Stimulus and listener factors affecting age-related changes in competing speech perception

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The purpose of this study was to examine associations among hearing thresholds, cognitive ability, and speech understanding in adverse listening conditions within and between groups of younger, middle-aged, and older adults. Participants repeated back sentences played in the presence of several types of maskers (syntactically similar and syntactically different competing speech from one or two other talkers, and steady-state speech-shaped noise). They also completed tests of auditory short-term/working memory, processing speed, and inhibitory ability. Results showed that group differences in accuracy of word identification and in error patterns differed depending upon the number of masking voices; specifically, older and middle-aged individuals had particular difficulty, relative to younger subjects, in the presence of a single competing message. However, the effect of syntactic similarity was consistent across subject groups. Hearing loss, short-term memory, processing speed, and inhibitory ability were each related to some aspects of performance by the middle-aged and older participants. Notably, substantial age-related changes in speech recognition were apparent within the group of middle-aged listeners.

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I. INTRODUCTION

People face numerous challenges as they age. Many tasks that are performed effortlessly in earlier years become more difficult to accomplish. One example is the understanding of speech in adverse listening environments. Although younger adults have a remarkable ability to negotiate complex listening situations successfully, older individuals often struggle in these environments (e.g., Desjardins and Doherty, 2013; Helfer *et al.*, 2010; Helfer and Freyman, 2008; Humes and Coughlin, 2009; Humes *et al.*, 2006; Lee and Humes, 2012; Rossi-Katz and Arehart, 2009; Tun and Wingfield, 1999).

Being able to successfully communicate in a situation with multiple talkers requires the listener to call upon many functional abilities. On the most basic level, individuals must be able to hear the sounds that make up an auditory message in order to understand that message. Lack of audibility from age-related hearing loss adversely affects speech understanding. But audibility is not sufficient to ensure understanding when the message of interest is embedded in a background of one or more other voices (e.g., Humes *et al.*, 2006; Humes and Coughlin, 2009; Lee and Humes, 2012) as competing messages potentially cause interference on both a peripheral level (from energetic masking) as well as on a more central level (because of informational masking). In competing speech situations, multiple cognitive functions must be engaged to identify which voice or message is of interest, segregate that information from the background talkers, inhibit the irrelevant messages, and maintain attention on the target speech. Difficulty performing any of these functions

could lead to misunderstanding in situations with multiple talkers. Indeed, there is evidence to support the role of cognition in speech understanding in adverse listening situations, especially among older adults. The most consistent associations found to date are with working memory (e.g., Akeroyd, 2008; Anderson *et al.*, 2013; Desjardins and Dougherty, 2013; Lee and Humes, 2012; Humes *et al.*, 2006; Koelweijn *et al.*, 2012) and with processing speed (e.g., Tun *et al.*, 2002; Tun and Wingfield, 1999; Woods *et al.*, 2013).

The current project focused on examining two facets of speech-on-speech masking in younger, middle-aged, and older listeners: The number of masking talkers (which has potential impact on both energetic and informational masking) and the confusability of the target and masking speech (which falls into the realm of informational masking). Past research suggests that, for younger adult listeners, a two-talker masker can be much more detrimental than a one-talker masker, even when the resultant increase in masker energy is taken into account (Brungart *et al.*, 2001; Carhart *et al.*, 1969; Durlach, 2006; Freyman *et al.*, 2004; Iyer *et al.*, 2010; Miller, 1947; Rosen *et al.*, 2013; Simpson and Cooke, 2005). It appears that the impact of combining speech maskers follows more complex rules than what occurs when non-speech maskers are combined.

It is likely that both auditory and cognitive changes that accompany aging influence the relative impact of energetic masking and informational masking for different numbers of masking talkers. Adding a second competing voice invariably produces an increase in overall masker energy, which likely proves more detrimental to older and/or hearing impaired individuals who need a more advantageous signal-to-noise ratio (SNR) to obtain good levels of speech recognition in complex listening environments (e.g., Li *et al.*, 2004). The addition of a

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second masker also fills in the dips or gaps in the masking complex, leading to a reduction in the ability to “glimpse” the target (e.g., [Brungart et al., 2009](#)). However, there are data to suggest that the additional masking from a second voice cannot be explained solely by acoustic factors related to dip listening and increased masking energy. For example, results of [Iyer et al. \(2010\)](#) support the idea that a second masker affects the ability to use prosody and voice characteristics to hold together the individual speech streams across time. Moreover, a second masker likely places greater demand on processing resources, as it necessitates the separation of three voices and adds additional words that must be processed in the total complex. This might be especially problematic for older adults—although all individuals have a limited-capacity attentional pool that is called upon to select relevant information from background competition, this pool is diminished with aging (e.g., [Verhaeghen and Cerella, 2002](#)).

It is possible that the addition of a second competing message may actually prove less detrimental to older listeners (assuming the increase in masking energy is taken into account), as compared to younger adults. One reason is that the cochlear hearing loss that typically accompanies aging reduces the ability to use spectrotemporal gaps in a masker (e.g., [Festen and Plomp, 1990](#); [Summers and Molis, 2004](#); [Takahashi and Bacon, 1992](#); [Vongpaisal and Pichora-Fuller, 2007](#)). Individuals who are less able to take advantage of the gaps in a single competing speech masker should be less affected when a second masking signal (that obscures those gaps) is added. Another reason why, in relative terms, older adults may be less handicapped by the addition of a second masker is that it may lead to less lexical interference because the two masking messages obscure one another, making each less understandable. Older adults’ increased susceptibility to energetic masking would likely cause this to play a larger role in their performance, as compared to younger adults.

Another aspect of competing speech perception that might be especially relevant for older listeners is the potential confusability between the target and interfering voices. There is evidence that problems experienced by older adults are amplified when the target and masking speech are potentially confusable. For example, older adults experience greater deficits than younger listeners when switching from an unintelligible masker that consists of speech played time-reversed to a normally presented version of the same masker (e.g., [Humes and Coughlin, 2009](#); [Rossi-Katz and Arehart, 2009](#)) or when a masker spoken in an unfamiliar language is compared to masking speech spoken by the same talker, but in the listeners’ native language (e.g., [Tun et al., 2002](#)). However, results of [Agus et al. \(2009\)](#) suggest that older adults are not inordinately affected by highly confusable maskers/targets (that is, they show similar amounts of informational masking as compared to younger adults). In the present study, we manipulated syntactic/temporal structure to examine confusability, similar to that done with young, normally hearing listeners by [Iyer et al. \(2010\)](#). To use their terminology, we compared performance with a contextually irrelevant masker (one that was syntactically and lexically different from the target utterance) with performance obtained using a contextually relevant masker that was identical in syntactic structure to the target

speech (and therefore more confusable). Since these two types of maskers were each recorded from the same talkers, differences in performance in their presence cannot be attributed to differences in average long-term spectrum between masking conditions. Examining whether the effect of confusability changes with age will give insight into higher-level factors in competing speech perception.

In summary, the present study was designed to explore two previously unexamined variables related to aging and speech understanding in competing speech situations: how the number of masking talkers influences age-related differences and the effect of target-masker syntactic confusability on performance across groups of listeners. Results of this study should also help clarify some unresolved questions about why older adults experience challenges in these situations, particularly the degree to which hearing loss and selected cognitive abilities (short-term memory, working memory, inhibitory ability, and processing speed) contribute to age-related changes in speech understanding. We also assessed self-perceived communication difficulty using selected items from the Speech, Spatial, and Qualities of Hearing Scale (SSQ; [Gatehouse and Noble, 2004](#)) in order to learn how our lab-based measures relate to real-life hearing difficulty. Finally, the inclusion of middle-aged participants will lead to a greater understanding of when these age-related difficulties begin.

II. METHODS

A. Participants

Forty-five adults participated in this study. Of these individuals, 15 were middle-aged adults (45–59 years, mean 53 years), 15 were older adults (61–85 years, mean 68 years), and the remaining 15 were younger, normally hearing individuals [19–28 years, mean 22 years, with pure-tone thresholds at audiometric frequencies between 250 and 8000 Hz no poorer than 20 dB hearing level (HL)]. Older and middle-aged participants were individuals in the general community who responded to press releases and flyers posted in libraries, houses of worship, community centers, and businesses. None of these participants used hearing aids. They earned \$10 per hour for participating in the study. Younger subjects were undergraduate students at the University of Massachusetts who earned partial class credit for participating. Potential participants with a history of neurological or otologic disorder were excluded from participating, as were individuals who did not speak English as a first language and/or who had a high-frequency (2, 3, 4, and 6 kHz) pure-tone average in either ear >65 dB HL. Middle-aged and older participants were required to score at least 26 out of 30 points on the Mini-Mental State Exam ([Folstein et al., 1975](#)) which represents normal cognitive performance. Additionally, each participant had bilaterally normal tympanograms on the test days in order to rule out a middle-ear component to any observed hearing loss. Composite audiograms for the middle-aged and older groups are shown in Fig. 1.

B. Cognitive tests

All participants completed a battery of cognitive tests (described below). The specific cognitive tests were selected

FIG. 1. Composite audiograms for the older (upper panel) and middle-aged (lower panel) participants (right ear thresholds, closed circle; left ear thresholds, "x"). Lines represent the upper and lower bounds of measured thresholds.

based on past research identifying associations of each measure with speech understanding in adverse and/or complex listening conditions. For example, a number of studies have found that auditory working and/or short-term memory is related to speech perception within a competing speech background (e.g., Akeroyd, 2008; Anderson *et al.*, 2013; Helfer *et al.*, 2013; Humes *et al.*, 2006). Performance on processing speed tasks also is associated with competing speech perception (Tun and Wingfield, 1999; Tun *et al.*, 2002; Desjardins and Dougherty, 2013; Woods *et al.*, 2013) and inhibitory ability as measured by the Stroop task has been shown to be related to older adults' performance on a single-talker interference task (Jesse and Janse, 2012). Middle-aged and older subjects completed the audiometric and cognitive tests in one visit and the speech perception assessment in a second visit, each lasting approximately 1–1.5 h. Younger participants completed all measures in one visit of approximately 2–2.5 h.

1. Working memory and short-term memory

A letter-number sequencing task (Gold *et al.*, 1997) was used to measure both auditory working memory and auditory short-term memory. For working memory assessment

(LNSe), an experimenter read series of alternating letters and numbers at a rate of approximately 1 item/s. The participant had to repeat back first the numbers in numerical order, then the letters in alphabetic order. Testing began with 2-item sequences (there were four trials per item length) and ended when a participant missed all four trials at a given item length (with a maximum of 7-item sequences). The score on this test was the total number of sequences recalled correctly. The short-term memory testing (LNSe) was identical, except that participants were instructed to repeat the sequences in the order heard.

2. Processing speed/executive function

The Connections Test (Salthouse *et al.*, 2000) was completed by each participant to measure processing speed and executive function. In this modification of a trail-making task, participants were given grids that contained numbers and/or letters encased in circles. For the Numbers condition, subjects were instructed to connect the circles in numerical sequence as quickly as possible. For the Letters condition, participants connected the circles in alphabetic order. For the Numbers-Letters condition, participants alternated numbers and letters (e.g., 1-A-2-B...) and for the Letters-Numbers condition they did the same, but beginning with the letter A. There were two practice forms followed by eight experimental forms (two for each condition). Participants were told to work as quickly as possible and were allowed to work on each form for 20 s. The score for this task was the number of correctly connected items averaged across all eight forms.

3. Inhibitory ability

A computerized version of a Stroop task (Jesse and Janse, 2012) was used as an index of inhibitory ability. Participants viewed colored rectangles that contained either an ambiguous text string ("###") or a color name (red, blue, or green) that was not the color of the rectangle. They were instructed to name the color of the rectangle as quickly as possible. Participants' verbal responses were picked up by a head-worn microphone and were recorded onto a PC. After eight practice trials, 100 experimental trials were presented in interspersed fashion, with half containing ambiguous text and half color names. An experimenter who was blinded to trial type measured onset of the participants' verbal response time for each trial from the audio recordings of subjects' responses. The waveforms of these recordings were displayed using an audio editing program. Response time was measured from these waveforms as the time between the onset of presentation of the rectangle to the onset of the subject's verbal response. Trials that were incorrect or that contained non-word utterances at the onset (e.g., "uh...") were not scored. The Stroop effect score was computed as the difference in mean response time for each subject's ambiguous vs incongruent trials.

C. Self-assessed hearing

In order to gain insight into real-life speech understanding problems, participants rated aspects of their hearing

ability via five items from the SSQ (Gatehouse and Noble, 2004). This questionnaire uses an 11-point rating scale, where 0 implies so much difficulty in the given situation that it cannot be performed and 10 is perfect self-perceived performance. The Appendix displays the actual questions used in this study. Specific items chosen were those that tap into performance in competing speech situations.

D. Speech understanding

Stimuli for this study included a revised version of the Theo-Victor-Michael (TVM) sentences (Helfer and Freyman, 2009). These sentences take the form “Cue name discussed the ____ and the ____ today” where cue name is Theo, Victor, or Michael and the blanks are common one- or two-syllable nouns used for scoring. The revised version of the corpus contains sentences in which both keywords in each sentence have the same number of syllables (either one or two). All keywords were commonly used nouns, mostly from the Thorndike-Lorge lists (Thorndike and Lorge, 1952). Sentences were audio recorded from four female talkers who were instructed to speak in a conversational manner but were also told to attempt to put equal emphasis on each of the two scoring words. Recordings were made in a sound-treated audiometric chamber. The output from a remote microphone was routed to a preamplifier (PreSonus TubePre) then to the input of a PC. Each sentence was excised, saved in a file, then equalized for rms amplitude. Two college-aged adults listened to each sentence to verify intelligibility; sentences in which the keywords were not identifiable were re-recorded. Recordings of each of the four talkers reading the Rainbow Passage (Fairbanks, 1960) also were made using the same instructions (that is, to speak in a conversational manner) and the same equipment.

The target signal for this experiment was always a TVM sentence beginning with the cue name “Theo,” which was spoken by a talker randomly selected from trial to trial. Target TVM sentences were presented in the presence of five types of maskers: A single competing TVM sentence; two TVM sentences; one randomly selected segment of the Rainbow Passage; two different segments of the Rainbow Passage; and steady-state speech-shaped noise derived from sentences recorded from one of the talkers. In cases where one or two TVM sentences were the maskers, masking sentences had keywords with the same number of syllables as in the target TVM sentence. On each trial, different talkers were used for the target and for the one or two masking utterances. Target and maskers began simultaneously and ended at approximately the same time. TVM sentences used as maskers started with either “Victor” or “Michael.” Rainbow Passage segments were selected randomly by a computer program without regard to whether or not the start of the segment was at the beginning of a sentence. These maskers were intended to be less confusable with the target speech (as compared to the TVM maskers) because they had a different (and variable) syntactic structure.

Target and masking stimuli were presented from a single loudspeaker located 1.3 m from the listener at a height approximating that of a seated adult (1.2 m). Target

sentences were presented at an average RMS of 68 dB A. Three SNRs were used: -3 dB, 0 dB, +3 dB. It should be noted that the SNRs are expressed in relation to the total masker energy. For example, in the 0 dB SNR/one-talker masker condition, both the target and the masking sentence were presented at 68 dBA; in the two-talker masker condition at 0 dB SNR, the target was presented at 68 dBA while each individual masker was presented at 65 dBA (so the combined two-talker masker was 68 dBA). Presentation was blocked by masker type and each participant heard the sentences presented in one of 15 randomized orders of the blocks. Each block contained 50 trials (100 scoring words). Before data collection began, a practice block of 12 trials was completed. Participants responded verbally and an experimenter scored the responses in real-time using a customized program.

III. RESULTS

A. Cognitive functioning, hearing thresholds, and self-perceived hearing

Group results for each of the cognitive measures, the better-ear high-frequency pure-tone average (2, 3, 4, and 6 kHz) and the average rating for the five SSQ items are displayed in Table I. Analysis of Variance (ANOVA) indicated statistically significant group differences for each of these indices, with *p* values <0.01. *Post hoc* testing (using Bonferroni correction for multiple comparisons) found that older and younger groups differed significantly for each of these measures (LNSe: *p* = 0.020; LNSc: *p* = 0.002; Stroop: *p* = 0.002; Connections: *p* = 0.006). Additionally, middle-aged subjects had significantly larger Stroop interference values (*p* = 0.004) and significantly more self-reported hearing difficulty (*p* = 0.035) as compared to younger participants. There also were significant differences between the middle-aged and younger (*p* = 0.002), and middle-aged and older (*p* = 0.011) groups for the better-ear high frequency average. It should be noted that there were no significant differences between older and middle-aged adults on any of the cognitive abilities measured in this study.

TABLE I. Mean values (and standard errors in parentheses) for the hearing, cognitive, and self-reported hearing problem indices.^{a)}

	Younger	Middle-Aged	Older
Better-ear HFPTA (dB HL)	3 (0.9)	15 (2.2)	25 (3.9)
LNSe (# items correct)	17.87 (0.87)	15.80 (0.71)	14.67 (0.79)
LNSc (# items correct)	21.07 (0.68)	18.47 (0.98)	16.60 (0.91)
Stroop effect (sec.)	0.096 (0.012)	0.151 (0.008)	0.156 (0.014)
Connections (# items connected)	25.51 (1.08)	21.29 (1.04)	19.64 (1.61)
SSQ average score	7.9 (0.3)	6.2 (0.5)	5.7 (0.6)

^{a)}LNSe is a measure of auditory working memory; LNSc is an index of auditory short-term memory; Stroop effect is a measure of inhibitory ability (smaller values = better inhibitory ability); Connections measures processing speed (higher values = faster processing speed); and SSQ is self-reported hearing problems as measured by selected items from Gatehouse and Noble (2004) (larger values = less self-perceived difficulty). Values in parentheses are standard errors.

B. Accuracy of keyword identification

Figure 2 shows the percentage of keywords correctly identified by each subject group in the presence of each type of masker. It can be observed that there was an orderly progression of performance accuracy from younger to middle-aged to older adults, and from better SNRs to poorer SNRs, for all masker types. The percent-correct scores were converted to Rationalized Arcsine Units (RAU; Studebaker, 1985) prior to analysis. Repeated-measures analysis of variance (ANOVA) with SNR and masker type as within-subjects variables and group as a between-subjects variable was completed. The main effects of SNR [$F(2, 42) = 1270.27$, $p < 0.001$], masker type [$F(2, 42) = 500.03$, $p < 0.001$], and group [$F(2, 42) = 25.44$, $p < 0.001$] were significant, as were all two-way interactions [masker type $\times$ group: $F(4, 42) = 2.95$, $p = 0.005$; SNR $\times$ group: $F(4, 42) = 3.19$, $p = 0.021$; masker type $\times$ SNR: $F(4, 42) = 26.72$, $p < 0.001$]. The three-way interaction did not reach statistical significance. *Post hoc* testing (using Bonferroni correction) on the group $\times$ masker type interaction showed statistically significant ($p < 0.01$) differences between the older and younger groups for all types of maskers, as well as significant differences between the middle-aged and younger groups for all conditions except steady-state noise ($p < 0.01$ for both TVM maskers and for the single Rainbow Passage masker, $p = 0.012$ for the two Rainbow Passage masker). Differences between the older and middle-aged groups were significant for both two-talker maskers (TVM: $p = 0.019$; Rainbow passage: $p = 0.005$) but failed to reach statistical significance for the single-talker maskers or for the noise masker.

Performance also was examined in terms of SNR necessary to achieve a given level of performance. This was done by visually examining the psychometric functions in Fig. 2. As has been noted in other competing speech tasks (e.g., Li *et al.*, 2004), older participants needed approximately 3 dB better SNR (as compared to younger adults) when the masker consisted of either two TVM sentences or two Rainbow passage segments. However, with a single TVM masker, the difference between older and younger participants at the 50% point was somewhat larger (approximately 5 dB). We were unable to examine performance at the 50% point for a single Rainbow Passage masker, but the approximate 5 dB difference in SNR between these two groups can be observed at the 80%-correct point on that function. It should be noted that the relatively shallow slopes of the psychometric functions with single maskers (TVM sentences, Rainbow Passage segments, and steady-state noise) should be taken into account when considering these comparisons, as gradual slopes tend to exaggerate differences across conditions when comparing SNRs for a criterion level of performance. It should be noted, however, that the same patterns of group differences emerge whether the comparisons between one vs two maskers is made in terms of percent-correct at discrete SNRs or in terms of SNRs for criterion performance.

Another noteworthy finding is how the middle-aged subjects performed in relation to that of the other two groups. In terms of either percent-correct scores or SNR for criterion performance, the middle-aged subjects' data fell essentially halfway between that of the older and younger groups for both types of two-talker maskers. However, in the presence

FIG. 2. Percent-correct performance measured in the presence of each type of masker. Error bars represent 1 standard error.

of the single TVM masker, middle-aged participants performed more similarly to the older adults than to younger listeners. In the presence of steady-state speech shaped noise, the middle-aged listeners' performance was actually more similar to that of the younger subjects than to that of the older participants.

The goal of this study was to examine how the effect of changing from one to two maskers, and from more confusable to less confusable maskers, differed among the listener groups. We calculated difference scores from percent-correct performance (averaged across SNR) for one vs two maskers for the TVM and Rainbow Passage competition. Recall that our experimental procedure adjusted for the increase in masker energy that occurs from adding a second masker (that is, the overall masker energy at a given SNR was the same for one vs two maskers). We also examined the difference in performance in the presence of a speech masker vs that in steady-state noise, for each of the two types of speech maskers, as well as the difference between Rainbow Passage and TVM maskers. Figure 3 displays these difference scores.

For all groups, the most substantial difference in performance was found between the steady-state noise masker and the single TVM masker. This difference was considerably larger for middle-aged and older participants than for younger participants. Differences between one and two speech maskers were comparable for TVM maskers and Rainbow passage maskers for all participant groups, with the contrast between one and two TVM maskers largest for the younger participant group. The difference between TVM and Rainbow Passage maskers also was about the same for one-talker and two-talker competition.

C. Error patterns

We examined error patterns in trials using the TVM maskers, specifically the percentage of all responses that were words from a masker. These masker error responses can be seen in Fig. 4. It should be noted that there were other types of error responses (e.g., random words, errors of omission) which were not analyzed because they were tangential to the goal of examining confusability between target and masking speech. Interestingly, different patterns of results

FIG. 3. Difference in percent-correct performance between one and two maskers, averaged across SNR. Error bars represent 1 standard error.

FIG. 4. Percentage of all participant responses in the TVM masking conditions that were words from a masker rather than from the target utterance. Error bars represent 1 standard error.

were seen when there was one vs two maskers. In the presence of a two-talker masker, younger listeners made more masker errors (as compared to the other two groups), especially at the poorest SNR. However, this pattern was reversed in the presence of a single TVM masker, where, in general, older and middle-aged participants made more masker errors than younger subjects. This observation was verified with a repeated-measures ANOVA that showed significant (<0.001) effects of masker type [$F(2, 42) = 134.48$], SNR [$F(2, 42) = 339.08$], masker type $\times$ group [$F(4, 42) = 21.11$], masker type $\times$ SNR [$F(4, 42) = 11.78$], and masker type $\times$ group $\times$ SNR [$F(4, 42) = 5.03$].

In order to produce a masker error, subjects needed to be able to understand the individual words within the masker. It is possible that older and middle-aged listeners made fewer masker errors in the two-masker condition because they were less likely to correctly perceive these words. In order to examine this, we identified responses that were considered masker approximations—trials on which subjects were clearly making a response that was phonetically similar to one of the masker words, rather than to a target word. In most cases, these masker approximations were lexical neighbors of a word in the masker (e.g., “rail” for “hail”) or were words that rhymed with but were not exact lexical neighbors of the masker (e.g., “firm” for “burn”). Figure 5 displays how often masker approximations were noted for each group, averaged

FIG. 5. Percentage of all participant responses in the TVM masking conditions (averaged across SNR) that were masker approximations (typically, lexical neighbors of a word in the masker). Error bars represent 1 standard error.

across SNR. ANOVA on these data showed a significant group difference for the one-TVM masker trials [$F(2, 42) = 4.92, p = 0.012$], for which older adults were more likely to make masker approximations than were younger participants. Hence, with a single TVM masker, older listeners were more likely to respond with an actual masker word or with a word that was phonetically similar to the masker. However, older and middle-aged adults were no more likely to make these responses than were younger listeners in the presence of two competing sentences.

D. Individual differences in performance

In order to identify the associations among speech understanding, hearing loss, and cognitive skills, Pearson r correlations were run on the data from the 30 middle-aged and older participants. This analysis used the following variables: The RAU transformed percent correct scores averaged across SNR for each masker (one TVM, two TVM, one Rainbow Passage, two Rainbow Passages, SSN); the percentage of masker errors in the -3 dB SNR condition for the one- and two-talker TVM maskers; better-ear HFPTA; age; LNSE (working memory); LNSc (short-term memory); Stroop difference score (inhibition); Connections (processing speed/executive function); and averaged SSQ score. The correlation matrix can be found in Table II.

This analysis showed that better-ear high-frequency hearing was significantly associated with each of the cognitive measures except for the Stroop score, as well as with accuracy scores in all conditions and with the percentage of masker errors in the presence of the two-talker TVM masker. It should be noted that the connection between age-related hearing loss and cognition is well-established (e.g., Baltes and Lindenberger, 1997; Humes *et al.*, 2013; Lin *et al.*, 2011). Each of the corresponding r values was negative, indicating that greater hearing loss was associated with poorer speech

understanding and poorer cognitive functioning, but fewer masker errors in the two-talker condition. Age also was moderately correlated with HFPTA ($r = 0.46$) and was associated with each of the accuracy scores as well as with the proportion of masker errors in the two-talker masker. Within this sample of middle-aged and older adults, age was not significantly correlated with any of the measured cognitive skills.

Several associations were noted between speech understanding and cognitive tests. Short-term memory (LNSc) was correlated with performance in the two-talker TVM masker; the working memory index (LNSe) was not significantly associated with speech recognition. The Connections test score was significantly correlated with performance with both one- and two TVM maskers as well as with one Rainbow Passage masker, while the Stroop interference effect was not significantly associated with any of the accuracy measures. However, percentage of masker errors in the two-talker masker was related to both the Stroop effect and to LNSc scores. These associations were in a perhaps unexpected direction, as participants with better short-term memory (high LNSc scores) and better inhibitory ability (smaller Stroop effects) made more masker errors; one might expect that individuals with better short-term memory would make fewer errors of any type because they would be better able to remember the target words. Finally, self-perceived hearing difficulty (as measured by selected items from the SSQ) was significantly associated with performance in the presence of one or two Rainbow Passage maskers, but not with performance in the presence of TVM maskers.

IV. DISCUSSION

A. Number of masking talkers

Results of this study show a clear effect of aging on the ability to understand the speech of one talker in the presence

TABLE II. Results of Pearson r correlation analysis on data from the 30 middle-aged and older participants.^{a)}

	Age	HFHL	1TVM	2TVM	1RB	2RB	SSN	LSNe	LNSc	Connx	Stroop	MErr1	MErr2	SSQ
Age	—	0.46**	-0.51**	-0.65**	-0.49**	-0.52**	-0.50**	-0.26	-0.21	-0.25	0.23	0.10	-0.43*	-0.14
HFHL		—	-0.63**	-0.75**	-0.67**	-0.74**	-0.51**	-0.45**	-0.42**	-0.37*	0.35	-0.11	-0.51**	-0.30
1TVM			—	0.79**	0.88**	0.71**	0.39*	0.32	0.35	0.45*	-0.25	0.01	0.42*	0.21
2TVM				—	0.79**	0.79**	0.57**	0.27	0.42*	0.42*	-0.17	0.11	0.57**	0.35
1RB					—	0.87**	0.53**	0.22	0.28	0.40*	-0.29	0.18	0.48**	0.37*
2RB						—	0.49**	0.22	0.33	0.26	-0.25	0.29	0.49**	0.42*
SSN							—	0.16	0.30	0.31	-0.03	0.10	0.42*	0.24
LNSe								—	0.78**	0.56**	-0.43*	-0.41	0.29	0.16
LNSc									—	0.59**	-0.30	0.11	0.37*	0.28
Connx										—	-0.36	-0.19	0.30	0.33
Stroop											—	-0.03	-0.38*	-0.31
MErr1												—	0.32	0.07
MErr2													—	0.14
SSQ														—

^{a)}HFHL = better-ear high-frequency pure-tone average; 1TVM and 2 TVM = accuracy (in RAU) for one TVM masker and two TVM maskers, respectively; 1RB and 2 RB = accuracy (in RAU) for one Rainbow Passage masker and two Rainbow Passage maskers, respectively; SSN = accuracy (in RAU) in the presence of steady-state noise. Each accuracy score was averaged across the three SNRs. LNSe and LNSc = working memory and short-term memory, respectively; Connx = processing speed; Stroop = inhibitory ability; MErr1 and MErr2 = percentage of all responses that were words from the masker in one-TVM and two-TVM masking conditions at -3 dB SNR, respectively; SSQ = self-perceived hearing difficulty.

* = significant at the 0.05 level;

** = significant at the 0.01 level.

of one or more messages from same-sex competing talkers. This has been observed in a number of previous studies (Anderson *et al.*, 2013; Desjardins and Doherty, 2013; Helfer *et al.*, 2010; Helfer and Freyman, 2008; Humes and Coughlin, 2009; Humes *et al.*, 2006; Lee and Humes, 2012; Mackersie *et al.*, 2001; Neher *et al.*, 2012; Rossi-Katz and Arehart, 2009; Tun *et al.*, 2002; Tun and Wingfield, 1999; Woods *et al.*, 2013). As is the case in most previous work, age-related hearing loss is an important determinant of age-related changes in speech understanding. One new finding in the present study is that the magnitude and the nature of these changes differ depending on the number of masking talkers. The presence of a single same-sex masking voice appears to be particularly difficult for older adults, as compared to younger listeners. Differences between older and younger listeners were larger in the presence of a one-talker masker than with a two-talker masker, confirming results found by Tun and Wingfield (1999) using opposite-sex target and masking talkers. Moreover, the difference in performance between a one-talker masker and a steady-state noise masker having the same energy was larger for our older than for our younger participants.

Some proportion of these age-related changes is undoubtedly due to the hearing loss that accompanies aging. However, our results also could suggest that older adults experience greater lexical interference from the presence of a single competing message. The finding that, as compared to younger participants, older and middle-aged adults made more masker errors and more masker approximations in the presence of a single masking talker supports the idea that they were experiencing difficulty inhibiting the masking signal. Other studies using closed-set competing speech tasks have not found age-related differences in the proportion of masker errors (Humes *et al.*, 2006; Lee and Humes, 2012), who found that older adults made more masker errors than younger adults only when there was relatively large onset asynchrony between the target and masker). We do not know *why* the participants in our study responded with words from the to-be-ignored stream. It is possible that, when faced with the choice of either not responding at all or making a response, participants repeated any word they heard, regardless of whether or not it was in the target sentence. Nevertheless, other data from our lab using tasks that minimize the effect of energetic masking support the idea that older listeners experience greater lexical interference from a single-talker masker. Helfer *et al.* (2013) used a temporally interleaved sentence task which essentially eliminated energetic masking. Although younger and older adults performed similarly on trials with no interleaved words, older adults were at a substantial disadvantage when they had to ignore the intervening speech. In an eye-tracking paradigm that used dichotic listening, Helfer and Staub (2014) also demonstrated that older adults were affected to a greater extent by the presence of a single unattended speech message, as compared to younger listeners.

The detrimental effect of adding a second masking talker was larger for our younger than for our older subjects, especially for the more-confusable TVM maskers. For example, the difference between performance in the presence of a single TVM masker vs that in the two-talker TVM masker, averaged across SNR, was 10–11 percentage points for

middle-aged and older listeners, but 17 percentage points for younger participants. We believe that this was due, at least in part, to the fact that our younger participants were able to benefit from the spectrotemporal gaps in the single-talker masker, which were obscured by the addition of a second masking voice. Based on previous research (e.g., Festen and Plomp, 1990; Summers and Molis, 2004; Takahashi and Bacon, 1992; Vongpaisal and Pichora-Fuller, 2007), we assume that our older participants were less able to use gaps in the single-masker condition, so the obscuring of these gaps by a second masking voice did not lead to as much of a reduction in performance. However, if differences between groups were due only to a reduced ability to use gaps in a masking signal, we would have expected to see younger adults having a greater difference than older participants between the speech maskers and the steady-state noise masker—and the opposite was found.

A second potential reason why our younger listeners were more affected by the addition of a second competing speech signal is that they were better able to understand individual words in the two-talker masking complex, thereby leading to greater lexical interference. Examination of psychometric functions, masker errors, and correlation results all support this idea. The fact that the decline in performance from adding a second masker was greater for the more confusable TVM maskers than for the Rainbow Passage maskers with these listeners suggests that lexical interference played a role in performance. Younger adults made more masker errors than older listeners in the presence of the two-talker masker and, among middle-aged and older participants, proportion of masker errors in the two-talker condition was negatively associated with both age and amount of hearing loss. However, degree of hearing loss did not account for individual variability in the difference between one and two maskers, which might have been expected if a decrease in lexical interference from an inability to understand the maskers contributed to middle-aged and older participants' performance.

B. Potential confusability between target and masking speech

Substantial differences were found between accuracy scores obtained in the presence of the two types of maskers (TVM sentences and Rainbow Passage segments). These differences, averaged across SNR, were 24–27 percentage points for one-talker maskers and 23–24 percentage points for two-talker maskers. Iyer *et al.* (2010) found similarly large differences in a closed-set task of speech recognition. Recall that, in the present study, the same talkers were used for both types of maskers, so these substantial differences cannot be explained by voice characteristics such as F0. The primary differences between the two speech maskers were in how they were presented and their syntactic structure. For the Rainbow Passage maskers, a section of the ongoing recording was randomly selected, which began anywhere within a sentence, while the TVM maskers for a given trial were discrete sentences that began at the same time as the target. The TVM maskers were syntactically identical to the (TVM) target sentences, and, therefore, were likely more

confusable. Notably, the magnitude of the TVM/Rainbow Passage difference was similar among subject groups, supporting the idea that some aspects of informational masking are resistant to age-related change (Agus *et al.*, 2009; Li *et al.*, 2004). Although our results appear to be in contrast to some work suggesting that older adults are less able to take advantage of differences between target and masker (Helfer and Freyman, 2009; Humes and Coughlin, 2009; Lee and Humes, 2012; Rossi-Katz and Arehart, 2009), in the present study the nature of the differences between maskers was more subtle than those used in other studies (e.g., male vs female talkers, or normally presented vs time-reversed speech). It also is possible that the moment-to-moment amount of energetic masking was greater for TVM maskers because the target and masking words were time-aligned to a larger extent for this type of competition (as compared to the Rainbow Passage masker), complicating a purely top-down explanation for the large differences between maskers.

C. Associations between speech recognition, hearing loss, and cognitive abilities

Correlation analyses performed on data from the middle-aged and older adults indicated that both age and degree of hearing loss were associated with accuracy of word identification in the presence of each type of masker. Moreover, high-frequency hearing loss was related to three out of the four cognitive variables. Among the middle-aged and older adults, working memory (as measured by the LNSe task) was not associated with competing speech perception, consistent with findings from several studies (Desjardins and Dougherty, 2013; Helfer *et al.*, 2013; Humes and Coughlin, 2009; Humes *et al.*, 2006; Woods *et al.*, 2013) but at odds with a number of others (Anderson *et al.*, 2013; Koelewijn *et al.*, 2012; Neher *et al.*, 2012). It is likely that differences in the specific tests used to measure working memory contributed to this variability in results. In the present study, short-term memory (as quantified by the LNSe) was associated with both percent-correct performance and with the proportion of masker errors for the two-talker TVM masker; participants with better short-term memory had more accurate performance but also made more masker errors. Our tentative explanation is that individuals with better short-term memory were able to remember more words from the entire target/masker complex but had difficulty determining which were from the target and which were from the masker. Perhaps consistent with this finding, a recent report by Zekveld *et al.* (2013) noted that individuals with larger working memories have more self-reported problems with speech understanding in noise.

Other cognitive abilities measured in this study (inhibitory ability, as measured by the Stroop task and processing speed/executive functioning, assessed using the Connections test) were associated with some aspect of performance among middle-aged and older participants. A significant correlation was found between the Stroop effect and masker errors in the two-talker condition, but in perhaps an unexpected direction: Individuals with better inhibitory ability made more masker errors. Our expectation was that stronger inhibition would

make it easier to ignore words in the competing message. The cognitive variable that appeared most important for word identification was processing speed/executive function, which was significantly correlated with percent-correct scores in both one-talker maskers as well as in the two-talker TVM masker. Several other studies using versions of trail-making tests (as is the Connections test used in the present study) also found significant associations with competing speech perception (Anderson *et al.*, 2013; Desjardins and Dougherty, 2013; Tun *et al.*, 2002; Tun and Wingfield, 1999) and a recent longitudinal study found that processing speed accounted for a significant proportion of age-related changes in speech recognition in noise (Pronk *et al.*, 2013). It should be noted that processing speed is not only a proxy for how fast individuals can carry out mental operations in the time domain (such as understanding a rapidly changing speech waveform); it also is thought to be involved in other aspects of cognitive aging (e.g., Salthouse, 1996).

D. Real world speech recognition in midlife and beyond

One important finding in terms of translating our results to real-life listening was uncovered in how performance related to self-perceived hearing problems as measured by selected items from the SSQ. Among the middle-aged and older subjects, self-perceived problems were significantly associated with how accurately individuals could understand target speech in the presence of either the one- and two-talker Rainbow Passage maskers, but not in the presence of TVM maskers. Masking by the Rainbow Passage segments likely reflects the more realistic situation of competing messages that are not time-aligned with the message of interest. This finding warrants further investigation as we move toward developing laboratory-based measures that are better able to relate to real-life communication performance.

Our results clearly show that changes in the ability to successfully negotiate difficult competing speech situations are apparent by middle age. Although performance by the middle-aged participants in the present study fell between that of younger and older subjects, it was closer to that of the older group in most masker conditions. Moreover, as a group, middle-aged participants indicated substantial real-world problems on the SSQ questions. A number of other studies also have found functional auditory changes that begin in middle age (e.g., Demeester *et al.*, 2012; Grose *et al.*, 2006; Gross and Mamo, 2010; Helfer and Vargo, 2009; Koelweijn *et al.*, 2012; Ross *et al.*, 2007; Schwartz *et al.*, 2008; Wambacq *et al.*, 2009; Zekveld *et al.*, 2011). Larger-scale studies of middle-aged adults would be helpful in teasing out the relative contributions of hearing loss and cognition to these changes.

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APPENDIX

Selected questions from the SSQ (Gatehouse and Noble, 2004) used in the present study.

You are talking with one other person. There is continuous background noise, such as a fan or running water. Can you follow what the person says?

0	1	2	3	4	5	6	7	8	9	10
Not at all					Perfectly					

You are listening to someone talking to you, while at the same time trying to follow the news on TV. Can you follow what both people are saying?

0	1	2	3	4	5	6	7	8	9	10
Not at all					Perfectly					

You are in conversation with one person in a room where there are many other people talking. Can you follow what the person you are talking to is saying?

0	1	2	3	4	5	6	7	8	9	10
Not at all					Perfectly					

You are listening to someone on the telephone and someone next to you starts talking. Can you follow what's being said by both speakers?

0	1	2	3	4	5	6	7	8	9	10
Not at all					Perfectly					

Can you easily ignore other sounds when trying to listen to something?

0	1	2	3	4	5	6	7	8	9	10
Not easily ignore					Easily ignore					

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