Auditory measures of selective and divided attention in young and older adults using single-talker competition

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In this study, two experiments were conducted on auditory selective and divided attention in which the listening task involved the identification of words in sentences spoken by one talker while a second talker produced a very similar competing sentence. Ten young normal-hearing (YNH) and 13 elderly hearing-impaired (EHI) listeners participated in each experiment. The type of attention cue used was the main difference between experiments. Across both experiments, several consistent trends were observed. First, in eight of the nine divided-attention tasks across both experiments, the EHI subjects performed significantly worse than the YNH subjects. By comparison, significant differences in performance between age groups were only observed on three of the nine selective-attention tasks. Finally, there were consistent individual differences in performance across both experiments. Correlational analyses performed on the data from the 13 older adults suggested that the individual differences in performance were associated with individual differences in memory (digit span). Among the elderly, differences in age or differences in hearing loss did not contribute to the individual differences observed in either experiment. © 2006 Acoustical Society of America. [DOI: 10.1121/1.2354070]

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I. INTRODUCTION

A common complaint of older adults is that they can hear speech, but cannot understand it. This is especially true when listening to speech in a background of noise or while other people are talking. A working group of the Committee on Hearing and Bioacoustics and Biomechanics (CHABA) of the National Research Council, reviewing the work on the speech communication problems of older adults available through the early 1980s, offered several hypotheses regarding the causes of such communication problems (CHABA, 1988). Briefly, these hypotheses were (1) the peripheral auditory hypothesis, which suggested that the difficulties were primarily attributable to the sensorineural hearing loss and cochlear pathology that is common among older adults; (2) the central-auditory hypothesis, which posited age-related, modality-specific, changes in the auditory portions of the central nervous system from the lower brainstem through auditory centers of the cortex; and (3) the cognitive hypothesis, which suggested age-related decline in general cognitive functions, such as memory, attention, and speed of processing. The working group also recognized that it was possible to have various combinations of these factors at work in a given individual.

In the years since this CHABA working group report, our laboratory, among others, has demonstrated repeatedly that hearing loss, or audible bandwidth, represents the primary (but not sole) factor underlying the problems experienced by older adults when listening to speech in quiet or in noise (van Rooij, Plomp and Orlebeke, 1989; Jerger, Jerger, and Pirozzolo, 1989; van Rooij and Plomp, 1990, 1992; Helfer and Wilber, 1990; Humes and Roberts, 1990; Humes and Christopherson, 1991; Lee and Humes, 1993; Humes et al., 1994; Souza and Turner, 1994; Humes, 1996; Divenyi and Haupt, 1997a, 1997b; Humes, 2002). Most recently, we found this to be true even for time-compressed speech presented at high sound levels designed to reduce, but not eliminate, the negative impact of high-frequency sensorineural hearing loss (Humes, 2005).

For most older adults with speech-communication problems, the best way to address these problems is through amplification, such as that provided by personal hearing aids. Hearing aids fit to older individuals following typical clinical procedures, however, do not always guarantee the full audibility of speech to the wearer (Humes, 1991; Humes and Halling, 1993). In that regard, it is not surprising that other studies, including another study from our laboratory, examining aided speech communication in quiet and noise in older adults and using hearing aids fit under typical clinical procedures, still found that audibility of the speech stimuli played a primary role in determining individual differences in performance (Humes, 2002; Walden and Walden, 2004).

In more recent work in our laboratory with older adults, we have used laboratory-based approaches to amplification to assure suitable audibility of the speech stimuli through at least 4000 Hz. The first such study in this series (Coughlin, 2004) examined the speech-identification differences between young normal-hearing adults and older hearing-impaired listeners when the Coordinate Response Measure (CRM; Bolia et al., 2000) was used as both the target and competing speech, with separate talkers used for each. The CRM is a sentence-length test that requires the listener to identify the last two words of the sentence from a closed set of alternatives (one of four colors followed by one of eight numbers; e.g., “red 4”, “blue 2”). When audibility through 4000 Hz was assured, hearing loss no longer explained individual differences in speech-identification performance among the 19 older adults in that experiment. Yet, when the
performance of young adults was compared to older adults, the latter still needed about a 6-dB better target-to-competition ratio than the young adults to achieve the same levels of performance under otherwise equivalent conditions. Thus, it would appear that, when audibility has been eliminated as a factor, other factors may emerge that impact differences in performance between younger and older adults or among older adults.

In keeping with the conceptual framework laid out by the CHABA working group (CHABA, 1988), other possibilities could include age-related modality-specific changes in central-auditory processing or amodal cognitive processing. In the CRM speech-identification task used by Coughlin (2004), two similar sentences were presented simultaneously to the same ear and the target message was identified by a name (or “call sign”) at the beginning of the target sentence. Thus, the listeners needed to attend to the target sentence associated with a particular call-sign (“Baron”) and ignore a very similar competing message spoken by a different talker and using a different call sign (e.g., “Charlie,” “Laker,” etc.). As a result, the task required the listener to selectively attend to the target sentence identified by the target call sign. Consequently, it is possible that age-related differences in selective attention could have contributed to the older adults’ need for a better target-to-competition ratio than required by the young adults. Age-related differences in selective attention have been observed previously [see reviews by McDowd and Shaw (2000) and Rogers (2000)], although, for at least some measures of selective attention, these age effects have been attributed to memory deficits or age-related mental slowing (Verhaeghen and De Meersman, 1998a, 1998b) rather than attention deficits per se.

In the present study we sought to examine age-related differences in auditory measures of attention using the same CRM single-talker-competition paradigm used by Coughlin (2004). Auditory measures of both selective and divided attention were included in this study to provide a broader picture of possible age-related changes in attention. Age-related deficits in divided attention have also been reported previously (see the review by McDowd and Shaw, 2000), although general age-related mental slowing may again play a role in such deficits (Verhaeghen et al., 2003).

Another issue examined in this study had to do with the relative strength of various auditory cues in selective and divided attention. In particular, does it matter whether the cue for the auditory measures of attention is one based on localization/lateralization (ear), lexical information (call sign), or acoustical/indexical information in the speech stimulus (talker gender)? In Experiment 1, monaural and dichotic presentation conditions were used to measure auditory selective and divided attention with the cues being either ear or call sign. The match between the gender of the target and competing talkers was also manipulated as a repeated-measures independent variable in this experiment. In general, for young normal-hearing listeners, the CRM speech-identification task is easier when the gender of the target and competing talker differ, presumably due to better segregation of the two auditory objects (Brungart, 2001; Coughlin, 2004). It was hypothesized that those cues associated with physical aspects of the perceived auditory object, such as its location (ear) or fundamental frequency (gender), will prove stronger than the arbitrary lexical labels (call signs) attached to those objects.

In experiment 2, the effect of talker uncertainty on measures of attention was also examined, with the range of conditions varying from the same male and female talkers for a given block of trials to the specific talker randomly selected from a set of four for each gender from trial to trial. Brungart and Simpson (2004) have previously reported little effect of talker uncertainty on the CRM task for young adults, whether the testing was conducted monaurally or dichotically. In other contexts, however, older adults have been found to show larger decrements in performance with increasing talker uncertainty (Sommers, 1997). In addition, Coughlin (2004) demonstrated the effects of talker uncertainty with the CRM test in both young normal-hearing and elderly hearing-impaired adults. As a result, the effects of talker uncertainty were examined further in experiment 2.

Finally, as noted, one of the important procedural aspects of the earlier study by Coughlin (2004) was the use of spectrally shaped speech materials for the older adults with hearing loss. In particular, in that study spectral shaping was applied to ensure audibility of the CRM speech materials through 4000 Hz. By doing so, there was no significant correlation between performance on the CRM and high-frequency hearing thresholds. Steps were taken in this study as well to ensure sufficient audibility of the CRM speech stimulus through at least 4000 Hz for all listeners. Details are provided in the next section.

II. METHODS

A. Participants

Two groups of listeners differing in age and hearing loss were tested: (1) elderly hearing impaired (EHI) and (2) young normal hearing (YNH). There were 10 YNH participants, 5 males and 5 females, for experiment 1 and 2 with 7 of the 10 who participated in experiment 1 also participating in experiment 2. The mean age for the YNH participants in experiment 1 was 25.4 years and ranged from 21 to 34 years whereas the mean age was 25.9 years and ranged from 22 to 34 years for those in experiment 2. All YNH subjects passed a pure-tone air-conduction screening at 20 dB HL (ANSI, 1996) from 250 through 8000 Hz in octave intervals, passed the Mini-Mental Status Exam (a MMSE score of at least 27 of 30; Folstein, Folstein, and McHugh, 1975), and had forward digit spans of at least 5 (i.e., could recall sequences of at least 5 digits) and backward digit spans of at least 4.

There were 13 EHI participants, 9 male and 4 female, and the same 13 completed both experiments in this study. These individuals ranged in age from 61 to 81 years with a mean age of 76.2 years. The EHI listeners had varying degrees of sensorineural hearing loss, as illustrated in Fig. 1. Three EHI listeners had interaural asymmetries in pure-tone thresholds exceeding 15 dB for at least one frequency, but all such asymmetries were at frequencies of 4000 Hz or higher.

All 13 participants passed the MMSE (a score of at least 27) and had forward digit spans of at least 5 and backward digit spans of at least 4.

All EHI subjects were community dwelling at the time of testing. They were paid $10/hour for their participation. The YNH participants were recruited from the general Indiana University (IU) campus community via flyers and the undergraduate and graduate divisions of the IU Department of Speech and Hearing Sciences via e-mail. They were paid $7/h for their participation.

B. Stimuli and apparatus

The Coordinate Response Measure corpus (CRM; Bolia et al., 2000) was chosen as a sentence-level speech test for this project. The structure of each sentence is identical, with each sentence using the form “Ready (call sign), go to (color) (number) now.” By instructing the listener to attend only to the designated call sign while ignoring competing sentences, it is possible to investigate the effectiveness of masking or interference from competing speech signals. The corpus consists of every combination of the eight call signs (arrow, baron, charlie, eagle, hopper, laker, ringo, tiger), four colors (blue, green, red, white) and eight numbers (1–8), resulting in 256 phrases for each talker. Four male and four female talkers yield a total of 2,048 phrases or sentences. Brungart (2001) reported that two talkers, one of each gender, yield scores when used as a target or competing talker that differ somewhat from the remaining talkers. Therefore, in experiment 1, only six talkers (three males and three females) were used. In experiment 2, in which talker uncertainty was manipulated, it was decided that all eight talkers should be used to expand the amount of talker uncertainty available.

Using CoolEdit Pro 2000 (Syntrillium, version 1.2a), the CRM sentences were converted from binary files (*.bin) to wave files (*.wav) and from stereo to mono recordings for use in a custom MATLAB (Mathworks, version 6.5) program. The MATLAB program was designed to present two stimuli simultaneously through Tucker Davis Technologies (TDT) System-III equipment. The sampling rate was 48 828 Hz. The stimuli were either added digitally and routed through one channel of a 16-bit digital-to-analog converter (DA1) for monaural presentation or presented separately through channel 1 (target) and 2 (competition) of the DA1 for dichotic presentation. The stimuli were then sent to a headphone buffer (TDT HB7) and finally output via matched insert earphones (E-A-R, ER-3A).

1. Calibration

The CRM corpus was designed so that each sentence was equated for the total rms power. For a calibration of the unshaped CRM used with the YNH listeners, a 30 s calibration noise and calibration tone (1000 Hz) were created and equated using Cool Edit Pro 2000. The calibration tone was matched to the peak levels for the speech materials and was used to determine the maximum possible presentation level without peak clipping. Once this maximum output setting was established, the calibration noise was used to measure the maximum levels in one-third octave bands from 125 through 8000 Hz.

The calibration noise was matched in spectrum and average rms amplitude to the long-term spectrum and average rms amplitude of the CRM materials. To determine the long-term average speech spectrum values of the CRM stimuli, the target CRM sentences used in this study were digitized using Cool Edit Pro 2000 and concatenated to create one large file of all eight talkers. The average amplitude spectrum of the concatenated wave file was then measured and the calibration noise was shaped digitally using a 1/3-octave-band graphic equalizer within Cool Edit Pro 2000 until the shaped noise was within 3 dB of the long-term-average speech spectrum for the CRM materials from 100 through 7500 Hz. This calibration stimulus was then presented through the TDT hardware and insert earphones.
coupled to an HA-2 2 cm³ coupler (ANSI, 1996). Overall (linear) and one-third-octave band sound pressure levels were measured using a Larson Davis model 800B sound level meter (with a Larson Davis model 2575 1 in. microphone) and recorded. An overall sound pressure level of 87 dB SPL for the unshaped CRM materials was used with all YNH listeners.

Next, given the presence of varying degrees of sloping, high-frequency sensorineural hearing loss in all the older listeners (see Fig. 1), the CRM materials underwent spectral shaping to increase the amplitude at 125, 250, 500, 1000, 2000, 4000, and 6000 Hz by 2, 2, 2, 5.5, 10.5, 11.5, and 20 dB, respectively. This effectively flattened the one-third-octave-band spectrum acoustically at 100 dB SPL (±2 dB) from 200 through 4000 Hz in the HA-2 2 cm³ coupler. A comparison of the amplitude spectra for the shaped and unshaped stimuli is provided in Fig. 2 for a sample of CRM sentences (those making use of the call sign, “Hopper”). The digital wave files for the spectrally shaped CRM sentences were examined to find the peak amplitude following shaping, which turned out to be the color “red” spoken by one of the talkers. This segment of the waveform was excised, copied, and concatenated to produce a long calibration file that was used to set the peak amplitude of the playback system to avoid peak clipping. The same spectral shaping was then applied to the calibration noise and the overall sound pressure level and 1/3-octave-band levels in the HA-2 2 cm³ coupler were measured for this calibration noise using a Larson Davis model 800B sound level meter (with a Larson Davis model 2575 1 in. microphone) and recorded. The maximum sound pressure level, with no attenuation in the system and without peak clipping, was 114 dB SPL. With full attenuation at the headphone buffer, the presentation level was 87 dB SPL. The 1/3-octave-band level at a center frequency of 4000 Hz (73 dB SPL) was then noted for this default presentation level. As long as the listener’s pure-tone hearing threshold at 4000 Hz in the right ear, expressed in dB SPL re: 2 cm² coupler, was at least 15 dB lower (≤58 dB SPL) than 1/3-octave-band level of the CRM calibration noise at a center frequency of 4000 Hz, then the default overall presentation level of 87 dB SPL was used. This ensured that the rms spectrum of the speech stimulus would be at least 15 dB above the hearing threshold through 4000 Hz. The assumption here is that hearing threshold for pure tones and 1/3-octave-band noises are equivalent in hearing-impaired listeners (Cox and McDaniel, 1986). If the listener’s hearing threshold at 4000 Hz was such that the 1/3-octave-band level of the CRM stimuli at that same frequency was not at least 15 dB above threshold, then the attenuation of the headphone buffer was decreased in 3-dB steps until this goal was achieved. Given the headphone-buffer step size of 3 dB, this means that the speech energy at 4000 Hz was 15–17 dB above threshold at that frequency. Given the speech spectra (Fig. 2) and the patterns of hearing loss (Fig. 1), this also ensured that the long-term-average rms speech spectrum was at least 15 dB above threshold at lower frequencies as well. All of the YNH subjects and 5 of the 13 EHI subjects were tested at the default level of 87 dB SPL, although, as noted, the YNH listeners did not listen to the spectrally shaped CRM materials. For the remaining 8 EHI listeners, 2 were tested at 90 dB SPL, 5 at 99 dB SPL, and 1 at 105 dB SPL. For all conditions in this study, the target and competing sentences were presented at the same sound pressure level for a 0 dB target-to-competition ratio (TCR).

C. General procedures

After administering the initial MMSE and digit-span measures, similar procedures were followed in experiments 1 and 2. The procedural details in common to both experiments are reviewed here.

The subject was seated in a single-walled sound booth in front of a computer monitor and was given written instructions for the CRM test. CRM test presentation was designed so that participants would hear 32 presentations of competing sentence pairs per test block. Thirty-two presentations per test block allowed for representation of each color and number combination as the target without repetition. The participants first received one 32-sentence block as practice. The participants listened to a total of 4 blocks of 32 sentence pairs, or 128 sentence pairs per condition. The listener indicated the color and number coordinates of the target sentence by selecting one of four rectangular buttons arranged in a column on the left side of the computer screen, labeled by both the color name and the color itself (i.e., a red rectangle with a text label of “red”), and then selecting a number from a column of numbers listing 1 through 8 on the right side of the computer screen. Most subjects in both groups used a computer mouse to make their color-number selections, but if any subjects, particularly among the EHI group, had difficulty with the use of the computer mouse, a touch-screen monitor was used instead. Trial-to-trial feedback was not provided.

In both experiments, a large-font (40-point, Times New Roman) orthographic cue (call sign, right/left, or male/female), which signaled the target sentence for that particular block of trials, was presented three times in the upper left portion of the computer screen. To minimize confusion with...
other colors displayed simultaneously on the screen, the cue was displayed in a purple font, centered within a white rectangular box measuring 1.5 cm vertically and 4.5 cm horizontally. The duration of the orthographic cue was 0.8 second, with an interval of 0.2 second between each presentation. Thus, the orthographic cueing of the target sentence required a total duration of 3 s. For measures of selective attention, on each trial in a block, the 3 s cue interval ended immediately before the presentation of a sentence pair. For selective attention, the listener could respond by selecting the target color-number coordinates immediately after the presentation of the sentence pair had been completed. For divided attention, the 3 s cue interval was initiated immediately following the presentation of the sentence pair and responses were not possible until the end of the cue interval. Because of the different memory constraints imposed on the measures of selective and divided attention in this study, these two measures are considered to be separate dependent variables in subsequent analyses (rather than two values of a single independent variable, attention type).

When the cue was ear (experiment 1), the words “Right” or “Left” were used as the orthographic cue. When the cue was call sign (experiment 1), the cue was one of the eight possible call signs for the CRM (e.g., “Charlie”). When the cue was talker gender (experiment 2), the words “Male” or “Female” were used as the orthographic cue. In each block of 32 trials for a given cue condition, each possible cue value occurred an equal number of times and the order was randomized. For example, when the call sign was the cue, in a given block of 32 trials, each of the 8 possible call signs appeared as a target four times, in random order, and competing call sign values were also equally distributed in random order (with the exception that the same call sign could not be used for both target and competing sentences on a given trial).

The EHI listeners also received a control condition in which two blocks of 32 trials of the CRM were presented to each ear without a competing stimulus. This was used to verify that these listeners could, in fact, identify the color-number coordinates with a high degree of accuracy given the spectral shaping provided.

The CRM testing was self-paced with the inter-trial interval controlled by the subject. The elderly subjects showed some variability in the time required to complete the testing. In general, with each session requiring 90–120 min to complete, older listeners required more sessions (6–8) than the younger listeners (5) to complete all testing. Additional experiment-specific procedural details are provided below.

III. EXPERIMENT 1

A. Experiment-specific procedures

There were a total of six conditions examined in this experiment for selective attention and six for divided attention. For both selective and divided attention, two of six conditions made use of dichotic stimulus presentation and the ear cue, two used dichotic presentation and the call-sign cue, and two used monaural presentation and the call-sign cue. An additional independent variable examined in experiment 1 was the agreement between talker genders for the target and competing speech stimuli. Target and competing talkers were either the same or different gender for a given block of trials. When the talkers were the same gender, each was chosen randomly without replacement from among a pool of 3 talkers on each trial. When the talkers were of opposite gender, each was chosen randomly from a pool of 3 talkers for each gender on each trial. For target and competing talkers of either the same or different gender, random selection was constrained so that male and female talkers were each used as the target talker half the time. For all dichotic stimulus presentation conditions, half the trials in a block presented the target stimulus to the right ear and half to the left ear in random order. For monaural presentation, the right ear was always the stimulus ear. As noted previously, three of the elderly subjects had an interaural asymmetry of pure-tone thresholds exceeding 15 dB, but these were all confined to frequencies of 4000 Hz or higher, and the right ear (test ear) always had the better hearing thresholds.

The six conditions for each type of attention measure in this experiment represent an unbalanced research design because it is not possible to use the ear cue in monaural listening. As a result, there are two overlapping sets of $2 \times 2$ factorial repeated-measures combinations represented in the six conditions. When the dichotic ear-cue conditions are compared to the dichotic call-sign-cue conditions, the $2 \times 2$ factorial design represents all combinations of type of cue (ear or call sign) and gender match between the target and competing talkers (same or different) for both selective and divided attention. When the results for the dichotic and monaural call-sign cue conditions are analyzed, then the two repeated-measures independent variables are gender match and presentation mode (monaural or dichotic) for measures of both selective and divided attention. The subject group was the only between-subject independent variable and there were two values for this variable (young normal hearing, elderly hearing impaired).

B. Results and discussion

For the control conditions, in which two blocks of 32 trials of a single talker, without a competing talker, were presented to each ear, all scores for each ear and each of the 13 older adults exceeded 96% and 21 of the 26 scores were 100%. Thus, with the spectral shaping used in this study, none of the EHI listeners had any difficulty identifying the correct color-number coordinates when the spectrally shaped target stimulus was presented without a competing sentence.

The individual percent-correct scores for all subjects were transformed into rationalized arcsine units (RAU; Studebaker, 1985) to stabilize the error variance. Means and standard errors for both groups of listeners and all six test conditions are shown in Fig. 3 for the measures of selective attention (top panel) and divided attention (bottom panel). As noted previously, given the unbalanced design across the six conditions in this experiment, the six conditions were divided into two overlapping sets of four conditions each, for statistical analysis. For both selective attention and divided attention, one set of four conditions included those for which
dichotic stimulus presentation was employed (left and center portions of each panel in Fig. 3), whereas the other set of four conditions included those for which the call sign was the cue (center and right portions of each panel in Fig. 3). A total of four mixed-model General Linear Model (GLM) analyses were conducted using a 2 × 2 factorial design for the repeated-measures variables and a between-subject factor of group (YNH or EHI). In the first two analyses, the repeated-measures variables were cue type (ear versus call sign) and gender match (same versus different), with separate analyses performed on the measures of selective and divided attention. In the next two analyses, the repeated-measures variables were presentation mode (monaural versus dichotic) and gender match (same versus different), with separate analyses again performed for measures of selective and divided attention.

1. Effects of cue type, gender match, and group

For the first GLM analysis involving selective attention in dichotic listening conditions, significant \( p < 0.01 \) main effects of cue type \( F(1, 21) = 67.7 \) and gender match \( F(1, 21) = 26.5 \) were observed such that scores were generally higher in dichotic listening for the ear cue than for the call-sign cue and for different talker genders rather than same talker genders. In addition, the main effect of the subject group was not significant \( F(1, 21) = 2.8 \). There was, however, a significant interaction between gender match and group \( F(1, 21) = 9.1 \). An inspection of the data in the left and center portions of the top panel reveals that the older subjects show a greater increase in performance than the younger subjects when gender match changes from the same to different.

In the corresponding GLM analysis involving divided attention and dichotic listening conditions (left and center portions of lower panel in Fig. 3), significant main effects of cue type \( F(1, 21) = 110.5 \) and subject group \( F(1, 21) = 20.8 \) were observed, but the effect of gender match was not significant \( F(1, 21) = 0.9 \). Two interactions, however, were found to be significant as well, both involving the subject group. Specifically, subject group interacted significantly with cue type \( F(1, 21) = 11.0 \) and gender match \( F(1, 21) = 5.6 \). Regarding the interaction of group and cue type, the ear cue yielded higher scores than the call-sign cue, but the difference was larger for the young, normal-hearing listeners. With regard to the interaction of group with gender match, there appears to be a slight effect of gender match for the older subjects only, such that performance was higher when the gender of the target and competing talkers differed.

In summary, for both young and older adults and selective and divided attention, the ear cue yielded higher performance in dichotic listening than the call-sign cue. In addition, for both selective and divided attention, the gender match between target and competing talkers was a significant factor in dichotic listening for the older adults such that scores were higher in these subjects when the two talkers differed in gender. It is interesting that gender match of the two talkers had a significant effect for the EHI listeners, even when the two talkers were delivered to opposite ears. This clearly cannot be an issue related to increased “energetic” masking in the EHI group, as there is no physical or peripheral interaction among the target and competing stimuli when delivered to opposite ears.

To examine group differences for each of the four dichotic conditions, a series of independent-group \( t \) tests were performed. Here, given four comparisons, the criterion \( p \) value of 0.05 was divided by 4 and \( p < 0.0125 \) was established as the criterion for significance (i.e., \( p \) was adjusted for multiple comparisons). Using this significance criterion, none of the group comparisons were significant for selective attention, but three of the four group comparisons were significant for divided attention. These significant group differences have been marked in the left and center panels of Fig. 3 with asterisks.

2. Effects of mode of presentation, gender match, and group

A parallel set of analyses were performed for the four conditions in the center and right portions of Fig. 3 for both selective attention (top panel) and divided attention (bottom panel).
In this case, significant main effects were observed for each of the three independent variables [presentation mode: $F(1,21)=422.5$; gender match of talkers: $F(1,21)=190.4$; and group: $F(1,21)=7.6$], but one two-way and one three-way interaction involving various combinations of these variables were also significant. Specifically, the interaction between the presentation mode and gender match [$F(1,21)=75.7$] and the three-way interaction of presentation mode, gender match, and group [$F(1,21)=11.1$] were significant. Overall, from an inspection of Fig. 3, these results indicate that there was a significant effect of gender match in both presentation modes, but it was larger for monaural presentations and the younger listeners. Clearly, this complex pattern of significant findings is driven by the extremely low performance of both subject groups for the monaural presentation mode when the target and competing talkers were the same gender. Finally, the asterisk in the right portion of the top panel of Fig. 3 indicates that the older adults performed more poorly than the young adults in this condition (independent-sample $t$ test with $p$ values adjusted for multiple comparisons, as previously).

For divided attention (the center and right portions of the bottom panel of Fig. 3), parallel GLM analyses revealed identical statistical findings as those reported for selective attention. Specifically, significant main effects were observed for each of the three independent variables [presentation mode: $F(1,21)=106.0$; gender match of talkers: $F(1,21)=43.3$; and group: $F(1,21)=16.0$], but one two-way and one three-way interaction involving various combinations of these variables were also significant. The interaction between presentation mode and gender match [$F(1,21)=50.9$] and the three-way interaction of the presentation mode, gender match, and group [$F(1,21)=12.8$] were significant. As before, from an inspection of the bottom panel of Fig. 3, these results indicate that there was a significant effect of gender match in both presentation modes, but it was larger for monaural presentations and the younger listeners. Once again, this complex pattern of significant findings appears to be driven by the low performance of both subject groups for the monaural presentation mode when the target and competing talkers are the same gender. This clearly was the most challenging listening situation for both groups of listeners and for both the selective- and divided-attention tasks. Finally, the asterisks in the center and right portions of the bottom panel of Fig. 3 indicate that the older adults performed more poorly than the young adults for three of the four divided-attention conditions (independent-sample $t$ tests with $p$ values adjusted for multiple comparisons).

In Fig. 3, note that the data for the monaural, call-sign cue, same-gender listening condition revealed the lowest performance for both groups and both types of attention. In this listening condition, it is most difficult to segregate the target and competing stimuli and both groups perform poorly when it is difficult to perform this segregation. When segregation of the target and competing stimuli has been facilitated through differences in talker gender (monaural presentation, call-sign cue, different gender) or laterality/location (dichotic presentation, call-sign cue, same gender), the relative improvements in performance are more sizable for the young adults than for the older adults. Thus, the younger adults appear to benefit more than the older adults, on average, from the segregation of the target and competing messages.

### 3. Correlations and individual differences

Correlational analyses of the individual data for all 23 subjects were performed for the six selective-attention measures and the six divided attention measures. Correlations were computed for each group separately as well, but the patterns of correlations were very similar for each group and for both groups combined so only the latter are summarized here. For the 6 measures of selective attention there are 15 possible pairwise correlations, and 10 of these were positive, strong ($r>0.75$ in 9 of the 10 cases), and statistically significant ($p<0.01$). All five nonsignificant correlations were between performance measured for the monaural condition using the call-sign cue and the same gender for target and competing talkers and performance measured for the other five conditions. That is, performance in this very difficult condition was not correlated with performance in any of the other conditions. Performance in the other five conditions, however, was strongly correlated such that those who did well in one of those five conditions tended to do well in the others.

For the divided-attention conditions, the pattern of correlations was somewhat similar to that observed for selective attention. The five correlations with performance for the monaural listening, call-sign cue, same-gender condition were once again lower than the rest, but here the correlations were stronger ($0.46<r<0.71$) than observed for selective attention with four of the five being statistically significant. Further, for the remaining ten correlations involving performance measured in the other five conditions, all were significant and the correlations ranged from 0.78 to 0.94. All told, 14 of the 15 correlations for divided attention were significant and 13 of them were at least 0.70.

Six correlations were also calculated between the measures of selective and divided attention; one correlation for each of the six test conditions. These correlations ranged from 0.51 to 0.83 with five of the six being significant ($p<0.01$). Thus, those who did better on the measures of selective attention tended to do better on the measures of divided attention, at least for conditions that were otherwise identical (presentation mode or cue type and gender match).

Correlations were also computed between each of the six measures of selective and divided attention and age, average high-frequency hearing loss (1000, 2000, and 4000 Hz) in both ears, hearing loss asymmetry (the average high-frequency hearing loss in the right ear minus that in the left ear), and average digit-span score (average of forward and backward digit span measures) for the 13 older adults. It should be noted that there were no significant correlations among these four potential “explanatory” variables themselves. For the six measures of selective attention, there was only one significant ($p<0.05$) correlation observed. This was a negative correlation ($r=-0.62$) between hearing loss asymmetry and performance in the ear-cue, same-gender condition. However, the correlation with hearing loss asymmetry approached significance ($r=-0.52$, $p=0.07$) for the

Humes, Lee, and Coughlin: Auditory selective and divided attention
corresponding condition with the call-sign cue. In addition, two other moderate correlations \( r = 0.53 \) and \( 0.54 \) for measures of selective attention approached significance \( (p = 0.06) \) and these were with the digit-span measure. For divided attention, the only significant correlations were with digit span. Four of the six measures of divided attention were significantly correlated \( (0.61 < r < 0.77) \) with digit span and the other two \( (r = 0.54 \) and \( 0.52) \) approached significance \( (p = 0.06 \) and \( 0.07, \) respectively).

The foregoing analysis of individual data suggests that there may be common mechanisms underlying the identification of speech from one talker with another talker speaking in the background, regardless of whether the competing talkers are presented to the same ear (monaural) or to different ears (dichotic). Further, these two attentional mechanisms (selective and divided) are strongly correlated.

The scatter plot in Fig. 4 further emphasizes that the differences in performance on dichotic selective- and divided-attention tasks are closely related to similar differences observed for monaural presentations of these same stimuli. In this figure, only the data for the different-gender conditions and call-sign cue are presented. The same-gender conditions were very difficult for monaural presentations, not correlated with other measures, especially for selective attention, and likely reflected an inability of the subject to segregate the two messages. As such, it is probably not appropriate to examine attention for two competing stimuli if the stimuli cannot be perceived as two separate stimuli. In addition, the scatter plot was generated only for conditions using the call-sign cue because that is the only cue in common across the monaural and dichotic presentation conditions. In Fig. 4, note that, for both age groups, as performance in either the selective- or divided-attention task increases for monaural presentation \( (x \) axis), performance also increases for the corresponding task with dichotic presentation \( (y \) axis). In fact, the correlation coefficient between scores for monaural and dichotic conditions is 0.94 for young adults and 0.87 for older adults. This suggests, at least for these stimuli and conditions, that the performance in dichotic conditions may reflect individual differences in the same cognitive mechanisms underlying performance in monaural conditions and not necessarily central-auditory factors, such as binaural processing, that are modality specific and unique to dichotic processing.

IV. EXPERIMENT 2

A. Experiment-specific procedures

There were a total of six conditions in this experiment; three each for selective and divided attention. All presentations were monaural (right ear) and the cue was always talker gender (male or female). The sole repeated-measures independent variable was talker uncertainty for both dependent variables (measures of selective and divided attention). There were three levels of talker uncertainty examined: minimum, medium, and maximum uncertainty. For “minimum uncertainty,” the same male talker and the same female talker were used for all 32 trials in a block and for all four blocks. For “medium uncertainty,” the same talker of one gender was used as one talker across trials while the other talker was randomly selected on each trial from among four possible talkers of the opposite gender. There were two variations of this “medium uncertainty” case: one in which the fixed talker was male and the variable talkers were female and one in which the fixed talker was female and the variable talkers were male. Four blocks of 32 trials were completed for each of these variations of the “medium uncertainty” conditions and the results for all eight blocks were averaged. Finally, for “maximum uncertainty” one male and one female were chosen randomly for each trial from the four possible talkers for each gender. The randomization was constrained such that each of the eight talkers appeared four times as the target talker and four times as the competing talker in a block of 32 trials. Thus, there was one repeated-measures independent variable (talker uncertainty) with three values. The subject group was again the only between-subject independent variable and there were two values for this variable (young normal hearing, elderly hearing impaired).

B. Results and discussion

1. Effects of stimulus uncertainty and group

In this experiment, the use of talker gender as a cue for selective and divided attention was examined in the same 13 elderly adults and 10 young adults, 7 of whom had participated in experiment 1. Given the use of talker gender as the cue, the genders of the target and competing talkers were always different and gender match was no longer a viable independent variable. Instead, the variation in talker voices from trial to trial, referred to here as talker uncertainty, was manipulated systematically.
FIG. 5. Means and standard errors (error bars) of the transformed percent-correct scores for the CRM for each of the six listening conditions in experiment 2 and both groups of subjects (grey bars: YNH; black bars: EHI). Asterisks mark significant \((p < 0.01)\) differences between the two groups.

Figure 5 presents the means and standard errors, in RAUs, for the three levels of stimulus uncertainty included in experiment 2, with the selective-attention measures in the left half of the figure and the divided-attention measures in the right half. Casual visual inspection of these data suggests that, in general, performance was lower in the divided-attention tasks than in the comparable selective-attention tasks and that older adults generally performed worse than young adults. Two \(2 \times 3\) mixed-model GLM analyses were performed, one for the measures of selective attention and one for the measures of divided attention.

The GLM analysis on the measures of selective attention (the left half of Fig. 5) revealed a significant main effect of subject group \([F(1,21)=8.1]\), but not uncertainty \([F(2,42) =2.1]\). In addition, there was no interaction between uncertainty and group \([F(2,42)=1.0]\). Multiple independent-sample \(t\) tests were computed to examine the differences in performance between groups for each uncertainty condition. The criterion \(p\) value was again adjusted for multiple comparisons \((p=0.05/3=0.0167)\) and the asterisks in the left half of Fig. 5 mark those conditions for which a significant difference between groups was observed. The older adults performed significantly worse than the younger adults on all three divided-attention tasks.

To summarize the group data, the EHI adults performed significantly worse than YNH adults in five of the six conditions included in this experiment. These findings are consistent with the findings of experiment 1, but using talker gender as the cue rather than the call sign or ear. The results from this experiment with regard to uncertainty were less clear. There was no effect of uncertainty on measures of selective attention, but there was on measures of divided attention. Although a statistically significant effect of stimulus uncertainty was observed between the minimum and maximum uncertainty conditions for the measures of divided attention, the mean differences in performance over this range of uncertainty were not large (4-5 RAU) for either group. This small effect could be due to the restricted range of talker uncertainty available for the CRM materials used in this experiment. Moreover, a significant interaction between the effects of uncertainty and group was not observed for either measure of attention suggesting that the effects of uncertainty, or lack thereof, were equivalent for both young normal-hearing subjects and elderly hearing-impaired listeners. As noted previously, others have found older adults to be more vulnerable to such talker uncertainty or variability in other contexts (Sommers, 1997), although a much wider range of uncertainty was encompassed in that study than in this experiment. In addition, Brungart and Simpson (2004) found no significant effects of talker uncertainty on the CRM task in young adults, whereas Coughlin (2004) observed significant effects of talker uncertainty in both young and older adults on the CRM task (for selective attention).

2. Correlations and individual differences

With regard to the individual data from experiment 2, correlations across the three stimulus uncertainty conditions for each measure of attention were all strong, positive, and statistically significant \((p < 0.05)\). Specifically, the three pairwise correlations for selective attention were 0.91, 0.89, and 0.92 and those for divided attention were 0.95, 0.91, and 0.93 for the entire set of 23 subjects. Similar correlations were also observed within each group separately. Finally, when the three measures of selective attention were correlated with the three measures of divided attention for all 23 subjects, the nine correlations ranged from 0.68 to 0.87 and were all statistically significant. Thus, an individual who performed well on any of the tasks in this experiment tended to perform well on all of the tasks, regardless of the type of attention being measured or the amount of stimulus uncertainty.

Correlations were also computed between each of the six measures of selective and divided attention and age, average high-frequency hearing loss (1000, 2000, and 4000 Hz) in both ears, and average digit-span score (average of forward and backward digit span measures) for the 13
memory.vided attention is known to place greater demands on selective-attention tasks. This was not unexpected since di-

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individual differences in memory (digit span). As noted in the Introduction, the observations of age differences in performance on selective- and divided-attention tasks, as well as the association of individual differences in performance with memory among the older adults, have been noted before (Verhaeghen and De Meersman, 1998a, 1998b; Verhaeghen et al., 2003). In our particular implementation of attention measurements in experiments 1 and 2, the subjects were required to hold the orthographic cue (ear, call sign, or gender) in memory for about 1.5–2.0 s before responding with the color-number coordinates for measures of selective attention. For divided-attention measures, the subjects had to hold the stimuli in memory for about 3 s before the orthographic cue was completed and response collection enabled. Thus, in this study, as in previous studies, age-related differences in attention could be mediated by corresponding differences in memory.

The absence of other correlations, with age, hearing loss, or hearing loss asymmetry (with one exception in experiment 1), is perhaps as important as these significant correlations. Among the elderly, differences in age or differences in hearing loss did not contribute to individual differences in performance from either experiment. Use of spectral shaping to minimize audibility limitations appeared to be effective, as was also the case in Coughlin (2004), although a slightly different approach was taken to ensure audibility through 4000 Hz in the previous study.

The percentage of errors in each experiment, for each type of attention and each group of subjects, that resulted from intrusions of the color or number coordinates, or both, from the competing stimulus was examined. An “intrusion” of the competing color-number coordinates simply means that the listener’s response included the color, number, or color-and-number coordinates from the competing talker. GLM analyses of the percentage of intrusions for each experiment, revealed only significant ($p<0.01$) main effects of type of attention in each experiment, but no significant ($p > 0.05$) differences between groups or interactions between group and type of attention. Selective attention revealed a greater percentage of intrusions than divided attention. Since the competing response coordinates could not have the same color or number as the target, on any given trial, that left three possible colors and seven possible numbers for use as coordinates in the competing message. Thus, there is a $1/3$ chance the color alone from the competing stimulus would be reported by guessing, a $1/7$ chance for the number alone, and a $1/21$ chance that both the color and number of the competing stimulus would be reported randomly. Summing all these possible intrusion probabilities results in a total intrusion percentage of errors of $1/21$ (i.e., $(1/3+1/7 +1/21)$ or $52.4\%$.

For color-only intrusions, the percentage of errors that were of this type were not unlike those expected by chance, except for the divided attention conditions for the EHI subjects. In this case, the percentage of color-only intrusions was quite a bit less than would be expected by random guessing. For number-only intrusions, the percentages of errors that were of this type were fairly consistent across all subject and attention combinations and were also not unlike

V. GENERAL DISCUSSION

Across both experiments 1 and 2, several consistent trends were observed when using the CRM and two competing talkers to measure attention in young and older adults. First, in general, for both young and older adults, divided-attention tasks yielded lower scores than comparable selective-attention tasks. This was not unexpected since divided attention is known to place greater demands on memory (Pashler, 1998). This was true for both monaural and dichotic presentation modes and all three types of attention cue used (ear, call sign, talker gender). The lone exception probably being when monaural, same-gender conditions were used in experiment 1. This was also the condition yielding overall performance for both age groups that was well below that of any other test condition in either experiment. It is likely that, in this condition, the two competing talkers were difficult to segregate given similar fundamental frequencies (Assmann and Summerfield, 1990; Culling and Darwin, 1993; Arehart, King, and McLean-Mudgett, 1997; Summers and Leek, 1998) and energetic forms of masking predominated, making it extremely difficult to hear out or segregate the two auditory stimuli and respond accordingly.

A second general trend across experiments was related to the difference between the performance of young and old adults. In particular, in eight of the nine divided-attention measures across both experiments, the EHI subjects performed significantly worse than the YNH subjects. This was true regardless of the presentation mode, the type of cue used, the gender match between target and competing talkers, or the amount of talker uncertainty. By comparison, significant differences in performance between age groups were only observed on three of the nine selective-attention tasks.

Another common finding across both experiments pertained to the strong correlation among CRM scores for a given experiment, suggesting considerable redundancy and a common underlying factor or factors. There were consistent individual differences in performance in both experiments such that high performers tended to score high on all conditions and lower performers tended to score low on all conditions. Subsequent correlations between performance and age, digit span, and hearing loss for the 13 older adults suggested that, at least for this age group, the individual differences in performance were associated frequently with individual differences in memory (digit span). As noted in the Introduction, the observations of age differences in performance on selective- and divided-attention tasks, as well as the association of individual differences in performance with memory among the older adults, have been noted before (Verhaeghen and De Meersman, 1998a, 1998b; Verhaeghen et al., 2003). In our particular implementation of attention measurements in experiments 1 and 2, the subjects were required to hold the orthographic cue (ear, call sign, or gender) in memory for about 1.5–2.0 s before responding with the color-number coordinates for measures of selective attention. For divided-attention measures, the subjects had to hold the stimuli in memory for about 3 s before the orthographic cue was completed and response collection enabled. Thus, in this study, as in previous studies, age-related differences in attention could be mediated by corresponding differences in memory.

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those expected by chance. The situation was considerably different, however, for the color+number intrusions and these intrusions are illustrated in Fig. 6. As shown, the percentages of errors that were of this type were about three to five times greater than those expected by chance. The analysis of the percentage of errors that are intrusions from the competing stimulus, especially for the color+number intrusions, provides further support for the notion that the underlying processing reflects attentional capabilities. The listeners were less able to tune out, inhibit, or suppress the competing coordinates and these coordinates surface as responses in the errors much more frequently than would be expected by chance alone. It has frequently been shown that older adults are less able to inhibit irrelevant or competing sensory information (e.g., Hasher and Zacks, 1988; Hasher et al., 2006), including the situation of attending to a target talker and ignoring a competing talker (Sommers and Danielson, 1999; Tun, O’Kane, and Wingfield, 2002), although age differences in the interference of a competing talker with the target talker have not always been observed (e.g., Li et al., 2004). In the present study, however, although the older adults made more errors than the young adults in most conditions, the relative percentage of color + number intrusion errors was lower for older adults (Fig. 6). Thus, it was more often the case that neither the target or competing coordinates were identified correctly by the older adults whereas younger adults were superior at recalling both (incorrectly in the case of color + number intrusions).

It should be kept in mind that the target-to-competition ratio in this study was 0 dB and, for the EHI listeners, both stimuli underwent the same amount of spectral shaping. Overall, therefore, the target and competing stimuli are equivalent in energetic terms and it is impossible to state which stimulus is the energetic “masker” and which is the “signal.” That is, it is not the case that the competing coordinates emerged more frequently among the errors because the competing stimulus masked, in an energetic sense, the target coordinates. Rather, given acoustically, and presumably perceptually, equivalent target and competing stimuli, attention and memory processes determined both the percentage of target coordinates recalled correctly and the large percentage of the errors attributable to the competing coordinates.

The use of the same stimuli and same call-sign cue for four dichotic and four monaural conditions in experiment 1 enabled a comparison of the individual differences in performance for both presentation modes (Fig. 4). Strong correlations of about 0.9 between monaural and dichotic performance for selective and divided attention and in young and elderly adults strongly suggests that there are common underlying mechanisms for these two presentation modes. It is suggested here that the common underlying mechanism is attention or attention+memory; in either case, a cognitive process. Thus, individual differences in performance on other dichotic speech-identification or speech-recognition tasks may also be attributable to underlying individual differences in attention. As such, these measures of dichotic speech processing should not be considered to be pure measures of “central auditory” processing, especially when used with older adults (e.g., Jerger et al., 1989; Hallgren et al., 2001; Humes, 2005).

Finally, the mean CRM scores for selective and divided attention conditions across experiments 1 and 2 for both age groups (Figs. 3 and 5) were compared. Mean values were computed for each group and for the four cue/presentation mode conditions used in the two experiments. For experiment 1, only the conditions using talkers of different genders were averaged since different genders were always used in experiment 2. In addition, since the trial-to-trial uncertainty in experiment 1 was most like the medium-uncertainty conditions from experiment 2, the medium-uncertainty condition from that experiment was used in this across-experiment comparison. From these across-experiment comparisons, the spatial/laterality (ear) cue in dichotic listening yielded the highest mean performance for both age groups and for both selective and divided attention. Likewise, the call-sign cue in the monaural listening condition yielded the lowest performance within each attention type and for both groups. The ordering of the two middle cues/conditions, however, was not as clear. For selective attention, for example, the call-sign cue in dichotic listening tended to produce somewhat higher scores than the gender cue in monaural listening conditions, whereas there was no such trend, or even an opposite trend, for these two cue/condition combinations in the divided-attention task. Caution should be exercised when comparing performance across cues and conditions, however, because, despite attempts to equate various factors across experiments and conditions, this has not been fully accomplished. For example, for the call sign as a cue, there were eight alternatives, whereas for the other two cues, gender and ear, there were only two alternatives. In that sense, there was more uncertainty with regard to the potential cues from trial to trial when call sign was used. To examine the role of cue uncertainty, additional experiments with call sign restricted to only two choices, just as gender and ear, would be required. Nonetheless, it appears that those cues associated with physical aspects of the perceived auditory object,