Temporal order discrimination of tonal sequences by younger and older adults: The role of duration and rate^{a)}

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(Received 18 December 2007; revised 20 March 2008; accepted 28 April 2008)

The effect of tone duration and presentation rate on the discrimination of the temporal order of the middle two tones of a four-tone sequence was investigated in young normal-hearing (YNH) and older hearing-impaired (OHI) listeners. The frequencies and presentation level of the tone sequences were selected to minimize the effect of hearing loss on the performance of the OHI listeners. Tone durations varied from 20 to 400 ms and presentation rates from 2.5 to 25 tones/s. Two experiments were conducted with anisochronous (nonuniform duration and rate across entire sequence) and isochronous (uniform rate and duration) sequences, respectively. For the YNH listeners, performance for both isochronous and anisochronous sequences was determined primarily by presentation rate such that performance decreased at rates faster than 5 tones/s. For anisochronous tone sequences alone, the effects of rate were more pronounced at short tone durations. For the OHI listeners, both presentation rate and tone duration had an impact on performance for both isochronous and anisochronous sequences such that performance decreased as rate increased above 5 tones/s or duration decreased below 40 ms. Temporal masking was offered as an explanation for the interaction of short durations and fast rates on temporal order discrimination for the anisochronous sequences. © 2008 Acoustical Society of America. [DOI: 10.1121/1.2932089]

PACS number(s): 43.66.Mk, 43.66.Sr [MW]

Pages: 462–471

I. INTRODUCTION

It is well documented that hearing acuity worsens with advancing age (e.g., CHABA, 1988). Along with elevated hearing thresholds, older listeners also seem to have difficulty with suprathreshold auditory processing tasks. For example, older hearing-impaired listeners seem to consistently perform worse than young normal-hearing adults on a variety of tasks on the TBAC (Test of Basic Auditory Capabilities) (Watson *et al.*, 1982; Humes and Christopherson, 1991; Humes *et al.*, 1994; Humes, 2002). The TBAC is comprised of individual subtests that each tests one aspect of suprathreshold auditory discrimination ability. One such subtest is the temporal order subtest, in which the listener discriminates the order of the two middle tones in a four-tone sequence. It has been consistently shown, based on studies measuring the reliability of the various subtests of the TBAC (Christopherson and Humes, 1992) and those involving factor analyses on young normal-hearing (YNH) listeners (Watson *et al.*, 1982; Surprenant and Watson 2001) and older hearing-impaired (OHI) listeners (Humes *et al.*, 1994), that older listeners perform worse than younger adults on the temporal order subtest of the TBAC. Based on the fact that

the tonal sequences in the temporal order subtest are comprised of low- and midfrequency tones, and that these studies ensured full audibility of the sequences for all listeners, the poor performance of the older listeners is not likely attributable to hearing loss.

It is possible that this difference in performance between the two groups might be related to the nature of the tonal sequences themselves. Figure 1 provides a schematic representation of the tonal sequences used in the temporal order subtest. The top two panels (A and B) of this figure depict four-tone sequences from the temporal order subtest. The first and last tones of each sequence are 625 Hz tones, while the two middle tones are 550 and 710 Hz, with one of two possible orders (550 Hz followed by 710 Hz or 710 Hz followed by 550 Hz). Discrimination is tested using a three-interval two-alternative forced choice procedure, in which the standard was always presented first. The task of the listener is to determine which of the two comparison intervals that follow differ from the standard in terms of the order of the two middle tones.

Test difficulty across the 48 trials of the subtest is manipulated by varying the duration of the two middle tones (in log steps over a range of 20–200 ms) with a fixed and brief interstimulus interval (ISI) of 2 ms throughout. Note that along with the change in duration of the two middle tones from short (more difficult, panel A of Fig. 1) to long (less difficult, panel B of Fig. 1), this method also concurrently impacts the overall rate of presentation from fast (panel A) to

^{a)} Portions of this work were presented at the 145th meeting of the Acoustical Society of America, Nashville, Tennessee, 2003, and at the Aging and Speech Communication: An International and Interdisciplinary Research Conference, Bloomington, Indiana, 2005.

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FIG. 1. Schematic illustration of anisochronous four-tone sequences used in the Test of Basic Auditory Capabilities (TBAC) to measure temporal order discrimination. Panels A and B represent sequences with different durations of the two middle tones as well as the overall rate. Panels B and C represent sequences with different durations of the two middle tones but with the same overall rate. Finally, panels A and C represent sequences with the same duration of the two middle tones, but with different overall rate. Note that for Experiment I, duration and rate changes apply only to the two middle tones, while for Experiment II, these changes apply to all four tones.

slow (panel B). Hence, when older listeners perform worse than young listeners on this task, it is not clear whether this is due to the shorter duration of the stimuli or due to the faster rates of presentation. When the duration of the individual components is reduced (as in panel A), errors may result due to insufficient processing time. For example, [Newman and Spitzer \(1983\)](#), based on the results of a backward masking paradigm, suggested that older listeners might require prolonged auditory processing times for stimuli when compared to younger listeners. On the other hand, a faster rate of presentation might be more challenging for older adults due to a generalized age-related slowing of speed of processing. For example, [Fitzgibbons and Gordon-Salant \(2004\)](#) measured auditory discrimination of the overall temporal pattern of spectrally and temporally complex tonal sequences in younger and older listeners. They found that older listeners performed worse than the younger listeners, with the age-related differences being highest at faster presentation rates. However, other studies such as [Trainor and Trehub \(1989\)](#) found that age-related differences in performance on temporal order discrimination tasks were obtained independent of the presentation rate used. Similar results were obtained by [Fitzgibbons et al. \(2006\)](#) for a temporal order recognition task for tonal sequences in which the sequence rate and duration were independently manipulated. They found that temporal order recognition was determined primarily by sequence rate and not by tonal duration. However, age-related differences were not limited to the faster sequence rates; rather, they were observed for all values of sequence rate tested. Hence, it appears that the decline in temporal processing abilities cannot be attributable entirely to reduced speed of processing.

Another explanation for poorer performance of listeners at higher presentation rates might be because of increased susceptibility to temporal masking of the two middle tones by the first and last tones in the sequence. Similar explana-

tions have been presented for age-related differences in frequency discrimination tasks ([Raz et al., 1990](#)). It is impossible to determine the independent effects of duration and presentation rate using the tonal sequences of the original temporal order subtest of the TBAC. However, one could sort this out by combining various durations with various ISIs to produce various rates of presentation. One such manipulation is illustrated in panel C of Fig. 1. Note that the tonal sequence shown in panel C has the same presentation rate (in units of tones/s) as that shown in panel B, but has the same tonal duration (for the two middle tones) as the sequence shown in panel A. If the performance on this task is governed by the duration of the two middle tones, then listeners should perform similarly for stimuli shown in panels A and C. On the other hand, if it is the overall presentation rate that determines performance, then stimuli shown in panels B and C should elicit similar performance. Finally, if both duration and presentation rate affect performance, listeners should perform the worst for the stimuli shown in panel A, compared to those in panels B and C. The experiments described here attempted to determine the independent effects of presentation rate and duration by manipulating duration and presentation rate in the manner just described. Two experiments were conducted because of the anisochronous or nonuniform nature of the four-tone sequence used in the temporal order discrimination task of the TBAC. As shown in Fig. 1, note that only duration of the two middle tones varies from trial to trial on this task, while that of the first and last tones remains constant (at 100 ms). This means that the duration of the first and last tones could be either greater or smaller than that of the two middle tones. Hence, the presentation rate in this condition is not uniform across the entire sequence, sometimes speeding up in the middle of the sequence and sometimes slowing down. As a result, a second experiment using isochronous four-tone sequences (same duration and ISI for all four tones in the sequence) was conducted with different participants to better examine the roles of presentation rate and stimulus duration in a temporal order discrimination task. In all other aspects, the tonal sequences used in the second experiment were similar to those used in the first experiment. The details of the two experiments are described below.

EXPERIMENT I: ANISOCHRONOUS TONE SEQUENCES METHODS

II. METHODS

A. Participants

There were 21 YNH listeners and 18 OHI listeners participated in this experiment. Of these, ten YNH and six OHI were recruited and tested at Indiana University, Bloomington, while 11 YNH and 12 OHI listeners were recruited and tested at the University of Florida, Gainesville. The testing procedures were exactly the same for all participants. The 21 YNH listeners included 20 females and one male and ranged in age from 19 to 25 years. None of them had a history of hearing loss. All the YNH listeners had pure-tone air-conduction thresholds less than 20 dB hearing level (HL) for

TABLE I. Age and air-conduction hearing thresholds in dB HL reference ANSI (1996) for the test ear for the 18 OHI participants in Experiment I. NR indicates no response at audiometric limits.

Sub. No.	Age (Years)	Air conduction hearing thresholds (dB HL)						Test ear
		250 (Hz)	500 (Hz)	1000 (Hz)	2000 (Hz)	4000 (Hz)	8000 (Hz)	
1	77	35	35	25	50	55	45	R
2	81	35	35	45	55	70	80	L
3	85	25	20	15	40	70	70	L
4	69	45	50	45	50	60	95	L
5	77	30	35	40	65	70	70	R
6	80	40	30	40	45	60	75	R
7	72	10	20	30	35	60	70	L
8	83	5	5	15	45	55	55	R
9	75	10	10	10	25	50	75	R
10	71	15	15	30	50	60	65	R
11	77	20	35	25	60	65	60	R
12	72	25	25	20	35	70	NR	L
13	76	20	30	45	40	70	NR	R
14	77	20	25	30	65	65	55	L
15	74	15	15	35	40	55	55	L
16	75	10	20	35	60	80	80	L
17	79	15	20	35	60	80	80	L
18	77	10	25	10	50	60	70	L
Mean	76.5	21.4	25	30	46.9	63.1	67.8	

frequencies ranging from 250 to 8000 Hz. OHI listeners were recruited from the patient database of the Speech and Hearing Clinic at Indiana University, Bloomington and from the community in Gainesville, Florida. This group of listeners included ten males and eight females, ranging in age from 69 to 85 years ($M=76.5$ yr). All the listeners in the OHI group had sensorineural hearing loss with thresholds ranging from normal at the low frequencies to profound at the highest frequency (8000 Hz) tested. Their ages and hearing thresholds in the test ear are presented in Table I.

B. Stimuli

The stimuli were four-tone sinusoidal sequences that were patterned after those of the temporal order subtest of the TBAC. The first and last tones of the sequences were 625 Hz sinusoids, and the two middle components were 550 and 710 Hz sinusoids. All the tones had 10-ms-long onset and offset ramps, created using a Blackman window. The order of the two middle components was varied randomly. Thus, a given sequence could have one of the two orders: 625-550-710-625 or 625-710-550-625. These sequences were generated with 21 combinations of duration and ISI to give five different rates of presentation. The rate of presentation, duration, and ISI values ranged from 2.5 to 25 tones/s, 20 to 400 ms, and 0 to 380 ms, respectively. These values were chosen such that a wide range of durations and ISIs could be tested, while including those that are encompassed by the TBAC temporal order discrimination task. In addition, the ranges selected for each of these temporal parameters encompass those commonly observed in speech. The specific values and combinations of stimulus duration, ISI, and rate parameters are presented in Table II. It should be noted that these values apply only to the middle

two tones in the anisochronous sequences and the ISIs surrounding them. The leading and trailing tones were always fixed in duration at 100 ms, as in the TBAC task. Although the specification of tone durations and ISI in Table II are not

TABLE II. Rates of presentation and combinations of duration and ISI that were used for the tonal sequences. These stimulus parameters apply to the middle two tones (and the adjacent ISIs) of the sequences in Experiment I and to the entire four-tone sequence in Experiment II.

Rate (tones/s)	Duration (ms)	ISI (ms)
25	20	20
	40	0
20	20	30
	40	10
10	20	80
	40	60
	80	20
5	20	180
	40	160
	80	120
	120	80
	160	40
	180	20
2.5	200	0
	20	380
	40	360
	80	320
	160	240
	200	200
	320	80
	400	0

impacted by the presence of these fixed duration leading and trailing tones, the rate of presentation for the entire four-tone sequence is affected. Hence, for this experiment, the rates reported in Table II apply only to the middle two tones of the sequence.

The stimuli consisted of these sequences presented in a modified two-alternative forced choice format. The first four-tone sequence was the standard, against which the second and third four-tone sequences were compared. The second and third four-tone sequences differed in the order of the two middle tones of the sequence. For each combination of duration and ISI, the task of the listener was to discriminate the order of the four-tone sequences by indicating which of the two comparison tone sequences differed from the standard tone sequence. The standard stimulus and the order of the two comparison stimuli were randomized from trial to trial. The participants at the two locations (Indiana University and the University of Florida) were tested with different versions of the recordings that varied only in this randomization. All other testing procedures were exactly the same.

The stimuli were generated using the mathematical platform MATLAB (The Mathworks, Inc.) on a Dell Optiplex GXI computer. The sequences were then recorded directly from the computer to digital audio tapes. The stimuli were presented in blocks of 50 trials, with the duration-ISI combination maintained within each block. The order of presentation of the 21 duration-rate combinations was varied randomly across listeners.

All testing was done with the participant seated comfortably in a double-walled sound-treated booth. The recorded stimuli on DAT were presented to the listeners through an audiometer, and all testing was conducted monaurally using ER-3A insert earphones. In young normal listeners, maximum scores on the TBAC are achieved at presentation levels of at least 65–75 dB sound pressure level (SPL) (Christopherson and Humes, 1992). In the present study, the stimuli were presented at 85 dB SPL as measured in an HA-2 2 cm³ coupler. This level was high enough for all stimuli to be audible to the hearing-impaired listeners, while not being uncomfortably loud for the YNH listeners. The presentation levels for the signals were set using a continuous 625 Hz calibration tone matched to the peak level of the tones in the stimulus sequences. All but three of the YNH listeners were tested in the right ear, while the older listeners were tested in their better ear. Insert earphones were also worn in the non-test ear. All testing was carried out individually and participants were paid for their participation.

C. Procedure

The testing was carried out in two sessions, each around 120 min in length. Prior to testing, the participants' air-conduction hearing thresholds were measured while they were seated in a double-walled sound-treated booth. The participants were then given written instructions as follows.

"You will hear three sound sequences: a standard sequence, followed by two test sequences. On the response sheet, the standard sequence is labeled as "S," and the two test sequences are labeled "T1" and "T2." One of the two test

sequences T1 or T2 is different from the standard sequence S. Your task is to listen to the three sequences, and mark (X) the test sequence (T1 or T2) that is *different* from the standard S. The S on the response sheet is just to remind you that you will always hear the standard sound sequence first. Only mark T1 or T2 as your answer.

You will be given a practice version of the task consisting of eight trials. If you want to listen to further practice trials after this, you will be given a chance to do so. Some of the differences in sound sequences will be easier to hear, while others will be more difficult. Do not get discouraged, as some of the trials are designed to be more difficult. In case you are not sure of your responses, please guess, but make sure you respond for every trial."

The participants were then presented with eight practice trials. The practice trials included various duration-ISI combinations so as to familiarize the listeners with the range of stimuli used in the actual test. The same set of eight practice trials, in the same order, was presented to all listeners. Listeners marked their responses on the provided response sheets. Unlike the actual test, feedback was provided after each response for the practice trials. The test sequences were presented after the completion of the practice trials, and the participants had indicated that they were comfortable with the task. The tape was paused briefly after the first 25 trials in every block to verify that the participant was on the correct trial number. At the end of the 21 test conditions (Table II), each listener had completed a total of 1050 (21 × 50) trials. Frequent breaks were given throughout the test sessions as needed.

III. RESULTS AND DISCUSSION

One of the 18 older participants (number 7, Table I) could not complete three of the test conditions (20-20, 20-30, 20-80, where the two values represent tone duration and ISI, respectively) because of the high level of difficulty of these conditions. Note that these conditions fall under the fastest presentation rates of 25, 20, and 10 tones/s, respectively, and that of these three rates, the slowest (10 tones/s) was included in all subsequent analyses (see below). Hence, the analyses described in the following sections included all 21 YNH and only 17 of the 18 OHI listeners.

Figure 2 provides the mean percent-correct scores for the 21 YNH listeners (top panel) and the 17 OHI listeners (bottom panel). Performance is plotted as a function of duration+ISI (lower x-axis label) or presentation rate (top x-axis label) for the middle two tones of the sequence. The parameter for the plots in both panels is the stimulus duration. As was noted previously, given the anisochronous nature of the four-tone sequences used in this experiment, these definitions (duration+ISI and rate) apply only to the middle two tones of the sequence. In general, both groups show substantial increases in performance as rate decreases from 20 to 5 tones/s, and then slight or no increase in performance with further reductions in presentation rate below 5 tones/s (or a duration+ISI value of 200 ms). Further, this pattern holds regardless of tone duration, although the over-

FIG. 2. Mean percent-correct performance from Experiment I (aniso-chronous sequences) for young normal-hearing (YNH) listeners (top) and elderly hearing-impaired (OHI) listeners (bottom). The parameter is the duration of the middle two tones of the four-tone sequence. The solid gray lines in the bottom panel represent the data for the YNH listeners from the top panel for tone durations of 20 and 40 ms. Standard deviations for each stimulus parameter are shown by using the unconnected symbols at the bottom of the graph.

all performance level appears to vary for the shorter durations (20 and 40 ms) with lower levels of performance achieved for these durations.

The data for tone durations of 20, 40, and 80 ms and presentation rates of 10, 5, and 2.5 tones/s were selected for subsequent statistical analysis. Percent-correct scores were arcsine transformed (Studebaker, 1985) to stabilize the error variance prior to analysis. Independent-samples t-tests with adjustment for multiple comparisons revealed no significant effects of test ear within the OHI group. Hence, data were combined across test ear for both OHI and YNH listeners. Data across testing sites (Indiana University and the University of Florida) were combined for each listener group as independent-samples t-tests revealed no significant differences between the two sites. The data for all nine stimulus conditions were found to be normally distributed (Kolmogorov-Smirnov Z , $p > 0.01$). As a result, the general linear model (GLM) was used to examine the within-subject effects of presentation rate and tone duration and the

between-subject effect of listener group. The following effects were found to be statistically significant ($p < 0.01$): presentation rate [$F(2, 72) = 86.9$]; duration [$F(2, 72) = 60.1$]; and the rate $\times$ duration interaction [$F(4, 144) = 5.0$]. The main effect of group [$F(1, 36) = 11.1$] and the two-way interaction of duration $\times$ group [$F(2, 72) = 10.4$] were also significant ($p < 0.01$).

Based on the results of these analyses, additional follow-up analyses were performed. First, two additional GLM analyses were conducted to examine the effects of presentation rate and stimulus duration within each group separately. For the YNH listeners, presentation rate [$p < 0.01$; $F(2, 40) = 60.7$] and duration [$p < 0.01$; $F(2, 40) = 18.7$] both had significant effects on temporal order discrimination. The interaction of rate and duration was also significant [$p < 0.01$; $F(4, 80) = 4.5$]. Subsequent analysis of the estimated marginal means for pairwise comparisons of rate using t-tests with the Bonferroni adjustment for multiple comparisons revealed that the performance for the rate of 10 tones/s was significantly ($p < 0.01$) worse than that for the 5 and 2.5 tones/s rates, and that performance for the 5 tones/s rate was significantly ($p < 0.05$) worse than that for the 2.5 tones/s rate. Similar analysis for pairwise comparisons of duration revealed that the YNH listeners performed significantly worse for the 20 ms duration than for the two longer durations (40 and 80 ms), but that the performances for the two longer durations were not significantly different from each other.

For the OHI listeners, the analysis revealed significant ($p < 0.01$) main effects of presentation rate [$F(2, 32) = 31.3$] and duration [$F(2, 32) = 36.7$] and a significant ($p < 0.05$) interaction between these two variables [$F(4, 64) = 2.6$]. Subsequent examination of the estimated marginal means for all pairwise comparisons of presentation rate using t-tests with the Bonferroni adjustment for multiple comparisons revealed that the performance for the rate of 10 tones/s was significantly lower ($p < 0.01$) than that of the two slower rates included in this analysis (5 and 2.5 tones/s). There was no significant difference between performances for the two slower rates. Similar *post hoc* analysis for stimulus duration revealed that the performance for the 80 ms duration was significantly better ($p < 0.01$) than that for the two shorter durations (20 and 40 ms), and that the performance for the 20 ms duration was significantly poorer ($p < 0.01$) than that for the 40 ms duration.

Finally, nine independent-samples t-tests with adjustment for multiple comparisons, one for each combination of the three presentation rates and three stimulus durations, were conducted to examine the effects of listener group. Two of these between-group differences were found to be significant ($p < 0.006$). The OHI group performed worse than the YNH group for the 20 ms durations at the presentation rates of 10, 5, and 2.5 tones/s. None of the other differences were significant.

Why might stimulus duration interact with presentation rate, especially at the highest presentation rates? To answer this question, let us consider the temporal structure of the anisochronous four-tone sequence when the middle two tones are 20 ms in duration [see panels A and B of Fig. 1].

TABLE III. Age and air-conduction hearing thresholds in dB HL reference ANSI (1996) for the test ear for the ten OHI participants in Experiment II. NR indicates no response at audiometric limits.

Sub. No.	Age (Years)	Air conduction hearing thresholds (dB HL)						Test ear
		250 (Hz)	500 (Hz)	1000 (Hz)	2000 (Hz)	4000 (Hz)	8000 (Hz)	
1	79	20	25	55	65	70	80	R
2	70	20	30	40	60	55	60	L
3	87	20	25	40	60	55	60	L
4	80	30	25	10	45	70	60	L
5	69	25	20	20	30	60	70	R
6	81	30	35	35	45	65	75	L
7	67	15	15	20	60	60	70	R
8	68	25	30	25	25	35	80	R
9	82	25	40	45	60	75	NR	R
10	78	35	40	60	70	85	85	L
Mean	76.1	24.5	28.5	31	52.0	63.0	71.1	

Recall that the leading and trailing tones in each anisochronous sequence were each fixed in duration at 100 ms. For the 20 ms tone duration and the fastest presentation rate of 25 tones/s, the ISI was 20 ms. As a result, the middle two tones are within 80 ms of both the end of the leading tone and the beginning of the trailing tone. Thus, both tones likely are subject to forward masking from the 100 ms leading tone and backward masking from the 100 ms trailing tone in each sequence. Kelly and Watson (1986) have demonstrated previously that the presence of a leading tone, trailing tone, or both, degrades temporal order discrimination for the middle tones of tonal sequences. As the rate of presentation is decreased, however, the temporal masking effects from the leading and trailing tones should also decrease. Further, temporal masking of the two middle tones will also decrease as the duration of the middle tones increases, possibly due both to a decrease in temporal masking for tones of longer duration and to the consequent lengthening of the interval between the offset of the leading tone and onset of the trailing tone associated with increases in the duration of the middle tones.

The data for the 40 ms tone duration are consistent with this temporal masking explanation in that performance for this duration only differs significantly from the longer durations at the faster rates of presentation (>5 tones/s). Note, however, that the data for the 20 ms duration are significantly lower than those for other durations at *all* rates of presentation, including the slowest rate studied (2.5 tones/s). At the slowest rate, the time interval between offset of the leading tone and the second tone in the sequence is 380 ms. This same interval exists between the two middle tones and between the end of the third tone and the onset of the trailing tone. This ISI is well beyond one at which temporal masking effects can be expected. For the 20 ms duration, therefore, there is an effect on performance that must be attributable to the short duration itself and not to potential masking effects from the surrounding tones. Since the tones were well above detection threshold, even when taking temporal integration of signal energy into account, the 20 ms tones were clearly audible to all listeners. However, it may be that a duration of 20 ms is insufficient to allow for the development of a clear

pitch percept that is sufficient to enable the listener to distinguish the order of the two middle tones or that the long ISI (e.g., 380 ms at 2.5 tones/s) is too long for retention of that percept through the sequence to enable comparison to subsequent sequences.

For a given short signal duration, temporal masking is known to decrease as the duration of the masker decreases (e.g., Kidd and Feth, 1982), at least for detection thresholds. In order to determine if results of Experiment I could be attributed at least partly to temporal masking, a subsequent experiment was then conducted that involved the use of isochronous tone sequences. Unlike the anisochronous sequences shown in Fig. 1, in these sequences, short-duration middle tones were surrounded by equally short leading and trailing tones, which would reduce the temporal masking of the middle two tones by the leading and trailing tones of the four-tone sequences. The details of Experiment II are described below.

EXPERIMENT II: ISOCHRONOUS TONE SEQUENCE

IV. METHODS

A. Participants

Ten YNH listeners and ten OHI listeners were recruited as listeners for the experiment. All listeners were recruited and tested at Indiana University, Bloomington, and none of them had participated in the first experiment. The YNH listeners were graduate students and included two males and eight females. They ranged in age from 22 to 35 years, and none of them had any history of hearing disorders. All had audiometric thresholds less than 20 dB HL for a range of frequencies from 250 to 8000 Hz. The OHI listeners were recruited from the patient database of the Speech and Hearing Clinic at Indiana University, Bloomington, and included six males and four females, ranging in age from 67 to 87 years ($M=76.1$ yr, $SD=7.0$ yr). All the listeners in the OHI group had mild to profound sensorineural hearing loss in both ears. Their ages and hearing thresholds in the test ear are presented in Table III.

B. Stimuli and procedures

The materials and apparatus used in this experiment were identical to those in Experiment I except that isochronous four-tone sequences were used throughout. The combinations of presentation rate, duration, and ISI parameters outlined previously in Table II now apply to the entire four-tone sequence, rather than to just the middle two tones of the sequence as in the first experiment. Other than this, all aspects of the equipment and procedures for Experiment II were identical to that of the Experiment I.

V. RESULTS AND DISCUSSION

One of the older participants could not complete four of the test conditions (20-20, 20-30, 40-0, and 40-10, where the two values represent tone duration and ISI, respectively) because of the high level of difficulty of these conditions. Note that all these conditions fall under the fastest presentation rates of 25 and 20 tones/s, which were not included in subsequent data analyses (see below). Hence, the analyses described in the following sections included all ten YNH and ten OHI listeners.

Figure 3 provides the mean percent-correct scores for the YNH listeners (top panel) and the OHI listeners (bottom panel). Performance is plotted as a function of duration + ISI (lower x-axis label) or presentation rate (top x-axis label). In general, both groups show substantial increases in performance as rate decreases from 20 to 5 tones/s, and then a slight or no increase in performance with further reductions in presentation rate below 5 tones/s (or a duration + ISI value of 200 ms). As with the anisochronous patterns in the previous experiment, this general pattern holds regardless of tone duration (the parameter for the plots in both panels). Further, for the YNH listeners (top panel), the overall performance level does not vary much with tone duration, whereas it does appear to vary with duration for the OHI listeners (bottom panel).

Only the data for tone durations of 20, 40, and 80 ms and presentation rates of 10, 5, and 2.5 tones/s were selected for subsequent statistical analyses since the rest of the duration values (120, 200, 320, and 400 ms) were only tested at the slowest presentation rates of 5 and 2.5 tones/s). Percent-correct scores were arcsine transformed to stabilize the error variance prior to analysis. Independent-sample t-tests with adjustment for multiple comparisons revealed no significant effects of test ear within the OHI group. Hence, data were combined across each of these variables for both OHI and YNH listeners. The data for all nine stimulus conditions were found to be normally distributed (Kolmogorov–Smirnov Z , $p > 0.01$) for both groups of listeners. As a result, the GLM was used to examine the within-subject effects of presentation rate and tone duration and the between-subject effect of listener group. The main effects of rate of presentation, duration, and group were all found to be significant statistically [$p < 0.01$; $F(2,36)=26.4$, $F(2,36)=8.2$, $F(1,18)=9.0$, respectively]. Among the possible interactions, only the two two-way interactions with group were found to be significant [rate $\times$ group, $F(2,36)=4.1$, $p=0.025$; duration $\times$ group, $F(2,36)=4.7$, $p=0.015$].

FIG. 3. Mean percent-correct performance from Experiment II (isochronous sequences) for YNH listeners (top) and OHI listeners (bottom). The parameter is the duration of the tones comprising the four-tone sequence. The solid gray lines in the bottom panel represent the data for the YNH listeners from the top panel for tone durations of 20 and 40 ms. Standard deviations for each stimulus parameter are shown by using the unconnected symbols at the bottom of the graph.

Based on the results of these analyses, additional follow-up analyses were performed. First, two additional GLM analyses were conducted to examine the effects of presentation rate and stimulus duration within each group separately. For the YNH listeners, presentation rate [$p < 0.01$; $F(2,18)=6.8$] and duration [$p < 0.05$; $F(2,18)=3.8$] both had significant effects on temporal order discrimination. However, subsequent analysis of the estimated marginal means for pairwise comparisons of rate and duration using t-tests with the Bonferroni adjustment for multiple comparisons revealed no significant effects. This is entirely consistent with the visual impression of the data in the top panel of Fig. 3. Note that this figure includes many additional data points not included in the statistical analysis. For these listeners, it appears that the rate alone mediates performance on this temporal order discrimination task with sizable declines in performance when the presentation rate exceeds 10 tones/s. Note that these higher presentation rates (20 and 25 tones/s) were not included in the statistical analyses described here. For the OHI listeners, the analysis revealed

significant ($p < 0.01$) main effects of presentation rate [$F(2, 18) = 20.2$] and duration [$F(2, 18) = 6.8$] and no interaction between these two variables [$F(4, 36) = 0.7$]. Subsequent examination of the estimated marginal means for all pairwise comparisons of presentation rate using t-tests with the Bonferroni adjustment for multiple comparisons revealed that performance for the rate of 10 tones/s was significantly lower ($p < 0.01$) than that of the two slower rates included in this analysis (5 and 2.5 tones/s). Similar *post hoc* analysis for stimulus duration revealed that the performance for 80 ms was significantly better ($p < 0.05$) than that for the 20 ms duration, but not from that for the 40 ms duration. There was no difference between performances for the 20 and 40 ms durations. Thus, the performance of the OHI listeners begins to decrease significantly when either the presentation rate exceeds 5 tones/s or tone duration decreases below 40 ms.

Finally, the effect of listener group on performance was determined by conducting nine independent-sample t-tests with adjustment for multiple comparisons, one for each combination of the three presentation rates and three stimulus durations. Only two of the nine between-group differences were found to be significant ($p < 0.006$). The OHI group performed worse than the YNH group for the 20 ms duration at the two highest presentation rates examined in these analyses (10 and 5 tones/s). There were no significant differences between groups for longer stimulus durations (i.e., 40 and 80 ms) or slower presentation rates (i.e., 2.5 tones/s).

VI. GENERAL DISCUSSION

Some previous studies have reported that females perform worse than males in temporal order judgment tasks (Wittmann and Szegel, 2003), while others (e.g., van Kesteren and Wiersinga-Post, 2007) have reported no effect of gender on these tasks. In both experiments in the present study, the younger group that was dominated by females performed better than the older group of listeners that was more gender balanced. Further, within the older group, independent-sample t-tests with adjustment for multiple comparisons revealed no significant effects of gender. Hence, in the present study, it appears that gender did not have a significant effect on performance.

The results of these two experiments suggest that the mechanisms underlying temporal order discrimination for isochronous tone sequences (Experiment I) differ from those underlying the discrimination of anisochronous tone sequences (Experiment II), especially for YNH listeners. For this group of listeners, presentation rate alone appeared to underlie performance for isochronous sequences, whereas both presentation rate and stimulus duration affected performance for anisochronous sequences. In particular, for the YNH listeners and the anisochronous patterns, performance was worse for stimulus durations less than 80 ms and high presentation rates (> 5 tones/s). As discussed with regard to the results from Experiment I, this combination of conditions could result in substantial forward and backward masking of the brief middle tones by the longer leading and trailing tones of the sequence. When the leading and trailing tones

were equivalent in duration to the middle two tones of the sequence (Experiment I), the forward and backward masking effects were likely reduced and only presentation rate appeared to underlie performance. For the OHI group, however, stimulus duration was an important factor underlying performance in both experiments. These listeners performed worse for the 20 ms tone duration in Experiment I even for large temporal separations between the tones in the sequence, including temporal separations far exceeding those relevant for forward or backward masking (i.e., 380 ms). Even in Experiment II, which minimized the temporal masking of the middle two tones by the leading and trailing tones of the sequence, the OHI listeners showed significant effects of stimulus duration for durations less than 40 ms. Thus, for the OHI listeners, both presentation rate and stimulus duration have an impact on performance in these temporal order discrimination tasks such that performance decreases substantially as rate increases above 5 tones/s and tone duration decreases below 40 ms. These results are different from those reported by Fitzgibbons *et al.* (2006), who found that for uniform three-tone sequences (in which the presentation rate remained the same throughout the entire sequence), only presentation rate seemed to affect performance for both younger and older listeners. Also, the age-related differences observed in that study were obtained for even the slowest presentation rate (2 tones/s) and were not limited to the fastest rates as in the present study. These differences are likely related to the nature of the listeners' tasks in the two experiments; Fitzgibbons *et al.* (2006) used a temporal order recognition paradigm involving labeling, a task with increased processing demands (Fitzgibbons and Gordon-Salant, 1998) when compared to the discrimination task used in the present experiment.

It is possible that some of these age-related differences might be related to differences between the younger and older listeners in learning the task. The present study did not incorporate feedback and training, and it is possible that given sufficient training, the performance of the older adults would have improved. It would be interesting to see if the age-related differences observed in the present study would diminish or disappear with sufficient training.

Figure 4 shows the mean results for the YNH (top) and OHI (bottom) listeners from Experiments I and II for the three shortest tone durations examined (20, 40, and 80 ms). From this figure it is apparent that for both groups, the largest changes in performance from the isochronous to anisochronous tone sequences occurred for the shortest durations (20 and 40 ms) and the fastest presentation rates (> 5 tones/s). Again, this pattern of performance change is generally consistent with an increase in temporal-masking effects from the isochronous to the anisochronous sequences. The duration of the leading and trailing tones (100 ms) in the anisochronous sequences was greater than in the isochronous sequences, especially for the fast presentation rates (> 5 tones/s) and short tone durations (< 80 ms). Since forward masking decreases with decrease in masker (leading/trailing tone) duration (e.g., Kidd and Feth, 1982), one would expect performance to be better for the isochronous (less forward masking) sequences than the anisochronous sequences, espe-

FIG. 4. Mean percent-correct performance from Experiments I and II combined for YNH listeners (top) and OHI listeners (bottom). The parameter is the duration of the middle two tones comprising the anisochronous four-tone sequence and all four tones comprising the isochronous sequence.

cially for this combination of rates (>5 tones/s) and tone durations (<80 ms). As noted, such a pattern is clearly apparent in the data for the YNH listeners in the top panel of Fig. 4. It is somewhat less clear, however, that this is also the case for the data from the OHI listeners in the bottom panel. There is a trend in the same direction, but the two sets of data are not as clearly separated as in the top panel of this figure. Interestingly, Kidd *et al.* (1984) reported that pure-tone forward masking was greater in hearing-impaired listeners, but was also much less dependent on masker duration than in normal-hearing listeners. Thus, if one can extrapolate from forward masking detection experiments to forward masking discrimination experiments, this finding would suggest that the change from anisochronous to isochronous tonal sequences would have a lesser impact on the data from the OHI participants in this study than was observed for the YNH participants.

One of the striking features in the data in Fig. 4 results from a comparison of the performance of the YNH listeners for the anisochronous patterns to that of the OHI listeners for the isochronous patterns. Visualization of this comparison has been facilitated by plotting these two sets of data from

FIG. 5. A comparison of the results from the YNH listeners for the anisochronous tone sequences (filled symbols and dashed lines) to the comparable data from the OHI listeners for the isochronous sequences (unfilled symbols and solid lines). The parameter is the duration of the middle two tones comprising the anisochronous four-tone sequence and all four tones comprising the isochronous sequence.

Fig. 4 together in Fig. 5. If increased temporal masking from the leading and trailing tones of the sequences mediates the difference in performance between the anisochronous and isochronous tone sequences for the YNH listeners, then the comparison in Fig. 5 would indicate that the YNH listener with increased temporal masking might be a reasonable model for the performance of OHI listeners on this task. The use of masking, including temporal masking, as a simulation of the effects of sensorineural hearing loss on a variety of psychoacoustic tasks has been suggested previously (e.g., Humes *et al.*, 1988; Humes and Jesteadt, 1991). However, given the stimulus levels used, the frequencies of the tones, the audiograms of the OHI listeners, and the results of prior studies with simulated hearing loss using simultaneous masking (e.g., Humes and Christopherson, 1991), temporal masking might be more effectively simulating the effects of aging or the combined effects of aging and hearing impairment, rather than the effects of hearing loss alone. That is, audibility differences alone are unlikely to underlie the observed differences in performance between the YNH and OHI listeners. Forward masking has been linked to neural adaptation mechanisms in the auditory nerve (e.g., Smith, 1979) or more central mechanisms of persistence (e.g., Oxenham, 2001). It is also possible that aging results in greater adaptation or persistence, a phenomenon that can be simulated in YNH listeners via forward masking. The mechanisms underlying backward masking appear to be centrally located, and age-related changes have been observed in backward masking paradigms involving the detection of (e.g., Gehr and Sommers, 1999), discrimination (e.g., Raz *et al.*, 1990) and recognition (e.g., Newman and Spitzer, 1983) of auditory stimuli. Further research is required, however, to substantiate the use of some form of temporal masking as a model for age-related decline in auditory performance.

VII. SUMMARY

The following is a summary of the main findings of the study.

- (1) For the YNH listeners, performance for the isochronous sequences was affected primarily by presentation rate, while that for the anisochronous sequences was affected by both rate and stimulus duration.
- (2) For the OHI listeners, both presentation rate and stimulus duration affected performance for both isochronous and anisochronous sequences.
- (3) For both groups of listeners, performance was better for the isochronous sequences, especially for conditions in which short durations were combined with fast presentation rates. This was attributed to an increase in temporal masking (of the two middle tones of the sequence by the leading and trailing tones) for the anisochronous sequences when compared to the isochronous sequences.

ACKNOWLEDGMENTS

This work was funded, in part, by NIA R01 AG08293 awarded to the second author.

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