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Research Article

The Impact of Age, Background Noise, Semantic Ambiguity, and Hearing Loss on Recognition Memory for Spoken Sentences

Margaret A. Koeritzer,[a] Chad S. Rogers,[b] Kristin J. Van Engen,[c] and Jonathan E. Peelle[b]

Purpose: The goal of this study was to determine how background noise, linguistic properties of spoken sentences, and listener abilities (hearing sensitivity and verbal working memory) affect cognitive demand during auditory sentence comprehension.

Method: We tested 30 young adults and 30 older adults. Participants heard lists of sentences in quiet and in 8-talker babble at signal-to-noise ratios of +15 dB and +5 dB, which increased acoustic challenge but left the speech largely intelligible. Half of the sentences contained semantically ambiguous words to additionally manipulate cognitive challenge. Following each list, participants performed a visual recognition memory task in which they viewed written sentences and indicated whether they remembered hearing the sentence previously.

Results: Recognition memory (indexed by d') was poorer for acoustically challenging sentences, poorer for sentences containing ambiguous words, and differentially poorer for noisy high-ambiguity sentences. Similar patterns were observed for Z-transformed response time data. There were no main effects of age, but age interacted with both acoustic clarity and semantic ambiguity such that older adults' recognition memory was poorer for acoustically degraded high-ambiguity sentences than the young adults'. Within the older adult group, exploratory correlation analyses suggested that poorer hearing ability was associated with poorer recognition memory for sentences in noise, and better verbal working memory was associated with better recognition memory for sentences in noise.

Conclusions: Our results demonstrate listeners' reliance on domain-general cognitive processes when listening to acoustically challenging speech, even when speech is highly intelligible. Acoustic challenge and semantic ambiguity both reduce the accuracy of listeners' recognition memory for spoken sentences.

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Age-related hearing loss is extremely common, and its effects can be seen at every stage of the auditory system (Peelle & Wingfield, 2016). In addition, as listeners, we frequently have to deal with speech in the presence of background noise, competing talkers, or other types of acoustic challenge (Mattys, Davis, Bradlow, & Scott, 2012). One common consequence of acoustic interference is reduced intelligibility. However, there has been increasing interest in the more subtle effects of acoustic challenge on cognitive processing (Besser, Festen, Goverts, Kramer, & Pichora-Fuller, 2015; Humes, Kidd, & Lentz, 2013; Wingfield, Tun, & McCoy, 2005). There is an emerging consensus that when speech is acoustically degraded, listeners are forced to engage additional cognitive processes for perception, leaving fewer resources available for other tasks (Peelle, 2017; Pichora-Fuller et al., 2016; Rönnberg et al., 2013). Identifying tasks that reflect the engagement of cognitive processes during listening is required to understand how these cognitive demands are affected by individual listener characteristics (such as cognitive and hearing ability), the acoustic environment, and the characteristics of the message (e.g., acoustic clarity).

Perhaps the broadest behavioral evidence supporting the reliance on cognitive resources for understanding acoustically degraded speech comes from the observation that episodic memory is consistently poorer for single words (or word pairs) under conditions of acoustic challenge (Heinrich, Schneider, & Craik, 2008; Murphy, Craik, Li, & Schneider, 2000; Rabbitt, 1968). In one influential study, McCoy and

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[a]Program in Audiology and Communication Sciences, Washington University in St. Louis, MO
[b]Department of Otolaryngology, Washington University in St. Louis, MO
[c]Department of Psychological and Brain Sciences and Program in Linguistics, Washington University in St. Louis, MO
Correspondence to Dr. Jonathan Peelle: jpeelle@wustl.edu

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colleagues (2005) presented listeners with lists of words that stopped at unpredictable locations, at which point participants were instructed to repeat the last three words they heard. Recall for the most recent word was high, indicating good audibility and intelligibility. However, older adults with hearing loss showed worse memory for prior word positions when semantic context was not available. These results suggest that increased cognitive activity during perception interfered with memory encoding or rehearsal, which was revealed when memory was tested. Similar findings have been found in additional studies using a variety of list memory paradigms (Cousins, Dar, Wingfield, & Miller, 2014; Piquado, Cousins, Wingfield, & Miller, 2010). These studies suggest that when listening to acoustically challenging speech, listeners must rely to a greater extent on cognitive domains that are also needed to encode speech to memory (such as verbal working memory). Thus, reduced memory for speech reflects increased cognitive demand during listening.

However, a weakness of many prior studies is that they rely on memory for unrelated single words, which are rare in everyday listening situations. More frequently, everyday speech comprehension comes with semantic and syntactic context that can provide linguistic support for speech perception (Dubno, Ahlstrom, & Horwitz, 2000; Kalikow, Stevens, & Elliott, 1977; Lash, Rogers, Zoller, & Wingfield, 2013; Obleser, 2014; Pichora-Fuller, Schneider, & Daneman, 1995; Strand, Simenstad, Cooperman, & Rowe, 2014). Our primary objective was to see whether memory deficits for acoustically challenging speech could also be observed in the context of spoken sentences. In other words, given the linguistic support available when listening to sentences, do listeners still need to engage additional cognitive resources?

Acoustic degradation is not the only reason listeners might need to engage additional cognitive resources during speech comprehension: Linguistic challenges are also frequently present. A prime example is the frequent occurrence of semantically ambiguous words. For example, “bark” could refer to either the sound made by a dog or the outer covering on a tree. As listeners, we must determine the appropriate meaning based on the surrounding context in order to make sense of what we are hearing. Although we are typically not aware of this process, it is not entirely automatic: Semantic disambiguation requires conscious attention (Davis et al., 2007), and listening to sentences containing ambiguous words results in increased brain activity in regions associated with semantic processing (Rodd, Davis, & Johnsrude, 2005; Rodd, Johnsrude, & Davis, 2012; Rodd, Longe, Randall, & Tyler, 2010). To study the effect of semantic ambiguity, we created a set of high-ambiguity sentences, each of which contained one or more semantically ambiguous words. We contrasted these high-ambiguity sentences with length-matched control sentences without such words (low-ambiguity sentences). Evidence from dual-task studies suggests that semantic disambiguation relies on domain-general cognitive processes (Rodd, Johnsrude, & Davis, 2010). Thus, if cognitive demands of listening to speech in noise similarly rely on domain-general executive systems, we would expect memory for high-ambiguity sentences to be worse than low-ambiguity sentences. That is, an effect of ambiguity would lend additional support for a domain-general account of cognitive demand during listening.

Memory plays an important role in everyday conversation, where we may need to remember having heard spoken information, even if we do not necessarily need to be able to recall it unprompted. Our current study also builds on the findings of prior studies by measuring recognition memory as opposed to overt recall. Although recall and recognition memory can be dissociated (e.g., Balota & Neely, 1980), they are widely considered to reflect similar underlying cognitive processes (Anderson & Bower, 1974; Yonelinas, 2002) and can be used as a way to provide converging evidence of memory phenomena (Yonelinas & Jacoby, 2012). The use of a recognition memory task also avoids confounds related to explicit rehearsal mechanisms. That is, if instructed to remember an eight-word list, many listeners will rehearse by saying the words to themselves during the memory period, creating additional cognitive demands related to the memory task but not to the initial processing. This type of memory strategy is not possible with a list of sentences as we use here, which encourages attentive listening but not rehearsal. Finally, we chose to use a visual recognition memory task, which ensures memory is for linguistically encoded items rather than surface features (i.e., because the test sentences are written, the content must have been processed to a level abstracted from the input speech). Our intent was not to use a memory task that we expect most listeners to frequently encounter on an everyday basis, but rather a paradigm that would be sensitive to memory effects and practical to implement with spoken sentences as a means to quantify cognitive effort during speech understanding.

There is some preliminary evidence suggesting acoustic properties can affect recognition memory for spoken sentences. Van Engen, Chandrasekaran, and Smiljanic (2012) presented listeners with short declarative sentences in either conversational or clear speaking styles (with clear speech being more strongly articulated and projected). They found enhanced recognition memory for clear speech (in quiet), suggesting acoustic clarity indeed affected memory for sentences. Similar results have been observed in noise (Gilbert, Chandrasekaran, & Smiljanic, 2014). However, to our knowledge, similar studies looking at effects of semantic ambiguity on memory for degraded speech are absent. Investigating the effect of semantic ambiguity is useful because it allows us to begin to understand how acoustic and linguistic challenges interact and whether meeting these two types of challenge relies on domain-general executive resources.

In the current study, we examined the degree to which background noise and semantic ambiguity would impact young and older adult listeners’ recognition memory for auditory sentences, all spoken in a conversational style. Older adults demonstrate age-related changes in both auditory and cognitive factors, making them an ideal group in which to study speech comprehension. Rather than effects of age per se, however, our primary interest is the degree to which hearing, cognitive, and linguistic factors affect successful perception and memory for speech. Critically, we chose signal-to-noise ratios (SNRs) and an overall intensity level that ensured the sentences were highly intelligible, allowing us to attribute memory decrements primarily to the cognitive challenge associated with processing speech in noise, rather than failures of perception.

Materials and Method

Participants

We examined two groups of participants with self-reported normal hearing (which we further assessed with audiometry, see below): 30 young adults (24 women, six men) and 30 older adults (22 women, eight men). The young adult participants were an average of 23.0 years old (*SD* = 3.4 years), and the older adults were an average of 69.7 years old (*SD* = 3.1 years). Full demographics are listed in Table 1. All participants were native speakers of American English. Exclusion criteria for this study were a diagnosed central neurological condition or a conductive hearing loss. Participants provided written informed consent and were paid for participation under a protocol approved by the Washington University Institutional Review Board.

In addition to pure-tone audiometry, we collected several additional measures: Shipley vocabulary (Zachary, 1986) as a measure of verbal knowledge, a reading span task as a measure of verbal working memory (Oswald, McAbee, Redick, & Hambrick, 2015), and the Montréal Cognitive Assessment (Nasreddine et al., 2005) as a measure of general cognitive ability. Scores on these tests are also listed in Table 1. We note that, compared to the young adults, the older adults had significantly higher vocabulary scores, lower reading span scores, higher (i.e., poorer) ear pure-tone averages, and lower Montréal Cognitive Assessment scores.

Materials

The experimental stimuli consisted of 192 sentences (nine to 12 words each), presented in six blocks of 32 sentences each. The sentences were recorded by a female native speaker of American English onto a digital video recorder, with an audio sampling rate of 44.1 kHz. The audio track was subsequently stripped off and trimmed to eliminate silent periods preceding and following each sentence. Sound files were equated on root mean square amplitude. Half of the sentences within each block were high ambiguity, and half were low ambiguity. An example of a high-ambiguity sentence is “Emily found the band to be too tight around her waist,” because the intended meaning is only apparent given the other content of the sentence (“band” could refer to a musical group or an item of clothing, and “waist” could refer to the body part or the heterographic homophone “waste”). An example of a low-ambiguity sentence is “The ache in John’s arm became worse during the winter.”

Sentences were presented in quiet and at two different SNRs, +15 dB and +5 dB, which were chosen to increase listening challenge while maintaining high levels of intelligibility. The noise was an eight-talker babble, created from read speech (native speakers of American English reading aloud from a book of their choice), with the recordings edited to remove silent periods of more than 200 ms, any mispronunciations, coughs, and other errors. We combined the babble with the target sentences using custom MATLAB scripts (function *jp_addnoise,* retrieved from http://github.com/jpeelle/jp_matlab). There was a 2-s pause between sentences. When present, the babble started 1 s prior to each list of sentences and ran continuously throughout the list. When adding babble to sentences, the amplitude of the target sentence was held constant while the level of babble was adjusted for each SNR.

We used Match software (Van Casteren & Davis, 2007) to equate total number of words, number of content words, number of ambiguous words, mean frequency of the content words (Brysbaert & New, 2009), and sentence duration across presentation blocks. Sentence blocks were counterbalanced across acoustic conditions so that, across participants, all sentences were presented in all acoustic conditions (Quiet, +15 dB SNR, +5 dB SNR). An additional 192 sentences were used as foils during the recognition memory task. Target sentences and foil sentences were matched with the above criteria. Pilot testing suggested that, to avoid ceiling effects in recognition memory, the foil sentences needed to share some words with the target sentences. We therefore created foils that were similar to

Table 1. Range of participant characteristics (mean ± standard deviation).

	Young adults	Older adults	Group difference
n	30	30	
Age (years)	22–34 (*M* = 22.97 ± 3.37)	65–77 (*M* = 69.70 ± 3.08)	
Education (years)	14–21 (*M* = 16.92 ± 2.15)	11–24 (*M* = 16.98 ± 3.11)	*t*(58) = 0.09, *p* = .93
Vocabulary	10–34 (*M* = 13.97 ± 2.07)	11–34 (*M* = 15.30 ± 2.27)	*t*(58) = 2.38, *p* = .021
Reading span (total words)	12–34 (*M* = 22.83 ± 4.98)	2–34 (*M* = 16.67 ± 8.47)	*t*(58) = 3.44, *p* = .001
PTA left ear (dB HL)	−10–11.25 (*M* = 2.42 ± 4.59)	6.25–33.75 (*M* = 18.05 ± 7.48)	*t*(53) = 9.50, *p* < .001
PTA right ear (dB HL)	−10–10 (*M* = 1.67 ± 3.94)	2.50–30 (*M* = 17.70 ± 7.53)	*t*(53) = 10.12, *p* < .001
PTA better ear (dB HL)	−10–10 (*M* = 0.83 ± 3.97)	2.50–26.25 (*M* = 16 ± 7.11)	*t*(53) = 9.98, *p* < .001
MoCA	25–30 (*M* = 28.60 ± 1.63)	24–30 (*M* = 27.17 ± 1.72)	*t*(58) = 3.31, *p* = .002

Note. PTA = pure-tone average; MoCA = Montréal Cognitive Assessment.

target sentences (e.g., target: “The staff used on the set was made of hickory and leather”; foil: “The staff made out of hickory was purchased at a market”). Ambiguous words were sometimes, but not always, included and did not always have the same meaning. The full set of target and foil sentences is available at https://osf.io/yng36/.

Procedure

Otoscopy was performed prior to placement of Telephonics TDH-50P headphones, which were used both for audiometry and presentation of the experimental materials. The audiological equipment, including the GSI-61 audiometer (Grason-Stadler, Inc.), is maintained and calibrated annually by the Washington University School of Medicine in St. Louis, Division of Aural Rehabilitation and Cochlear Implants. Both External A and External B input dials on the GSI-61 audiometer were calibrated via the VU meter and set to 0 before testing each day.

Audiological Evaluation

All participants received pure-tone audiometry, during which they heard pulsed tones and were instructed to press a button whenever they perceived a tone. We used the Hughson-Westlake procedure to find the softest level (measured in dB HL) at which a tone was perceived at least 50% of the time, and this was considered the participant’s threshold for a given frequency. Air conduction thresholds were found for 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz for each ear. Interoctaves 750 and 1500 Hz were included if a 20-dB HL difference was found between 500 and 1000 Hz or between 1000 and 2000 Hz, respectively. We used a pure-tone average across 1000, 2000, and 4000 Hz in each participant’s better ear to summarize hearing sensitivity.

Sentence Memory Task

We used E-Prime 2 (Psychology Software Tools, Inc.) to present the sentence materials and record participant responses. Prior to beginning the sentence memory task, participants completed an intelligibility test to ensure understanding of the sentences in each of the acoustic conditions (SNRs). Two sentences (five to seven words each) were presented in each of the three acoustic conditions. Participants were asked to repeat each sentence aloud, and their responses were scored in real time by the researcher (who heard the sentences via a microphone placed in the sound booth). These intelligibility sentences were scored on a verbatim basis, with changes in verb tense or pluralization counted as correct. Where speech recognition thresholds were available, the speech was presented at speech recognition threshold of +40 dB; otherwise, the speech was presented at a comfortable listening level of approximately 70 dB SPL.

A practice phase followed the intelligibility check. The first practice set consisted of four spoken sentences presented in quiet, followed by a visual recognition memory test that included those four sentences and four foils. After reading each test sentence, participants tapped on a touchscreen to indicate whether the item was new or old. Participants were instructed to judge each sentence in its entirety: that is, the entire sentence needed to have been heard previously for them to correctly indicate they had heard it before. (This instruction was critical as the unheard sentences shared some, but not all, words in common with the presented sentences.) As soon as the participant gave a response, the next sentence appeared on the screen. A second practice set consisted of four sentences presented at +15 dB SNR (with eight written sentences presented for the visual recognition memory test).

After the participant had successfully completed the practice, they were reminded of the task and response procedures via written instructions on the screen. Participants were asked if they had any questions prior to beginning the experimental task. Participants signaled that they were ready to continue by raising their hand.

There were six blocks in the experimental task: two blocks of each SNR condition (Quiet, +15 dB, +5 dB), with 32 sentences per block. SNRs were held constant within each block, with two blocks devoted to each SNR condition. These blocks were counterbalanced across participants, such that each level of acoustic difficulty was heard first, second, or third an equal number of times. Following each block, 64 sentences (all 32 targets and 32 foils) were presented visually for a recognition memory test. The recognition memory test was conducted on the computer screen in a self-paced fashion: For each sentence that appeared, participants pressed one of two buttons to indicate whether they had heard the sentence in the previous block or not (“old” or “new”).

Memory Discriminability Using d'

Recognition memory was assessed using d', a sensitivity index proposed by the Signal Detection Theory (Macmillan & Creelman, 2005), which assesses the extent to which participants can discriminate between old and new items. This metric is useful because it is not affected by potential response biases on the part of the participant (e.g., how often a participant says “old” in the experiment, regardless of the stimuli). We calculated d' as the difference between z-transformed hit rates to probes of old sentences and z-transformed false alarm rates to probes that were new sentences. To avoid undefined values of d' when hit or false alarm rates equaled 1.00 or 0.00, we applied the log-linear rule recommended by Hautus (1995).[1]

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[1] Calculating d' requires a contingency table of hits, misses, false alarms, and correct rejections. Perfect performance (or perfectly inaccurate performance) makes d' impossible to calculate, and various approaches have been developed to correct these instances (evaluated by Hautus, 1995). The log-linear correction involves adding 0.50 to each cell of the 2 (probe type: target, foil) × 2 (participant response: old, new) contingency table that defines how a participant could perform in the recognition task. Row and column totals are increased by one, which makes hit, miss, false alarm, and correct rejection rates of 0.00 of 1.00 impossible to obtain. In simulations, the log-linear correction results in less bias than do other approaches.

It is important to note that we chose visual presentation for the recognition memory task. To correctly identify a sentence that had been previously heard, participants needed to have encoded the linguistic information and not simply rely on acoustic or talker-specific memory.

Results

Data, analysis scripts, and figures are available from https://osf.io/53tmq/.

Intelligibility

Intelligibility data are shown in Supplemental Materials S1 and S2. Our intention was to select SNRs that left the sentences highly intelligible, which would let us examine the effects of acoustic challenge on cognitive processing during successful perception. To assess the degree to which we were successful at this, we analyzed our intelligibility data using a 3 (acoustic clarity: Quiet, +15 dB SNR, +5 dB SNR) × 2 (age: young, older) analysis of variance (ANOVA) on the intelligibility scores. There was a main effect of clarity, $F(2, 116) = 6.61$, partial $\eta^2 = .10$, $p = .002$, indicating that intelligibility was poorer in the more difficult SNR conditions. There was a main effect of age as a result of older adults' overall poorer performance, $F(1, 58) = 9.38$, $\eta^2 = .14$, $p = .003$. There was also a significant interaction of clarity and age, $F(2, 116) = 8.16$, $\eta^2 = .12$, $p < .001$, due to older adults' differential difficulty at +5 SNR. (These patterns were also true on rationalized arcsine transformed data, included in Supplemental Material S5.) It is important to note that, even in the most difficult acoustic condition, 100% of the young adults and 93% of the older adults had 92% intelligibility or better. Nevertheless, our memory results need to be considered in the context of sentence intelligibility.

Recognition Memory

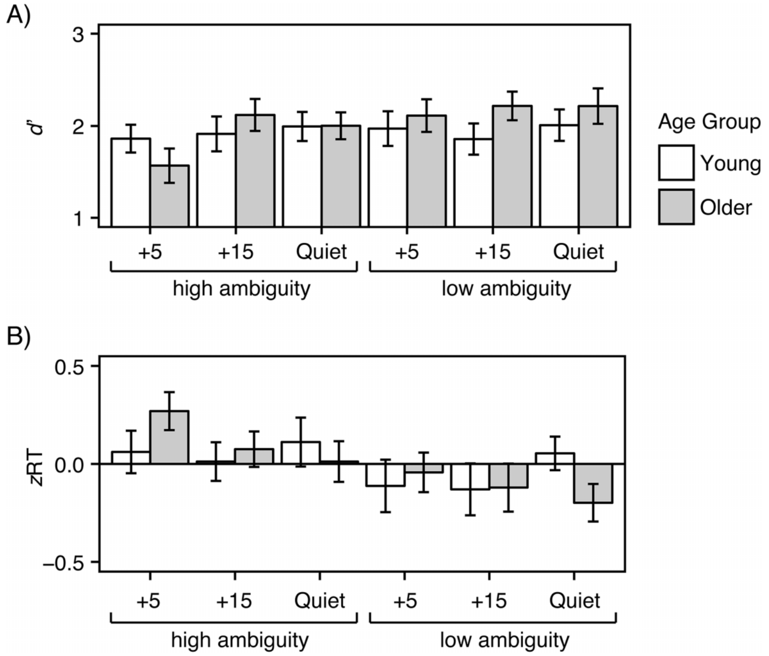
Recognition memory results for young and older adults are shown in Figure 1A, and accuracy (hits and correct rejections) is shown in Supplemental Material S6. We submitted these data to a 2 (ambiguity: high-ambiguity, low-ambiguity) × 3 (acoustic clarity: Quiet, +15 dB SNR, +5 dB SNR) × 2 (age: young, older) ANOVA. There was a main effect of ambiguity, $F(1, 58) = 13.05$, partial $\eta^2 = .18$, $p = .001$, such that high-ambiguity sentences were more poorly recalled than low-ambiguity sentences. There was also a main effect of acoustic clarity, $F(2, 116) = 4.49$, partial $\eta^2 = .07$, $p = .01$, driven by poorer memory for speech in greater amounts of noise. The effect of ambiguity differed as a function of acoustic clarity, indicated by a significant Noise × Ambiguity interaction, $F(2, 116) = 4.71$, partial $\eta^2 = .08$, $p = .01$. There was not a significant effect of age, $F(1, 58) < 1$, partial $\eta^2 = .005$, $p = .594$. However, there was a significant interaction between Age × Ambiguity, $F(1, 58) = 9.52$, partial $\eta^2 = .14$, $p = .003$, and between Age × Noise, $F(2, 116) = 4.02$, partial $\eta^2 = .07$, $p = .02$. These interactions suggest older adults' recognition memory was more affected than that of young adults for high-ambiguity sentences (older adults' memory dropped more for high-ambiguity sentences than low-ambiguity sentences compared to that of young adults) and for noise (young adults' recognition memory was worse when sentences were presented at difficult SNRs, but older adults' recognition memory was differentially worse than young adults' recognition memory). The three-way Ambiguity × Noise × Age interaction was not significant, $F(2, 116) = 1.08$, partial $\eta^2 = .02$, $p = .34$.

Response times for the recognition memory task are shown in Figure 1B. For each participant, we omitted any responses more than 2.5 *SD*s from their individual, within-condition mean response latency, and then calculated *z* scores across all conditions. This procedure minimizes the chance that overall response latency differences (e.g., older adults being slower) would affect our interpretation of Group × Condition interactions (Faust, Balota, Spieler, & Ferraro, 1999).

As with the memory data, we submitted the *z*-transformed response time data to a 2 (ambiguity: high-ambiguity, low-ambiguity) × 3 (acoustic clarity: Quiet, +15 dB SNR, +5 dB SNR) × 2 (age: young, older) ANOVA. There was a main effect of ambiguity, $F(1, 58) = 95.32$, partial $\eta^2 = .62$, $p < .001$, with participants generally taking longer on the high-ambiguity sentences than the low-ambiguity sentences. Somewhat surprisingly, there was no effect of acoustic clarity, $F(2, 116) = 1.37$, partial $\eta^2 = .02$, $p = .26$, but clarity did interact with ambiguity, $F(2, 116) = 5.26$, partial $\eta^2 = .08$, $p < .01$, as response times were more affected by acoustic clarity when the sentences were of high-ambiguity (with participants taking longer for degraded sentences, amplified for high-ambiguity sentences relative to low-ambiguity sentences). As expected based on the *z* transformation, there was no effect of age, $F(1, 58) = 0.49$, partial $\eta^2 = .008$, $p = .49$. However, there was a significant Age × Ambiguity interaction, $F(1, 58) = 9.57$, partial $\eta^2 = .14$, $p < .01$, as older adults took differentially longer on the high-ambiguity sentences compared to the young adults. There was also a significant Age × Acoustic Clarity interaction, $F(2, 116) = 4.86$, partial $\eta^2 = .08$, $p = .01$, with older adults taking longer than young adults to respond to acoustically challenging speech. The three-way Ambiguity × Acoustic Clarity × Age interaction was not significant, $F(2, 116) = 1.21$, partial $\eta^2 = .02$, $p = .30$.

We were also interested in whether individual differences in auditory or cognitive factors related to memory performance. We conducted uncorrected exploratory correlation analyses separately in young adults (see Table 2) and older adults (see Table 3). We focus our discussions on correlations in the most difficult behavioral task, that is, high-ambiguity sentences at +5 dB SNR, shown in Figure 2. It is notable that, for older adults, poorer hearing was associated with poorer recognition memory, and higher verbal working memory was associated with better recognition memory, for these difficult sentences. We emphasize these correlations need to be interpreted in the context of their exploratory nature.

Figure 1. Results for recognition memory task. Error bars show 95% confidence intervals. (A) Recognition accuracy (*d′*) for young and older adults. (B) *Z*-transformed response times to recognition memory judgments for young and older adults. Figure available via a CC-BY4.0 license from https://osf.io/53tmq/.



A critical point in this study is that the speech is highly intelligible in all conditions: if speech intelligibility suffers, it becomes difficult to assess memory effects, as it is impossible to accurately remember a word that was not heard in the first place. To help ensure the effects we observed were not driven by participants who did not hear all of the words, we recalculated the main figures and statistics using only data from participants who scored 100% on all intelligibility tests, shown in Supplemental Materials S3 and S4. These analyses included 28 young adults and 13 older adults. The results on *d′* (Supplemental Material S3) revealed a significant three-way Ambiguity × Acoustic Clarity × Age interaction, where 100% intelligibility young adults' *d′* was uninfluenced by ambiguity or acoustic clarity. Older adults with 100% intelligibility showed significant interactive effects of acoustic clarity and ambiguity, such that acoustic clarity had a large effect on older adults' *d′*, but only when sentences were ambiguous.

For *z*-transformed latencies, the pattern of significant effects was the same for 100% intelligibility participants as for the full complement of participants. The same was true for the correlations between hearing, reading span, and memory performance in the most difficult condition (high-ambiguity sentences at +5 dB SNR), which are displayed in Supplemental Material S4. For older adults with 100% intelligibility, poorer hearing was associated with poorer

Table 2. Correlations for recognition memory performance (*d′*) in young adults.

		1	2	3	4	5	6	7	8	9	10
1	High ambiguity +5	–									
2	High ambiguity +15	.79**	–								
3	High ambiguity Quiet	.77**	.77**	–							
4	Low ambiguity +5	.81**	.79**	.73**	–						
5	Low ambiguity +15	.69**	.81**	.74**	.70**	–					
6	Low ambiguity Quiet	.62**	.68**	.75**	.66**	.67**	–				
7	Vocabulary	.47**	.49**	.19	.51**	.35	.25	–			
8	Better ear PTA	−.07	−.25	−.11	−.20	−.20	−.16	−.22	–		
9	Reading span	−.08	−.07	−.01	−.16	−.17	−.02	−.20	.20	–	
10	MoCA	.16	.19	.25	.28	.21	.16	.18	−.03	.39*	–

Note. PTA = pure-tone average; MoCA = Montréal Cognitive Assessment.

*$p < .05$. **$p < .01$ (uncorrected).

Table 3. Correlations for recognition memory performance (*d*′) in older adults.

		1	2	3	4	5	6	7	8	9	10
1	High ambiguity +5	–									
2	High ambiguity +15	.76**	–								
3	High ambiguity Quiet	.75**	.73**	–							
4	Low ambiguity +5	.78**	.77**	.81**	–						
5	Low ambiguity +15	.74**	.78**	.79**	.72**	–					
6	Low ambiguity Quiet	.76**	.66**	.80**	.74**	.76**	–				
7	Vocabulary	.54**	.63**	.38*	.59**	.42*	.34	–			
8	Better ear PTA	−.45*	−.32	−.36	−.34	−.45*	−.27	−.35	–		
9	Reading span	.53**	.50**	.36	.41*	.50**	.39*	.57**	−.35	–	
10	MoCA	.62**	.38**	.59**	.61	.52**	.50*	.30	−.23	.22	–

Note. PTA = pure-tone average; MoCA = Montréal Cognitive Assessment.
*$p < .05$. **$p < .01$ (uncorrected).

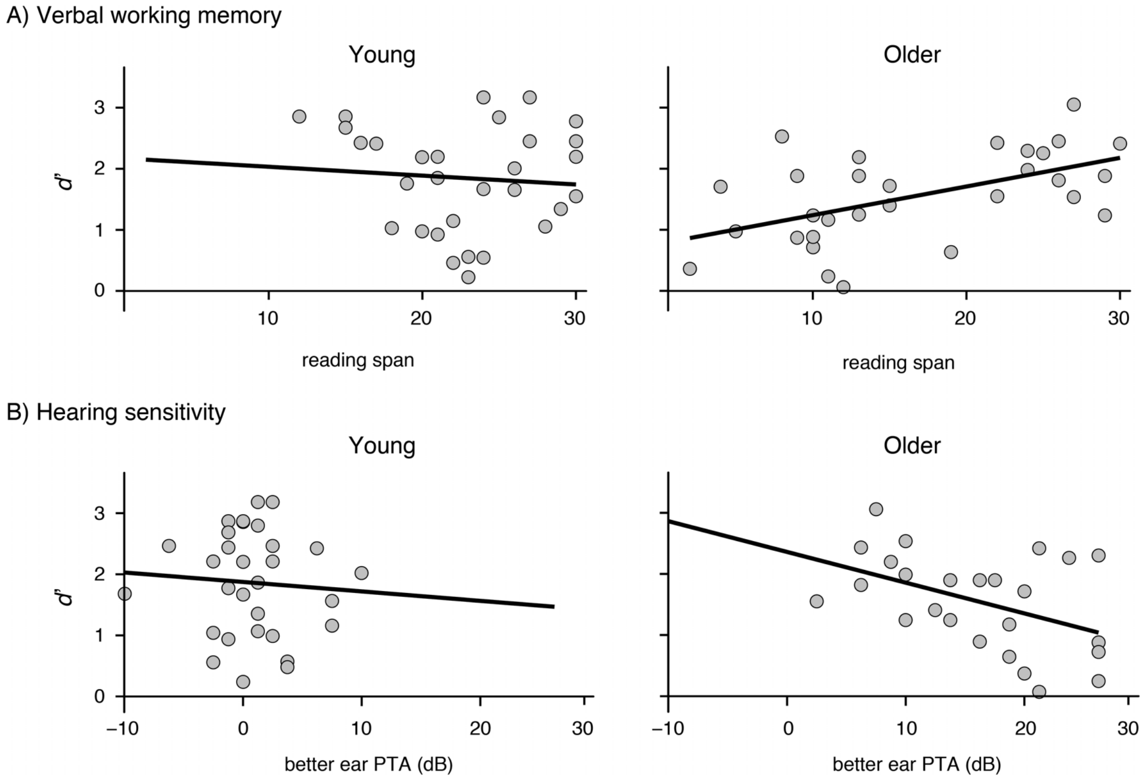
recognition memory, and higher verbal working memory was associated with better recognition memory. No significant correlations of this kind were observed among the young adults with 100% intelligibility.

These analyses show comparable patterns to those in the full data set and bolster our claim that the memory effects are due to increased cognitive challenge rather than decrements in intelligibility. The significant three-way interaction between age, ambiguity, and acoustic clarity of *d*′ strongly highlights the role of ambiguity and acoustic challenge in older adults, even under conditions of perfect intelligibility.

Discussion

Understanding the impact of acoustic and linguistic challenges on memory for speech provides a window into the cognitive processes that are engaged during perception: Differences in memory for what has been heard imply differences in encoding or maintenance that can be attributed

Figure 2. Correlations between hearing and memory performance for the most difficult sentence condition (high-ambiguity sentences at +5 dB SNR). dB = dB HL. Figure available via a CC-BY4.0 license from https://osf.io/53tmq/.



to acoustic factors (such as background noise or hearing loss). Of equal importance, as listeners we frequently want to remember what we have heard. Thus, understanding how auditory and cognitive factors affect our memory for speech has clear implications for everyday listening.

In the current study, we found that recognition memory was poorer for sentences presented in noise, as reflected in both poorer discriminability and longer response times. This memory challenge was exacerbated for sentences containing semantically ambiguous words. Critically, the memory decrement occurred at moderate levels of noise that did not significantly harm speech intelligibility. We discuss the implications of these findings below.

Background Noise Affects Recognition Memory for Spoken Sentences

Of course, speech in noise is always more difficult to understand than speech in quiet—the noise obscures acoustic details in the speech signal and frequently makes it less intelligible, particularly for older adults (e.g., Gordon-Salant & Fitzgibbons, 2004; Rogers & Wingfield, 2015). Numerous studies have found effects of noise that have a cognitive locus: In addition to poorer memory for speech, studies have reported larger pupil dilation (a marker of cognitive challenge; Kuchinsky et al., 2013; Zekveld & Kramer, 2014), increased dual task costs (Gosselin & Gagné, 2011; Tun, McCoy, & Wingfield, 2009), and greater brain activity in various regions of frontal cortex (Davis & Johnsrude, 2003; Eckert et al., 2009). When listening to lists of unrelated words, it is likely that this increased cognitive demand during listening interferes with both memory encoding and rehearsal (Cousins et al., 2014; Miller & Wingfield, 2010), leading to deficits on a variety of episodic memory tests. Here we show that, even in the context of meaningful sentences, the increased perceptual challenge associated with background noise interferes with recognition memory for what has been heard.

When considering the effect of background noise on memory for spoken sentences, it is worth noting that a small number of studies have examined the effect of acoustic challenge on memory for narrative speech (i.e., short stories), with mixed results. Some, using free recall, have observed poorer memory in participants with hearing loss (Piquado, Benichov, Brownell, & Wingfield, 2012) or when the stories are noise-vocoded (Ward, Rogers, Van Engen, & Peelle, 2016). Others, using comprehension questions, have not observed any memory decrements (Schneider, Daneman, Murphy, & Kwong See, 2000). It is likely that both the specific story materials and type of testing play important roles here.

Semantic Ambiguity Affects Recognition Memory for Sentences

In terms of linguistic challenge, prior studies have shown that older adults with hearing loss have more difficulty comprehending syntactically complex sentences in quiet (DeCaro, Peelle, Grossman, & Wingfield, 2016; Wingfield, McCoy, Peelle, Tun, & Cox, 2006). Here we showed that the increased processing required for semantic disambiguation can also reduce memory for what has been heard. One possibility is that semantic disambiguation interferes specifically with semantic processes occurring during degraded speech perception. For example, listeners benefit more from semantic context in noisy situations, and semantic context modulates cortical speech processing networks (Obleser, Wise, Dresner, & Scott, 2007). An alternative interpretation is that, during challenging listening situations, domain-general executive processes are required, some of which are also needed for semantic disambiguation. Converging evidence for a domain-general explanation comes from dual-task experiments in semantic ambiguity (Rodd, Johnsrude, et al., 2010), the reliance of semantic disambiguation on conscious attention (Davis et al., 2007), and the involvement of executive attention networks in degraded speech processing (Erb & Obleser, 2013; Vaden, Kuchinsky, Ahlstrom, Dubno, & Eckert, 2015; Vaden et al., 2013; Wild et al., 2012). Although there may certainly be separate effects of noise and ambiguity, our finding of a significant interaction between the two suggests at least some shared resources, which we view as most consistent with a shared reliance on domain-general executive networks.

The effect of sentence context on speech understanding is also important to consider. Sentence context has long been known to aid speech intelligibility (Miller, Heise, & Lichten, 1951), as the context provides linguistic constraints on the range of possible words. Sentences that provide more contexts are generally more intelligible (Kalikow et al., 1977), and more predictable sentence-final words are processed more quickly (Lash et al., 2013). Although these findings reflect grammatical constraints (e.g., hearing "the ______" suggests a noun or adjective rather than a verb; Strand et al., 2014), they also indicate a level of semantic processing that can aid word identification. A critical role for semantic processing is highlighted by studies showing differences in processing between semantically congruent speech and semantically anomalous speech, which preserves grammatical structure but contains incoherent content words (Davis, Ford, Kherif, & Johnsrude, 2011; Van Engen et al., 2012). In the case of ambiguous words, surrounding context is critical in determining the intended meaning, and thus, semantic processing related to disambiguation plays an important role in our chosen task. Although older adults are often reported to benefit more from semantic context in speech processing than do young adults (Wingfield, Aberdeen, & Stine, 1991), this finding is not universal and may depend on the specific SNRs tested or the type of context available (Dubno et al., 2000; Pichora-Fuller et al., 1995).

Domain-General Executive Resources for Understanding Acoustically Degraded Speech

A critical question is *what* domain-general resources are required to understand acoustically degraded speech. One strong possibility is verbal working memory, generally defined as the ability to manipulate verbal information held in mind. Verbal working memory is frequently associated with rehearsal processes in episodic memory. Here we found that individual differences in reading span, frequently used as a measure of verbal working memory ability, related to older adults' recognition memory accuracy. This finding is consistent with a number of prior studies showing an association between verbal working memory and speech perception or memory (Ng, Rudner, Lunner, Pedersen, & Rönnberg, 2013; Rudner, Rönnberg, & Lunner, 2011; Ward et al., 2016), though in some cases for older adults only. Thus, it may be that understanding noisy speech required increased working memory resources that reduced rehearsal capacity.

A second possibility relates to executive attentional processes that are required for memory encoding. Attentional load during encoding modulates subsequent memory for studied items (Craik, Govoni, Naveh-Benjamin, & Anderson, 1996; Fernandes & Moscovitch, 2000). To the degree that listening to a degraded acoustic signal relies more heavily on attention, it follows that memory would be poorer for the heard items.

A final possibility is that a combination of increased attention and working memory is required for understanding degraded speech—attentional and working memory processes are not independent but can exert mutual influence during perception and memory (Awh, Vogel, & Oh, 2006; Gazzaley & Nobre, 2012). Although the reading span task is frequently assumed to relate to verbal working memory, there are undoubtedly attentional components to that task as well, and our data would be consistent with joint effects of attention and verbal working memory contributing to memory deficits.

In addition to verbal working memory, we also observed positive correlations between vocabulary score and recognition memory for both young and older adults, such that listeners with better vocabulary knowledge performed better on the recognition memory task. Although vocabulary tests explicitly measure lexical knowledge, they also positively correlate with overall verbal ability (Kemper & Sumner, 2001). Not surprisingly, vocabulary generally increases with advancing age (Verhaeghen, 2003) and is related to increased language experience in older adults. The positive correlations between vocabulary score and memory suggest that verbal ability contributed to memory success for both young and older adults. We also note that the older adults tested had higher vocabulary scores (as is common; Verhaeghen, 2003); it could be that the increased verbal ability in the older adults gave them a performance benefit (as seen in their numerically higher d' scores, even though these did not reach statistical significance and had relatively small effect sizes: The average age difference in d', collapsed across condition, was 0.11). Although our data are not able to identify the mechanism for the influence of verbal ability and memory, one possibility is that increased linguistic knowledge decreases the challenge associated with listening, freeing up cognitive resources (such as verbal short-term memory) for memory encoding (Peelle, 2017). It is also important to interpret the d' scores in the context of response time latencies, in which older adults showed a greater effect of acoustic manipulations. Thus, it could be that age-related changes in hearing and verbal working memory increased cognitive challenge, an effect that was partly reduced by increased verbal knowledge.

Limitations and Other Considerations

There are a number of important issues to keep in mind when interpreting our current results. One of these is the specific task we used: a visual recognition memory task. We visually presented probes specifically to require items to be linguistically encoded, which avoids responses based on surface acoustic properties. That being said, the duration of the task blocks makes it unlikely echoic memory would play a large role, and we would predict comparable results had we used auditory probe sentences.

A second and related issue concerns the content of our foil sentences, which were constructed to have overlapping words with the target sentences. We took this approach so that listeners would not be able to make a memory judgment based solely on one or two salient target words (e.g., seeing the word "hickory" in a probe and remembering hearing "hickory," even if the rest of the sentence was not well remembered). Creating challenging foils was important in our case as we tested memory after each block of trials, in part to minimize effects of time. Waiting a longer time before the recognition memory tests would make the task more challenging and potentially eliminate the need for highly overlapping foil sentences (Davis et al., 2007). Of course, the effects of acoustic challenge or semantic ambiguity on memory might be different if sentence recognition were done with auditory sentences, which might rely to a greater extent on episodic memory, or if we had constructed our foil sentences differently.

An important point is that, given our relatively modest sample size, the correlations between individual measures of vocabulary, reading span, and recognition memory must be viewed with some caution and as being exploratory rather than definitive.

Finally, our goal in this study was to assess the cognitive processing required to maintain high levels of speech intelligibility—when intelligibility declines, executive attention systems related to error monitoring and sustained attention are engaged (Eckert et al., 2009; Erb, Henry, Eisner, & Obleser, 2013; Erb & Obleser, 2013; Kuchinsky et al., 2016; Vaden et al., 2013, 2016; Wild et al., 2012), changing cognitive demands and affecting memory (Vaden, Teubner-Rhodes, Ahlstrom, Dubno, & Eckert, 2017).

Conclusions

Taken as a whole, our current results add to mounting evidence that acoustically challenging speech is remembered more poorly, even when it is intelligible and even when supporting semantic context is present. Acoustic challenge interacts with semantic ambiguity effects, implicating domain-general cognitive resources. These findings indicate that improving acoustic clarity can help not only with the perception of speech but also in its processing and encoding into memory.

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Margaret A. Koeritzer, Chad S. Rogers, Kristin J. Van Engen, and Jonathan E. Peelle designed the study. Margaret A. Koeritzer collected the data. Chad S. Rogers performed the statistical analyses. Margaret A. Koeritzer and Jonathan E. Peelle drafted the manuscript with input from Chad S. Rogers and Kristen J. Van Engen. All authors discussed the results and implications and provided critical input to the manuscript at all stages.

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