

Effects of Age and Working Memory Capacity on Speech Recognition Performance in Noise Among Listeners With Normal Hearing

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Objectives: This study aimed to determine if younger and older listeners with normal hearing who differ on working memory span perform differently on speech recognition tests in noise. Older adults typically exhibit poorer speech recognition scores in noise than younger adults, which is attributed primarily to poorer hearing sensitivity and more limited working memory capacity in older than younger adults. Previous studies typically tested older listeners with poorer hearing sensitivity and shorter working memory spans than younger listeners, making it difficult to discern the importance of working memory capacity on speech recognition. This investigation controlled for hearing sensitivity and compared speech recognition performance in noise by younger and older listeners who were subdivided into high and low working memory groups. Performance patterns were compared for different speech materials to assess whether or not the effect of working memory capacity varies with the demands of the specific speech test. The authors hypothesized that (1) normal-hearing listeners with low working memory span would exhibit poorer speech recognition performance in noise than those with high working memory span; (2) older listeners with normal hearing would show poorer speech recognition scores than younger listeners with normal hearing, when the two age groups were matched for working memory span; and (3) an interaction between age and working memory would be observed for speech materials that provide contextual cues.

Design: Twenty-eight older (61 to 75 years) and 25 younger (18 to 25 years) normal-hearing listeners were assigned to groups based on age and working memory status. Northwestern University Auditory Test No. 6 words and Institute of Electrical and Electronics Engineers sentences were presented in noise using an adaptive procedure to measure the signal-to-noise ratio corresponding to 50% correct performance. Cognitive ability was evaluated with two tests of working memory (Listening Span Test and Reading Span Test) and two tests of processing speed (Paced Auditory Serial Addition Test and The Letter Digit Substitution Test).

Results: Significant effects of age and working memory capacity were observed on the speech recognition measures in noise, but these effects were mediated somewhat by the speech signal. Specifically, main effects of age and working memory were revealed for both words and sentences, but the interaction between the two was significant for sentences only. For these materials, effects of age were observed for listeners in the low working memory groups only. Although all cognitive measures were significantly correlated with speech recognition in noise, working memory span was the most important variable accounting for speech recognition performance.

Conclusions: The results indicate that older adults with high working memory capacity are able to capitalize on contextual cues and perform as well as young listeners with high working memory capacity for sentence recognition. The data also suggest that listeners with normal hearing and low working memory capacity are less able to adapt to distortion of speech signals caused by background noise, which requires the allocation of more processing resources to earlier processing stages. These results indicate that both younger and older adults with low working

memory capacity and normal hearing are at a disadvantage for recognizing speech in noise.

Key Words: Aging, Speech recognition in noise, Working memory.

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INTRODUCTION

Because speech manifests itself as a rapid, time-varying signal, the listener's ability to follow the peaks and troughs of the signal and simultaneously store and process incoming information are critical for accurate recognition. Older listeners with and without hearing loss demonstrate a disproportionate decline in speech recognition compared with younger listeners when the signal is presented in background noise (e.g., Dubno et al. 1984; Pichora-Fuller et al. 1995; Stuart & Phillips 1996). In general, it is assumed that the age-related decrement in speech recognition in noise reflects reduced audibility of critical speech information, secondary to physiological changes in the peripheral auditory system (Humes 2002; Humes & Dubno 2010) and deficits in temporal resolution and temporal patterning of speech in a time-varying noise background (Gifford et al. 2007), the locus of which may be the central auditory nervous system (Schneider & Pichora-Fuller 2001; Anderson et al. 2012). However, declines in the peripheral and central auditory system do not fully account for the variance in speech recognition abilities among older hearing-impaired and normal-hearing listeners who have trouble understanding speech in noisy conditions (Pichora-Fuller 2003). These results have led researchers to study the association between age-related changes in cognitive processes and speech perception in everyday listening environments.

Working memory (WM) is conceptualized as a dual-function cognitive system in which recent visual-spatial, phonological, and episodic information is stored and manipulated temporarily until new input is either forgotten or consolidated into long-term memory (Lunner & Sundewall-Thoren 2007; Wingfield & Tun 2007; Baddeley 2012), while verbal information processing speed (PS) relates to the rate with which lexical information can be accessed (Baddeley 2012). These cognitive abilities are thought to support online language processing, which involves a sequence of phonological analysis, lexical identification, syntactic resolution, and integration of phrases and clauses to understand the meaning of the spoken message, all of which is conducted on a transient signal presented at fast rates (Wingfield & Tun 2007). However, the resources available to accomplish this task are finite, and thus an individual must allocate their limited resources among the competing demands of attention, processing, and storage to understand speech in complex situations (Wingfield & Tun 2007). Numerous studies in the

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field of cognitive hearing science have reported that PS (Waters & Caplan 2001; Brébion 2003) and WM capacity (Wingfield & Tun 2001; Vaughan et al. 2006; Rönnberg et al. 2013) as well as selective attention (McCoy et al. 2005) are necessary for the linguistic analysis of speech under adverse listening conditions. Changes in these cognitive domains are hallmarks of aging (Wingfield & Tun 2001; Park et al. 2002; Vaughan et al. 2006), suggesting that more limited processing resources are available in older than younger listeners for processing speech in challenging listening situations. Additionally, individuals with hearing loss will have more demands placed on their cognitive resources, relative to normal-hearing listeners because the acoustic signal being processed is degraded by reduced audibility and poorer spectral resolution. The challenges to the speech processing task are exacerbated further in noise when the listener must perceptually segregate the signal from the background noise and focus attention on the target spoken message. The interplay between WM, language processing in noise, and hearing impairment is clarified by the Ease of Language Understanding (ELU) model (Rönnberg et al. 2008, 2013), which specifies that WM is strongly associated with language processing among normal-hearing and hearing-impaired individuals when speech is masked by noise. The model suggests that in these adverse listening conditions, WM enables the listener to maintain a mental representation of speech while processing context and using knowledge of the language to fill in gaps in the information perceived. However, when there is limited WM capacity and processing demands are exceeded because the acoustic signal is impoverished through background noise or hearing impairment, speech recognition will be compromised. Empirical support for the ELU Model derives from studies showing strong associations between verbal WM and speech recognition in fluctuating noise among hearing-impaired listeners (Akeroyd 2008; Besser et al. 2013), including among older hearing-impaired listeners while using amplification (Foo et al. 2007; Lunner & Sunderwall-Thoren 2007; Rudner et al. 2011).

Previous investigations of the links between WM capacity and speech recognition have used a wide range of speech stimuli, including high and low context sentences (Lunner 2003; Vaughan et al. 2006; Foo et al. 2007; Lunner & Sunderwall-Thorn 2007; Rudner et al. 2011), words (Gatehouse et al. 2006a, 2006b), and nonsense syllables (Humes & Floyd 2005). The extent of phonological, lexical, syntactic, and semantic information for speech processing differs between these stimuli, and it may be expected that the advantage provided by top-down processes such as WM to facilitate speech processing varies with the redundancy of linguistic cues inherent in a specific speech stimulus. In particular, older adults take considerable advantage of contextual cues to improve speech understanding in challenging listening situations (Pichora-Fuller et al. 1995). Thus, it is possible that the impact of an older individual's WM ability to support speech understanding in noise will depend on the nature of the speech stimulus and the availability of contextual cues.

While the correlation between speech recognition in complex listening conditions and cognitive abilities for older hearing-impaired listeners with and without amplification has been established (Lunner 2003; Gatehouse et al. 2006a, 2006b; Craik 2007; Foo et al. 2007; Lunner & Sunderwall-Thoren 2007), previous studies often tested older listeners with typical age-related cognitive decline (Park et al. 2002) and some degree of

age-related hearing loss. Control groups of younger listeners who were well matched for *both* hearing sensitivity and cognitive abilities to the older listeners were often not included in prior investigations. Thus, it is difficult to discern if the observed speech recognition problems in noise were associated with domain-specific age-related cognitive decline (e.g., WM), mild age-related hearing loss, or some other aspect of aging such as decline in auditory temporal processing. At least one recent study examined the relationship between speech recognition in noise and cognitive abilities (including WM) for younger and older listeners with normal hearing who were matched for years of education but not cognitive ability (Füllgrabe et al. 2015). The findings showed that the older listeners performed more poorly than the younger listeners on the speech recognition measures in noise as well as on numerous cognitive tests, including WM. However, an association between speech recognition performance in noise and performance on measures of WM was not observed. This study illustrates the need to control for both hearing sensitivity and WM to clarify the contribution of WM capacity to speech recognition performance in noise by younger and older listeners. The goal of the current experiment was to use careful controls of hearing sensitivity and WM capacity in participants assigned to younger and older listener groups to examine the separate effects of age and cognitive abilities (especially WM) among individuals with normal-hearing sensitivity. It is well established that there are substantial individual differences in WM capacity (Daneman & Carpenter 1980; Just & Carpenter 1992; Lunner & Sunderwall-Thoren 2007). Therefore, the measurement of interindividual differences on the same test of WM span and intraindividual differences on diverse measures of WM span may provide an understanding of the associations between reduced WM span and deficits in speech recognition among older listeners with normal hearing. This knowledge would assist in the selection of appropriate audiological/cognitive remediation techniques for individuals with particular auditory and cognitive profiles (see Pichora-Fuller 2007 for a more in-depth discussion of the value of measuring interindividual and intraindividual differences in WM span). The aim of the proposed research project is twofold: (1) to determine if there is an interaction between the effects of age and WM capacity on speech recognition in noise among listeners with normal hearing; and (2) to determine if this interaction is modulated by type of speech material (words versus sentences).

MATERIALS AND METHODS

Participants

A total of 28 older listeners with normal peripheral hearing sensitivity (ONH) and 25 younger listeners with normal peripheral hearing sensitivity (YNH) participated in the current investigation. Normal hearing was defined as pure-tone air conduction thresholds not greater than 20 dB HL from 250 to 6000 Hz in at least one ear (ANSI 2010). Performance on the Listening Span Test (LSPAN), a verbally mediated WM task, was used to assign the participants into subgroups based on WM span. The LSPAN was chosen for assigning participants to WM groups because at least one study has shown that it is more sensitive to age-related differences in WM than the Reading Span Test (RSPAN; Pichora-Fuller et al. 1995). Individuals assigned to the high WM groups performed in the upper half of the range

of LSPAN scores (scores of 5 to 8 correct) and those assigned to the low WM groups performed in the lower half of the LSPAN score range (scores of 1 to 4). The listeners were assigned to one of four subgroups: (1) young high WM (YHWM) included individuals aged 18 to 25 years ($n = 18$, mean age = 20.4, $SD = 2.33$), (2) young low WM (YLWM) consisted of individuals aged 18 to 24 years ($n = 7$, mean age = 20.4, $SD = 2.07$), (3) older high WM (OHWM) were aged 61 to 75 years ($n = 16$, mean age = 67.81, $SD = 3.69$), and (4) older low WM (OLWM) were aged 67 to 75 years ($n = 12$, mean age = 69.83, $SD = 2.79$).

Audiometric data for the better ear (test ear) of the four subgroups are shown in Figure 1. Other audiometric criteria consisted of monosyllabic word recognition scores in quiet of $>80\%$ (recorded version of the Central Institute for the Deaf W-22 word lists); tympanograms indicating a normal pressure peak, peak admittance, tympanometric width, and volume (Roup et al. 1998); acoustic reflex thresholds elicited at levels within the 90th percentile range for equivalent pure-tone thresholds (Silman & Gelfand 1981); and negative findings for acoustic reflex adaptation at 1000 Hz.

Participants were native speakers of American English. All listeners reported good health, with no known history of neuropathology that might compromise their ability to carry out the study task. They also reported normal uncorrected or corrected visual acuity. General cognitive awareness was screened using the Mini-Mental State Examination developed by Folstein et al. (1975). The participants were recruited for the study via flyers posted in the community, on the University of Maryland campus, and at private audiological practices. Individuals were paid \$10.00 per hour for their participation in this study. This study was approved by the University of Maryland Institutional Review Board for Human Subjects Research.

Neurocognitive Tests and Speech Stimuli

The experimental strategy was to measure WM span and PS using standardized measures. Both measures of cognitive function were assessed for verbal materials presented in the visual modality and the auditory modality. These modalities were

administered to allow for the measurement of possible intra- and intersensory performance differences.

WM Span • There are many versions of WM span tests, and they vary in the stimulus items to be recalled, the decision task, presentation, and scoring. Two tests of WM span were selected that use verbal materials but vary in the mode of presentation (auditory and visual). The specific tests were chosen on the basis of three criteria: computer administration for standardization of stimulus presentation, availability of normative data, and prior research confirming a correlation between performance on the specific test and speech recognition in noise. In addition, the versions of the two tests were as similar as possible in terms of response task (e.g., final word recall). Both of the selected measures of WM span tax memory storage and processing abilities, and, as noted above, they were selected to evaluate the relationship between WM abilities assessed in different modalities (auditory or visual) with speech recognition in noise.

Listening Span Test • WM span for verbal materials presented in the auditory mode was measured using a computerized version of the LSPAN, which was based on the task described by Daneman and Carpenter (1980). The task includes 111 declarative sentences (6 for practice trials and 105 for test trials), recorded by a female speaker. Each sentence includes 5 to 10 words, ends in a noun, and makes assertions that are obviously true or false. The sentences were grouped to create three sets of 2, 3, 4, 5, 6, 7, and 8 sentences. In this task, the participant was asked to listen to each sentence played from a personal computer through Logitech external speakers at a comfortable level and decide whether or not it was true. If the sentence was true, the participant pressed the “y” key on the keyboard and if the sentence was not true the participant pressed the “n” key on the keyboard. Each sentence was presented for 30 sec and advanced automatically. When the participant saw a blank box on the computer screen, he or she typed in the last word of each of the sentences that were heard in the set in the same order in which they were presented. If the participant could not remember a word, he or she typed in the word “blank.” Three practice trials with two-sentence sets were followed by the test trials, which began with two-sentence sets and continued until the participant failed to recall correctly the final words in the correct order of all sets at a particular level at which point testing was terminated. The primary outcome measure (LSPAN score) was the level at which a participant correctly recalled the final words on two out of three sets.

Reading Span Test • The RSPAN is a WM test designed to tax memory storage and processing simultaneously; it was selected to evaluate WM for verbal materials presented in the visual modality (i.e., written materials). The current version of the RSPAN was described by Rönnberg et al. (1989) and is a modification of the original test introduced by Daneman and Carpenter (1980). The listener’s task is to comprehend written sentences and to recall the final words of a presented sequence of sentences in correct serial order. Each sentence is presented for 30 sec and advanced automatically. Half of the sentences are absurd (e.g., “The train sang a song”), and half are normal sentences (e.g., “The girl brushed her teeth”). The listener’s task is to respond “yes” verbally (for a normal sentence) and “no” verbally (for an absurd sentence). After a sequence of sentences (two to eight sentences), the word “RECALL” appears on the computer screen, indicating that the participant should start to recall the final words of each previously presented sentence (in that sequence) in their correct serial order.

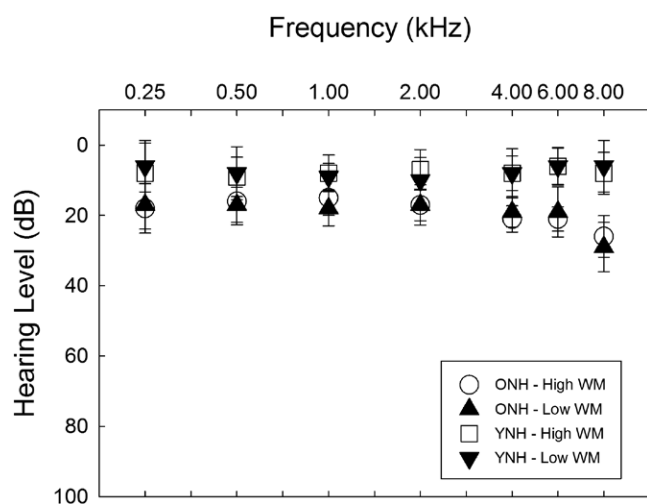


Fig. 1. Mean pure-tone air condition thresholds (dB HL) (± 1 SD) for the test ear of younger normal-hearing (YNH) and older normal-hearing (ONH) participants in each working memory group, plotted as a function of frequency (Hz).

The primary outcome measure (RSPAN score) was the level at which a participant correctly recalled two out of three sets. Data were not formally collected for the secondary task (“yes” for normal and “no” for absurd sentences).

PS Measures • Two measures were selected to assess PS for materials presented in the auditory modality and in the visual modality. Each measure has been standardized, and normative data are available.

Paced Auditory Serial Attention Test • The Paced Auditory Serial Attention Test (PASAT; Rao et al. 1989) is a measure of cognitive function that specifically assesses auditory PS. Single digits are presented in the auditory mode via computer every 3 sec, and the participant must sum the most recently presented digit to the one presented immediately before it as quickly as possible. The test score is the number of correct sums achieved out of 60 possible sums. The participant is provided one practice exercise before collection of experimental data.

The Wechsler Adult Intelligence Scale III (WAIS-III) Letter Digit Substitution Test • The Letter Digit Substitution Test (LDST; Wechsler 1997) is a speed-dependent task that taxes a number of neuropsychological functions, including visual scan, memory, learning, and mental flexibility, and overall is considered a test of PS (van der Elst et al. 2006). It is a paper-and-pencil test in which participants replace randomized letters with the appropriate digit indicated by a key provided at the top of the test sheet. The key gives the numbers 1 to 9, each paired with a different letter. The first 10 items are used as practice items to ensure that the participant understands the test instructions. After completion of the practice items, participants are instructed to replace the remaining items as quickly as possible. The number of correct substitutions made in 60 sec is the primary outcome measure.

Speech Recognition Measures

Two types of stimuli were used to assess speech recognition performance: monosyllabic words and sentences with limited contextual content. These stimuli were chosen to represent conventional speech stimuli utilized in the clinical setting, determine how perception of these widely used stimuli may be associated with cognitive abilities in older and younger listeners, and evaluate whether or not the availability of syntactic and semantic contextual cues affected performance patterns obtained from younger versus older listeners. Single-word stimuli were from the Northwestern University Auditory Test No. 6 (NU6) (Tillman & Carhart 1966), and the sentence stimuli were the Institute of Electrical and Electronics Engineers (IEEE) sentences (IEEE/Harvard 1969).

Monosyllabic Words • The monosyllabic words of the NU6 wordlists provide a good measure of basic auditory function because linguistic context is minimized, thereby requiring the listener to rely on acoustic cues of the target word to facilitate recognition. A pool of 100 phonemically balanced monosyllabic words from the NU6 wordlists was recorded by a young adult male speaker of American English. The recordings were made in a quiet room using a unidirectional Shure microphone (Model SM48) and a PC with Creative Soundblaster recording software. The stimuli were edited digitally, saved as separate .wav files, and equated for root mean square (rms) amplitude. Each test word was preceded by the carrier phase “Say the word.” A 1000-Hz calibration tone that was equivalent in rms amplitude to that of the word stimuli was created and saved.

Sentence Stimuli • The IEEE sentences were selected as stimuli because they exhibit complex structure and information but provide some limited semantic and contextual information to aid interpretation (e.g., “*The birch canoe slid on the smooth planks.*”). Stimuli included 100 IEEE sentences, taken from the full list of IEEE sentences, that were of comparable length, equated for number of keywords ($n = 5$), and judged as highly intelligible by a sample of young normal-hearing listeners in a pilot study. They were recorded by the same adult male speaker who recorded the monosyllabic words. The sentences were edited, saved as .wav files, and equated for rms amplitude. A 1000-Hz calibration tone was created and saved in a manner similar to that described for the word stimuli.

The long-term average speech spectra of the word and sentence stimuli were similar, with peak energy at 400 to 500 Hz (bandwidth from 215 to 700 Hz), and an attenuation rate of approximately 5 dB/octave above 1000 Hz. These long-term average speech spectra characteristics are comparable to those reported previously (Byrne et al. 1994).

Noise • The competing noise was the 12-talker babble originally recorded for use with the Speech Perception in Noise Test (Kalikow et al. 1977).

Procedure

Participants were seated in a double-walled sound booth during preliminary audiometric testing and speech recognition testing and in a quiet room for all cognitive testing. Participant qualification measures and experimental tasks were completed in two 2-hr sessions held on 2 separate days approximately 1 week apart. In session 1, preliminary audiometric test and tympanometric measures were completed. Upon meeting qualifications, the participant was scheduled for session 2 at which time cognitive and speech recognition tasks were completed. The order of presentation of the four cognitive tests was counterbalanced over all of the participants. A retrospective review of the assignment of listeners to WM groups indicated that there was no consistent relationship between LSPAN performance (and resulting group assignment) and the order in which the cognitive measures were administered.

During speech recognition testing, the stimuli and 12-talker babble were played on a compact disc player/recorder (Sony CDP-CE500) and routed to two channels of an audiometer (Grason-Stadler, GSI 61). The stimuli and babble were attenuated separately and mixed in the audiometer; the mixed signal was then delivered to an Eartone 3A insert earphone (E-A-R Auditory Systems, Aero Company, Indianapolis, IN). For all speech testing, the level of the 12-talker babble was held constant at 75 dB SPL, and the level of the speech signal (monosyllabic words or IEEE sentences) was varied adaptively to derive the signal-to-noise ratio (SNR) corresponding to 50% correct using the procedure described for the Hearing in Noise Test (HINT) test (Nilsson et al. 1994). The babble level of 75 dB SPL was selected to simulate difficult, real-world listening situations such as noisy restaurants, parties, or bars. This speech recognition threshold assessed in noise is referred throughout this article as the SNR score, consistent with previous literature (e.g., Dirks et al. 1982; Bentler et al. 2004; Killion et al. 2004). A total of 20 stimuli from a word or sentence list were presented to derive the SNR score. The listener's task was to repeat the word or sentence presented. No feedback was provided. A

TABLE 1. Mean performance (and standard deviations) of the four listener groups on four cognitive measures; mean high-frequency pure-tone averages and ages are also shown

Group	LSPAN	RSPAN	PASAT	LDST	HFPTA	Age
Young, HWM	6.17 (1.10)	5.11 (1.84)	55.61 (10.06)	62.33 (16.49)	6.33 (3.48)	20.39 (2.33)
Young, LWM	2.71 (0.95)	3.29 (0.49)	46.29 (7.04)	43.71 (7.39)	5.29 (5.53)	20.43 (2.07)
Older, HWM	5.63 (1.15)	4.88 (1.36)	48.69 (9.78)	56.00 (21.00)	18.19 (2.83)	67.81 (3.69)
Older, LWM	2.67 (0.49)	2.58 (0.90)	38.20 (7.02)	31.10 (5.92)	18.25 (3.44)	69.83 (2.79)

HFPTA, high-frequency pure-tone average; HWM, high working memory; LDST, Letter Digit Substitution Test; LSPAN, Listening Span Test; LWM, low working memory; RSPAN, Reading Span Test; PASAT, Paced Auditory Serial Attention Test.

response was marked correct for word stimuli if all phonemes in the word were repeated correctly, and a response was marked correct for sentence stimuli if all keywords in the sentence were repeated correctly.

The order of the two speech test conditions was randomized over participants. Before word recognition testing, participants were administered a practice list consisting of 20 word stimuli recorded by the native English speaker that were not used in the experiment. A similar procedure was followed before sentence recognition testing. Breaks were provided at the listener's discretion.

Acoustic calibration was performed daily using a Larson-Davis 824 sound-level meter, 2-cm³ coupler (HA2 with rigid tube), and a 1" condenser microphone. Signal levels were specified by the sound pressure level of a 1000-Hz calibration tone whose rms level was equal to the average rms level of each speech or noise signal.

RESULTS

The average performance on the four cognitive measures as well as mean ages and high-frequency pure-tone averages (HFPTA) of the four listener groups are shown in Table 1. One-way analyses of variance (ANOVAs) conducted on the measures of WM span showed a significant effect of listener group for the LSPAN [$F(3,52) = 43.16, p < 0.001$] and the RSPAN [$F(3,52) = 10.12, p < 0.001$]. Post hoc Bonferroni testing confirmed that the high and low WM subgroups of each age group showed significantly different performance on both the LSPAN and RSPAN measures ($p < 0.05$, both comparisons), but there were no significant differences on either measure between the two age groups matched for WM (i.e., YHWM versus OHWM and YLWM versus OLWM; $p > 0.05$). ANOVA testing also showed a significant effect of listener group on the PASAT [$F(3,52) = 8.05, p < 0.001$] and the LDST [$F(3,52) = 9.26, p < 0.001$] speed of processing measures. On both of these measures (PASAT and LDST), the older listeners with high WM showed significantly higher scores than the older listeners with low WM ($p < 0.05$, both comparisons), but there were no significant differences in performance between the two younger WM subgroups ($p > 0.05$, both comparisons). Finally, there was a significant main effect of listener group on the high-frequency pure-tone averages (average of thresholds at 1000, 2000, and 4000 Hz) [$F(3,52) = 50.09, p < 0.001$]. Post hoc multiple comparison testing showed that the two older groups (OHWM and OLWM) had significantly poorer HFPTAs than the two younger groups (YHWM and YLWM), despite the fact that the HFPTA was within the range of normal-hearing sensitivity for all groups ($p < 0.05$, both comparisons). However, there were no significant differences in HFPTA between the high and low WM subgroups within each age group

($p > 0.05$). These data confirm that the listeners assigned to the two WM subgroups (within each age group) did not differ significantly in high-frequency hearing sensitivity and that the listeners assigned to the two age subgroups (within each WM group) did not differ significantly in WM span.

Figure 2 shows the SNRs for NU6 words across the two age groups as a function of cognitive WM subgroup. It appears that younger adults generally show lower SNRs, indicating better speech recognition in noise than older listeners and that within each age group, the listeners with high WM achieve lower SNRs than the listeners with low WM. An ANOVA was conducted on the SNR scores using two between-subjects variables, each with two levels: age (ONH and YNH) and WM (HWM and LWM). The results indicate a significant main effect of age [$F(1,49) = 11.20, p < 0.01$] and a significant main effect of WM [$F(1, 49) = 25.01, p < 0.001$]. The interaction effect between age and WM was not significant [$F(1,49) = 0.80, p > 0.05$]. The analysis therefore confirms the observations above that younger adults exhibited lower SNRs than older adults, and adults with high WM capacity exhibited lower SNRs than those with low WM capacity.

Recognition performance of the four listener groups on the IEEE sentences presented in noise is shown in Figure 3. In this figure, it appears that older adults with low WM capacity exhibit higher (poorer) SNRs than those with high WM capacity and that older adults with low WM capacity perform more poorly than young adults with low WM capacity. A second

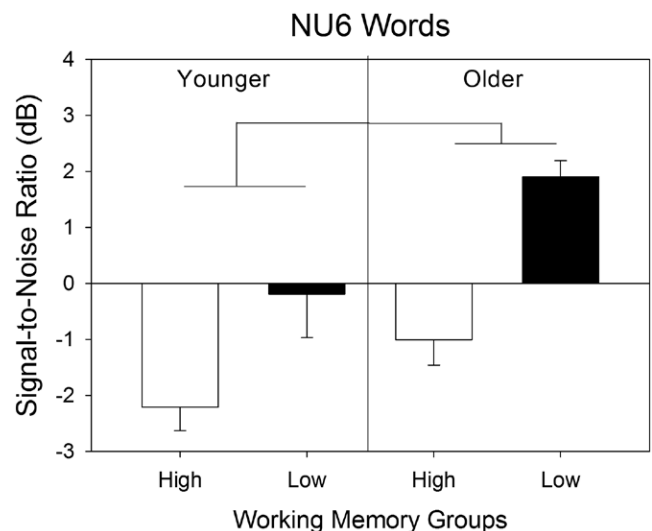


Fig. 2. Mean signal-to-noise ratio required for 50% correct performance for Northwestern University Auditory Test No. 6 (NU6) words by younger and older listeners assigned to high and low working memory groups. Error bars indicate one standard error of the mean. Horizontal bars indicate significant differences observed between groups.

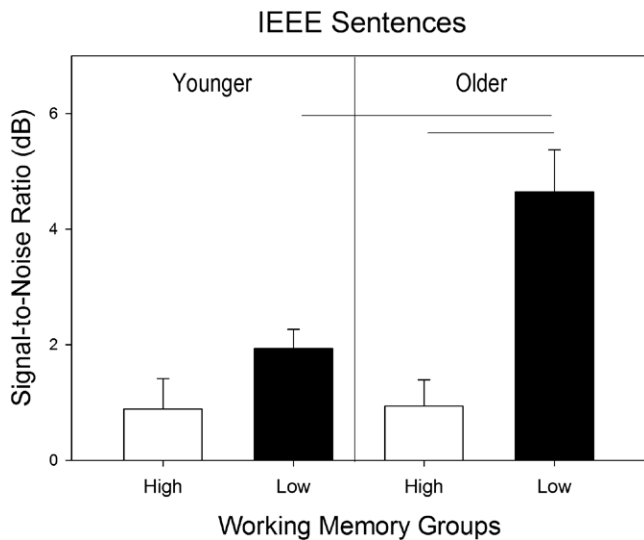


Fig. 3. Mean signal-to-noise ratio required for 50% correct performance for Institute of Electrical and Electronics Engineers (IEEE) sentences by younger and older listeners assigned to high and low working memory groups. Error bars indicate one standard error of the mean. Horizontal bars indicate significant differences observed between groups.

ANOVA was conducted to confirm these impressions, also with two between-subjects variables (age, WM), but with the IEEE SNR scores as the dependent variable. The results showed significant main effects of age [$F(1,49) = 5.18, p < 0.05$] and WM [$F(1,49) = 15.34, p < 0.001$]. There was also a significant interaction between age and WM [$F(1,49) = 4.82, p < 0.05$]. Post hoc analysis using independent samples t tests with Bonferroni adjustment revealed a significant age effect for listeners with low WM capacity. That is, young listeners with low WM showed lower (better) SNRs than older listeners with low WM capacity [$t(17) = -2.71, p < 0.05$]. However, there were no age-related differences in SNRs between the two high WM groups [$t(32) = -0.07, p > 0.05$]. In addition, older listeners with high WM showed lower SNRs than those with lower WM [$t(26) = -4.51, p < 0.001$], but younger listeners differing in WM status did not show a difference in SNRs on IEEE sentences [$t(23) = -1.19, p > 0.05$].

Pearson's product-to-moment correlations (r) with 95% confidence limits were calculated to determine if the cognitive measures are correlated with speech recognition in noise. First, the correlations between the two speech recognition measures and the four cognitive measures for all participants were calculated; the results are shown in Table 2. From these data, it can be observed that among the cognitive measures assessed, the LSPAN scores correlated most highly with both speech recognition measures for all participants combined, although the significance of these correlations was similar to that of the RSPAN for both measures. Next, correlations were calculated separately for the younger and older listeners (shown in Table 3), including correlations between the speech recognition measures and HFPTA, as well as between the speech recognition measures and the four cognitive measures. Overall, LSPAN scores correlated most highly with the two speech recognition measures for both younger and older listeners. LSPAN scores in relation to SNR performance are shown in scatterplots separately for the two speech measures for each of the two age groups (collapsed

TABLE 2. Pearson product-moment correlation coefficients between the cognitive measures and the speech recognition measures (all participants combined)

Cognitive Measures	Speech Recognition Measures	
	NU6 SNR	IEEE SNR
LSPAN	-0.63*	-0.63*
RSPAN	-0.48*	-0.55*
PASAT	-0.59*	-0.36†
LDS	-0.52*	-0.33†

*Correlation is significant at the 0.01 level (two tailed).

†Correlation is significant at the 0.05 level (two tailed).

IEEE, Institute of Electrical and Electronics Engineers; LDS, Letter Digit Substitution; LSPAN, Listening Span Test; NU6, Northwestern University Auditory Test No. 6; PASAT, Paced Auditory Serial Attention Test; RSPAN, Reading Span Test; SNR, signal-to-noise ratio.

across WM groups) in Figure 4. The older listeners (top panels) showed significant correlations between speech recognition in noise and WM. The correlation between the older listener's LSPAN scores and SNRs for NU6 words was $r = -0.71$ ($p < 0.01$) and between their LSPAN scores and SNRs for IEEE sentences was $r = -0.70$ ($p < 0.01$). The young participants (bottom panels) also showed a significant correlation between their LSPAN scores and SNRs for NU6 words ($r = -0.48, p < 0.05$) and for IEEE sentences ($r = -0.53, p < 0.01$).

A stepwise multiple regression analysis was conducted to determine how well the criterion variable, speech recognition in noise (SNR for 50% correct), was predicted by the predictor variables of WM, PS, HFPTA, and age. To reduce the set of predictor variables, one measure/each of WM and PS was selected. These selections were the LSPAN measure of WM and the PASAT measure of PS because each of these cognitive measures overall had higher correlations with both speech recognition measures than the visually presented cognitive measures (RSPAN and LDST). Results of the stepwise multiple regression analysis are shown in Table 4 and indicate that only one significant variable, LSPAN ($r^2 = 0.40, p < 0.001$), was retrieved from the multiple regression analysis conducted for IEEE sentences. For NU6 words, there were two significant variables: LSPAN score ($r^2 = 0.36, p < 0.001$) and PASAT score ($r^2 = 0.09, p < 0.01$), which together accounted for 45% of the variance in NU6 scores. Thus, among the variables assessed, verbal WM (as presented in the auditory

TABLE 3. Pearson product-moment correlation coefficients between the speech recognition measures and HFPTA and between the speech recognition and cognitive measures, for the younger and older participants

Measure	Younger		Older	
	NU6 SNR	IEEE SNR	NU6 SNR	IEEE SNR
HFPTA	-0.01	0.12	0.00	0.05
LSPAN	-0.48*	-0.53*	-0.71†	-0.70†
RSPAN	0.28	-0.54†	-0.58†	-0.54†
PASAT	-0.43*	-0.15	-0.60†	-0.39
LDST	-0.23	0.07	-0.65†	-0.46*

*Correlation is significant at the 0.05 level (two tailed).

†Correlation is significant at the 0.01 level (two tailed).

HFPTA, high-frequency pure-tone average; IEEE, Institute of Electrical and Electronics Engineers; LDST, Letter Digit Substitution Test; LSPAN, Listening Span Test; NU6, Northwestern University Auditory Test No. 6; PASAT, Paced Auditory Serial Attention Test; RSPAN, Reading Span Test; SNR, signal-to-noise ratio.

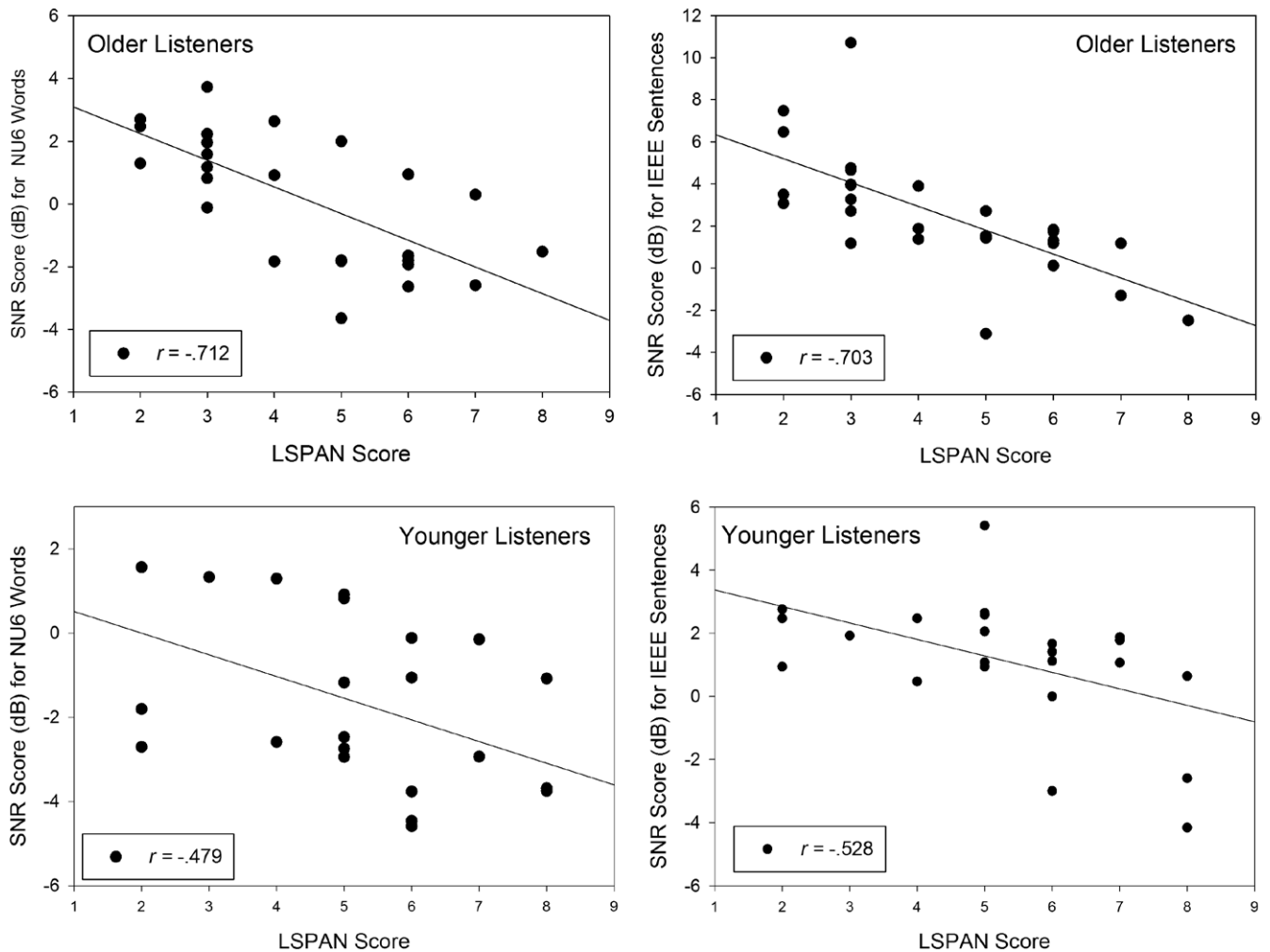


Fig. 4. Scatterplots of performance between Listening Span Test (LSPAN) scores and signal-to-noise ratio (SNR) as measured with Northwestern University Auditory Test No. 6 (NU6) words (left panels) and Institute of Electrical and Electronics Engineers (IEEE) sentences (right panels), presented separately for older listeners (top panels) and younger listeners (lower panels).

mode) was the most important predictor of speech recognition scores in noise achieved by normal-hearing listeners.

DISCUSSION

The overall objective of this study was to determine whether there is an interaction between the effects of age and WM capacity on speech recognition performance in noise. Participants were selected with normal hearing to remove variation in hearing sensitivity as another factor that could potentially confound the results. The study design of comparing the performance of listeners assigned to one of four groups based on age and WM capacity permitted the assessment of these two variables as independent factors, as well as the interaction between them. In general, an interaction between age and WM capacity was observed for the sentence test, but not for the word test. Main effects of age and WM capacity were observed for both speech materials presented in noise.

Effect of Age on Speech Recognition in Noise

As expected, the data showed that younger listeners with normal hearing exhibited better speech recognition scores

in noise than older listeners with normal hearing, consistent with previous findings (e.g., Dubno et al. 1984; Pichora-Fuller et al. 1995; Stuart & Phillips 1996; Füllgrabe et al. 2015). This age effect was observed among both WM groups for the NU6 words when performance was measured using an adaptive procedure to determine the SNR corresponding to 50% correct performance. Some investigations do not

TABLE 4. Summary of stepwise multiple linear regression analysis results for two speech recognition measures; only significant variables entered into the model are shown

Variable	IEEE Scores		NU6 Scores	
	Coefficient	R^2 Change	Coefficient	R^2 Change
Constant	6.12 (0.81)		2.75 (0.72)	
LSPAN	-0.63* (2.01)	0.40	-0.60* (1.79)	0.36
PASAT			-0.36† (1.68)	0.09

Coefficient standard error in parentheses.

*Significant at 0.001 level.

†Significant at 0.01 level.

IEEE, Institute of Electrical and Electronics Engineers; LSPAN, Listening Span Test; NU6, Northwestern University Auditory Test No. 6; PASAT, Paced Auditory Serial Attention Test.

report a significant age effect for word recognition in noise among normal-hearing individuals (Surr 1977; Townsend & Bess 1980) or when audibility is controlled (Studebaker et al. 1997), but this has been attributed in part to the use of a fixed SNR procedure rather than to an adaptive SNR procedure (Gordon-Salant 1987).

The age effect was also observed for recognition of the IEEE sentences among listeners assigned to the low WM groups, but not among those assigned to the high WM groups. It is notable that an effect of age was observed among the two low WM groups despite the relatively small number of participants in the young normal-hearing subgroup with low WM ($n = 7$) but was not observed for the comparison of the two high WM groups that each included a relatively high number of participants ($n = 18$ YHWM and 16 OHWM). Thus, a possible concern about low power for these comparisons does not seem to be warranted. There are no other studies evaluating age effects for IEEE sentences, except those that used the Quick SIN test. In this test, six IEEE sentences are presented in four-talker babble using a method of constants (Killion et al. 2004). Reports of the significance of age effects among listeners with normal hearing on the Quick SIN have been inconsistent. In some studies, there are no age-related differences in performance among listeners with normal hearing (e.g., Sheft et al. 2012), but in other studies, significant age-related differences are reported (e.g., Veneman et al. 2013). Possible reasons for these discrepancies across studies include differences in the criteria for classifying participants as having normal hearing, the number of participants in each age group, and the age range for the two age groups. The current findings suggest that an additional factor that may contribute to discrepant findings across studies is the WM capacity of the older listeners recruited to the study.

Effect of WM Capacity on Speech Recognition in Noise

There was considerable variability in WM span (i.e., LSPAN scores) among the older and younger listeners recruited for this investigation. This confirms prior observations that WM capacity differs among individuals of various ages (Daneman & Carpenter 1980; Just & Carpenter 1992), despite the fact that there is an average decline in WM capacity with advancing age throughout the adult life span (Park et al. 2002).

The current findings confirmed that speech recognition performance in noise was poorer among normal-hearing listeners with low WM span than those with high WM span. This was observed for both younger and older groups on the measure of NU6 SNR scores, but only for older listeners on the measure of IEEE SNR scores. Thus, it appears that the effect of low WM capacity is stronger for older than for younger listeners. This conclusion is supported by the correlation analyses conducted between the LSPAN scores and the SNR scores. Specifically, the correlations were strong between SNRs and LSPAN scores among the older normal-hearing listeners ($r = -0.712$ and $r = -0.703$ for NU6 words and IEEE sentences, respectively) compared with only moderate correlations between SNRs and LSPAN scores in the data obtained from the younger normal-hearing listeners ($r = -0.479$ and $r = -0.528$ for NU6 words and IEEE sentences, respectively), indicating that WM ability is more strongly associated with speech recognition performance of older listeners. The observation that WM capacity is more strongly correlated with speech recognition performance in

noise of the older adults than the younger adults could not be attributed to differences in the range of WM scores between the two age groups because both younger and older adults showed LSPAN scores in the range of 2 through 8 (Fig. 4). Although previous studies have shown a link between WM capacity and speech recognition in noise (e.g., Lunner 2003; Foo et al. 2007; Rudner et al. 2008; Arehart et al. 2013), the presence of significant hearing impairment among the participants makes it difficult to discern the effects of hearing loss from those associated with typical age-related cognitive decline. Additionally, these earlier studies tested older listeners exclusively. A few studies have evaluated the relationship between working capacity and speech recognition in noise among normal-hearing younger and older adults (e.g., Schurman et al. 2014; Füllgrabe et al. 2015), but participants in the two age groups differed markedly in WM capacity. Thus, the current study appears to be the first to match younger and older listener groups on both hearing sensitivity and WM capacity and demonstrate that low WM capacity, independent of listener age and hearing sensitivity, is strongly associated with the ability to understand speech in noise.

The contribution of WM capacity to speech recognition in noise is underscored also by the results of the multiple regression analysis, which showed that verbal WM, as measured by the LSPAN, was the most important variable retrieved in the analyses for both NU6 words and IEEE sentences. The other variables entered into the analyses were HFPTA, age, and PASAT score (reflecting PS as measured in the auditory mode). The pattern of results suggests that verbal WM is a more important contributor than PS to speech recognition in noise, at least for the cognitive measures evaluated in this study. Other investigations have reported significant correlations between verbal WM span and speech recognition in noise (e.g., Besser et al. 2013; Koelewijn et al. 2012), which is consistent with the current findings, but at least one study (Füllgrabe et al. 2015) did not observe an association between verbal WM span (as measured with the RSPAN) and speech recognition in noise. Although the current investigation did not directly assess the relative contributions of RSPAN and LSPAN to speech recognition in noise, it is possible that the high correlation between LSPAN and speech recognition is related to presentation of these measures in the same modality, as observed previously (Pichora-Fuller et al. 1995; Humes et al. 2007). It is notable that HFPTA was not retrieved in this analysis, confirming that the listeners assigned to the four subgroups were well matched for hearing sensitivity and thus systematic variation in hearing sensitivity did not contribute significantly to the performance of younger and older listeners.

Words Versus Sentence Materials

One question of interest in the present investigation was whether or not the level of linguistic processing required for different types of speech materials would differentially affect listener performance. More specifically, recognition of the monosyllabic NU6 words requires accurate perception of the sequence of phonemes in each word as well as knowledge of the lexicon, whereas recognition of the IEEE sentences is influenced additionally by perception of prosody (stress and grouping of words) and knowledge of syntax and semantics. Although the IEEE sentences are not typical everyday sentences (and hence, are not highly predictable), they contain syntactic and semantic (i.e., contextual) information. It was predicted that the contextual cues in the IEEE sentences,

while limited, would provide an advantage for older listeners, thus possibly reducing age-related differences for these stimuli. The findings support this hypothesis. Age-related differences were observed for NU6 scores, suggesting that younger listeners (regardless of WM capacity) were better able to fill in phonological information that was masked by the noise and successfully identify the lexical match to the signal presented compared with older listeners. The source of this age-related difference may be associated with a decline in auditory temporal processing among older listeners, which has the effect of reducing the ability to “listen in the dips” (Dubno et al. 2002; Gifford et al. 2007; Helfer & Vargo 2009). However, for IEEE sentences, age-related differences were observed for the low WM groups but not for the high WM groups. This performance pattern suggests that the advantage afforded by even limited contextual information provided in the IEEE sentences was accessible to the older listeners with high WM capacity. The older listeners with low WM capacity, however, were less able to deploy their limited cognitive resources to resolve the sentence stimuli in the babble. This general pattern of results is also predicted by the current model for ELU (Rönnberg et al. 2013), which states that individuals with high WM capacity have more resources available to resolve both phonological and semantic attributes of a listening task. That is, when context is available for speech signals presented in noise, older listeners with high WM capacity have greater cognitive resources to deploy for explicit processing than older listeners with low WM capacity, thus demonstrating better performance than older listeners with low WM capacity and similar performance to younger listeners with high WM capacity for the IEEE sentences.

CONCLUSIONS

The present data suggest that listeners with normal hearing and low WM capacity, regardless of age, are less able to adapt to distortion of speech signals caused by background noise. In the presence of background noise typical of many everyday listening situations, listeners are required to allocate more processing resources to earlier processing stages. When listeners with low WM capacity have to rely on WM to decode and understand such degraded speech signals, their ability to process and identify linguistic content may be particularly compromised. This impact of low WM capacity on recognition of speech in time-varying noise is apparent for both younger and older listeners. Taken together, the findings suggest that assessment of WM capacity may provide important insights into the source of an adult's complaint of difficulty understanding speech in noise.

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