Age effects in discrimination of intervals within rhythmic tone sequences

Peter J. Fitzgibbons[a] and Sandra Gordon-Salant

Department of Hearing and Speech Sciences, University of Maryland, College Park, Maryland 20742

(Received 14 July 2014; revised 17 November 2014; accepted 26 November 2014)

This study measured listener sensitivity to increments of a target inter-onset interval (IOI) embedded within tone sequences that featured different rhythmic patterns. The sequences consisted of six 50-ms 1000-Hz tone bursts separated by silent intervals that were adjusted to create different timing patterns. Control sequences were isochronous, with all tonal IOIs fixed at either 200 or 400 ms, while other patterns featured combinations of the two IOIs arranged to create different sequential tonal groupings. Duration difference limens in milliseconds for increments of a single sequence IOI were measured adaptively by adjusting the duration of an inter-tone silent interval. Specific target IOIs within sequences differed across discrimination conditions. Listeners included younger normal-hearing adults and groups of older adults with and without hearing loss. Discrimination performance measured for each of the older groups of listeners was observed to be equivalent, with each group exhibiting significantly poorer discrimination performance than the younger listeners in each sequence condition. Additionally, the specific influence of variable rhythmic grouping on temporal sensitivity was found to be greatest among older listeners.

[http://dx.doi.org/10.1121/1.4904554]

[FJG] Pages: 388–396

I. INTRODUCTION

This study examines some potential effects of rhythmic grouping on listener sensitivity to temporal cues within an auditory sequence. A goal of the investigation is to determine how the rhythmic characteristics of a sequence influence temporal sensitivity in younger and older listeners. Interest in the topic was prompted initially by recent reports about speech recognition indicating that older listeners exhibit difficulty understanding speech that is spoken with a foreign accent; for example, English sentences spoken by native Spanish talkers (Burda *et al.*, 2003; Ferguson *et al.*, 2010; Gordon-Salant *et al.*, 2010). Sources of these recognition difficulties are likely to be varied and complex, although some of the available data appear to implicate age-related deficits in temporal processing for certain types of consonant sounds (Gordon-Salant *et al.*, 2010). Other analyses of the speech stimuli also reveal characteristic changes to various component sound durations (e.g., vowels, words, sentences), suggesting that older listeners must be at least minimally sensitive to duration cues for accurate recognition (Shah, 2004; Gordon-Salant *et al.*, 2013). Unfortunately, much of the evidence from psychophysical studies indicates that older listeners frequently exhibit diminished sensitivity to changes in the duration of various stimuli (Bergeson *et al.*, 2001; Grose *et al.*, 2006; Fitzgibbons *et al.*, 2007). In addition to concerns about the effects of changed duration cues, other questions posed in the speech reports implicate the need to examine alterations in the rhythmic properties of speech as a potential source of processing difficulty for some listeners. These general questions about rhythmic properties, as reflected in stress and timing patterns, prompted the present investigation to examine processing in older listeners, many of whom can be presumed to exhibit diminished temporal sensitivity.

Despite general interest in questions derived from speech studies, the specific influence of rhythmic effects on listener processing has not been investigated extensively with older listeners. Many of the obstacles to investigation relate to the inherent temporal and spectral complexity of the speech, rendering it difficult to control the stimulus parameters of experimental interest. However, some of the questions are equally relevant to issues concerning sequential processing of various non-speech stimulus patterns, which generally afford a greater degree of experimental control. Sequences of this type are utilized in the present investigation to examine questions about rhythmic variation and its influence on temporal sensitivity in older listeners. It is evident from some earlier psychophysical experiments conducted with non-speech sequences that older listeners often exhibit substantial changes in sequential processing accuracy, depending on the overall timing characteristics of the auditory stimulus pattern. For example, one investigation (Fitzgibbons and Gordon-Salant, 1995) used sentence-length sequences of five contiguous tones differing in pitch, and found that older listeners had substantial difficulty discriminating changes in the duration of a single targeted tonal component, even when the listeners had prior knowledge about the sequence position of the target tone. By comparison, younger listeners in the study exhibited relatively little difficulty with the same discrimination task, even in sequence conditions that featured considerable spectral complexity and random changes of sequence position for the target component. Of particular relevance to issues concerning rhythmic variation, the younger listeners in this study invariably

[a]Author to whom correspondence should be addressed. Electronic mail: pete.fitzgibbons@gmail.com

reported that overall rhythmic changes in the sequences, induced by changes in the duration of the embedded target tone, served as their primary discrimination cue. Older listeners appeared less able to make use of the rhythmic cues, and relied instead on less efficient strategies to perform the discrimination task. Other investigators have noted also that older listeners appear to have difficulty with sequencing tasks that feature rhythmic variation (Humes and Christopherson, 1991; Grose *et al.*, 2006).

Another relevant study revealed that even simple alterations in accent patterns within an auditory sequence can influence measures of temporal sensitivity, particularly for older listeners (Fitzgibbons and Gordon-Salant, 2010). This study used sequences of six brief tone bursts, separated by silent intervals, to form isochronous patterns with equal tonal inter-onset intervals. Within the sequences, the tone bursts were usually equal in duration, except that in some patterns, a single tonal component was elongated in order to produce a perception of stress, or accent, within the sequence. Tonal lengthening was selected to induce component accent, because segment duration is known to be an important acoustic correlate of syllable stress in speech, along with other correlated changes in pitch contour and amplitude (Fry, 1958; Fant *et al.*, 1991; Pickett, 1999; Cutler, 2005). With the accented tone sequences, younger and older listeners were asked to discriminate changes in the duration of a single targeted tonal inter-onset interval located at different sequence positions across several discrimination conditions. Discrimination results collected with the accented patterns were then compared to corresponding measures taken with unaccented tone sequences that lacked the elongated tonal component. Results collected from the younger listeners revealed only small effects of accent on temporal discrimination, with little or no influence of either the sequence position of the accented component, or the target-interval position. The older listeners exhibited substantially poorer interval discrimination than the younger listeners in each sequence condition, and also showed significant performance deficits in conditions featuring accented sequences compared to corresponding conditions with unaccented sequences. For the older listeners, it was anticipated that the effects of accent, if any, would be observed for target intervals located at, or adjacent to, the position of the accented component within a sequence. Instead, the results showed that the simple presence of an accented component, independent of its sequence position, influenced temporal sensitivity at several distributed sequence positions, independent of proximity to the accented component. It became evident that, despite the uniformity of timing within the stimulus sequences, the longer accented component introduced a degree of perceived rhythmic variation within the sequences that affected the performance of older listeners. In this case, it appeared that the older listeners found it difficult to ignore rhythmic changes, when attempting to process temporal cues associated with individual sequence components.

The above two discrimination experiments utilized reference tonal stimulus patterns that featured isochronous timing, with rhythmic variation introduced by changes in the duration of a single sequence component. In each study, the discrimination performance of older listeners was observed to be significantly poorer than that of younger listeners, although the specific effects of rhythmic variation on listener performance appeared to differ across the experiments. That is, in one task, older listeners appeared unable to utilize rhythmic cues to enhance their discrimination performance, while the other task revealed an apparent inability of older listeners to ignore rhythmic cues, when doing so could have enhanced their performance. Despite the different consequences of rhythmic variation in the studies, each shows that rhythmic factors can play an important role in auditory sequential processing. However, it is not clear from these preliminary experiments with simple stimuli that rhythmic effects on sequential processing operate in a similar manner with many of the more complex auditory patterns that feature irregular timing and rhythmic variation. Examination of this issue is the focus of the present investigation.

Of particular interest to the present study are some observations about timing cues made in some earlier discrimination experiments with tonal stimulus sequences. For example, if one or more silent intervals, or pauses, are introduced within a sequence of sounds, then certain perceptual changes frequently occur. That is, even a single elongated pause within a sequence is likely to be perceived as accented (Hirsh *et al.*, 1990). Also, one or more pause intervals within a sequence can alter the perceived timing structure of many patterns in a manner that is similar to dividing a sequence into subsets of components that feature different (faster or slower) presentation rates. Both Hirsh *et al.* (1990) and Monahan and Hirsh (1990) observed some of these perceptual grouping effects using six-tone sequences with mixed temporal spacings, and reported that the ability of younger listeners to discriminate a temporal cue occurring within a perceptual grouping appeared to be greater than that for discriminating the same cue positioned between two different groupings. Added empirical support for this observation was provided recently by Geiser and Gabrieli (2013), who presented tone sequences with irregular timing to groups of young adult listeners and found that listeners could discriminate localized interval changes within the tone sequences better if the interval changes occurred within a rhythmic tonal grouping rather than between different groupings. Thus, it appears that younger listeners, including many with substantial listener training, can show diminished temporal sensitivity depending on the rhythmic properties of stimulus sound sequences. The corresponding effects of rhythmic grouping, and component accent, on sequential processing in older listeners have not been investigated, and will be examined in the present study.

II. METHOD

A. Participants

A total of 43 adults participated in the experiments. These individuals were assigned to three groups based on age and hearing status. Two of the groups had normal hearing, defined as pure tone thresholds ≤ 20 dB hearing level (HL) from 250–4000 Hz (re: ANSI, 2010). A young normal-hearing group (Yng Norm, $N = 15$) included individuals aged 18–27 yr (mean = 20.9 yr) and an older normal-hearing group (Older Norm, $N = 13$) included listeners aged 66–80 yr (mean = 69.5 yr) A third group, older hearing impaired (Older Hrg Imp, $N = 15$) included adults aged 65–80 yr (mean = 71.8 yr) with bilateral mild-to-moderate sloping high-frequency sensorineural hearing losses from 250–4000 Hz. The listeners had a negative history of otologic disease, noise exposure, and family history of hearing loss. The probable etiology of hearing loss in these older listeners was presbycusis.

Additional criteria for subject selection included monosyllabic word recognition scores in quiet exceeding 80% (Northwestern University Auditory Test No. 6, Tillman and Carhart, 1966). The participants also exhibited tympanograms with peak admittance, pressure peaks, tympanometric width, and equivalent volume within normal values for adults (Roup *et al.,* 1998), and acoustic reflex thresholds that were within the 90th percentile for a given pure tone threshold (Gelfand *et al.,* 1990). These criteria were established to ensure that listeners with hearing loss had primarily a cochlear site of lesion, and that all listeners had normally functioning middle ear systems. The listeners were in general good health, with no history of stroke or neurological impairment, had at least a high-school education, and showed normal performance on a screening test of cognitive function (Short Portable Mental Status Questionnaire: Pfeiffer *et al.,* 1977). Additionally, each listener possessed sufficient motor skills to provide responses using a computer keyboard.

B. Stimuli

The tonal sequences used for the experiments were generated using an inverse fast Fourier transform procedure with a digital signal processing board (Tucker-Davis Technologies, AP2) and a 16-bit D/A converter (Tucker-Davis Technologies DD1, 20-kHz sampling rate) that was followed by low-pass filtering (Frequency Devices 901F, 6000-Hz cutoff, 90 dB/oct). The sequences were constructed using six 1000-Hz tone bursts separated by silent intervals, with each tone burst having a fixed duration of 50-ms that included 5-ms cosine-squared rise/fall envelopes. The use of brief tone bursts of fixed frequency and duration in stimulus construction was implemented to minimize stimulus complexity, rather than simulate any specific spectral or durational properties of speech. Instead, the goal in stimulus design was to create sound sequences that allowed control of timing patterns in order to examine the influence of rhythmic grouping on listener discrimination performance. Toward that goal, each of five silent intervals between the six successive tones of a sequence was set to achieve a tonal inter-onset interval (IOI) that was either short (S), with a value of 200 ms, or long (L) with a value of 400 ms. A sequence of these S and L intervals was then used to create specific timing patterns within the tonal stimulus patterns to be used in different conditions of the experiment. Depending on the S and L intervals selected for a pattern, the overall sequence durations ranged from 1.05–2.05 s. For each stimulus condition, the listener's task was to discriminate changes in the duration of a single sequence IOI, designated as the target interval, in order to measure a duration difference limen (DL).

Eleven sequences were used to measure duration DLs for the target IOI. Four of the sequences used isochronous patterns that were included as control conditions to assess discrimination with stimulus patterns that featured no accented components or variation in rhythmic grouping. These sequences featured either all long tonal IOIs (LLLLL and LLLLL), or all short IOIs (SSSSS and SSSSS), with the underscored 3rd or 4th interval indicating the sequence position of the target IOI for a particular discrimination condition. Three additional sequences contained a single long interval inserted among a sequence of short intervals to introduce a single deviation in timing and point of accent within the patterns. These three sequence conditions were designated as SSLSS, SSLSS, and SSSLS, with the underlined target IOI positioned at, or adjacent to, the long interval. Two other conditions included the presence of two successive long intervals within the timing patterns (SLLSS and SSLLS). Finally, two sequence conditions incorporated a single tonal component with a half-octave frequency increment (1414 Hz) in order to examine the added effects of a component pitch shift, which is another known acoustic correlate of stress, or accent, as cited previously. These two sequences were labeled as $SSS_{F}SS$ and $SSL_{F}SS$, with the subscripted target IOI indicating that the sequence interval began with the elevated frequency component. Figure 1 shows a schematic of the timing patterns for each of the seven standard sequences that featured anisochronous timing or an elevated frequency component. These seven stimulus patterns are referred to as "rhythmic sequences" for purposes of the present experiment, although it is understood that the isochronous reference patterns (not shown in Fig. 1) also could be considered as having a characteristic rhythm. For discrimination testing in the experiment, standard and comparison sequences presented on each listening trial were the same, except the comparison sequence featured a specified target interval that was varied adaptively over trials to measure a duration DL.

C. Procedure

The measurement of duration DLs for the target IOI in each of the 11 sequence conditions was obtained using an adaptive three-interval, two-alternative forced-choice procedure. Each discrimination trial contained three listening intervals spaced 750 ms apart. The first listening interval of each trial contained a sample of the standard tonal sequence, with the second and third listening intervals containing samples of the standard and comparison tone sequences in either order selected randomly across listening trials. For each condition, the standard and comparison tone sequences of a listening trial differed only by the duration of the target IOI, which was always longer in the comparison sequence. The location of the target IOI was also fixed at either the third or fourth sequence position within a block of listening trials. Listeners used a keyboard to respond to the comparison sequence in the second or third listening interval of each trial. Each listening interval of a trial was marked by a visual

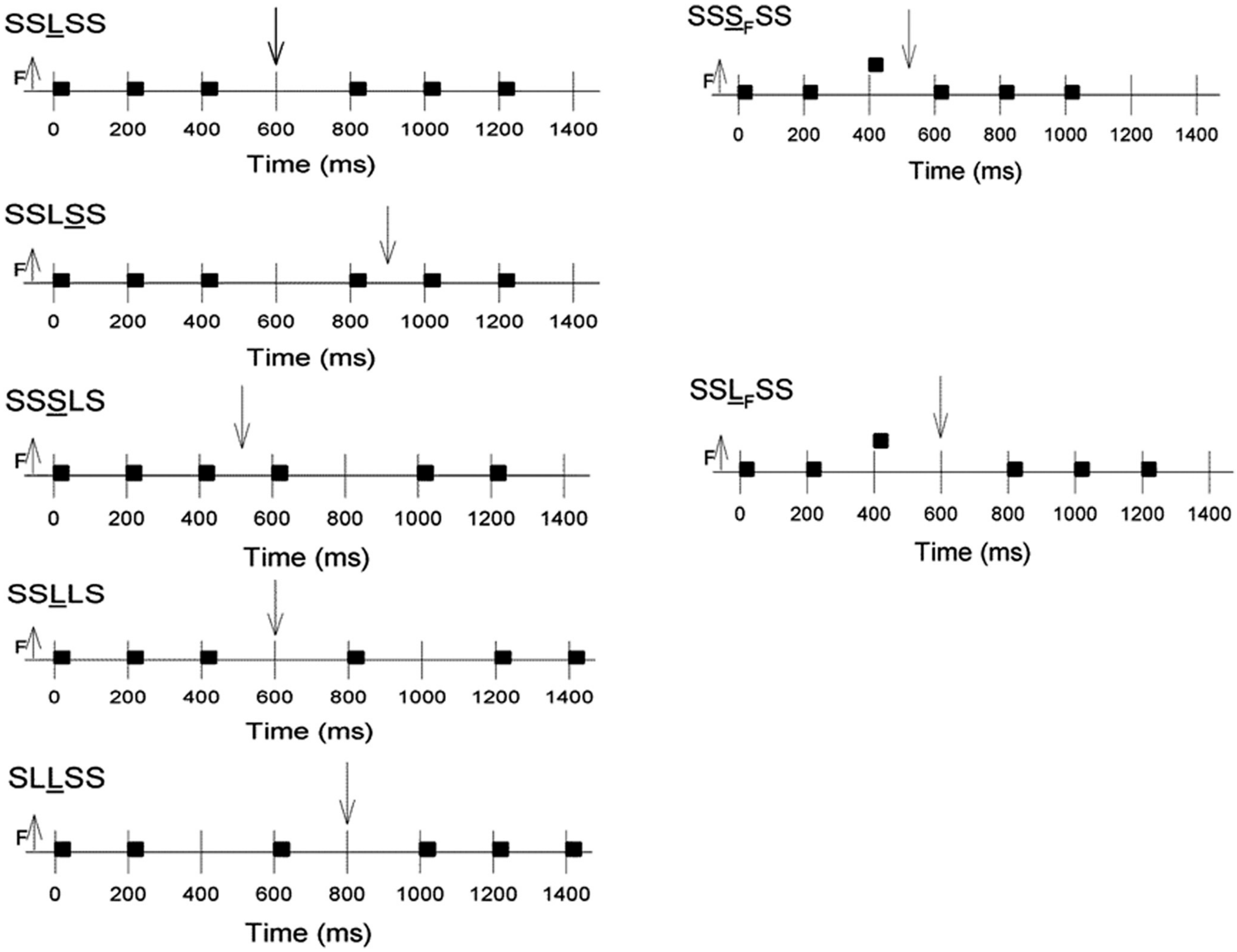

FIG. 1. Schematic diagram of the rhythmic stimulus patterns that featured anisochronous timing or an elevated frequency component. The label for each pattern indicates the order of the sequence tonal inter-onset intervals (IOI), either S (short) or L (long); the underlined interval indicates sequence position of the target IOI, which is also marked with an arrow on the schematic of the sequence. The two patterns on the right also show a single tonal component that is shifted vertically to indicate a half-octave frequency increment.

display that also provided correct-response feedback for each trial.

Estimates for all duration DLs in ms were obtained using an adaptive rule for varying the IOI in the comparison sequence, such that the IOI decreased in magnitude following two consecutive correct responses by the listener and increased in magnitude following each incorrect response. Changes in the IOI were accomplished by varying the silent interval between tones, with no change of tone duration. Threshold estimates obtained by this adaptive rule corresponded to values associated with 70.7% correct discrimination (Levitt, 1971). Testing in each condition was conducted in 50-trial blocks with a starting value of the silent interval 1.5 times the reference value and a step size for interval change that decreased logarithmically over trials to produce rapid convergence on threshold values. Following the first three reversals in direction of interval change, a threshold estimate was calculated by averaging the reversal-point interval values associated with the remaining even-numbered reversals. An average of three threshold estimates was used to derive a final DL for each discrimination condition. It should be noted that the target interval in each condition is designated as a reference tonal IOI, rather than an inter-tone silent interval. The rationale for this designation stems from collective earlier studies, which have documented the relevance of component onset separations for discrimination of timing within tonal sequences (Hirsh *et al.*, 1990; Fitzgibbons and Gordon-Salant, 2010). Prior to data collection, each listener received approximately 1−2 h of practice for sequence discrimination, with all listeners showing performance stability after three to four trial blocks in each condition.

The listeners were tested individually in a sound-treated booth. The 11 discrimination conditions were tested in a different order for each listener. The sequence stimulus levels were fixed at 85 dB sound pressure level in order to insure adequate signal audibility for the listeners, including those with hearing loss, who exhibited only mild sensitivity losses in the frequency region of the stimuli. Testing was monaural through an insert earphone (Etymotic ER-3A) that was calibrated in a 2-cm^3 coupler (DB0138). All listening was conducted in 2-h sessions over the course of several weeks. Total test time varied across listeners, but averaged about 6 h. Listeners were given frequent breaks as needed. The experimental protocol was approved by the Institutional Review Board of the University of Maryland.

III. RESULTS

For the purpose of analysis and the facilitation of performance comparisons across discrimination conditions, absolute values of the duration DLs (ms) measured for the target interval were divided by the relevant reference IOI value (200 or 400 ms) to produce relative IOI DL values (i.e., Weber fractions). The conversion of absolute DLs to relative DLs is a common procedure for data collected with auditory sequences, particularly when comparing discrimination performance across reference intervals that differ in magnitude (Hirsh *et al.*, 1990; Drake and Botte, 1993; Friberg and Sundberg, 1995). Results for the unaccented control sequences for each of the three listener groups are shown in the two panels of Fig. 2, which displays the group mean relative IOI DLs in percent as a function of the target position within the sequence; error bars shown in each figure represent standard errors of the means. The left panel of Fig. 2 shows results for the isochronous control sequences featuring all long intervals (LLLLL), while the right panel shows results for the sequences with all short intervals (SSSSS). It appears from the figure that IOI DLs are shorter for younger than older listeners and performance was somewhat better for target interval 3 than 4. An analysis of variance (ANOVA) was conducted on the individual relative DLs using a repeated measures design with two within-subjects variables (control sequence condition: LLLLL vs SSSSS; and target location: 3 vs 4) and one between-subjects variable (listener group). Results of the analysis revealed significant main effects of sequence condition [$F(1, 40) = 18.1$, $p < 0.001$], target-interval position [$F(1, 40) = 14.8$), $p < 0.001$] and listener group [$F(2,40) = 12.1$, $p < 0.001$], with no significant interaction effects. The sequence condition effect indicates that discrimination performance across listeners for the L targets was better than for the S targets. Additionally, the target position effect indicates that discrimination of targets located in the third sequence position was better than discrimination of targets in the fourth sequence position. Multiple comparison testing of group differences (Bonferroni) revealed that discrimination performance of the younger listeners in each condition was significantly better than that of the older listener groups ($p < 0.001$), with no significant performance difference observed between the two older groups. The performance equivalence between the older groups of listeners indicates that potential factors related to mild-to-moderate hearing loss had no systematic influence on discrimination performance in the conditions using the unaccented control sequences.

The results for the sequence conditions featuring different rhythmic groupings are shown in Fig. 3, which displays the mean relative DLs for long (L) targets in the third sequence position for each group of listeners; results for the corresponding control sequence (LLLLL) are also displayed. An ANOVA was conducted on the individual relative DLs using a repeated-measures design with one within-subjects variable (sequence condition) and one between-subjects variable (listener group). Results of the analysis revealed significant main effects of sequence condition [$F(3,120) = 31.5$, $p < 0.01$], listener group [$F(2, 40) = 14.6$, $p < 0.01$], and a significant interaction between condition and group [$F(6, 120) = 2.33$, $p < 0.036$]. Follow-up analysis of simple main effects revealed that the condition effect was significant for each of the listener groups ($p < 0.01$). Additionally, for each listener group, paired-sample t-tests, with Bonferroni corrections for the critical alpha-level, revealed that the DLs for the control sequence (LLLLL) in Fig. 3 were significantly smaller than values shown for each of the three conditions featuring rhythmic grouping ($p < 0.01$). Inspection of Fig. 3 indicates that the mean DLs for the sequence SSLSS are somewhat larger than those for SLLSS and SSLLS, although these DL differences were not found to be significant in the data analysis. Multiple-comparison testing of the listener group differences (Bonferroni) showed that the performance of the young listeners was significantly better than that of the older listeners ($p < 0.05$) in each condition, with the two older groups performing essentially the same.

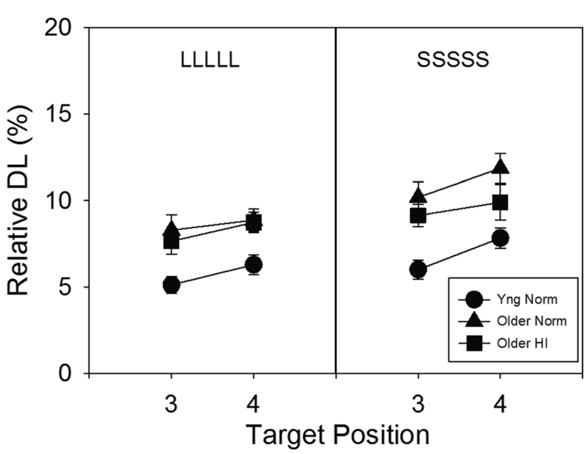

FIG. 2. Mean relative IOI DLs (in percent) of the three listener groups for isochronous control sequences featuring long (L) intervals (left panel) or short (S) intervals (right panel), at each of two sequence target positions (interval 3 and interval 4).

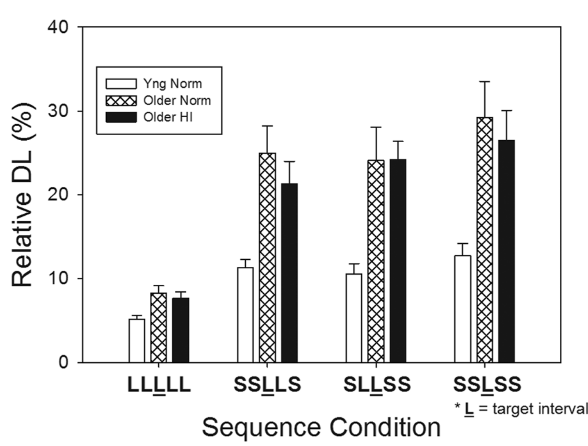

FIG. 3. Mean relative IOI DLs (in percent) of the three listener groups for the isochronous control sequence and three rhythmic sequences, with a long (L) interval target in position 3 for each sequence condition.

Two other sequence conditions containing a single long (L) interval (SSSLS and SSLSS) were introduced to examine the potential influence of the L interval on listener discrimination of an adjacent target interval located within a preceding or following group of S intervals. The mean relative DLs collected from each listener group for these two sequence conditions are shown in Fig. 4, with error bars representing standard errors of the means. An ANOVA was conducted on the individual relative DLs using a repeated-measures design with one within-subjects variable (sequence condition) and one between-subjects variable (listener group). Results of the analysis revealed significant main effects of sequence condition [$F(1,40) = 22.4$, $p < 0.01$] and listener group [$F(2, 40) = 12.2$, $p < 0.01$], with no significant interaction. The condition effect showed that DLs for SSSLS were larger than those for SSLSS, with the DLs for both of these conditions being larger than those shown previously with the control sequence (SSSSS) for corresponding sequence target locations (Fig. 2, right panel). Multiple-comparison testing for group differences (Bonferroni) also revealed that the younger listeners performed significantly better than the older listeners ($p < 0.01$), but there were no significant differences in performance of the two older groups.

Last, two of the discrimination conditions included a single component frequency increment to examine the potential influence of a pitch-induced accent within either an otherwise unaccented sequence (SSS$_F$SS), or within a sequence that also included an interval-based accent (SSL$_F$SS). Discrimination performance measured for each of the two sequences was then compared, respectively, to that for the same two corresponding sequence conditions without the component frequency increment (i.e., SSSSS and SSLSS). These results are displayed in Fig. 5, which shows the mean relative DLs for each group of listeners in the four conditions. Two separate ANOVAs were conducted, each using a mixed design with one within-subjects variable (sequence condition) and one between-subjects variable (listener group). The first analysis compared the two sequences with the short (S) targets (i.e., SSSSS and SSS$_F$SS)

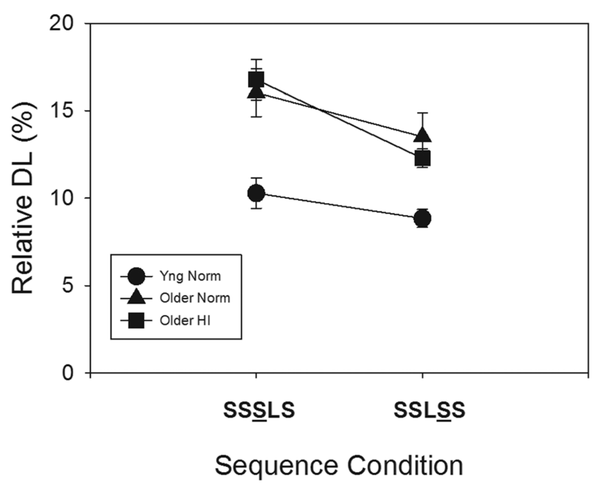

FIG. 4. Mean relative IOI DLs (in percent) of each listener group for a short (S) interval target that either preceded or followed a long (L) sequence interval.

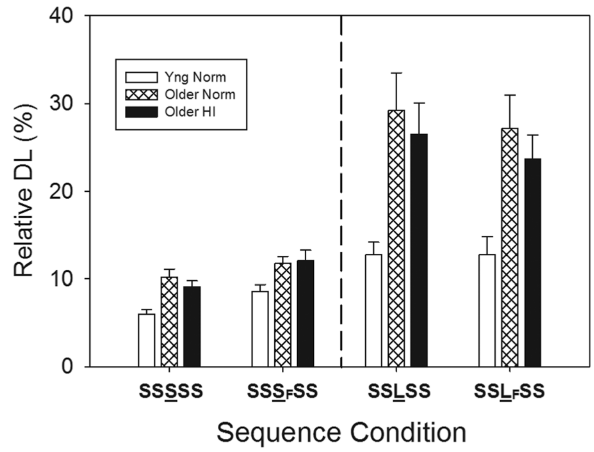

FIG. 5. Mean relative IOI DLs (in percent) of the three listener groups for sequences with and without a tonal frequency shift, for target intervals in sequence position 3. The left panel shows isochronous sequences, and the right panel shows anisochronous rhythmic sequences.

and revealed significant main effects of condition [$F(1, 40) = 33.1$, $p < 0.01$], and listener group [$F(2, 40) = 7.5$, $p < 0.01$], with no significant interaction effects. The condition effect indicated that the measured DLs for each listener group in the condition with the frequency shift were significantly larger than those for the unaccented control condition. The second analysis compared DLs for SSLSS and SSL$_F$SS and revealed a significant main effect of listener group [$F(2, 40) = 9.02$, $p < 0.01$], but no significant condition effect [$F(1, 40) = 1.19$, $p > 0.05$]. Follow-up testing of the group effect in each analysis (multiple-comparisons, Bonferroni) revealed that the DLs of the younger listeners were smaller than those of each older group ($p < 0.01$), with no significant performance differences observed between older groups.

IV. DISCUSSION

The experiments were designed to investigate questions about the influence of rhythmic grouping on the ability of younger and older listeners to discriminate temporal cues within auditory stimulus sequences. For purposes of experimental control, all but two of the stimulus sequences used in the experiments were created with brief tone bursts of equal frequency, duration, and intensity, and with inter-tone silent intervals that could be adjusted to create different timing patterns. Each sequential timing pattern was used to assess the ability of younger and older listeners to discriminate changes in the duration of a single target interval at different sequence positions. The testing revealed a significant influence of rhythmic grouping on discrimination performance, and substantial age-related differences in temporal sensitivity. Some of the results also showed a potential influence of sequential target position on listener performance, but this effect was not consistent across all discrimination conditions.

A. Isochronous control sequences

Discrimination measures were collected from the listeners using unaccented control sequences that featured uniform tonal IOIs of either 200 or 400 ms. The data collected with the isochronous sequences served as baseline measures of temporal sensitivity for subsequent comparison to corresponding measures collected with the anisochronous rhythmic sequences. For the control sequences, the relative DLs of the younger listeners showed a small dependency on sequence position of the target interval, with mean relative DL values for 200-ms target intervals shifting from 6.0% to 7.8% for third and fourth sequence locations, respectively. Corresponding mean relative DLs for 400-ms targets changed from 5.2% to 6.3% across the same two sequence locations, with these values being smaller than those measured for the shorter 200-ms target intervals. These measured relative DLs for the younger listeners are consistent with those reported previously for isochronous tone sequences featuring 200-ms tonal inter-onset intervals (Hirsh *et al.*, 1990; Fitzgibbons and Gordon-Salant, 2010), and also for tone sequences featuring 400-ms IOIs (Friberg and Sundberg, 1995; Geiser and Gabrieli, 2013). Although the particular stimulus parameters of the sequences used in some of the earlier studies differed in terms of component frequencies or durations, each described a discrimination target that was defined as a tonal inter-onset interval, a factor that undoubtedly accounts for the degree of agreement among the relative DLs reported across studies.

Discrimination measures collected from the older listeners with the control sequences exhibited the same trends as seen with the younger listeners, except the relative DLs of the two older groups were larger than those observed for the younger listeners. For the third and fourth sequence target positions, mean relative DLs of the older listeners were 9.7% and 10.9%, respectively, for the 200-ms targets, decreasing to values of 7.9% and 8.8% for the corresponding 400-ms target positions. These performance measures reflect a consistent deficit in temporal sensitivity for the older listeners, with their mean relative DLs being approximately 3% larger than corresponding values of the younger listeners. Additionally, no systematic performance differences were observed for the older listeners with and without hearing loss, an outcome that was not entirely surprising given the high audibility levels of the stimuli and the relatively mild degrees of hearing loss among listeners in the frequency region of the stimuli. A similar absence of hearing-loss effects has been reported in the earlier discrimination study with accented sequences (Fitzgibbons and Gordon-Salant, 2010), and also in other studies of aging and temporal processing that measured detection or discrimination of temporal intervals using clearly audible stimuli (e.g., Schneider *et al.*, 1994; Grose *et al.*, 2006).

B. Rhythmic sequences

Each group of listeners exhibited declines in discrimination performance for the accented stimulus sequences with different rhythmic groupings compared to the isochronous control sequences, as shown in Fig. 3. Aside from the results shown for the unaccented control condition, the other three sequences depicted in the figure featured one or two long intervals interspersed among short intervals. For each of these conditions, the mean relative DLs displayed are for a long target IOI in a mid-sequence position. Mean relative DLs of the younger listeners for the three rhythmic sequences were similar in magnitude, ranging from 10.6%–12.7%. Each of the three rhythmic sequences produced relative DLs in the younger listeners that were significantly larger than the corresponding relative DL of 5.2% measured for the same target and sequence position with the unaccented control sequence (i.e., LLLLL). The older listeners produced mean relative DLs ranging from 21.7%–26.9% for the same three rhythmic sequence conditions. These DLs for the older listeners were also significantly larger than the value of 7.9% measured for the same target and position in the control sequence. Performance comparisons across conditions for each listener group indicate that the detrimental influence of rhythmic grouping on discrimination performance was greatest among the older listeners. These effects with the rhythmic sequences differ somewhat from those reported previously for sequences with an accent induced by a tonal duration lengthening (Fitzgibbons and Gordon-Salant, 2010). While results from this earlier study revealed a significant influence of accent on discrimination performance of older listeners, there was relatively little influence of accent on the performance of younger listeners. This differential effect of accent in the two studies is likely related to timing characteristics of the sequential stimuli. That is, the earlier experiments used isochronous sequences and introduced accent without altering the tonal onset-to-onset timing within sequences, whereas the present stimulus sequences featured both an interval accent and variations in rhythmic timing.

Another consequence of accent within rhythmic sequences can be seen in the results displayed in Fig. 4. The two sequence conditions referenced in the figure, SSSLS and SSLSS, compare the effects of a single long-interval accent on listener discrimination of an adjacent target within a preceding or following grouping of short intervals. For the younger listeners, the mean relative DLs for the two sequence conditions were 10.3% and 9.0%, with each value being significantly larger than corresponding relative DL values for the same targets and positions in the unaccented control sequences (SSSSS and SSSSS), as displayed in the right panel of Fig. 2. By comparison, the older listeners produced mean relative DLs of 16.4% and 12.9%, values that are also larger than those for the corresponding control sequences, and also significantly larger than those of the younger listeners. Thus, the detrimental effects of an interval accent on discrimination performance can be measured not only at the sequence position of the accent, but also at adjacent sequence positions preceding and following the accent. In this regard, the results indicate that discrimination of targets preceding the interval accent was more affected than targets following the accent. As a result, the performance trend showing smaller relative DLs for targets in the third vs fourth sequence position observed for the unaccented control sequences (Fig. 2) is reversed for the results displayed in Fig. 4, especially evident in the data for the older listeners. Overall, there appears to be an influence of sequence target position on discrimination performance for all listeners, but the effects are more robust for the older listeners, at least for the rhythmic sequences. Explanations of these target position effects observed for the older listeners are not readily apparent, and suggests the need to determine if such effects generalize to sequence target positions other than the two studied in this experiment. Also, it is interesting to note that no corresponding effects of target interval position on listener discrimination performance were observed for sequential accent induced by tonal elongation (Fitzgibbons and Gordon-Salant, 2010). It may be simply that the disruptive effects of interval accent on listener discrimination are greater than those of tonal accent, but this conclusion also requires further confirmation.

C. Pitch accent

The sequence conditions that examined a shift in component frequency as a source of sequence accent produced somewhat different outcomes. This tonal parameter was examined primarily because a frequency shift is a well-known correlate of stress and accent in both speech and music. For example, Grant (1987) observed that a rise in voice fundamental frequency of about one-third octave was sufficient to produce perceived stress of a syllable within a sentence. Hirsh *et al.* (1990) also observed, for isochronous tone sequences, that the introduction of a single component with elevated frequency could produce a perception of accent, and also cause a reduction in listener temporal sensitivity in the vicinity of the accented component. In the present experiments, two sequence conditions were created to examine the effects of a frequency shift on perceived accent, with the results displayed in Fig. 5. One analysis of the data shown in the figure compared listener discrimination performance for isochronous control sequences with and without a half-octave frequency shift imposed on the third sequence component, SS$\underline{S}_F$SS and SS$\underline{S}$SS, respectively. For this comparison, the mean relative DLs for the younger listeners were found to be significantly larger for the sequence with the frequency increment (DLs equal 8.5% vs 6.0%), a result that is consistent with the Hirsh *et al.* (1990) observations. Corresponding relative DLs for the older listeners were 11.9% and 9.7% with and without the frequency increment, respectively. The other analysis looked at effects of a frequency shift within a rhythmic sequence that already featured an accent by virtue of its single long interval, SS$\underline{L}_F$SS vs SS$\underline{L}$SS. For these two sequence conditions, discrimination performance of the younger listeners was essentially the same (DLs equal to 12.8% and 12.7%), with corresponding equivalent values of 25.5% and 26.9% for the older listeners. Thus, no independent effect of frequency shift on discrimination performance was evident for either the younger or older listeners with these rhythmic sequences. Therefore, it appears that a pitch-induced accent can have an important influence on discrimination performance if it occurs within an otherwise unaccented sequence, but not when it is added to a rhythmic sequence that already features a salient interval accent.

D. Perceptual grouping

The anisochronous timing properties of the stimuli referred to as rhythmic sequences in the present experiment featured temporal groupings of sequential components with different tonal onset-to-onset intervals, defined here as either short (S) or long (L). Perceptually, the effect of such temporal grouping for the listener is to hear a succession of identical sounds that shifts between faster and slower presentation rates within each sequential pattern. The experimental question of interest concerns what influence such rhythmic grouping within an auditory sequence might have on listeners' temporal processing abilities. Similar questions were asked in the past concerning the consequences of pitch-based perceptual grouping within auditory sequences, where it was found that listener temporal processing was relatively good for sequential stimuli occurring within the same perceptual grouping, but poor for stimuli crossing between different perceptual groupings (Bregman and Campbell, 1971; Fitzgibbons *et al.*, 1974). Similar outcomes were predicted by Hirsh *et al.* (1990) and Monahan and Hirsh (1990) for rhythmic groupings that were based on the temporal proximity of components within a sequence. More recently, Geiser and Gabrieli (2013) used rhythmic tone sequences incorporating five longer inter-onset intervals and three shorter ones, and measured the duration DLs of younger listeners for one of the longer interval targets. Their results supported the contention of Hirsh *et al.* in showing that discrimination was better for targets located within the same interval grouping than for targets located at a boundary between different interval groupings. Results of the present experiment, when compared across all sequence discrimination conditions, also provide some added support for these predicted rhythmic grouping effects. That is, discrimination performance for target intervals positioned within the control sequences (common interval groupings) was found to be much better than that observed for the targets positioned at the boundary between short and long intervals, as was the case for each condition with the rhythmic sequences. The relevance of the present observations concerning rhythmic variation and temporal sensitivity to the age-related processing difficulties observed for accented speech is not clear. However, it seems reasonable to expect that the rhythmic properties of any auditory sequence, including speech, can influence listener sensitivity to embedded temporal cues in a manner that affects discrimination or recognition performance. These expected outcomes, however, remain to be determined through further investigation.

E. Summary and conclusions

The experiments were conducted to examine the extent to which the overall rhythmic properties of an auditory sequence influence listener sensitivity to alterations in timing cues. The stimuli for the investigation were tone sequences with rhythmic patterns that featured the grouping of shorter and longer tonal onset-to-onset intervals. Younger and older listeners in the study were asked to discriminate changes in the duration of a targeted interval within each of several tone sequences, some of which featured equal timing between successive tones, and some that featured unequal timing, referred to as rhythmic patterns. All listeners demonstrated better discrimination performance for target intervals located within equally timed sequences, compared to targets within rhythmic sequences. Older listeners with and without hearing loss performed similarly and exhibited poorer discrimination than younger listeners for all sequences. The largest age-related performance differences were observed for target intervals located within the rhythmic sequences. Specific sources of accent within a sequence, such as interval elongation, or a frequency increment, can have detrimental effects on discrimination performance, though interval accents appear to exert the stronger effects. The observed effects of component accent and rhythmic grouping on listener temporal sensitivity demonstrate an important influence of global stimulus characteristics on the processing of individual components within complex sound sequences.

ACKNOWLEDGMENTS

This research project was supported by grant R37 AG09191 from the National Institute on Aging. The authors are grateful to Julie I. Cohen, Chris Waldroup, and Keena James for their assistance in data collection.

ANSI (**2010**). ANSI S3.6-2010, *American National Standard Specification for Audiometers* (Revision of ANSI S3.6-1996, 2004) (American National Standards Institute, New York).

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

Bregman, A. S., and Campbell, J. (**1971**). "Primary auditory stream segregation and perception of temporal order in rapid sequences of tones," J. Exp. Psychol. **89**, 244–249.

Burda, A. N., Scherz, J. A., Hageman, C. F., and Edwards, H. T. (**2003**). "Age and understanding speakers with Taiwanese or Spanish Accents," Percept. Mot. Skills **97**, 11–20.

Cutler, A. (**2005**). "Lexical Stress," in *The Handbook of Speech Perception*, edited by D. B. Pisoni and R. E. Remez (Blackwell, Oxford, UK), Chap. 5, pp. 264–289.

Drake, C., and Botte, M-C. (**1993**). "Tempo sensitivity in auditory sequences: Evidence for a multiple-look model," Percept. Psychophys. **54**, 277–286.

Fant, G., Kruchenberg, A., and Nord, L. (**1991**). "Durational correlates of stress in Swedish, French and English," J. Phonet. **19**, 351–365.

Ferguson, S. H., Jongman, A., Sereno, J. A., and Keum, K. A. (**2010**). "Intelligibility of foreign-accented speech for older adults with and without hearing loss," J. Am. Acad. Audiol. **21**, 153–162.

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. (**2010**). "Age-related differences in discrimination of temporal intervals in accented tone sequences," Hear. Res. **264**, 41–47.

Fitzgibbons, P. J., Gordon-Salant, S., and Barrett, J. (**2007**). "Age-related differences in discrimination of an interval separating onsets of successive tone bursts as a function of interval duration," J. Acoust. Soc. Am. **122**, 458–466.

Fitzgibbons, P. J., Pollatsek, A., and Thomas, I. (**1974**). "Detection of temporal gaps within and between perceptual tonal groups," Percept. Psychophys. **16**, 522–528.

Friberg, A, and Sundberg, J. (**1995**). "Time discrimination in a monotonic isochronous sequence," J. Acoust. Soc. Am. **98**, 2524–2530.

Fry, D. B. (**1958**). "Experiments in the perception of stress," Lang. Speech **1**, 126–152.

Geiser, E., and Gabrieli, J. D. E. (**2013**). "Influence of rhythmic grouping on duration perception: A novel auditory illusion," PLoS One **8**(1), e54273.

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

Gordon-Salant, S., Yeni-Komshian, G. H., and Fitzgibbons, P. J. (**2010**). "Recognition of accented English in quiet by younger normal-hearing listeners and older listeners with normal hearing and hearing loss," J. Acoust. Soc. Am. **128**, 444–455.

Gordon-Salant, S., Yeni-Komshian, G. H., Fitzgibbons, P. J., Cohen, J. I., and Waldroup. C. (**2013**). "Recognition of accented and unaccented speech in different noise backgrounds by younger and older listeners," J. Acoust. Soc. Am. **134**, 618–627.

Grant, K. W. (**1987**). "Identification of intonation contours by normally hearing and profoundly hearing-impaired listeners," J. Acoust. Soc. Am. **82**, 1172–1178.

Grose, J. H., Hall, J. W., and Buss, E. (**2006**). "Temporal processing deficits in the pre-senescent auditory system," J. Acoust. Soc. Am. **119**, 2305–2315.

Hirsh, I. J., Monahan, C. B., Grant, K. W., and Singh, P. G. (**1990**). "Studies in auditory timing: I. Simple patterns," Percept. Psychophys. **47**, 215–226.

Humes, L., 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.

Levitt, H. (**1971**). "Transformed up–down methods in psychoacoustics," J. Acoust. Soc. Am. **49**, 467–477.

Monahan, C. B., and Hirsh, I. J. (**1990**). "Studies in auditory timing: 2. Rhythm patterns," Percept. Psychophys. **47**, 227–242.

Pfeiffer, E. (**1977**). "A short portable mental status questionnaire for the assessment of organic brain deficit in elderly patients," J. Am. Geriatr. Soc **23**, 433–441.

Pickett, J. M. (**1999**). *The Acoustics of Speech Communication* (Allyn and Bacon, Needham Heights, MA), pp. 75–98.

Roup, C. M., Wiley, T. L., Safady, S. H., and Stoppenbach, D. T. (**1998**). "Tympanometric screening norms for adults," Am. J. Audiol. **7**, 55–60.

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.

Shah, A. (**2004**). "Production and perceptual correlates of Spanish-accented English," *Proceedings of the MIT Conference: From Sound to Sense: 50+ Years of Discoveries in Speech Communication* (MIT, Cambridge, MA), pp. C-79–C-84.

Tillman, T. W., and Carhart, R. C. (**1966**). "An expanded test for speech discrimination utilizing CNC monosyllabic words: N.U. Auditory Test No. 6," USAF School of Aerospace Medicine, Report No. SAM-TR-66-55.