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Age Effects on Measures of Auditory Duration Discrimination

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This study examined auditory temporal sensitivity in young adult and elderly listeners using psychophysical tasks that measured duration discrimination. Listeners in the experiments were divided into groups of young and elderly subjects with normal hearing sensitivity and with mild-to-moderate sloping sensorineural hearing loss. Temporal thresholds in all tasks were measured with an adaptive forced-choice procedure using tonal stimuli centered at 500 Hz and 4000 Hz. Difference limens for duration were measured for tone bursts (250 msec reference duration) and for silent intervals between tone bursts (250 msec and 6.4 msec reference durations). Results showed that the elderly listeners exhibited diminished duration discrimination for both tones and silent intervals when the reference duration was 250 msec. Hearing loss did not affect these results. Discrimination of the brief temporal gap (6.4 msec) was influenced by age and hearing loss, but these effects were not consistent across all listeners. Effects of stimulus frequency were not evident for most of the duration discrimination conditions.

KEY WORDS: duration discrimination, aging, hearing loss, temporal processing

This paper reports results of psychoacoustic discrimination experiments that were conducted to examine the ability of elderly listeners to process durational aspects of simple sounds. The study was motivated in part by reports on aging and audition that suggest a need for better understanding of the temporal processing capacities of the aging auditory system (Marshall, 1981; Olsho, Harkins, & Lenhardt, 1985).

Evidence from some listening experiments indicates that temporal processing may be abnormal in some elderly persons. For example, age-related deficits in the speed of perceptual processing are suggested from results of various backward recognition masking experiments (Newman & Spitzer, 1983; Raz, Millman, & Moberg, 1990). Additionally, the discrimination of temporal order for sequential patterns of brief sounds is observed to be difficult for older listeners (Humes & Christopherson, 1991; Trainor & Trehub, 1989). By contrast, recent psychophysical measures of auditory temporal resolution that derive from listeners' detection of amplitude modulation in noise signals (Takahashi & Bacon, 1992) or the detection of brief temporal gaps in noise (Lutman, 1991) or tonal signals (Moore, Peters, & Glasberg, 1992) do not show systematic age-related deficits in temporal processing. Differences among these various studies regarding age effects might be attributed to varying task demands and the nature of the processing required on the part of the listeners.

The present investigation is concerned with another aspect of temporal processing that relates to the ability of elderly listeners to perceive changes in the duration of sounds. The perceptual coding of signal duration is generally believed to occur within the central auditory system (Abel,1972a; Creelman, 1962; Divenyi & Danner, 1977), which many believe to be the predominant locus of age-related dysfunction and slowed auditory processing (e.g., Salthouse, 1985). The duration discrimination task typically requires a listener to distinguish incremental changes in the duration of some reference stimulus, such as a noise or tone burst, or a silent interval bounded by various acoustic markers. Collective results from previous studies reveal that the

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difference limen (DL) for duration increases monotonically as a function of the reference duration, with relatively little effect of stimulus type over a broad range of reference values exceeding 10–20 msec. For shorter reference intervals (below 10 msec) the effects of stimulus parameters and sensory processing limitations appear to exert stronger influences on the duration DL (Abel, 1972a; Divenyi & Danner, 1977; Penner, 1976; Small & Campbell, 1962). Some of the findings also indicate that reference stimuli defined by silent intervals are more difficult to discriminate than noise or tone burst references of equivalent duration (Abel, 1972a).

Age effects in duration discrimination have not been studied extensively. Abel, Krever, and Alberti (1990) evaluated duration discrimination as a function of age using one-third octave noise signals centered at 500 Hz and 4000 Hz, with reference durations of 20 msec and 200 msec. Listeners in the study included younger subjects (age 20–35 years) with normal hearing and three groups of older listeners (age 40–60 years) defined by differing degrees of hearing loss. Despite their relatively young age, the older subjects in this study exhibited significantly poorer discrimination performance than the younger listeners for the 20 msec reference duration. Mean performance of the older subjects was also poorer than that of the younger subjects with the 200 msec signal, but wide subject variability across groups precluded determination of significant age effects. No effects of hearing loss or degree of loss were evident in the discrimination data. An earlier study by Ruhm, Mencke, Milburn, Cooper, and Rose (1966) also reported that the difference limens for tonal durations were relatively normal in listeners of unspecified age with noise-induced hearing loss. By contrast, a later study by Tyler, Summerfield, Wood, and Fernandes (1982) reported significant effects of hearing loss on duration discrimination for filtered noises and reference durations similar to those employed by Abel et al. (1990). The extent to which listener age influenced results in the Tyler et al. study is uncertain, because this variable was not controlled among their subjects with hearing loss.

One purpose of the present study was to examine the independent and interactive effects of age and hearing loss on measures of duration discrimination. Toward this goal, performance was compared for four groups of listeners who were matched according to age and degree of hearing loss. Discrimination was measured using tonal stimuli at 500 Hz and 4000 Hz, in order to compare performance across frequency regions that coincided with minimal and maximal sensitivity loss in the listeners with hearing impairment. Additionally, these tonal signals were selected to examine a frequency effect reported by Abel et al. (1990), in which duration DLs for the listeners with normal hearing were significantly smaller for the one-third octave noise bands centered at 4000 Hz, relative to those centered at 500 Hz. The frequency effect observed by Abel et al. might have been attributed to differences in absolute noise bandwidths that could render the narrower band at 500 Hz a less efficient marker of stimulus duration. Similar effects of stimulus bandwidth have been observed to influence measures of temporal gap detection with filtered noise signals (Grose, Eddins, & Hall, 1989; Moore & Glasberg, 1988).

A second purpose of the experiments was to compare the performance of elderly listeners in several different discrimination conditions. In one set of discrimination tasks, duration DLs were compared for tone bursts (tone DL) and silent intervals between tone bursts (gap DL), using a 250 msec reference duration in each condition. For these conditions discrimination performance is presumed to be governed by central auditory processes, with relatively little influence of peripheral factors (e.g., hearing loss) or parameters of the stimulus. In other experimental conditions, gap DLs were measured using a brief reference interval (6.4 msec) between tone bursts in order to examine a temporal region where sensory processing and stimulus factors are thought to influence discrimination performance. For example, earlier results for gap DLs (Abel, 1972a; Penner, 1976) are consistent with the idea that listeners discriminate the duration of brief temporal intervals by comparing the amounts of decay in sensation occurring within reference and comparison gap intervals. The discrimination of brief temporal gaps is also observed to vary with the degree of spectral similarity between acoustic markers bordering the gap (Divenyi & Danner, 1977; Divenyi & Sachs, 1978). In the present experiments, age-related effects on gap DLs for the short reference interval are measured for two stimulus arrangements. In one of these, the tonal markers bordering the gap were the same in frequency (500 Hz or 4000 Hz). In the other condition, tones bordering the gap differed in frequency by approximately one-third octave about center frequencies near 500 Hz and 4000 Hz.

Methods

Subjects

Listeners in the experiments included 40 subjects assigned to four groups with 10 subjects each defined according to age and hearing status. Group 1 included elderly listeners (65–76 years) with normal hearing (pure tone thresholds ± 15 dB HL, re: ANSI, 1989, 250–4000 Hz). Group 2 consisted of young listeners (20–40 years) with normal hearing (pure tone thresholds ± 15 dB HL, re: ANSI, 1989, 250–4000 Hz). Group 3 consisted of elderly listeners (65–76 years) with mild-to-moderate, sloping sensorineural hearing losses. These subjects had a negative history for otologic disease, noise exposure, familial hearing loss, and ototoxicity. The presumed etiology of hearing loss for these subjects was presbycusis. Group 4 included young subjects (20–40 years) with mild-to-moderate, sloping sensorineural hearing losses. Each subject in Group 4 was matched audiologically to a subject in Group 3. The etiology of the hearing losses of the younger subjects was either heredity or unknown. None of these subjects had noise-induced hearing losses. Audiometric data for the four subject groups are displayed in Table 1. Immittance measures for all subjects showed tympanograms with normal peak pressure (−100–+50 daPa), normal acoustic admittance at the plane of the tympanic membrane (0.3–1.4 mmho), normal equivalent volume (.6–1.5 cm^3), and normal tympanometric widths (50–110 daPa) (American Speech-Language-Hearing Asso-

TABLE 1. Mean pure tone thresholds and standard deviations (in parentheses) in dB HL for the four subject groups.

	Frequency (Hz)				
Group	250	500	1000	2000	4000
YNH	4.0 (3.7)	0.5 (2.7)	2.0 (4.0)	2.0 (3.3)	3.0 (5.6)
YHI	17.5 (16.8)	22.0 (20.0)	28.5 (17.0)	44.5 (15.4)	51.5 (10.7)
ENH	7.5 (4.6)	7.5 (5.6)	7.0 (7.1)	7.0 (4.6)	13.5 (3.2)
EHI	24.0 (9.7)	26.5 (8.0)	29.5 (13.5)	38.0 (8.4)	56.0 (13.9)

Note. YNH = young normal hearing; YHI = young hearing impaired; ENH = elderly normal hearing; EHI = elderly hearing impaired.

ciation, 1990); acoustic reflexes were elicited at levels of 100 dB HL or lower in each ear. These immittance results are consistent with the presence of normal middle-ear function. Additionally, each subject exhibited good general health and passed the Short Portable Mental Status Questionnaire (Pfeiffer, 1975), a screening procedure for cognitive function.

Stimuli

Stimuli for the experiments were individual tone bursts for the tone DL measurements or pairs of tone bursts for the gap DL measurements. The stimuli were digitally constructed, stored, and delivered to listeners using a laboratory computer in conjunction with a 12-bit D/A converter (20 kHz sampling rate) and a low-pass filter (6000 Hz cutoff, 90dB/octave). Each tone burst segment had a total duration of 250 msec, which included a 240 msec steady-state portion and 5 msec cosine squared rise-fall envelopes. For each discrimination task a separate series of stimuli was generated and stored on the computer, with members of a series differing incrementally in the duration of a tone or the duration of a temporal gap between pairs of tones. Duration DLs for tones were measured for tonal frequencies of 500 Hz and 4000 Hz using a reference duration of 250 msec. Duration DLs were also measured for a silent gap of 250 msec that separated pairs of 250 msec tones of the same frequency, 500 Hz or 4000 Hz.

Other gap DL measurements were collected with pairs of 250 msec tones in which, for the reference stimulus pairs, the offset of the leading tone was followed immediately by the onset of the trailing tone. As a consequence of the tonal rise-fall envelopes, listeners perceived these reference pairs as discrete successive sounds with a brief temporal separation. For these tonal pairs the duration of the reference gap was assigned a value of 6.4 msec, which represents the measured interval between 3 dB-down points on the successive rise-fall envelopes at the juncture of the leading and trailing tone segments. Gap DLs for this brief reference interval were measured in conditions where tones within pairs were the same frequency (500 Hz or 4000 Hz) and where tones differed in frequency. For the latter conditions, leading and trailing tones in the reference pairs featured a low-to-high frequency shift of approximately one-third octave (450–560 Hz or 3500–4500 Hz) centered geometrically near 500 Hz and 4000 Hz. These frequency shifts were selected to be perceptually distinct, but not so large as to span regions of markedly different hearing sensitivity in the listeners with hearing loss.

Before collecting data we examined the potential influence of transient spectral cues on the measured gap DLs. The spectral cues in question might arise from the energy splatter associated with the rise-fall envelopes of the tonal signals. For stimuli of the present experiments, spectral cues were not of sufficient magnitude to cause audible clicks. Nevertheless, preliminary testing was conducted by measuring gap DLs for brief reference gaps in quiet and with a broadband background of continuous noise at a S/N ratio (spectrum levels) of 30dB (signal level = 85 dB SPL, overall noise level = 91 dB SPL, noise bandwidth = 4500 Hz). The performance of three young listeners with normal hearing showed little or no change with the noise added, indicating spectral cues had little influence on their discrimination. This result is also consistent with previous findings of Divenyi and Sachs (1978), who demonstrated that gap DLs measured with tonal stimuli (2.5 msec rise-fall envelopes) were essentially the same as those measured with broadband noise (Divenyi & Danner, 1977), even at brief reference intervals where spectral cues with tonal stimuli would be expected to have the greatest effects. On the basis of these examinations, it appears unlikely that spectral cues influenced the discrimination performance of listeners in the present experiments.

Procedures

The measurements of duration DLs were obtained using an adaptive three-interval forced-choice procedure (3IFC). Each listening trial consisted of three observation intervals with an inter-observation interval of 500 msec. Two of these three intervals contained the reference signal for a given condition, and the third randomly selected interval contained the variable target signal. The listening intervals of each trial were marked by a visual display that also provided correct-interval feedback. Subjects responded to the target interval using a three-button response box.

There were eight duration discrimination conditions, defined by the combination of two tone DL conditions and six gap DL conditions, as described in Table 2. In each case the listener responded to the trial interval containing the longest tone burst (tone DL conditions) or the longest silent interval between a pair of tone bursts (gap DL conditions).

The duration DLs were measured using an adaptive rule for varying the stimulus according to the listeners' responses on previous trials. The rule stipulated a decrease in stimulus duration following two consecutive correct response trials and an increase in stimulus duration following each incorrect response. This procedure estimates a threshold value corresponding to 70.7% correct discrimination (Levitt, 1971). Listening trials continued until the changes in the value of the stimulus reversed direction 15 times, using a step size that shifted from 5 msec to 1 msec after the third reversal. Threshold estimates for each run of trials were calculated by

TABLE 2. Eight experimental conditions.

Duration judgment	Reference duration in msec	Stimuli
Tone DL	250	tone burst (500 Hz)
Tone DL	250	tone burst (4000 Hz)
Gap DL	250	tone pair (500/500 Hz)
Gap DL	250	tone pair (4000/4000 Hz)
Gap DL	6.4	tone pair (500/500 Hz)
Gap DL	6.4	tone pair (4000/4000 Hz)
Gap DL	6.4	tone pair (450/560 Hz)
Gap DL	6.4	tone pair (3500/4500 Hz)

taking an average of alternate mid-point stimulus values associated with the final 10 reversals. The number of listening trials needed to track a stable trial-run threshold estimate varied across subjects, but was usually a minimum of 70 to 80 trials. Three of these trial-run threshold estimates were collected from each subject for each of the eight duration discrimination conditions.

Before data collection, subjects received approximately 2 hours of practice in the 3IFC procedure during the course of obtaining absolute thresholds for 250-msec tone bursts of 500 Hz and 4000 Hz. Subjects were also familiarized with the adaptive procedures, stimuli, and task demands in each of the discrimination experiments before testing.

The subjects were tested individually in a sound-attenuating chamber, with the eight conditions presented in a different random order for each listener. The stimuli for all conditions were presented at 85dB SPL, which corresponded to minimum sensation levels of 25–30dB at 4000 Hz for the subjects with high frequency hearing loss. The stimuli were delivered to subjects through an insert earphone (Etymotic ER-3A) calibrated in a 2 cm^3 coupler (B&K,DB 0138). This transducer was selected for listener comfort and to avoid possible collapsing of ear canals in the elderly subjects. Testing was monaural in the better ear of listeners with hearing loss and in the preferred ear of listeners with normal hearing. Non-test ears of the listeners were occluded with an EAR foam plug. The total testing time for each listener was about 10 hours, scheduled in 2-hour sessions at 1-week intervals. Subjects were reimbursed for their participation in the experiments.

Results

Reliability of Threshold Estimates

Initial analysis of the data was directed toward evaluation of the reliability of the data, because extensive training in each of the eight experimental conditions was not feasible with the elderly subjects. To that end, performance of all subjects was compared across the three trial run estimates of threshold for each condition.

The mean duration discrimination thresholds and their standard deviations for the 40 subjects in the eight experimental conditions for each of the three runs are shown in Table 3. Comparisons of mean scores across the three runs

TABLE 3. Duration discrimination scores (in msec) in each of the eight experimental conditions for three trials. Means and standard deviations are for 40 subjects.

	Run 1		Run 2		Run 3	
Condition	*M*	*SD*	*M*	*SD*	*M*	*SD*
Tone DL, 500 Hz 250 msec reference	59.24	24.8	60.12	37.0	51.20	32.4
Tone DL, 4000 Hz 250 msec reference	59.89	35.4	55.32	27.8	52.47	26.7
Gap DL, 500 Hz 250 msec reference	59.80	24.9	53.68	21.7	53.67	19.9
Gap DL, 4000 Hz 250 msec reference	61.08	27.6	67.26	31.4	58.06	24.1
Gap DL, 500 Hz 6.4 msec reference	21.5	13.4	19.66	12.8	17.41	11.2
Gap DL, 4000 Hz 6.4 msec reference	21.14	13.9	20.11	13.2	19.69	13.3
Gap DL, 500 Hz 6.4 msec reference, shifting frequency	25.19	16.5	21.77	14.7	20.75	15.1
Gap DL, 4000 Hz 6.4 msec reference, shifting frequency	27.40	17.2	23.80	16.0	23.42	15.7

TABLE 4. *F* values for trial run effects and interactions in the Gap DL measures with 6.4 msec reference stimulus conditions.

		Task and stimulus conditions			
		Constant frequency		Shifting frequency	
Source	*df*	500 Hz	4000 Hz	500 Hz	4000 Hz
Trial	2,72	4.72	0.89	4.36	7.75*
Age × trial	2,72	3.42	0.34	0.44	4.84
Hearing × trial	2,72	1.23	1.17	0.05	0.13
Age × hearing × trial	2,72	1.48	0.06	0.64	1.40

*p <.01

indicate that average performance does not change systematically across runs. Separate analyses of variance (ANOVA) were conducted for each of the eight experimental conditions using a split-plot factorial design with age and hearing loss as between-subjects factors and trial run as the within-subjects factor. Tables 4 and 5 summarize the ANOVA results for the trial run effect and its interactions. These analyses failed to reveal a significant main effect or interaction of trial run for any of the experimental conditions except for the gap DL (6.4 msec reference) with shifting frequencies centered at 4000 Hz. In this condition, performance was significantly poorer in run 1 than in runs 2 and 3.

The reliability of the threshold estimates was explored further by examining the Pearson product-moment coefficients of correlation across the three runs. Table 6 shows the correlation coefficients between run 1 versus run 2, run 2 versus run 3, and run 1 versus run 3. The vast majority of the correlations ranged from .64 to .89. All of the correlations were significant at the .01 level, indicating that there is a moderate to strong linear relationship between the scores across the three runs.

Because the comparisons of performance across the three runs failed to reveal systematic changes in performance, subsequent analyses of group and condition effects were based on individual scores averaged across the three runs.

Duration Discrimination Performance

Results of the duration discrimination experiments with the 250 msec references for each group of listeners are presented in Figure 1. The figure shows group means of the duration DLs in msec for the tone and gap DL conditions (250 msec reference duration) at 500 Hz and 4000 Hz. An ANOVA was performed on the raw data using a repeated measures design with two between-subjects factors (age and hearing status) and two within-subjects factors (stimulus frequency and task condition). The ANOVA table is summarized in Table 7. Results indicated a significant main effect of listener age as well as a significant interaction between age and signal frequency. Subsequent analysis of simple main effects revealed that the duration DLs of the two groups of elderly subjects were larger at 4000 Hz than at 500 Hz [$F(1,36) = 15.2$, $p < .01$], although there was no frequency effect for the younger subjects [$F(1,36) = 1.27$, $p = .15$]. In addition, simple main effects showed that the duration DLs of the elderly subjects were larger than those of the two groups of younger listeners at both 500 Hz [$F(1,36) = 36.4$, $p < .01$] and 4000 Hz [$F(1,36) = 130$, $p < .01$]. The data analysis (Table 7) failed to show significant effects of hearing loss on duration discrimination nor any significant differences between the tone DLs and gap DLs for any of the subject groups.

Figure 2 presents the mean gap DLs in msec and standard deviations (shown by error bars) of each subject group for the fixed-frequency and shifting-frequency conditions at 500 Hz and 4000 Hz, at the 6.4 msec reference duration. An ANOVA was also performed on these data using the between-subjects factors of age and hearing status, and the within-subjects factors of frequency (500 Hz vs. 4000 Hz) and task condition (fixed frequency vs. shifting frequency). Results

TABLE 5. *F* values for trial run effects and interactions in the Tone and Gap DL measures with 250 msec reference stimulus conditions.

		Task and stimulus conditions			
		Tone DL		Gap DL	
Source	*df*	500 Hz	4000 Hz	500 Hz	4000 Hz
Trial	2,72	2.47	2.05	3.62	3.08
Age × trial	2,72	0.39	0.09	1.37	0.84
Hearing × trial	2,72	1.93	1.15	1.21	0.51
Age × hearing × trial	2,72	0.45	1.02	0.50	1.96

Note. No significant effects at $p < .01$ level.

TABLE 6. Pearson Product Moment correlation coefficients for scores between each pair of three trials. Correlations are for scores of 40 subjects.

Condition	Run 1 vs. Run 2	Run 2 vs. Run 3	Run 1 vs. Run 3
Tone DL, 500 Hz 250 msec reference	.66	.72	.64
Tone DL, 4000 Hz 250 msec reference	.82	.66	.69
Gap DL, 500 Hz 250 msec reference	.76	.80	.64
Gap DL, 4000 Hz 250 msec reference	.51	.68	.75
Gap DL, 500 Hz 6.4 msec reference	.75	.82	.71
Gap DL, 4000 Hz 6.4 msec reference	.89	.87	.84
Gap DL, 500 Hz 6.4 msec reference shifting frequency	.86	.85	.72
Gap DL, 4000 Hz 6.4 msec reference shifting frequeny	.89	.95	.86

Note. All *r*'s are significant at .01 level.

(shown in Table 7) indicated that the frequency region of the signals (500 Hz and 4000 Hz) had no significant influence on gap DLs for any of the conditions. There was, however, a significant main effect of task condition, with gap DLs for

TABLE 7. *F* values for effects of Age, Hearing, Task, and Frequency in Tone and Gap DL conditions with 250 msec and 6.4 msec reference durations.

		Stimulus conditions	
		Tone and Gap DL	
Source	*df*	250 msec ref	6.4 msec ref
Age	1,36	10.49*	2.28
Hrg	1,36	.00	.03
Age × Hrg	1,36	.02	7.77*
Task	1,36	.61	11.07*
Age × Task	1,36	2.82	1.49
Hrg × Task	1,36	3.03	3.09
Age × Hrg × Task	1,36	.57	2.92
Freq	1,36	2.95	3.66
Age × Freq	1,36	14.43*	.18
Hrg × Freq	1,36	2.77	.03
Age × Hrg × Freq	1,36	5.73	.64
Task × Freq	1,36	1.69	.32
Age × Task × Freq	1,36	.10	1.00
Hrg × Task × Freq	1,36	1.37	3.95
Age × Hrg × Task × Freq	1,36	1.13	.49

*$p < .01$

tonal pairs with frequency shifts being larger than those for the fixed-frequency conditions. There was also a significant interaction between age and hearing status. A simple main effects analysis was conducted to explore the source of this interaction effect (Kirk, 1968). The results of the simple main effects analysis revealed a significant age effect for subjects with normal hearing [$F(1,36) = 9.2$, $p < .01$] but not for subjects with hearing loss [$F(1,36) = .82$, $p > .37$]. That is, gap DLs of the elderly listeners with normal hearing were

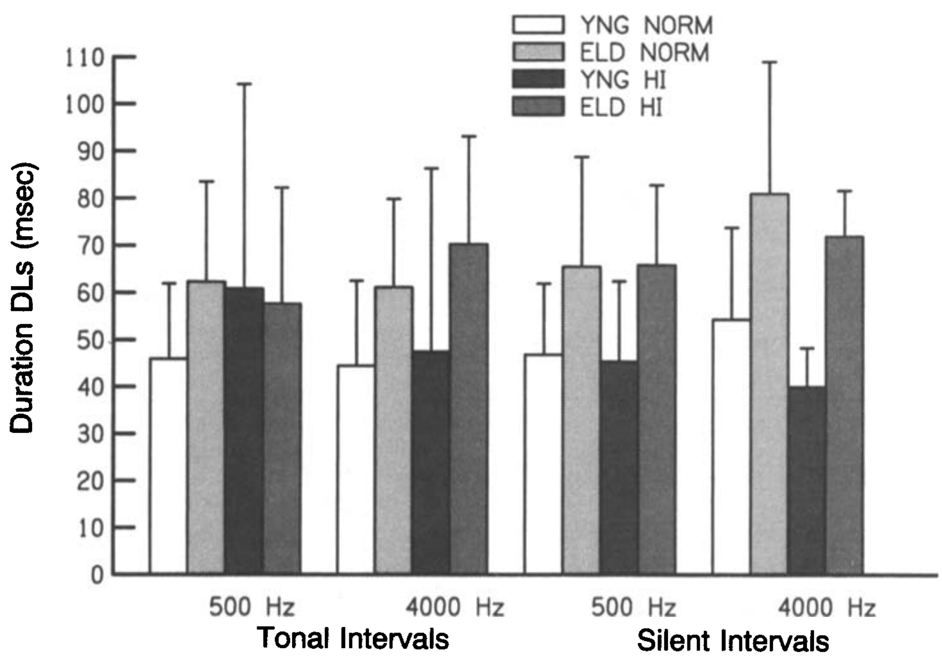

FIGURE 1. Mean duration discrimination performance of the four subject groups for tonal and silent-interval signals at the 250 msec reference duration in two frequency regions. Error bars represent one standard deviation.

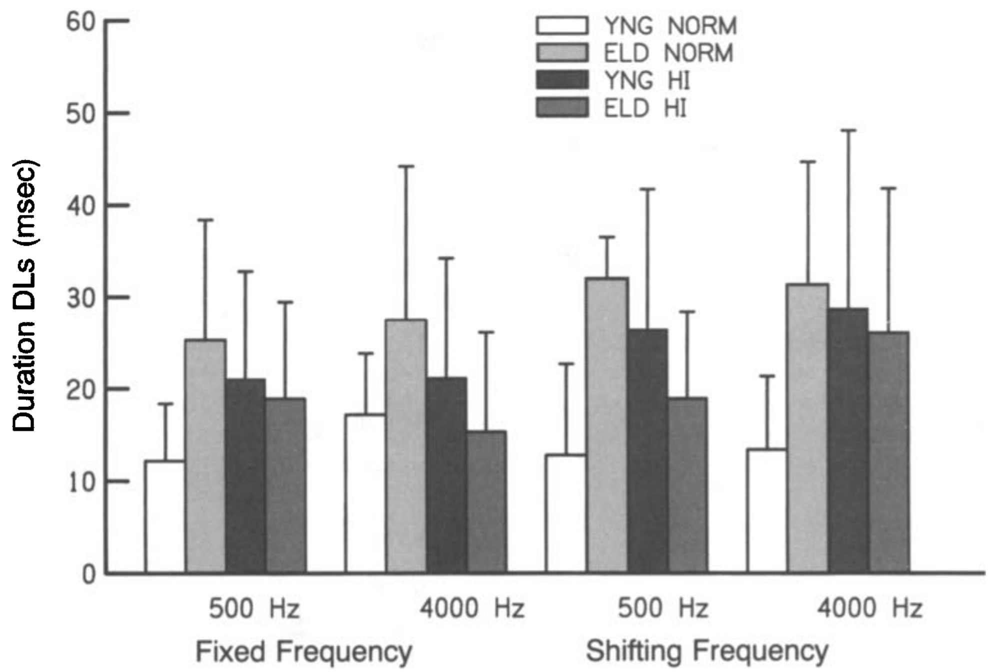

FIGURE 2. Mean duration discrimination performance of the four subject groups for silent-interval signals, with the 6.4 msec reference duration in two frequency regions. The left half of the figure shows results for fixed frequency signals surrounding the gap, and the right half of the figure shows results for changing frequency signals surrounding the gap. Error bars represent one standard deviation.

significantly larger than those of the young subjects with normal hearing. Although performance differences between the young and elderly subjects with hearing loss were apparent, these differences failed to reach statistical significance at the $\alpha = .01$ level of significance.

Discussion

Results of the discrimination testing revealed performance differences between subject groups that differed primarily by age of the listeners. The discrimination abilities of individual listeners within groups varied considerably, but with a few exceptions performance variability was relatively uniform across the four subject groups. Observations of individual differences in duration discrimination are not uncommon and are apparent in results of studies that examined both larger groups of minimally trained listeners (Abel et al., 1990; Tyler et al., 1982) and smaller numbers of extensively trained listeners (Divenyi & Sachs, 1978).

Performance of Listeners With Normal Hearing

The average tone and gap DLs of the young subjects with normal hearing in the present study was 48 msec for the 250 msec reference condition, yielding a Weber fraction (DL/reference duration) of .19. These data compare closely with other data collected from more experienced listeners. For example, the Weber fraction reported in several studies for tone and noise bursts (Creelman, 1962; Small & Campbell, 1962) or silent gaps (Abel, 1972a) converge on a value of about .2 for reference durations exceeding 40 msec. Results for the young subjects in the current study also agree with these previous reports showing no effects of stimulus frequency nor effects of filled versus unfilled reference intervals for the 250 msec reference duration. The latter finding, however, differs from that of Abel (1972b), who observed significant differences between DLs for temporal gaps and noise bursts of equivalent duration.

Fewer data are available for comparison of the gap DLs measured with the brief 6.4 msec reference duration. Earlier experiments by Abel (1972a) and Penner (1976) revealed that for brief reference intervals (<10 msec) gap DLs changed rapidly and nonmonotonically with changes in the reference duration. Abel reported gap discrimination data for two trained listeners using 300 msec broadband noise markers; Weber fractions of .64 and 1.91 were revealed for reference gaps of 5 msec and 10 msec, respectively. In the present experiment, the average data at 500 Hz and 4000 Hz of the young subjects with normal hearing produced a Weber fraction of 2.2 for the 6.4 msec reference interval. Exact comparisons of the data are complicated by differences in the reference gap intervals. If, for example, the reference gap in the present study was defined by its maximum width of 10 msec, rather than the 3-dB width of 6.4 msec, then the Weber fraction value would be 1.47. Either calculation suggests that there is reasonable agreement between the present results and those of Abel (1972a).

The gap DLs measured with the brief reference gap were essentially the same for fixed frequency tonal pairs centered at 500 Hz and 4000 Hz. However, stimulus pairs consisting of tonal markers of different frequencies produced larger gap

DLs compared to those measured for the fixed frequency markers. This result is consistent with observations by Divenyi and Danner (1977) and Divenyi and Sachs (1978), who found that gap DLs for brief reference gaps (>50 msec) increased progressively with increasing frequency differences between tones bordering the gap. These collective data are consistent with the argument (Abel, 1972a; Penner, 1976) that discrimination of brief temporal intervals is probably cued by the same sensory decay processes that are described in Plomp's (1964) model of temporal gap detection. Gap detection results with tonal stimuli (Formby & Forrest, 1991; Moore & Glasberg, 1988; Williams & Perrott, 1972) generally exhibit the same effects of stimulus frequency as those observed in studies of the discrimination of brief temporal gaps.

Hearing Loss Effects

The analysis of results failed to reveal systematic effects of hearing loss on duration discrimination. This conclusion was particularly clear for the discrimination data collected in conditions that used the 250 msec reference signals. For those conditions, the tone DLs and the gap DLs of most of the young listeners with hearing loss were equivalent to those of the young listeners with normal hearing. Two of the young subjects with hearing loss exhibited abnormally large tone DLs at 500 Hz and 4000 Hz, a result that accounts for most of the large performance variability seen in Figure 1 for this subject group. These same two subjects had gap DLs roughly equal to those for our subjects with normal hearing for the corresponding 250 msec reference duration.

Analysis of gap DLs for the 6.4 msec reference condition also failed to reveal a significant main effect of hearing loss. However, for these conditions, the effects of hearing loss were quite varied, especially for conditions with tonal markers of different frequencies. For conditions with fixed frequency markers, gap DLs for most of the young subjects with hearing loss were closer to those of the young listeners with normal hearing than were observed for conditions with tonal markers of different frequencies. None of the data collected from the young subjects with hearing loss revealed an effect of stimulus frequency (500 Hz vs. 4000 Hz) despite the marked differences in hearing sensitivity of these listeners at these two frequency regions.

The absence of systematic effects of hearing loss in the present study is in agreement with previous observations by Abel et al. (1990) and Ruhm et al. (1966). Abel et al. attempted to separate the effects of age and hearing loss by comparing the duration DLs of groups of older listeners with normal hearing and different degrees of sensitivity loss; no group differences were observed. The present results confirm and extend those of Abel et al. with the examination of hearing loss effects in both young and elderly listeners. Tyler et al. (1982) reached a different conclusion: Many of their listeners with hearing loss showed significantly abnormal duration discrimination abilities. However, the subjects with hearing loss in the Tyler et al. study varied widely in age (33–76 years), making it difficult to separate age and hearing loss factors that may have contributed to the poor discrimination performance observed.

Age Effects

The largest group differences that emerged from the analysis of results were related to the performance of the elderly listeners. For 250 msec reference durations, the tone and gap DLs of the elderly listeners with both normal hearing and hearing loss were equivalent and significantly larger than those of the younger listeners. These findings are consistent with some of the data collected by Abel et al. (1990), who reported age effects for discrimination of 20-msec noise bursts, but not 200-msec noise bursts centered at 500 Hz and 4000 Hz. Generally, listeners in the present study exhibited better and less variable discrimination performance than subjects tested by Abel et al. For example, inspection of Figure 4b in Abel et al. indicates average Weber fractions (500 Hz and 4000 Hz) for 200 msec noise bursts of about .38 for older listeners with normal hearing and about .26 for young listeners with normal hearing, compared to .24 and .18 for older and younger listeners with normal hearing in the present study (250 msec reference).

Abel et al. (1990) also reported significant frequency effects in their data of young and older listeners with normal hearing, showing smaller DLs at 4000 Hz compared to 500 Hz. These frequency effects can probably be attributed to differences in the absolute bandwidths of the one-third octave noises centered at 500 Hz and 4000 Hz. This contention is supported by earlier results of Divenyi and Danner (1977), who observed that short-term waveform fluctuations associated with narrowband noise signals influence the ability of listeners to perform duration judgments. The present data also showed an effect of signal frequency but in the opposite direction from that observed by Abel et al. and only for the elderly listeners. However, frequency effects in the present study were not systematic and were evident primarily for the gap DLs (250 msec reference) of the elderly listeners with normal hearing and the tone DLs of some elderly listeners with hearing loss. Effects of tonal frequency were not evident in the data of the young listeners.

The gap DLs measured for the brief 6.4 msec reference interval also revealed age-related deficits, but the effects were less consistent than those observed for the DLs measured with the longer 250 msec reference. For the brief gaps the principal finding was significantly larger gap DLs for the elderly listeners with normal hearing compared to those of the younger listeners with normal hearing. This result suggests a simple effect of age unconfounded by hearing impairment. Differences in the average performance of young and elderly listeners with hearing impairment were less evident primarily as a consequence of the reduced discrimination abilities of several of the younger subjects with hearing loss. However, several of the elderly subjects with hearing loss exhibited relatively normal gap DLs whether tested in frequency regions coinciding with normal or with reduced hearing sensitivity. Thus, age-related deficits for discrimination of these brief temporal gaps are evident in much of the present data, but the effects are not consistent across the elderly subjects tested.

Conclusions

The present study examined the independent effects of hearing loss and age on listeners' ability to discriminate duration changes in simple tonal signals. Age, but not hearing loss, contributed to discrimination deficits observed for the longer of two reference intervals examined in the experiments. Duration discrimination for brief intervals can be influenced by both age and hearing loss, but these effects were inconsistent across listeners. Previous investigators (Abel, 1972a; Creelman, 1962) have postulated that the coding of stimulus duration has a central auditory locus, with peripheral effects primarily operating for brief stimulus durations. The present findings are consistent with these contentions, but the limited number of stimulus conditions do not allow systematic exploration of central and peripheral effects on duration processing. The more consistent age-related deficits observed for the 250 msec tones and gaps suggest that aging probably has a predominant influence on central timing mechanisms. These age-related deficits in duration discrimination need to be examined further using a broader range of simple and complex sounds.

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