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Robust relationship between reading span and speech recognition in noise

Pamela Souza¹ and Kathryn Arehart²

¹Department of Communication Sciences and Disorders and Knowles Hearing Center, Northwestern University

²Department of Speech, Language and Hearing Sciences, University of Colorado at Boulder

Abstract

Objective—Working memory refers to a cognitive system that manages information processing and temporary storage. Recent work has demonstrated that individual differences in working memory capacity measured using a reading span task are related to ability to recognize speech in noise. In this project, we investigated whether the specific implementation of the reading span task influenced the strength of the relationship between working memory capacity and speech recognition.

Design—The relationship between speech recognition and working memory capacity was examined for two different working memory tests that varied in approach, using a within-subject design. Data consisted of audiometric results along with the two different working memory tests; one speech-in-noise test; and a reading comprehension test.

Study sample—The test group included 94 older adults with varying hearing loss and 30 younger adults with normal hearing.

Results—Listeners with poorer working memory capacity had more difficulty understanding speech in noise after accounting for age and degree of hearing loss. That relationship did not differ significantly between the two different implementations of reading span.

Conclusions—Our findings suggest that different implementations of a verbal reading span task do not affect the strength of the relationship between working memory capacity and speech recognition.

Keywords

hearing; age; working memory; cognition

Working memory refers to a cognitive system that manages information processing and storage while performing a task (Baddeley, 2000; Daneman and Carpenter, 1980; Miyake and Shah, 1999). Working memory can be thought of as a (finite) set of resources that can

Correspondence to: Pamela Souza, 2240 Campus Drive, Evanston, IL 60201. psouza@northwestern.edu. Telephone: 1-847-491-2433. Facsimile: 1-847-491-4975..

Declaration of Interest

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be deployed to deal with various tasks. Some models of working memory envision it to be domain-specific, with separate resource allocation for verbal and for visuospatial tasks (for review, see Miyake and Shah, 1999). A key concept which impacts test interpretation is the idea that working memory capacity varies among individuals. Previous work showed individual variability in older and younger adults, and also demonstrated a relationship between working memory capacity and task performance (e.g., Daneman and Carpenter, 1980; Ehrlich et al., 1994). Here, we consider the relationship between working memory capacity and speech recognition.

To recognize speech, a listener must process a rapidly-occurring auditory stream to extract information and store that information for integration with later input. We might reasonably expect speech recognition to draw upon working memory capacity, placing individuals with low working memory capacity at a disadvantage. Research relating working memory capacity to speech recognition has focused on two general areas. First, listeners with poor working memory capacity may have more difficulty recognizing speech in noisy environments (e.g., Zekveld et al., 2013; Desjardins and Doherty, 2013; Akeroyd, 2008). Second, listeners with poor working memory capacity may be susceptible to distortion from signal-processing amplification that alters the speech signal (Gatehouse et al., 2006; Ohlenforst et al., 2014; Lunner and Sundewall-Thoren, 2007; Sirow and Souza, 2013; Arehart et al., 2013; Ng et al., 2013; Foo et al., 2007).

This increased susceptibility to distortion may result in reduced amplification benefit for specific hearing-aid parameters compared to listeners of similar age and audiometric status who have better working memory capacity. In general, working memory capacity appears to be more strongly associated with speech recognition when speech is acoustically degraded and associated to a lesser extent when speech is audible and clear (Ronnberg et al., 2010).

A number of different test paradigms have been used to measure working memory. *Simple span* tests emphasize storage over processing. For example, the participant may be asked to recall a list of digits or letters in correct serial order. *Complex span* tests place greater emphasis on processing by asking the participant to recall and manipulate information. For example, the participant may be asked to recall a list of digits or letters in reverse serial order, to solve problems, or to make a qualitative judgment about the recall items (Unsworth and Engle, 2007). Span tests can be visuo-spatial (based on colors or object orientation) or verbal (based on linguistic information). We focus here on verbal working memory, which has been most closely linked to speech recognition (for reviews, see Akeroyd, 2008; Besser et al., 2013).

One way to measure verbal working memory capacity is to use a reading span test (Daneman and Carpenter, 1980; Baddeley et al., 1985). Participants are asked to read a set of sentences presented on paper or on a computer monitor. After reading each sentence the participant makes a processing judgment (such as whether the sentence is true or false). After a block of sentences, the participant is prompted to recall test items. Task load is controlled by varying the number of sentences in a recall block and the test score—usually the number of correctly recalled items—is used as an estimate of working memory capacity.

Reading span tests are structured in different ways. Some tests (e.g., Healey and Miyake, 2009; Unsworth et al., 2012; Barrouillet et al., 2004; Shah and Miyake, 1996) disengage the processing and storage aspects of the test by instructing participants to recall an item—a single word or digit—that is unrelated to the processing task. In other tests, the participant is asked to make a semantic judgment about a sentence and recall a word from that same sentence. Although both types of tests engage semantic processing to some extent, they may elicit different levels of *encoding*¹. Craik and Tulving (1975) argued that encoding a word which is congruent with the information being processed will result in a deeper encoding, a more distinctive representation and better recall. They also proposed that deeper encoding would be encouraged when an item for recall had greater meaning, inference or implication.

Such conditions are more likely to occur for test implementations in which the word for recall is part of the sentence to be processed. Those implementations have been common within hearing science, including several recent studies which focus on hearing aids (e.g., Ng et al., 2013; Arehart et al., 2013). Because subjects who cannot easily recall words may be able to use semantic knowledge to reconstruct what the words might be, the scores for such tests may engage linguistic knowledge and verbal ability to a greater extent than tests which require recall of unrelated items. As such, results of those tests may represent not just working memory capacity, but working memory capacity which relies to a great extent on language-based abilities. For the purposes of this paper, we will use the term *semantically-connected recall* to refer to tests which prompt recall of a word which is part of the sentence being processed, while recognizing that all verbal tests employ semantic processing at some level.

To extend the “speech-like” approach a step further, in some reading span tests participants are told they will be asked to recall a word from within the previously presented sentences, but are not told which word will be prompted for recall. Because this *uncertainty* requires participants to remember most (or all) of the sentence, that aspect of the test may mimic real-life listening in which any or all parts of an utterance may be required to derive meaning.

By examining the relationship between different working memory tests and speech recognition, we aimed to determine whether differences in test implementation might have been a factor in the strength of the working memory capacity-speech recognition relationship demonstrated in previous studies. Understanding different test approaches is of interest as scientists attempt to understand how and under what circumstances working memory capacity is related to speech recognition, and (if warranted) to design clinically-feasible test materials. The present study sought to address two questions. First, to what extent does the relationship between working memory capacity and speech recognition depend on semantically-connected recall, in which words to recall are embedded within the processing judgment? Second, is the relationship between working memory capacity and speech recognition affected by the uncertainty of the recall task? We hypothesized that the relationship between working memory capacity and speech recognition would be stronger

¹The cognitive process which underlies perception and comprehension (Craik, F. I. M. & Lockhart, R. S. 1972. *Levels of processing: A framework for memory research. Journal of Verbal Learning and Verbal Behavior*, 11, 671-684.)

when (1) the working memory test included semantically-connected recall and (2) the working memory test included uncertainty. We focused on older listeners as the population of greatest interest in the hearing-loss and hearing-aid literature. To assess other factors which might affect that relationship, we included measures of peripheral hearing loss and language-based abilities (reading comprehension).

Method

Participants

Participants were recruited at two sites, Northwestern University and University of Colorado at Boulder. We recruited listeners aged 50 years or older with no previous diagnosis of dementia, neurological illness, severe vision problems, reading problems, and who spoke American English as their first or primary language. Participants who required minor vision correction for myopia or hyperopia wore their corrective lenses during testing. The older group included 94 adults (56 female, 38 male) with a mean age of 69 years (SD 10.4 years, range 50-91 years). Figure 1 shows audiometric means and standard deviations for the older group. Higher age was significantly correlated with increasing hearing loss² ($r=.49, p<.005$), as is typical for samples drawn from this population. Fifteen of the participants were hearing aid users (13 binaural, two monaural). The individuals who were hearing-aid wearers were statistically similar in age to the rest of the group but had poorer hearing than those who did not wear hearing aids.

To support interpretation of the older participant data and to facilitate comparisons to previous work, we also recruited 30 younger adults (23 female, 7 male) with normal hearing. Normal hearing was defined as hearing thresholds of 20 dB HL or less (re: ANSI, 2004) at octave frequencies from .25 to 8 kHz. The mean age of the younger group was 24 years (SD 3.4 years, range 18-32 years).

Materials and Procedure

Study data consisted of audiometric results along with two different working memory tests; one speech-in-noise test; and a reading comprehension test, each described below. The audiometric testing and speech-in-noise tests were conducted without hearing aids, with appropriate signal presentation levels adjusted via the audiometer and insert earphones. To ensure they were able to hear instructions and communicate with the tester, participants who wore hearing aids used their aids during the working memory and reading comprehension tests. To minimize fatigue, participants were encouraged to take breaks as needed, including a mandatory 15-minute break at mid-session before completing the second working memory test. The working memory tests were always given in the same order (Test A, Test B). We were not concerned with a direct comparison across tests, but rather with the relationship between working memory capacity and speech recognition within each test. Accordingly, the fixed order of the two tests was a deliberate choice, such that all participants had similar exposure at the time that a specific test was given. To maintain a consistent energy level

²Average of pure-tone thresholds (PTA) at .5, 1, and 2 kHz

across all tests, participants were prevented from consuming caffeine or sugary snacks during the visit.

We selected two working memory tests that differed in terms of the key features of interest in this study, namely semantically-connected recall and uncertainty. The working memory tests were implemented on a Macintosh computer using PsyScope software (Cohen et al., 1993). All listeners were evaluated to confirm they could read 18 point type (the smallest font used in any of the study tests) on a computer screen. A large-font version of the reading comprehension test was available but was not required by any participant.

Working Memory Test A—Test A (Ronnberg et al., 1989) has been used in studies in our laboratory and others (e.g., Arehart et al., 2013; Rudner et al., 2009; Ohlenforst et al., 2014). Fifty-four sentences were displayed one phrase at a time: subject phrase; verb phrase, and object phrase. Each component was visible for 0.80 seconds. Half of the sentences were absurd (e.g., “The train sang a song”), and half were meaningful sentences (e.g., “The captain sailed his boat”). The absurd and normal sentences were interspersed in random order. After each sentence was shown, processing was engaged by asking the participant to indicate whether the sentence made sense or not. Each participant had 1.75 seconds for a semantic judgment before the next sentence was shown. A block of practice sentences was presented to familiarize the participant with the task. Following the practice block, twelve test blocks of sentences were presented to participants: three blocks of three sentences; three blocks of four sentences; three blocks of five sentences; and finally, three blocks of six sentences. After each block was presented, the participant was prompted to repeat words from the sentences in the block. Test A employs semantically-connected recall. In its conventional form, it also employs uncertainty. In the present study, participants were randomly assigned to one of three conditions: “first” where the subject word would be prompted for recall; “last” where the object word would be prompted for recall; or “uncertain” where either the subject or object word might be prompted for recall in a given sentence block. In each case the participant was told prior to testing which words they would be asked to recall. The test was scored by the experimenter on an answer key. The test score was the percentage of words correctly recalled.

Working Memory Test B—Test B (Shah and Miyake, 1996) consisted of 42 sentences. Half of the sentences were absurd (e.g., “The earth has only two continents”) and half were meaningful sentences (e.g., “Cola drinks sometimes come in cans”). The absurd and normal sentences were interspersed in random order. After a sentence was shown, processing was engaged by asking the participant to indicate whether the sentence was true. After the semantic judgment, the experimenter displayed a single target word that was unrelated to the sentence. That word was visible for 750 ms. After a block of sentences the experimenter prompted the participant to verbally list the target words they remembered. A block of practice sentences was presented to familiarize the participant with the task. Following the practice block, the sentences were shown in blocks of two to five sentences (with random order of block length). The test was scored by the experimenter. The test score was the percentage of words correctly recalled.

Reading comprehension—Because both working memory capacity tests relied on reading ability, each participant completed a Nelson-Denny Reading Comprehension test (Brown et al., 1993). The test consisted of short passages about various topics followed by multiple-choice questions pertaining to the passage. The test was administered according to standard instructions. Each subject's reading speed was evaluated by noting the number of words read after one minute. Participants were allotted 20 minutes to complete as much of the test as they could at their regular reading speed. The test was scored in percent correct, calculated as the number correct / total number of items.

Speech recognition—Ability to recognize speech in background noise was measured using the QuickSIN (Killion et al., 2004) administered binaurally via insert (ER-3) earphones. The test consisted of low-context sentences spoken by a female talker. Each sentence includes five key words (e.g., “Tend the sheep while the dog wanders”). Six sentences were presented, one each at signal-to-noise ratios from +25 dB to 0 dB in 5 dB steps. In each case the background noise was four-talker babble (3 males, 1 female). The test was recorded on compact disc and routed through a Grason-Stadler GSI-61 audiometer. As specified by the protocol for the QuickSIN, speech levels were set to 70 dB HL for most listeners and to a “loud but ok” level for subjects with a pure-tone average of 50 dB HL or greater in either ear. The levels judged to be “loud but ok” ranged from 75-85 dB HL. The test score represents the signal-to-noise ratio required for the listener to repeat 50% of the words correctly. One practice list and two test lists were presented for each participant, and the two test list scores were averaged for a final score.

Results

Working memory capacity

Figure 2 shows scores for working memory tests A and B, plotted for each subject as a function of age. Within the older group, working memory capacity declined with age at a rate of 4% per decade for test A and 3% per decade for test B.

Table 1 shows relevant older group data for the three conditions for test A. To confirm random condition assignment across the three conditions, we first verified via one-way analysis of variance that the three randomly-assigned older groups were statistically similar in age ($F_{2,91}=.01$, $p=.99$), hearing threshold (right PTA $F_{2,91}=.84$, $p=.44$; left PTA $F_{2,91}=1.25$, $p=.29$), reading comprehension ($F_{2,91}=1.53$, $p=.22$), and QuickSIN score ($F_{2,91}=1.0$, $p=.37$). There was a significant difference in working memory capacity across the test A conditions ($F_{2,91}=33.81$, $p<.01$). Post-hoc testing (Tukey's HSD) indicated that scores for test A were higher when the first word was prompted for recall than for either the uncertain or last word recall conditions ($p<.01$ in each case). Table 2 shows similar data for the younger group. For that group, there was no significant difference across the test A conditions ($F_{2,27}=2.51$, $p=.10$).

Reading comprehension

Results of the reading comprehension measure are summarized in Tables 1 and 2, and shown as a function of age in Figure 3. Within the older group, reading comprehension

(calculated as number correct / number of total items) decreased with age ($r=-.61, p<.01$). As shown in Figure 3, the difference was not straightforward; listeners aged 50-70 years performed quite similarly to the younger group, but the variance increased markedly for listeners 70 years and older. This is unlikely to be due to differences in reading speed, because there was no relationship between age and number of words read in a 1-minute period ($r=.15, p=.17$). Moreover, a similar age-reading comprehension relationship was found when percent correct was calculated as number correct / number of attempted items ($r=-.55, p<.05$);

Speech recognition

Older listeners' scores for the QuickSIN ranged from -2.5 to 25.5 dB, with a mean score of 2.9 dB (SD 3.9). According to scoring guidelines for the QuickSIN, 62% of the older group would be considered to have hearing in noise similar to listeners with normal hearing, and 38% would be considered to have impaired ability to hear in noise. The group with impaired speech-in-noise perception can be further subdivided into 22% with mild SNR loss (3-7 dB) and 16% with moderate or severe SNR loss (>7 dB). Note that these scores represent ability to hear in background noise after speech audibility has been controlled (here, by presenting the speech signal at an appropriate presentation level). In less-controlled everyday environments, participants' ability to understand conversational-level speech in noise may be poorer due to reduced audibility.

Relationship between working memory capacity and speech recognition

Figures 4 and 5 show the relationship between working memory and speech in noise for test A and B, respectively. Within the older group, working memory and QuickSIN were significantly correlated for both tests (test A³, across all conditions $r=-.40, p<.01$; test B, $r=-.36; p<.01$).

A hierarchical regression model was used to analyze the older listener data. We focused on relationships among working memory capacity, speech-in-noise, test paradigm and patient factors. The regression analysis used an alpha-level criterion of 0.05 for probability of entry into the model and 0.1 for probability for removal from the mode. Residual and scatter plots indicated that the assumptions of normality and linearity were satisfied (e.g., Hair et al., 2010).

The independent variables were significantly correlated (Table 3). When the predictors to be entered into a multiple regression model are correlated (known as collinearity), the results of the analysis with regard to any individual predictor may not be interpretable. We can quantify the extent of the collinearity by calculating two numbers. *Tolerance* is estimated as $1-R^2$, where R^2 is calculated by regressing each independent variable on the other independent variables. For a valid analysis, tolerance should be at least .10 (Hair et al., 2010). *Variance Inflation Factor*, or VIF, is the reciprocal of tolerance. The VIF refers to the increase in standard errors compared to a situation where the predictors are not correlated.

³Sub-analyses indicated a significant relationship between speech recognition and working memory for the uncertain ($r=-.48, p=.01$) and last ($r=-.62, p<.01$) conditions. The relationship was nonsignificant for the first condition ($r=-.16, p=.40$), likely due to the smaller range of working memory scores.

For a valid analysis, VIF should be no greater than 10 (Hair et al., 2010). In this case, collinearity within the model was acceptable (VIFs <2.0, tolerances > .5). Accordingly, the independent variables were entered in four blocks: (i) age and hearing loss, (ii) reading comprehension score (iii) type of working memory test and (iv) working memory capacity. The order of entry into the model was designed to examine the predictive variables of interest (type of test and working memory capacity) while controlling for the effects of age and hearing loss (pure-tone average), as well as the effects of reading comprehension on the working memory score.

Results of the regression analysis are shown in Table 4. The initial model (Step 1) explained 46% of the variance, most of it due to hearing loss ($F_{2,185}=78.00, p<.01$). When reading comprehension was added to account for any subjects for whom poor reading ability would affect reading span score (Step 2), the model was significant ($F_{3,184}=54.55, p<.01$) and the change in variance accounted for was significant. Next (Step 3), working memory test type was entered as indicator variables which coded the test itself (A or B) and the test A condition (first, last, uncertain). The addition of test type as a predictor did not account for any additional variance, although the overall model remained significant ($F_{6,181}=26.95, p<.01$). Adding working memory capacity (Step 4) accounted for additional variance but also reduced the role of reading comprehension. The partial correlation (*pr*) values indicated that once working memory capacity was considered, reading comprehension explained less than 2% of the total variance. The final model accounted for 49% of the variance ($F_{7,180}=24.54, p<.01$). Amount of hearing loss and working memory capacity were significant predictors of SNR loss. Test type, reading comprehension and age were not significant predictors in the final model (Step 4).

In interpreting these data, it may be of interest to consider the distribution of performance among the older group. Consider the data shown in Figure 4 for the relationship between working memory capacity (measured with Test A) and speech in noise score. The working memory capacity scores were normally distributed, with the majority of participants scoring between 20% and 80% correct and a minority of participants scoring above or below that range. Two participants scored less than 10% correct, indicating very poor working memory. However, those participants are not outliers when considered in the context of a peer group. The lowest-scoring participant was 87 years old, and that score for both Test A and B was within two standard deviations of the working memory mean when the working memory mean was calculated for older listeners (over 70 years). Similarly, that hearing-impaired participant's QuickSIN score is within the anticipated normal distribution (within three standard deviations of the mean) when that distribution was based on participants with hearing loss. Additional support for inclusion of extreme scores is obtained when we re-examine the relationship between working memory capacity and speech in noise, and find that the correlation remains significant (Test A: $r=-.267, p=.01$; Test B, $r=-.247, p=.018$) without the two low-scoring participants. Provided such participants meet all study inclusion criteria (as was the case here), they provide insight into the distribution of the population of interest.

Discussion

The focus of the project was the relationship between speech recognition and working memory capacity, when working memory capacity was measured using different reading span tests. Studies in the hearing science literature (e.g., Ng et al., 2013; Arehart et al., 2013) have typically used working memory tests that were congruent (Craik and Tulving, 1975); that is, participants were asked to recall words that were part of a semantically-interpreted sentence. Those tests often employed a high level of uncertainty, in that they required the listener to store most or all of the words in the sentence. Working memory tests that do not employ a deep level of encoding are weakly related to speech recognition (e.g., Foo et al., 2007, Rudner et al., 2009, Lunner and Sundewall-Thoren, 2007, Cox and Xu, 2010). Still other working memory tests (e.g., Healey and Miyake, 2009) employed linguistic materials (sentences) requiring semantic interpretation but in which the item for recall was incongruent (Craik and Tulving, 1975) from the processing task. In this paper, we focused on whether differences in test features influenced the strength of the relationship between reading span and speech recognition. In contrast to our hypotheses, Test A (including all three levels of uncertainty) and Test B both showed comparable relationships between working memory capacity and speech-in-noise recognition. Despite their differences, the two reading span tests appear to measure similar underlying cognitive processes.

Anecdotally, some participants reported that they used visual images as a strategy for recall of the sentences in Test A. Other participants volunteered that they felt Test B was more challenging than Test A. Most of the comments in this vein referred to difficulty forming a strategy for recall of isolated target words in Test B. Because our interest was in the working memory capacity-speech recognition relationship rather than a direct comparison of the two tests, these are ancillary comments, but they may be of interest to researchers who wish use these data to guide test selection.

As well as the features of the working memory test, the relationship between working memory capacity and speech in noise may also depend on the features of the speech-in-noise measure. Our measure employed low-context sentences presented in a background of multitalker babble. The background noise contains modulation (presumably requiring the listener to perceive, recall and assemble glimpses of the target). A working memory capacity-speech recognition relationship has been previously shown to occur under similar conditions (Ohlenforst et al., 2014; Lunner and Sundewall-Thoren, 2007). In contrast, presentation of speech in steady noise or with a high level of contextual information has been less likely to show such a relationship (e.g., Cox and Xu, 2010). Finally, the relationship might also be strengthened by use of similarly-structured sentences (e.g., He et al., 2004) in the working memory capacity and speech recognition tests.

Overall, the data agree with previous work in demonstrating that working memory capacity is related to recognition of speech in noise (e.g., Besser et al., 2013.). A recent model (Ronnberg et al., 2013) provides a theoretical background to the speech recognition-working memory capacity relationship as follows: a listener who receives a clear signal (as a listener with normal hearing presented with undistorted speech in a quiet room) will be able to make an effective lexical match with minimal engagement of working memory. In contrast, a

listener who receives a distorted auditory signal (as a listener with hearing loss who hears a conversation in a noisy room) may have difficulty making a lexical match, and may need to rely to a greater extent on working memory capacity to “fill in” missing acoustic information. Our data were consistent with that explanation. Distortion of speech cues (in this case, with background babble) is likely to disrupt the ease with which a lexical match can be made and tax working memory resources. Patients with fewer resources (i.e., poorer working memory capacity) may be most susceptible to poor speech recognition.

Relationship between reading span and reading comprehension

The reading span test is, after all, a test which relies on reading. As suggested by previous work, (Waters and Caplan, 1996; Friedman and Miyake, 2005; Ehrlich et al., 1994), participants with better reading comprehension had higher working memory capacity. Conversely, participants with poor reading skills may have artificially suppressed working memory scores. For adults who have poor reading comprehension due to low literacy or to difficulty decoding and encoding written information, auditory span tests are an alternative. In an auditory span test (Doherty et al., 2012; Baddeley et al., 1985; Smith, 2012), test materials (sentences and/or words) are presented via spoken or recorded speech. However, a spoken presentation introduces a new problem: auditory span tests may be confounded by hearing loss (Humes et al., 1993). In general, our experience in this study and in a typical clinical population of older adults (Souza and Sirow, 2014) suggest that reading span tests can be used for most older adults without difficulty.

It may also be of interest to consider the relationship between reading comprehension and age in these data. We found that reading comprehension decreased with age, with greatest variability in listeners over 70 years. In contrast to the present data, two previous studies (Caplan and Waters, 2005; Ehrlich et al., 1994) found no effect of age on reading comprehension. However, those studies tested older listeners of less advanced age than in the present data set. Figure 3 suggests that had we excluded our oldest listeners, we would have been unlikely to find a significant effect of age.

Cognitive ability in older listeners and clinical implications

Our test cohort consisted of a sample of older listeners with and without hearing loss. We expected our older participants to demonstrate a range of working memory capacity, as has been the case in other studies of older listeners. Our design did not include a pre-study cognitive screening measure to eliminate adults with atypical (impaired) cognitive abilities. No patient reported significant cognitive issues or dementia in their history. All of the individuals were able to complete the cognitive tests (highly unlikely in patients with dementia [Waters et al., 1995]); and the range of test scores was similar to other studies which did require a cognitive screening be passed. Therefore, we do not believe our cohort included any individuals with dementia.

With regard to mild cognitive impairment (Winblad et al., 2004), the issues are not as clear-cut. A comprehensive review completed for the U.S. Preventative Services Task force (Lin et al., 2013) found that some commonly used questionnaires had lower sensitivity to detect mild cognitive impairment compared to dementia. For example, Lin et al. report that the

Mini-Mental Status Exam (Folstein et al., 1975) has about 85-90% sensitivity to detect dementia, but only 45-60% sensitivity to detect mild cognitive impairment. Questionnaires designed to detect mild cognitive impairment (e.g., Nasreddine et al., 2004) have greater sensitivity, but scores for some of those questionnaires may be confounded by hearing loss (Dupuis et al., 2014). Consistent with a lack of clear-cut tools for to identify mild cognitive impairment, its prevalence is uncertain but may be as high as 42% of older adults (Ward et al., 2012). Considering those issues, past studies of older listeners with hearing loss may well have included participants with mild cognitive impairment. More generally, it may not be reasonable or practical to exclude individuals with mild cognitive impairment from hearing studies. Because the highest prevalence estimates suggest they may represent a significant group of older adults with hearing loss, their exclusion may affect generalizability of results.

Conclusions

Listeners with poorer working memory capacity had greater difficulty understanding speech in background noise, even after accounting for age and degree of hearing loss. Despite differences in specific implementation protocols, similar results were found for both of the reading span tests used here. The relationship between working memory capacity and speech recognition appears to be robust despite use of two different reading span tests that varied in the extent to which items for recall were congruent with items to be processed, and which likely required different levels of encoding (Craik and Tulving, 1975). Provided the working memory test has similar features to the tests evaluated here, the specific test may not matter. Nonetheless, it is important to not over-interpret the present data and conclude that *any* working memory test will give comparable measures of working memory capacity for a given participant. Visual (non-verbal) tests, for example, have been less likely to show the same relationships to speech recognition.

In closing, we consider the implications of these data for future work. Some authors have suggested that cognitive ability should be evaluated in individuals seeking hearing rehabilitation (Edwards, 2007; Meister et al., 2013; Sirow & Souza, 2013). For example, Smith (2012) recently proposed that memory and processing tasks could be incorporated within speech-recognition measures. Although a clinically-feasible working memory test was not evaluated in the present study, our data may provide some guidance in that effort.

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Abbreviations

PTA	Pure-tone average
dB HL	decibels hearing level

SIN	speech in noise
SNR	signal-to-noise ratio

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Figure 1. Mean audiometric thresholds for the older group. Error bars show $\pm$ one standard deviation about the mean.

Figure 2.

Working memory capacity as a function of age. Results for test A (top panel) are collapsed across condition.

Figure 3.

Filled triangles show reading comprehension for the older group, expressed as percent of correct responses as a function of age. Horizontal lines show reading comprehension for the younger group. For convenience in viewing, a dashed line is placed at age 70 years, or about the point where variance begins to increase dramatically.

Figure 4.
Relationship between speech in noise recognition and working memory capacity for test A.
Symbols show certainty condition.

Figure 5.
Relationship between speech in noise recognition and working memory capacity for test B.

Table 1

Older group means (and standard deviations) for randomly-assigned Test A groups. Test B scores are shown for each of the Test A groups. (Test B implementation was the same for all participants).

Test A condition	N	Age (years)	Right ear PTA (dB HL)	Left ear PTA (dB HL)	Reading comprehension (% correct)	QuickSIN (dB)	Test A (% correct)	Test B (% correct)
First	31	68.71 (10.03)	21.40 (13.64)	20.91 (14.11)	81.41 (12.84)	2.11 (2.09)	59.32 (14.23)	58.29 (14.23)
Last	30	68.80 (10.55)	23.33 (13.85)	26.78 (19.56)	73.07 (22.61)	3.04 (5.01)	36.17 (9.71)	51.67 (14.30)
Uncertain	33	69.09 (10.96)	25.86 (14.06)	26.77 (16.77)	77.51 (19.15)	3.50 (4.14)	36.43 (13.69)	52.02 (11.53)
All participants	94	68.87 (10.42)	23.58 (13.83)	24.84 (16.97)	77.38 (18.71)	2.90 (3.93)	43.90 (16.66)	53.98 (13.57)

Table 2

Younger group means (and standard deviations) for Test A groups. Test B scores are shown for each of the Test A groups. (Test B implementation was the same for all participants).

Test A condition	N	Age (years)	Right ear PTA (dB HL)	Left ear PTA (dB HL)	Reading comprehension (% correct)	QuickSIN (dB)	Test A (% correct)	Test B (% correct)
First	9	23.22 (2.73)	2.59 (2.06)	2.78 (1.69)	85.96 (11.09)	0.02 (1.34)	67.28 (12.04)	57.94 (12.49)
Last	9	26.78 (4.18)	4.63 (4.23)	3.89 (4.41)	88.01 (7.10)	−0.39 (2.14)	63.99 (19.56)	68.25 (12.71)
Uncertain	12	23.08 (2.19)	4.86 (5.10)	3.89 (4.28)	87.50 (7.20)	−0.21 (1.43)	54.32 (9.58)	68.40 (14.18)
All participants	30	24.23 (3.40)	4.11 (4.12)	3.56 (3.65)	87.19 (8.26)	−0.20 (1.60)	61.11 (14.62)	65.22 (13.69)

Table 3

Pearson product-moment correlations among the measures. Hearing is the across-ear pure-tone average (i.e., average hearing thresholds at .5, 1, 2 kHz)

	Age (years)	Hearing (dB HL)	Reading comprehension (% correct)	Working memory (Test A) (% correct)	Working memory (Test B) (% correct)
QuickSIN	.361 **	.676 **	-.444 **	-.401 **	-.355 **
Age		.529 **	-.611 **	-.268 **	-.472 **
Hearing			-.525 **	-.372 **	-.371 **
Reading comprehension				.369 **	.478 **
Working memory (Test A)					.475 **

** Significant at $p < .01$

Table 4

Summary of regression analysis for variables predicting speech recognition in noise. *F* and *p* values in this table refer to the effect of adding additional variables. *F* and *p* values for the overall models at each step are given in the text.

	Variable	β	<i>t</i>	<i>R</i>	<i>R</i> ²	<i>R</i> ²	<i>F</i>	<i>p</i>	<i>pr</i>
Step 1				.68	.46	.46	78.00	<.01	
	Age	.01	.09					.93	.01
	Hearing	.67	10.56					<.01	.61
Step 2				.69	.47	.01	4.60	.03	
	Age	-.07	-.91					.36	-.07
	Hearing	.63	9.52					<.01	.58
	Reading comp.	-.15	-2.15					.03	-.16
Step 3				.69	.47	.00	.13	.94	
	Age	-.06	-.89					.37	-.07
	Hearing	.63	9.35					<.01	.57
	Reading comp.	-.15	-2.13					.03	-.16
	Test type	.02	.22					.82	-.02
Step 4				.70	.49	.02	5.78	.02	
	Age	-.09	-1.28					.20	-.10
	Hearing	.61	9.06					<.01	.56
	Reading comp.	-.12	-1.66					.10	-.12
	Test type	-.05	-.67					.50	-.05
	Working memory	-.18	-2.40					.02	-.18