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The effect of filtering and inter-digit interval on the recognition of dichotic digits

Anne Strouse Carter, PhD and Richard H. Wilson, PhD
Veteran Affairs Medical Center, Mountain Home, Tennessee; Departments of Surgery and Communicative Disorders, East Tennessee State University, Johnson City, Tennessee

Abstract—The new compact disc from the Department of Veterans Affairs, *Tonal and Speech Materials for Auditory Perceptual Assessment, Disc 2.0 (1998)*, contains two lists of randomly interleaved 1-, 2-, and 3-pair dichotic digits. Two experiments are reported, in which the effects of low-pass filtering and inter-digit interval on dichotic digit recognition were investigated in adult listeners with normal hearing and with mild-to-moderate cochlear hearing loss. Results demonstrated that in the filtered condition, as the low-pass cutoff was increased, there was an increase in recognition performance for 1-, 2-, and 3-pair dichotic digits. When compared to normative data for the materials, findings indicate that the interleaved 1-, 2-, and 3-pair dichotic digit materials were essentially resistant to the effects of hearing loss. There was no significant change in recognition performance as a function of inter-digit interval. The studied 625-ms range of inter-digit intervals studied produced consistent recognition performance with both groups of listeners.

Key words: *aging, auditory perception, compact disc (CD), dichotic listening tests, filtered speech, speech perception, uncertainty.*

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Address all correspondence and requests for reprints to: Anne Strouse Carter, PhD, VA Medical Center, Audiology (126), Mountain Home, TN 37684; email: anne.strouse@med.va.gov; www.va.gov/621quillen/asp

INTRODUCTION

Since the introduction of dichotic digits by Broadbent (1) and the subsequent refinement by Kimura (2) and Bryden (3), tests of dichotic listening have proven effective in the evaluation of central auditory processing in both children and adults (4–6). Clinical application of such tests is based largely on the observation that recognition performance is better for materials presented to the right ear than it is for materials presented to the left ear (for a review see Hugdahl [7]).

In the evaluation of older adults, dichotic digit materials are ideal for use because digits: 1) are relatively immune to the effects of cochlear hearing loss (8–11), and 2) have demonstrated high inter-test reliability for both young and elderly adult listeners (10,12,13). Moreover, the digit stimuli generally are familiar to most listeners.

The new compact disc (CD) from the Department of Veterans Affairs, *Tonal and Speech Materials for Auditory Perceptual Assessment, Disc 2.0 (14)*, contains two lists of randomly interleaved 1-, 2-, and 3-pair digits in a free-recall paradigm. The tracks consist of 108 items divided into 2 lists of 54 stimulus sets (18 each of the 1-, 2-, and 3-pair digit sets). The inter-digit interval for the 2-pair and 3-pair digits is 500 ms, with an inter-stimulus interval of 500 ms for the 1-pair and 600 ms for the 2- and 3-pair digits. Using this free-recall paradigm, data from our laboratory, including normative data, on young and elderly listeners with hearing impairment demonstrate that as the complexity of the task increases from easy (1-pair) to difficult (3-pair), recognition performance decreases systematically (10,15).

This study contains two experiments in which the effects that low-pass filtering and inter-digit interval have on dichotic digit recognition were investigated. Previous studies using subjects with varying degrees of hearing loss suggest that the recognition of dichotic digit materials is not appreciatively affected by mild-to-moderate cochlear hearing loss (8–10,16). The effect of hearing loss on the intelligibility of speech signals is multi-faceted, including audibility, distortion, and filtering issues. Low-pass filtering emulates the restricted listening bandwidth imposed by cochlear hearing loss and offers a controlled, systematic method through which the effects on dichotic digit recognition of this aspect of hearing loss may be studied.

In Experiment 1, the digit materials were low pass filtered at five cutoff frequencies between 500 and 2000 Hz. These cutoff frequencies mimic the range of pure-tone threshold configurations commonly observed clinically and produce listening conditions that range from easy (2000-Hz cutoff) to difficult (500-Hz cutoff). Experiment 2 was conducted to examine the effect that inter-digit interval (IDI) has on dichotic digit recognition. The early Kimura studies (2) used 3-pair dichotic digits with inter-digit intervals that approximated 500 ms. Most reports on dichotic digit recognition have been based on the Kimura 3-pair materials and/or the subsequently reported 2-pair digit materials that also had a 500-ms IDI (8). Although 500 ms has been the standard inter-digit interval for the majority of multi-pair dichotic digit studies, substantiation that the 500-ms IDI produces optimum performance is lacking. To examine the effect that the inter-digit interval has on dichotic digit recognition, Experiment 2 evaluated recognition performance on four inter-digit intervals ranging from 125 to 750 ms.

METHOD

Materials

The preparation of the stimulus materials is detailed in an earlier paper (10). Briefly, the digital waveform files (1, 2, 3, 4, 5, 6, 8, 9, and 10, spoken by a male) used on the *Tonal and Speech Materials for Auditory Perceptual Assessment, Disc 1.0 (17)* were edited so that the onset of the stimulus coincided with the start of the data file. A silent interval was added to the end of the file to equalize the file lengths to the longest digit (561 ms). A 500-ms silent interval, which served as the inter-digit interval for the multi-pair digit sets, was added to the end of each 1-pair dichotic digit file. The 2-pair and 3-pair files were made by linking, as required, 2 or 3 of the compiled 1-pair dichotic digit files, with an inter-stimulus interval of 4, 5, and 6 s following the 1-, 2-, and 3-pair stimuli, respectively.

The following two rules were used in the compilation of each multi-pair digit list: 1) no digit was repeated in a stimulus set; and, 2) each of the 72, 1-pair dichotic sets was used once (randomly) in each presentation position. In this manner, a list of 108 items for the free-recall condition was complied that contained 36 stimulus sets from the 1-, 2-, and 3-pair digits. Additionally, a 10-item practice list was compiled. Both lists were recorded on CD (Pinnacle, Model RDC-1000). The 108-item list subsequently was divided into 2 lists of 54 stimulus sets (18 each of the 1-, 2-, and 3-pair digit sets) and recorded as Tracks 7 and 8 on Version 2.0 of the VA CD, *Tonal and Speech Materials for Auditory Perceptual Assessment (14)*. Normative data for these two tracks were described in an earlier paper (11).

Procedures

The dichotic digits were reproduced by a CD player (Sony, Model CDP-497) and fed through an audiometer (Grason-Stadler, Model 10) to TDH-50 earphones encased in P/N 510C017-1 cushions. All stimuli were presented at 70-dB HL (18). The subjects were instructed to recall, in any order, the digit pairs presented to both ears. All of the subjects were practiced on the dichotic listening task before data collection. Practice consisted of 10 presentations of the 1-, 2-, and 3-pair digit stimuli (two 1-pair items, four 2-pair items, four 3-pair items) in a free-recall condition.

Experiment 1.

For the first experiment, the 108 stimulus sets were digitally filtered using low-pass filter cutoffs of 500, 750, 1000, 1500, and 2000 Hz with rejection rates of 48 dB/octave. In addition to the five filtered conditions, an unfiltered condition was used in the protocol. The 108 stimulus sets for each of the 6 conditions were subdivided into 4 lists of 27 items each. The stimulus items were recorded as 24 tracks (6 conditions by 4 lists) on CD along with a calibration tone track. The order of presentation of the 24 lists was randomized for each subject.

Twelve right-handed subjects (2 male, 10 female) ranging in age from 20–29 y (mean age=23.7 y) participated in the experiment. All subjects had normal hearing [20 dB HL (18) at octave intervals from 250–8,000 Hz]. Word recognition was assessed with the Northwestern University Auditory Test No. 6 (N.U. No. 6) taken from the VA CD *Speech Recognition and Identification Materials, Disc 2.0 (19).* Word recognition scores were 80 percent in each ear, and were within 10 percent between ears for each subject.

Experiment 2.

For the second experiment, the inter-digit interval of the 108 stimulus sets was digitally modified. Inter-digit intervals of 125, 250, 500, and 750 ms were included in the protocol for a total of 5 listening conditions. The 108 stimulus sets for each of the conditions were subdivided into 4 lists of 27 items each. The stimulus items were recorded as 16 tracks (4 conditions by 4 lists) on CD (Pinnacle, Model RDC-1000) along with a calibration tone track. The order of presentation of the 16 lists was randomized for each subject.

Ten right-handed subjects (3 male, 7 female) ranging in age from 20–29 y (mean age=24.9 y) with normal hearing [(20 dB HL (18) at octave intervals from 250–8,000 Hz] and 10 right-handed subjects (8 male, 2 female) ranging in age from 60–76 y (mean age=66.6 y) with mild-to-moderate high-frequency cochlear hearing loss participated in the experiment (see **Table 1** for mean thresholds). For both groups, word recognition scores (N.U. No. 6) were 80 percent in each ear, and were within 10 percent between ears for each subject.

RESULTS AND DISCUSSION

The dichotic digit data were scored by presentation position, i.e., each digit in the pair was scored separately. Thus, for the 3-pair digits, there were six possible numbers to be scored as correct or incorrect. For the analysis of the 2- and 3-pair conditions, the data from the presentation positions were averaged for each subject. Before statistical analyses, all percentage scores were transformed into rationalized arcsine units (rau) (20). This had the effect of minimizing the relationship between mean score and variance that is characteristic of percentage scores, while providing a scoring unit that is similar to percentages. The data expressed in rau were used for statistical analysis; however, the figures in the following discussion of results are expressed in percent correct, which corresponds closely to rau.

Experiment 1

Results from 12 young adult subjects (20–29 y) with normal hearing are presented in **Figure 1**. The figure is a plot of the percent correct recognition for the 1-, 2-, and 3-pair digits presented to the right and left ear by presentation position. The data are shown for the unfiltered condition and the five filtered conditions. Statistical analysis using a repeated measures analysis of variance (ANOVA) demonstrated a significant main effect of *stimulus pair* [F (2,22)=22.9; p<.0001], *filter condition* [F (5,55)=160.6 p<.0001], and *ear* [F (1,11)=7.3; p<.05]. The significant finding of stimulus pair is consistent with findings from previous investigations (10,11), indicating that as the complexity of the free-recall listening task increased from easy (1-pair) to difficult (3-pair), there was a corresponding significant decrease in recognition perform-ance.

The unique finding from these data is the significant effect of *filter*. The data in **Figure 1** indicate as the low-pass cutoff was increased from 500 to 2000 Hz, there was

Table 1.
Mean thresholds (dB HL)* and standard deviations for the 10 subjects in the 60-76 years group.

	Frequence (Hz)					
Ear	**250**	**500**	**1000**	**2000**	**4000**	**6000**
Left	19.0	16.5	18.0	26.0	39.0	52.5
	(7.0)	(9.0)	(9.5)	(13.4)	(17.9)	(15.5)
Right	19.0	15.5	20.5	25.5	41.0	56.3
	(4.4)	(6.1)	(11.7)	(12.9)	(17.1)	(24.6)

* ANSI, 1996.

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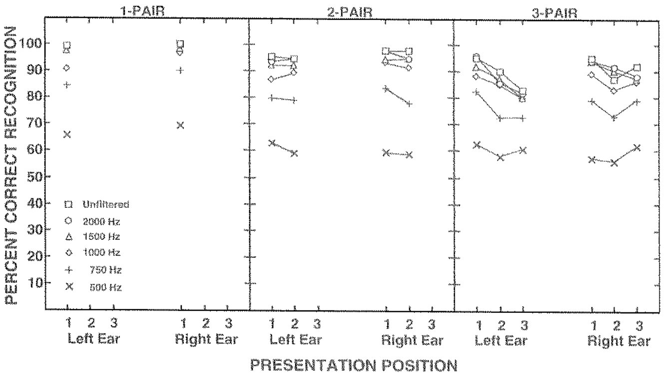

Figure 1.
The percent correct recognition for the 1-, 2-, and 3-pair filtered digits presented to the right ear and to the left ear by presentation position for the 12 listeners with normal hearing in Experiment 1.

a corresponding increase in recognition performance for 1-, 2-, and 3-pair dichotic digit materials. Percent correct recognition scores, fell below the range of normal (11) for only the 750 Hz and 500 Hz conditions. This result is encouraging because filtering at 500 Hz and 750 Hz mimics a substantial hearing loss. In the remaining conditions, the effects of filtering were small and did not significantly affect performance. For example, with the 1-pair digits, performance was near 100 percent for the left and right ears in the 2000-Hz filtered condition and was reduced to 65 percent and 69 percent for the left and right ears, respectively, in the 500 Hz filtered condition (**Figure 1**). The same pattern is evident for 2-pair and 3-pair digits.

To examine further the effect of filter, the data in **Figure 1** were averaged across presentation position and are depicted in the upper two panels of **Figure 2** as a function of the filter cutoff frequency. For reference, recognition data from the unfiltered condition are shown as the right-most data points. Also included within the upper two panels of the figure are similar data from filtered monosyllabic words presented monaurally (21). When viewed in this manner, the effect of increased filtering is evident, especially with 500-Hz and 750-Hz cutoffs. Comparison of the digit data and monosyllabic word data indicate that the effects of low-pass filtering were more pronounced on monosyllabic words than on digit materials. This finding is consistent with previous reports that dichotic digits are more resistant to the effects of cochlear hearing loss as compared to nonsense syllables and dichotic words (9).

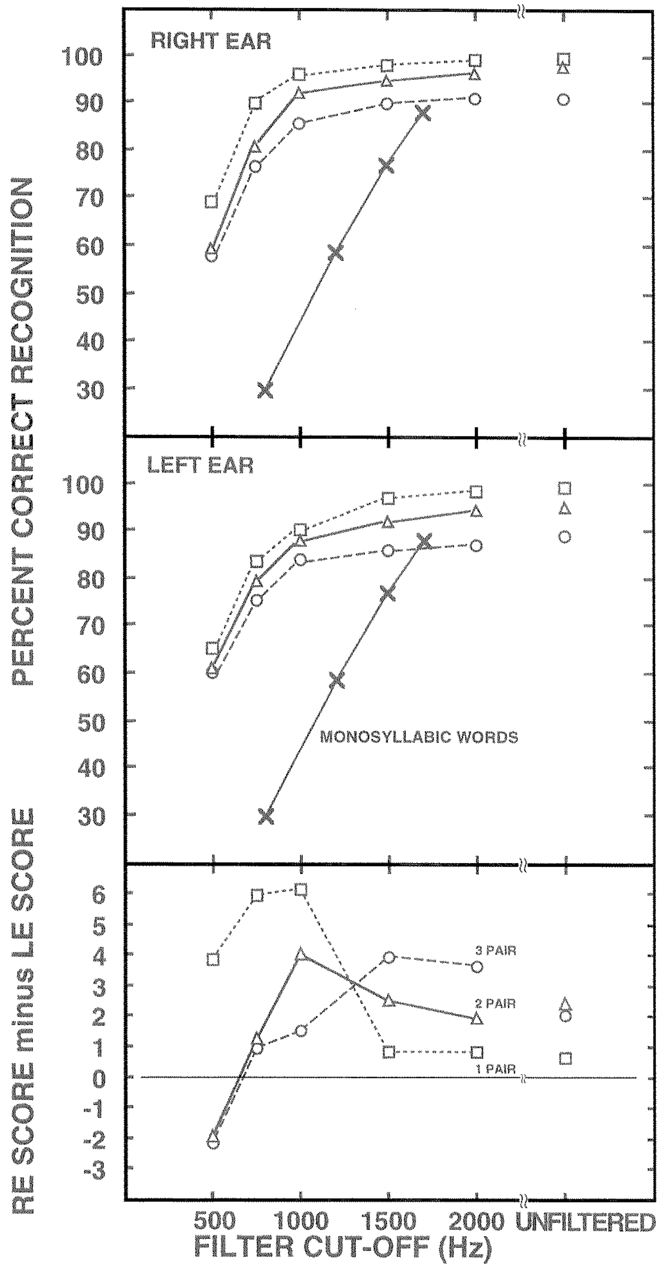

Figure 2.
Upper and middle panels: The mean percent correct recognition for 1-pair (squares), 2-pair (triangles), and 3-pair (circles) dichotic digits as a function of filter cutoff (Hz) for the 12 listeners in Experiment 2. Mean percent correct performance for monosyllabic words (N.U. No. 6) (crossed line) is added for comparison (21). Lower panel: Plot of the difference between the percent correct recognition for the right ear minus the percent correct recognition for the left ear as a function of the filter cutoff frequency.

Previous work using monosyllabic words indicated decreased performance when simulating hearing loss with low-pass filter cutoffs as high as 2,000 Hz (22). The difference between performance on non-digit, monosyllabic words and digits is attributable, in part, to the use of an open, as compared to a closed, response set. The comprehension of digit material is easier than the comprehension of words because the listener has a very limited response choice with digits, whereas the response choices with non-digit, monosyllabic words are substantially broader (23).

The lower panel of **Figure 2** is a plot of the difference between the percent correct recognition for the right ear (upper panel) minus the percent correct recognition for the left ear (middle panel) as a function of the filter cutoff frequency. Data points plotted above the zero line indicate a right-ear advantage, whereas data points falling below the zero line indicate a left-ear advantage. As seen in the figure, there was a right-ear advantage in all conditions with the exception of the 500-Hz filtered condition for 2-pair and 3-pair digits. This small, but significant overall right-ear effect is consistent with findings from previous investigations using the same dichotic digit paradigm (10,11).

For the 500-Hz condition, one may speculate that the small left-ear advantage found for the 2-pair and 3-pair digits may be due to the increased difficulty of the task. Given the closed-set nature of the task and the reduced intelligibility of the materials as a result of the extent of the filtering at 500 Hz, it is possible that the subjects performed near chance. They were encouraged to guess if not sure of the correct response but they were not forced to respond to all stimuli. If the responses for the 1-pair digits were based strictly on chance performance, then the likelihood of correctly guessing 2 of the 9 possible digits would be 22 percent. The subjects performed well above chance for 1-pair digits (65.5 percent and 69.4 percent, for the left and right ears, respectively). In the 2-pair condition, the chance of correctly guessing 4 of the 9 digits would be 44 percent. The percent-correct recognition in the 2-pair condition was 61 percent and 59 percent, in the left and right ears, respectively, which again is above chance performance. For the 3-pair digits, chance performance is 67 percent. The percent-correct recognition for the 3-pair condition was 60 percent and 58 percent, in the left and right ears, respectively, indicating that the subjects performed below chance.

Figure 3 shows the percent of responses per presentation as a function of filter cutoff frequency. The data indicate that in the 3-pair condition with the 500-Hz cutoff, the subjects actually responded (correctly and incorrectly) to only 70.6 percent of the digits presented, which would reduce chance performance to 47 percent [$(6\times0.706)\div9$]. A similar pattern was observed at 500 Hz for the 1-pair and 2-pair digits with 88 percent and 77 percent responses, respectively. When viewed from this perspective, all correct responses in Experiment 1 were above chance performance. The data in **Figure 3** also show that as the task increased in difficulty from 1-pair to 3-pair digits, the percentage of responses decreased for all filter cutoff frequencies. With the 1,000-, 1,500-, and 2,000-Hz cutoffs, the percentages of responses were similar (in the 88–99 percent range) for 1-pair, 2-pair, and 3-pair digits, and decreased with the 750- and 500-Hz cutoffs. Thus, as the difficulty of the task increased, either by decreasing the filter cutoff frequency or by increasing the number of digit pairs, the number of responses decreased. These patterns suggest that as the response task increased in difficulty, the subjects became more conservative in their responses.

There is a final relation of interest in the data displayed in **Figure 2**. The data in the upper two panels indicate that for the 500-Hz filtered condition, there was little difference in the mean percent correct performance between the 2- and 3-pair dichotic digits. For example, in the right ear, the mean percent correct recognition was 59.3 percent for 2-pair digits and 58.2 percent for 3-pair digits. Based on previous findings—namely, that recognition performance decreases substantially with increased

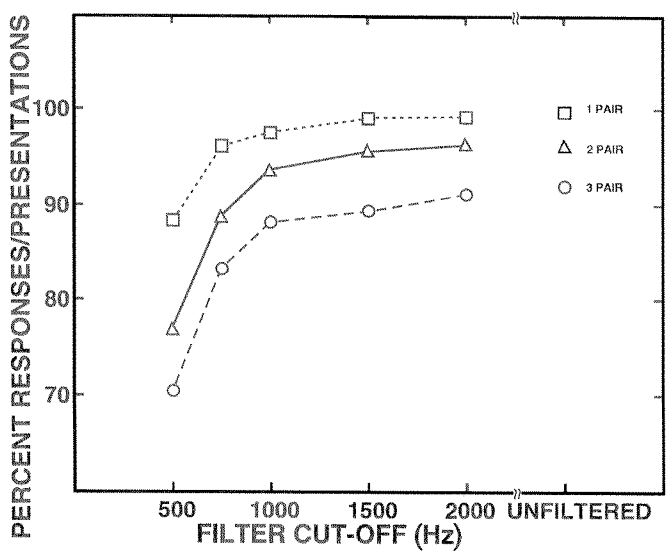

Figure 3.
The percent of subject responses per presentation as a function of filter cutoff for 1-pair (squares), 2-pair (triangles), and 3-pair (circles) dichotic digits.

task difficulty (10,11,15)—it follows that recognition performance for the 3-pair condition should be poorer than recognition performance for the 2-pair condition. In the 500-Hz filtered condition, it is likely that the increased difficulty of the 3-pair as compared to the 2-pair task is offset by chance performance. That is, overall recognition performance is the result of an interaction between difficulty of the task and chance performance. Recall in the 2-pair condition that the chance of correctly guessing 4 of the 9 digits is 44 percent, whereas for the 3-pair digits chance performance is 67 percent. Consequently, although recognition performance for 3-pair digits is typically poorer than recognition performance for 2-pair digits, the chance of correctly guessing the digits presented is increased for the 3-pair digits, resulting in similar performance for 2- and 3-pair digits in the 500-Hz condition.

Experiment 2

Results from 10 young adult subjects with normal hearing and 10 elderly subjects with mild-to-moderate cochlear hearing loss are presented in the two panels of **Figure 4**. The figure is a plot of mean percent correct recognition for the 1-, 2-, and 3-pair digits as a function of inter-digit interval. The data are displayed separately for the right and left ears. For the dependent variable (percent correct recognition), the influence of 1) age group; 2) inter-digit interval; 3) stimulus pair; 4) ear; and, 5) interactions of these factors, was assessed using a mixed-model ANOVA with *interval, stimulus pair,* and *ear* as within-subjects factors and age group as the between-subjects factor. The results indicated that the main effects of *stimulus pair* [F (2,36)=93.9; p<.0001] and ear [F (1,18)=33.1; p<.0001] were significant, whereas the main effect of *interval* [F (3,54)=2.5; p>.05] did not reach statistical significance. The main effect of *age group* was significant [F (1,18)=29.6; p<.0001].

To examine the effects of hearing loss, the four-frequency pure-tone averages (500, 1000, 2000, and 4000 Hz) for the right and left ears were used as covariates in separate analyses of covariance (ANCOVA) that examined the same variables. The results of the ANCOVA using the four-frequency [F (1,16)=5.6; p<.05] pure-tone average were not different than the ANOVA results, indicating that the differences in performance between groups could not be contributed solely to differences in hearing sensitivity. Thus, as previous research has demonstrated, the digit materials were not appreciatively affected by mild-to-moderate cochlear hearing loss (9,11,16,24).

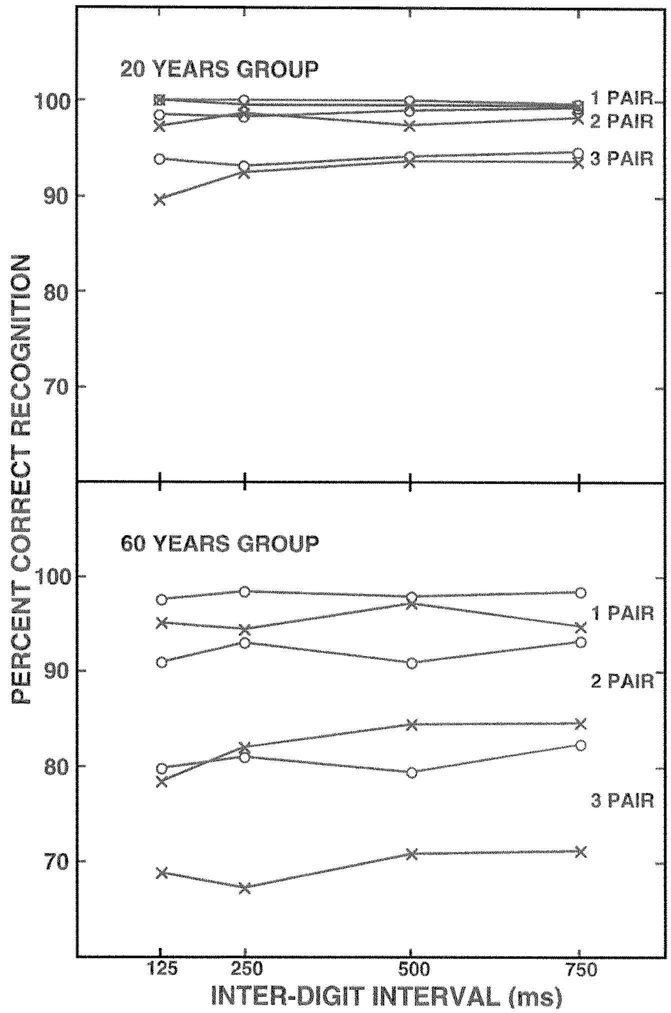

Figure 4.
The mean percent correct recognition for 1-, 2, and 3-pair dichotic digits as a function of inter-digit interval (ms) for the 20 y group (upper panel) and the 60 y group (lower panel).

The significant findings of *stimulus pair* and *ear* are consistent with findings from previous investigations (10,11,15), indicating a decrease in recognition performance with increased task difficulty and a right-ear advantage for digit materials presented dichotically. Likewise, the significant group difference and the mean percent correct results for both groups are in good agreement with previous investigations using 1-, 2-, and 3-pair digits in a free recall format (2,25,26) and with normative data for the same materials detailed in an earlier paper (11).

The unique finding from the data in Experiment 2 is the nonsignificant effect of inter-digit interval. The results of the ANOVA and the data in **Figure 4** demonstrate that there is little change in recognition performance as a function of inter-digit interval. The studied 625-ms range of inter-digit intervals produced consistent recognition performance with both groups of listeners. Neither the rapidity of the 125-ms inter-digit interval or the slowness of the 750-ms inter-digit interval was sufficient to degrade recognition performance.

CONCLUSION

The data from this study, in which the effects that low-pass filtering and inter-digit interval have on dichotic digit recognition, were investigated using a hierarchy of interleaved 1-, 2-, and 3-pair dichotic digits, indicated the following:

1. For filtered dichotic digits, as the low-pass cutoff increased from 500 to 2000 Hz, there was a corresponding increase in recognition performance for 1-, 2-, and 3-pair dichotic digit materials. Based on normative data for the materials, percent correct recognition scores were below normal for only the 750-Hz and 500-Hz conditions, indicating that the dichotic digit materials were essentially resistant to the effects of hearing loss.

2. There was little change in recognition performance as a function of inter-digit interval. The studied 625-ms range of inter-digit intervals studied produced consistent recognition performance with both groups of listeners, indicating that the standard 500-ms inter-digit interval is sufficient for clinical use.

From these data we propose that the randomly interleaved 1-, 2-, and 3-pair digits included on the *Tonal and Speech Materials for Auditory Perceptual Assessment, Disc 2.0* (14) are a useful tool for evaluating dichotic digit performance in adult listeners with normal hearing sensitivity and with mild-to-moderate cochlear hearing loss.

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