sequence presentation rate. However, measurements collected with the nonuniform sequences indicate that sequence rate, rather than tonal IOI, has the more important influence on temporal order recognition. On the basis of earlier discrimination data, we had anticipated that the mixing of tonal IOI values within a given sequence might be disruptive to the processing of temporal order. However, the recognition performance of most of the listeners was similar with the uniform and nonuniform sequences, if the presentation rate of the stimulus patterns was preserved. This equivalency in performance between the sequences with differing timing characteristics may be suggestive of the listening strategy employed by subjects in performing the temporal ordering task. For example, with uniformly timed sequences, the importance of tonal IOI implies that listeners may have attempted to identify and encode order information in a real-time serial manner during the course of sequence presentation. This strategy is based upon the assumption that component IOI is the relevant processing interval in sequential ordering tasks. However, this same listening strategy should produce different performance results if the tonal IOIs differ substantially within a sequence, as was the case for the nonuniform stimuli. This performance deficit with the nonuniform patterns did not occur, indicating that listeners may have extracted, or reconstructed, tone order information subsequent to sequence presentation. This processing strategy seems plausible, particularly for the relatively simple three-tone stimulus patterns used in this study.

The recognition performance of the older listeners in this study was poorer than that observed for the younger listeners, for both the uniform and nonuniform stimulus sequences. However, the source of the age-related performance differences is not evident. Unlike our previous findings with the contiguous sequences, the present results did not reveal an interaction between listener age and sequence presentation rate. Instead, the age-related performance differences were approximately equivalent across the range of sequence rate conditions tested. Of course, the fastest rate tested here (about 6.7 tone/s for 150 ms IOI) was slower than the fastest rate tested in our earlier study (10 tone/s), a rate difference that could explain some of the age-related performance differences between the studies. However, the observed stability of age effects across rate conditions may indicate a more general difficulty among older listeners with sequential pattern recognition, one that is not specifically related to sequence rate or diminished processing speed, at least at the sensory/perceptual level. Similar conclusions were reached by Trainor and Trehub (1989) from their temporal ordering experiments, as described previously. Recall that Trainor and Trehub also observed impaired temporal ordering abilities among older listeners, but the age-related difficulties were not specifically related to sequence presentation rates. However, these earlier experiments also featured a high degree of stimulus uncertainty, wherein stimulus presentation rates were randomly varied within a block of listening trials. The extent to which these procedural factors impacted the ordering performance of the older listeners is unknown.

As stated above, the present results did not reveal a specific interaction between sequence presentation rate and the magnitude of the age-related ordering differences. However, the observation of such an interaction may not be the only indicator of slowed processing among the elderly listeners. For example, inspection of the mean performance of the younger and older listeners (e.g., Figs. 3 and 4) shows that the older listeners required sequence IOI values of 350–500 ms to achieve the same performance levels demonstrated by the younger listeners for an IOI of 150 ms. These comparisons indicate that longer processing times were required by the older listeners to achieve the performance equivalence to the younger subjects. However, these comparisons do not indicate the source of slowed processing in the older listeners. Evidence exists for age-related differences in encoding of temporal information at various sites within the auditory pathway (e.g., Schneider and Pichora-Fuller, 2000; Simon *et al.*, 2004). Additionally, temporal order recognition involves a number of cognitive tasks, including those specific to sound component labeling, short-term memory, and the storing and retrieval of order information. Any of these processes could undergo changes with aging to affect slowed processing, whether the stimuli are tone sequences like those used here, or any of the time-altered speech sequences used in some of the earlier speech recognition experiments. Greater study of these potential cognitive influences on the auditory processing of elderly listeners is warranted. Added support for this argument was offered recently by Humes (2005), who demonstrated via statistical regression analysis that many measures of auditory processing among elderly listeners are partially related to individual differences in cognitive function.

In summary, the present experiments used relatively simple stimulus sequences consisting of three tones of differing frequency. Listeners were required to identify different random orders of the tones by using labels of relative pitch to identify individual tonal components. Tones within the stimulus sequences were either equal in their durations with uniform timing, or unequal in duration with nonuniform timing. For both types of sequences, the temporal order recognition performance of listeners was influenced primarily by sequence presentation rate, showing progressively better recognition as the rate slowed. Factors related to tone duration, or intertone interval, had no systematic influence on recognition performance. The older listeners generally exhibited poorer recognition performance than younger listeners for each sequence rate condition tested. Temporal ordering tasks that require the naming of components in a sequence are difficult for many listeners, and are likely to involve several perceptual and cognitive processing factors. Investigation of these factors needs to be incorporated into subsequent studies of aging and auditory processing, particularly for complex sequential sounds.

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Aaronson, D., Markowitz, N., and Shapiro, H. (**1971**). "Perception and immediate recall of normal and compressed auditory sequences," Percept. Psychophys. **9**, 339–344.

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

ANSI (**2004**). ANSI S3.6-2004, "American National Standard Specification Tor Audiometers" (American National Standards Institute, New York).

Divenyi, P., and Hirsh, I. (**1974**). "Identification of temporal order in three-tone sequences," J. Acoust. Soc. Am. **56**, 144–151.

Fitzgibbons, P. J., and Gordon-Salant, S. (**1995**). "Age effects on duration discrimination with simple and complex stimuli," J. Acoust. Soc. Am. **98**, 3140–3145.

Fitzgibbons, P. J., and Gordon-Salant, S. (**1998**). "Auditory temporal order perception in younger and older adults," J. Speech Lang. Hear. Res. **41**, 1052–1060.

Fitzgibbons, P. J., and Gordon-Salant, S. (**2004**). "Age effects on discrimination of timing in auditory sequences," J. Acoust. Soc. Am. **116**, 1126–1134.

Gelfand, S., Schwander, T., and Silman, S. (**1990**). "Acoustic reflex thresholds in normal and cochlear-impaired ears: Effects of no-response rates on 90th percentiles in a large sample," J. Speech Hear Disord. **55**, 198–205.

Gordon-Salant, S., and Fitzgibbons, P. J. (**1993**). "Temporal factors and speech recognition performance in young and elderly listeners," J. Speech Hear. Res. **36**, 1276—1285.

Grose, J. H., Hall, J. W., III., and Buss, E. (**2001**). "Gap duration discrimination in listeners with cochlear hearing loss: effects of gap and marker duration, frequency separation, and mode of presentation," J. Assoc. Res. Otolaryngol. **2**, 388–398.

Humes, L. (**2005**). "Do 'auditory processing' tests measure auditory processing in the elderly?" Ear Hear. **26**, 109–119.

Humes, L., and Christopherson, L. (**1991**). "Speech identification difficulties of hearing-impaired elderly persons: The contribution of auditory processing deficits," J. Speech Hear. Res. **34**, 686–693.

Lister, J., Besing, J., and Koehnke, J. (**2002**). "Effects of age and frequency disparity on gap discrimination," J. Acoust. Soc. Am. **111**, 2793–2800.

Lister, J., and Tarver, K. (**2004**). "Effect of age on silent gap discrimination in synthetic speech stimuli," J. Speech Lang. Hear. Res. **47**, 257–268.

Peters, R. W., and Wood, T. J. (**1973**). "Perceived order of tone pulses." J. Acoust. Soc. Am. **54**, 315.

Pfeiffer, E. (**1975**). "A short portable mental status questionnaire for the assessment of organic brain deficit in elderly patients," J. Am. Geriatr. Soc. **23**, 433–441.

Pichora-Fuller, M. D., Schneider, B. A., Benson, N. J., Hamstra, S. J., and Storzer, E. (**2006**). "Effect of age on detection of gaps in speech and nonspeech markers varying in duration and spectral symmetry," J. Acoust. Soc. Am. **119**, 1143–1155.

Pickett, J. M. (**1999**). *The Acoustics of Speech Communication* (Allyn & Bacon, Needham Heights, MA).

Pinheiro, M. L., and Musiek, F. E. (**1985**). "Sequencing and temporal ordering in the auditory system," in *Assessment of Central Auditory Dysfunction*, edited by M. L. Pinheiro and G. L. Musiek, Williams & Wilkins, Baltimore.

Salthouse, T. A. (**1996**). "The processing speed theory of adult age differences in cognition," Psychol. Rev. **103**, 403–428.

Schneider, B. A., and Pichora-Fuller, M. K. (**2000**). "Implications of perceptual deterioration for cognitive aging research," in *The Handbook of Aging and Cognition*, 2nd ed. edited by F. I. M. Craik and T. A. Salthouse (Lawrence Erlbaum Assoc, Mahwah, NJ), Chap. 3, pp. 155–219.

Schneider, B. A., Pichora-Fuller, M. K., Kowalchuk, D., and Lamb, M. (**1994**). "Gap detection and the precedence effect in young and old adults," J. Acoust. Soc. Am. **95**, 980–991.

Schneider, B. A., Speranza, F., and Pichora-Fuller, M. K. (**1998**). "Age-related changes in temporal resolution: Envelope and intensity effects," Can. J. Exp. Psychol. **52**, 184–191.

Simon, H., Frisina, R. D., and Walton, J. P. (**2004**). "Age reduces response latency of mouse inferior colliculus neurons to AM sounds," J. Acoust. Soc. Am. **116**, 469–477.

Snell, K. B. (**1997**). "Age-related changes in temporal gap detection," J. Acoust. Soc. Am. **101**, 2214–2220.

Trainor, L. J., and Trehub, S. E. (**1989**). "Aging and auditory temporal sequencing: Ordering the elements of repeating tone patterns," Percept. Psychophys. **45**, 417–426.

Tun, P. A. (**1998**). "Fast, noisy speech: Age differences in processing rapid speech with background noise," Psychol. Aging **13**, 424–434.

Vaughan, N., and Letowski, T. (**1997**). "Effects of age, speech rate, and type of test on temporal auditory processing," J. Speech Lang. Hear. Res. **40**, 1192–1200.

Warren, R. M. (**1974**). "Auditory temporal discrimination by trained listeners," Cogn. Psychol. **6**, 237–256.

Wingfield, A., Poon, L. W., Lombardi, L., and Lowe, D. (**1985**). "Speech of processing in normal aging: Effects of speech rate, linguistic structure, and processing time," J. Gerontol. **40**, 579–585.

Wingfield, A., Tun, P. A., Koh, C. K., and Rosen, J. J. (**1999**). "Regaining lost time: Adult aging and the effect of time restoration on recall of time-compressed speech," Psychol. Aging **14**, 380–389.