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## **EFFECTS OF AGE, ACOUSTIC CHALLENGE, AND VERBAL WORKING MEMORY ON RECALL OF NARRATIVE SPEECH**

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*Background/Study Context: A common goal during speech comprehension is to remember what we have heard. Encoding speech into long-term memory frequently requires processes such as verbal working memory that may also be involved in processing degraded speech. Here the authors tested whether young and older adult listeners' memory for short stories was worse when the stories were acoustically degraded, or whether the additional contextual support provided by a narrative would protect against these effects.*

*Methods: The authors tested 30 young adults (aged 18–28 years) and 30 older adults (aged 65–79 years) with good self-reported hearing.*

Received 15 August 2014; accepted 15 August 2015.

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*Participants heard short stories that were presented as normal (unprocessed) speech or acoustically degraded using a noise vocoding algorithm with 24 or 16 channels. The degraded stories were still fully intelligible. Following each story, participants were asked to repeat the story in as much detail as possible. Recall was scored using a modified idea unit scoring approach, which included separately scoring hierarchical levels of narrative detail.*

*Results: Memory for acoustically degraded stories was significantly worse than for normal stories at some levels of narrative detail. Older adults' memory for the stories was significantly worse overall, but there was no interaction between age and acoustic clarity or level of narrative detail. Verbal working memory (assessed by reading span) significantly correlated with recall accuracy for both young and older adults, whereas hearing ability (better ear pure tone average) did not.*

*Conclusion: The present findings are consistent with a framework in which the additional cognitive demands caused by a degraded acoustic signal use resources that would otherwise be available for memory encoding for both young and older adults. Verbal working memory is a likely candidate for supporting both of these processes.*

There is ample evidence that acoustic challenge can affect listeners' memory for speech. The cognitive demands associated with effortful listening are frequently studied by presenting words in noise: in these cases, memory is worse both for items presented in noise (Heinrich, Schneider, & Craik, 2008) and items presented *prior* to the noisy items (Rabbitt, 1968). Findings such as these have lent support to the hypothesis that listening effort reflects increased cognitive demand, and this can be measured indirectly by probing participants' memory (McCoy et al., 2005; Rabbitt, 1968).

Computational models suggest that memory deficits for spoken words are due in part to degraded items interfering with a buffering mechanism in short-term memory (Cousins, Dar, Wingfield, & Miller, 2014; Miller & Wingfield, 2010; Piquado, Cousins, Wingfield, & Miller, 2010). Such a buffering mechanism could be carried by verbal working memory, which has been suggested to support the processing of difficult-to-understand speech (Rönnerberg et al., 2013; Wingfield, Amichetti, & Lash, 2015). If verbal working memory is indeed required for perceptual processing, it will be less available to encode heard items into memory.

In contrast to the relatively rich literature on memory for single words in noise, much less is known about how acoustic challenge impacts memory for connected speech (sentences or stories). On one hand, connected speech involves increased linguistic processing demands that include calculating the syntactic and semantic relationships between words and

arriving at an integrated meaning. These demands typically result in greater areas of cortex being active during listening to connected speech compared with single words (Peelle, 2012), and might be expected to increase overall demands on a listener's cognitive systems (Fallon, Peelle, & Wingfield, 2006; Stewart & Wingfield, 2009; Wingfield, McCoy, Peelle, Tun, & Cox, 2006). On the other hand, it is precisely this type of linguistic context that can counteract a lack of perceptual clarity by providing a supporting scaffold during speech comprehension. Consistent with this latter view is the fact that older adults rely more frequently on context in speech perception (Lash, Rogers, Zoller, & Wingfield, 2013; Pichora-Fuller, Schneider, & Daneman, 1995), even at the expense of perceptual accuracy (Rogers, Jacoby, & Sommers, 2012; Rogers & Wingfield, 2015).

The small number of studies that have investigated memory for acoustically degraded narratives provide conflicting results. Using comprehension questions to assess listeners' memory and understanding of spoken passages presented in noise, Tye-Murray et al. (2008) showed that older adults' comprehension was worse than younger adults' at two different levels of noise, but that noise level did not differentially affect the two groups. Using a similar question-based assessment, Schneider and colleagues (2000) adjusted noise levels to match listeners on single word intelligibility, and no age differences were found in memory accuracy. Participants' accuracy was poorer at higher noise levels; however, this may have been in part because speech was less intelligible at these signal-to-noise ratios (SNRs). The results from comprehension questions suggest that, provided speech is intelligible for older adults, their comprehension of narrative speech may be relatively well preserved.

Findings such as these, in which young and older adults receive individually adjusted SNRs, have been used to argue against a primary role for cognitive factors in older adults' speech comprehension difficulties (Schneider, Daneman, & Murphy, 2005). However, it is also possible that individually adjusting SNRs alters not only the acoustic difficulty of the stimuli, but the cognitive demands placed on listeners. That is, verbal working memory capacity that would have been devoted to acoustic encoding can now be redirected to assisting with memory processing.

Free recall of short stories is another way of assessing memory accuracy without imposing outside structure on participants' recall and may thus be potentially more sensitive to individual differences in performance. Piquado and colleagues (2012) presented spoken stories to young adults with good or poor hearing and asked participants to repeat back as much as possible. Listeners with poorer hearing showed worse recall. However, when listeners were allowed to pace their own way through the story, the performance of the hearing-impaired listeners improved, suggesting a

cognitive locus for their recall difficulty (ameliorated with increased processing time; see also Wingfield & Ducharme, 1999; Wingfield, Tun, Koh, & Rosen, 1999).

In the current experiment, we used free recall to investigate the degree to which acoustic degradation affected memory for narrative speech. We played short stories for young and older adults at three different levels of acoustic clarity, asking participants to recall the stories afterward. We used free recall in order to avoid the potentially subjective nature of comprehension questions, allowing participants to provide whatever information they could remember from the story in an unconstrained way. We reduced the spectral detail of the speech signal using noise vocoding (Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995), a digital signal processing technique that preserves the overall temporal amplitude envelope while altering the spectral detail (i.e., temporal fine structure). Importantly, noise vocoding allowed us to degrade the speech while maintaining high levels of intelligibility. Thus, we are able to attribute differences in recall memory to cognitive processing differences across conditions rather than to participants simply not hearing the information in the first place. If narrative speech is affected similarly to single words, we would expect a decrease in memory accuracy for degraded speech conditions, particularly for listeners with lower verbal working memory capacity. On the other hand, if connected speech presents fundamentally different cognitive challenges to listeners, we may instead see relatively preserved episodic memory accuracy, even when speech is degraded.

## **METHODS**

### ***Participants***

Participant characteristics are given in [Table 1](#). All participants were native speakers of American English with self-reported good hearing and no history of auditory or neurological difficulty. Young adult participants (12 male) ranged in age from 18 to 29 years; older adults (12 male) ranged from 64 to 76 years. Young and older adults did not differ in their levels of formal education,  $t(58) = 1.46, p = .15$ , although older adults had significantly higher vocabulary scores,  $t(58) = 2.91, p = .005$ . Older adults' reading span scores were significantly worse than that of the young adults,  $t(58) = 3.92, p < .001$ , as was their better ear pure tone average (PTA),  $t(58) = 8.69, p < .001$ .

All participants gave written informed consent under a process overseen by the Washington University in Saint Louis Institutional Review Board.

**Table 1. Participant characteristics**

Characteristics	Young	Older
<i>n</i>	30	30
Age (years)	22.0 (2.95)	68.1 (3.12)
Years of education	15.4 (2.05)	16.3 (2.70)
Shipley vocabulary	13.5 (1.46)	15.0 (2.41)
Reading span (total score)	34.1 (7.14)	26.9 (7.10)
Better ear PTA (dB HL) <sup>a</sup>	-0.6 (4.19)	19.4 (11.47)

*Note.* Data are mean (*SD*).

<sup>a</sup>Audiometry was unavailable for two young adults.

## Materials

### *Narrative Speech Stimuli*

We used 12 short stories as experimental stimuli. To create the stimuli, we modified public domain versions of *Aesop's Fables*, rewriting them to ensure modern English wording and consistent length (between 60 and 80 words). The stories 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 isolated and trimmed to eliminate silent periods preceding and following each story. An example story is included in Appendix A, and the complete set is available at <http://jpeelle.net/stimuli/discourse/fables>.

### *Acoustic Degradation Using Noise Vocoding*

To degrade the speech, we used a noise vocoding algorithm in which the frequency spectrum of a sound is divided into a number of logarithmically spaced frequency bands, or channels. The acoustic amplitude envelope is extracted from each channel and used to modulate broadband noise, which is then filtered to be in the same frequency channel. Information from all channels is then combined to re-form the stimulus. Because spectral detail within a channel is lost, the overall amount of spectral information (and thus speech clarity) varies with the number of channels. Vocoding with 16 or more channels is typically fully intelligible for listeners with good hearing (Faulkner, Rosen, & Wilkinson, 2001). We chose noise vocoding because it largely preserves rhythmic speech cues while rendering the stimulus less clear.

Our vocoding algorithm extracted the amplitude envelope by low-pass-filtering half-wave-rectified signal from each channel at 30 Hz. Sound files were low-pass-filtered at 8 kHz. The code for signal processing (jp\_vocode.m) is available at [https://github.com/jpeelle/jp\\_matlab](https://github.com/jpeelle/jp_matlab).

*Sentence Stimuli for Intelligibility Check*

To verify that stimuli at various levels of degradation were intelligible to listeners, we conducted a separate intelligibility check using sentences recorded by the same speaker. We used short, five-word sentences to minimize demands on verbal working memory. These sentences were processed identically to the stories.

*Scoring of Narrative Recall*

We assessed participants' recall accuracy using a modified idea unit scoring method, an example of which is given in Appendix B. Each story was broken down into minimal idea units. Typically, the first (top) level consisted of a noun-verb coupling, with additional details (the recipient of the action, adjectives, etc.) forming sublevels. Scores for each level were independent: higher-level idea units could be recalled even if a participant failed to recall lower-level idea units. Each content word of a sentence was scored exactly once. Scoring of each content word was strict (no partial credit). However, full credit was awarded for synonyms. Conjugation was ignored during scoring. We adopted this method after experimenting with more traditional idea unit approaches (Turner & Greene, 1977; van Dijk & Kintsch, 1983) because we found it to be more transparent to score and required less training to achieve interrater consistency. Because subordinate levels contained progressively smaller numbers of observations, we collapsed levels 3 and higher into a single "level," resulting in approximately equal numbers of observations per level.

One important aspect of our scoring system is that participants had to correctly recall both the subject and the verb to receive credit for recalling the first level of an idea unit. All other types of content words were scored in isolation, so participants had to recall only a single content word to receive credit. Although subject-verb pairings appeared at multiple levels of detail, they were disproportionately found at level 1. If recalling both the subject and the verb of a clause was more difficult than recalling other content words (e.g., an adjective), then participants' level 1 scores would be lowered.

Participant responses (i.e., the recalled passages) were transcribed from digital recordings by a researcher blinded to experimental condition, and the transcriptions scored independently by two scorers (also blinded to experimental condition). Interrater reliability was good, Krippendorff's  $\alpha = .88$  (calculated using ReCal2; Freelon, 2010). We used the average of the two scores in all analyses.

## ***Procedure***

Participants first completed the baseline sentence task in which they heard nine short sentences (three at each level of acoustic clarity) and were instructed to repeat each sentence back verbatim. All participants were able to do this without error (i.e., intelligibility was 100%). Thus, intelligibility was matched across conditions at ceiling, consistent with our intent to keep speech highly intelligible for all conditions.

Each participant listened to a total of 12 stories. At the end of each story, the participant was given as much time as necessary to recall the story. Stories were blocked by acoustic condition, with the order of presentation varied over participants. The particular stories presented at each level of acoustic clarity were counterbalanced across subjects. Recall was digitally recorded for transcription and scoring.

We measured hearing sensitivity using pure tone audiometry, collecting thresholds at octave intervals between 250 and 8000 Hz (and 3000 and 6000 Hz) for left and right ears. To summarize hearing sensitivity, we used a pure tone average (PTA) of thresholds at 1, 2, and 4 kHz in each listener's better ear. Hearing was unavailable for two young adults due to technical difficulties.

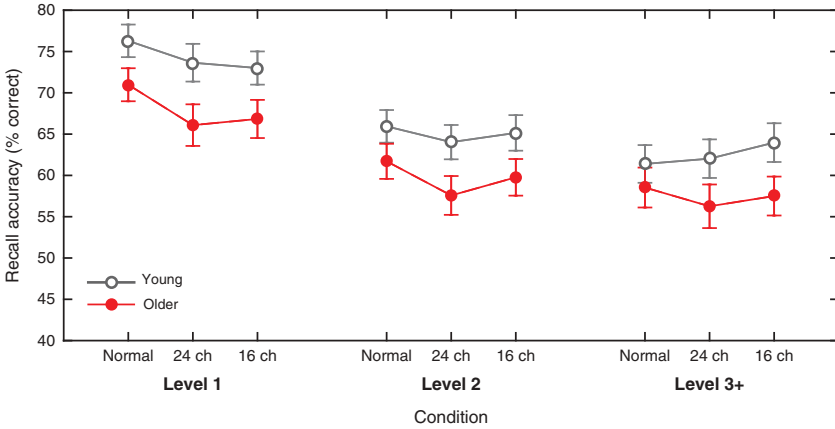
Participants also completed a reading span task as a measure of verbal working memory (Daneman & Carpenter, 1980; McCabe, Roediger, McDaniel, Balota, & Hambrick, 2010). This task requires subjects to read a series of sentences and determine if each is plausible while also remembering the last word of each one to report to the researcher at the end of the series. Series ranged in length from 1 to 5, with participants completing three series per length. The reading span total score was calculated by summing the total number of words correctly remembered, with no penalty for errors of commission (Conway et al., 2005).

Each participant also completed the Shipley Vocabulary test (Zachary, 1986) as a measure of general verbal ability.

## ***RESULTS***

### ***Narrative Recall***

Recall accuracy results are shown in [Figure 1](#). We analyzed the recall data using a mixed-design repeated-measures analysis of variance (ANOVA), with acoustic clarity (3: normal, 24 channel, 16 channel) and narrative detail (3: first level, second level, third+ level) as within-subject factors and age (2: young, older) as a between-subjects factor.



**Figure 1.** Narrative recall accuracy for young and older adults as a function of narrative detail level and acoustic clarity (normal speech, 24-channel vocoded speech, and 16-channel vocoded speech). The average number of observations per participant per condition was 46 ( $SD = 13$ ). Error bars indicate 1 standard error.

Overall, the older adults' recall was worse than the young adults,  $F(1, 58) = 4.45$ ,  $p = .04$ , partial  $\eta^2 = .07$ . Although there was a modest trend, the effect of acoustic clarity was not significant,  $F(2, 116) = 2.61$ ,  $p = .08$ , partial  $\eta^2 = .04$ , nor was there a significant Acoustic Clarity  $\times$  Age Group interaction,  $F(2, 116) = 0.66$ ,  $p = .52$ , partial  $\eta^2 = .01$ .

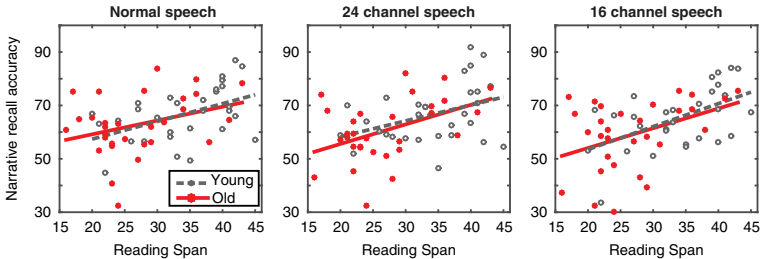
There was a main effect of level,  $F(2, 116) = 175.79$ ,  $p < .001$ , partial  $\eta^2 = .75$ , consistent with listeners' relatively poorer recall for increasing levels of detail. There was no interaction between level and age group,  $F(2, 116) = 0.60$ ,  $p = .55$ , partial  $\eta^2 = .01$  but there was a significant interaction between level and acoustic clarity,  $F(4, 232) = 2.53$ ,  $p = .04$ , partial  $\eta^2 = .04$ . Post hoc  $F$  tests applying Bonferroni correction for family-wise error rates revealed that the effect of acoustic clarity was significant on level 1 idea units,  $F(2, 57) = 3.59$ ,  $p < .05$ , partial  $\eta^2 = .11$ , with greater recall for the unprocessed speech condition ( $M = .74$ ,  $SD = .11$ ) than either the 24-channel ( $M = .70$ ,  $SD = .14$ ) or 16-channel ( $M = .70$ ,  $SD = .12$ ) condition. Post hoc  $F$  tests did not reveal significant effects of acoustic clarity for level 2 idea units,  $F(2, 57) = 2.78$ ,  $p = .07$ , partial  $\eta^2 = .09$ , or level 3+ idea units,  $F(2, 57) = 0.66$ ,  $p = .52$ , partial  $\eta^2 = .22$ . These results are consistent with the effects of degradation being most pronounced on more prominent idea units. The three-way interaction between acoustic clarity, level, and age group was not significant,  $F(4, 232) = 0.29$ ,  $p = .89$ , partial  $\eta^2 = .01$ .



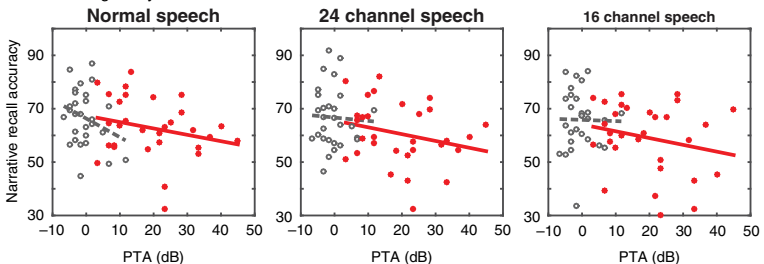
We next conducted a series of Pearson correlations to assess whether our verbal working memory or hearing measures related to recall accuracy at any level of acoustic clarity (collapsed across level of narrative detail). These are shown in [Figure 2](#) and summarized in [Table 2](#). In both age groups, listeners with better verbal working memory performed significantly better on the recall task when speech was degraded. For young adults, this relationship was also significant for unprocessed speech. There was no significant correlation between hearing and recall at any level of acoustic clarity.

Finally, we examined the degree to which verbal working memory and hearing could jointly predict participants' recall accuracy. Correlations between predictor variables are shown in [Table 3](#). We performed a step-wise linear multiple regression on participants' accuracy data for the level 1 recall in the 16-channel vocoded condition—that is, the condition in which accuracy was differentially affected. Predictor variables were age group, verbal working memory, hearing (better ear PTA), and the interaction between verbal working memory and hearing. The results for this

A) Correlations with reading span



B) Correlations with hearing ability



**Figure 2.** Correlations between narrative recall at each level of acoustic clarity for (A) reading span and (B) hearing ability (pure tone average; PTA). Lines show best-fit linear regression line for young adults (*dashed lines*) and older adults (*solid lines*); correlation coefficients are shown in [Table 2](#).

**Table 2. Pearson correlations between hearing, working memory, and narrative recall**

Hearing	Young			Older		
	Normal	24 channel	16 channel	Normal	24 channel	16 channel
Reading span	.47**	.38*	.54**	.32	.45*	.40*
Better ear PTA	-.28	-.05	-.02	-.24	-.25	-.22

\**p* < .05; \*\**p* < .01.

**Table 3. Pearson correlations between predictor variables**

	Age	Reading span	Left ear PTA	Right ear PTA	Better ear PTA	Vocabulary
Age	—					
Reading span	-.48**	—				
Left ear PTA	.77**	-.54**	—			
Right ear PTA	.77**	-.53**	.90**	—		
Better ear PTA	.79**	-.53**	.95**	.98**	—	
Vocabulary	.36**	.02	.20	.26*	.23	—

\**p* < .05; \*\**p* < .01.

**Table 4. Multiple regression results**

Model	<i>R</i>	<i>R</i> <sup>2</sup>	Adjusted <i>R</i> <sup>2</sup>	<i>SE</i>	Change statistics				
					<i>R</i> <sup>2</sup> change	<i>F</i> change	<i>df</i> <sub>1</sub>	<i>df</i> <sub>2</sub>	Significance <i>F</i> change
Age	.296	.088	.071	.133	.088	5.39	1	56	.024
Age, Hearing	.336	.113	.081	.132	.025	1.57	1	55	.215
Age, Hearing, Working memory	.504	.254	.212	.122	.140	10.16	1	54	.002
Age, Hearing, Working memory, Hearing × Working Memory	.521	.272	.217	.122	.018	1.33	1	53	.253

multiple regression are shown in Table 4. Consistent with the correlation analyses, the multiple regression results show a significant effect of age group and verbal working memory, but no effect of hearing, nor a significant interaction between verbal working memory and hearing. (These findings remained consistent across different orderings of predictors into the model, and using age as a continuous rather than dichotomous variable.)

## DISCUSSION

As listeners, we generally want to remember what we have heard. In the current study, we examined whether memory for short stories was affected by the acoustic clarity of the speech signal. Importantly, our sentence repetition task confirmed that speech in all conditions was fully intelligible. Thus, we were able to focus on the impact of additional cognitive processes required to successfully extract meaning from degraded speech, distinct from those that might be involved in error-monitoring (Vaden et al., 2013). Not surprisingly, we found that older adults' recall for short stories was significantly worse than that of young adults (Tye-Murray et al., 2008). Furthermore, recall accuracy dropped for degraded speech for the first level of narrative detail, but not for further levels; statistically, young and older adults were equally affected. Verbal working memory capacity correlated with recall accuracy for both young and older adults, whereas hearing ability did not. We discuss these findings and their implications below.

As noted in the introduction, many studies have found episodic memory declines for lists of unrelated word when acoustic clarity is low (Cousins et al., 2014; Miller & Wingfield, 2010; Piquado et al., 2010; Rabbitt, 1968). An especially nice demonstration of this is found in McCoy et al. (2005) in which the authors presented word lists to older adults who varied in their hearing ability. List presentation was stopped at unpredictable times, and listeners were asked to repeat back the most recent three words. The 1-back case provided a verification of intelligibility and perception, whereas words further back showed effects of memory load. Older adults with hearing loss showed poorer memory for word positions 2 to 3 prior, consistent with acoustic challenge (in this case, hearing loss) requiring additional cognitive resources during perception (Wingfield & Tun, 2001; Wingfield, Tun, & McCoy, 2005; Wingfield, Tun, McCoy, Stewart, & Cox, 2006). Our finding of decreased memory for degraded speech agrees with this conclusion and adds to a growing body of work suggesting increased cognitive demand during acoustic challenge. Evidence supporting a cognitive component to listening effort also comes from dual-task paradigms (Gosselin & Gagné, 2011), recognition memory for sentences (Van Engen, Chandrasekaran, & Smiljanic, 2012), pupillometry (Kuchinsky et al., 2013; Zekveld, Kramer, & Festen, 2010), and functional brain imaging (Eckert et al., 2009; Erb, Henry, Eisner, & Obleser, 2013; Hervais-Adelman, Carlyon, Johnsrude, & Davis, 2012; Wild et al., 2012). Findings from reading studies suggest cognitive demands that generalize across modality (Gao, Levinthal, & Stine-Morrow, 2012; Gao,

Stine-Morrow, Noh, & Eskew, 2011). Thus, the effects of acoustic challenge are not reflected only in auditory processing, but also in higher-level cognitive systems that operate on the outputs of perception.

Our finding that acoustic challenge had more of an effect for main ideas (level 1) than for subordinate ideas was unexpected—typically, we might expect main ideas to be retained and details to be forgotten. Indeed, effects of hearing loss were most apparent in detail-level idea units in Piquado et al. (2012). On the other hand, in the visual domain, Gao et al. (Gao et al., 2011, 2012) have reported that visual noise in reading differentially disrupted the recall of main ideas. It may be that the type of materials being tested impacts the narrative level where effects of perceptual challenge are observed. In our case, with relatively short, predictable narratives without a large number of details, participants perform relatively well overall (~20% better than participants in Piquado et al., 2012), which may decrease the fragility of detailed idea unit encoding. Our scoring of level 1 idea units required successful recall of both the subject and the verb of the sentence, which may have enhanced the sensitivity of those idea units to effects of noise. Regardless, our current results suggest effects of acoustic clarity that are reflected in memory for at least a subset of the information conveyed by short stories.

Although we observed decreased memory accuracy for acoustically degraded stories, it is important to note that the magnitude of decrease in memory was small: normal speech was recalled at an average of 65.4% correct, and 16-channel speech 63.0% (a drop of 2.4%). Considering level 1 only, recall was 74.3% correct for normal speech and 70.6% for 16-channel speech (a drop of 3.7%). Thus, although our results provide evidence of cognitive challenge during listening, they also highlight the support provided by linguistic context in connected speech. When remembering lists of unrelated single words, listeners have extremely little context available to aid memory—they are forced to rely heavily on verbal representations of individual items, placing a high demand on verbal working memory. The addition of any amount of semantic or syntactic constraint can reduce these memory demands. Indeed, when context was provided by using nonrandom word lists in McCoy et al. (2005), memory decrements for listeners with hearing loss disappeared. In our case, using meaningful narratives provided listeners a large amount of redundant and supportive information. Given that young and older adults process narrative structure in largely similar patterns (Stine-Morrow, Milinder, Pullara, & Herman, 2001; Stine-Morrow, Soederberg Miller, & Leno, 2001), it is not surprising that this type of context is equally supportive for both age groups. Thus, one implication of our study is that contextual support provided in connected speech reduces demands on verbal working memory and enables listeners to better remember what they have heard.

Of course, with narratives that are longer, more complex, or less cohesive than ours, listeners may have difficulty recalling what they have heard. However, such passages may also begin to stray from the constraints typically present in everyday conversation.

A critical distinction in measures of cognitive challenge during speech perception is whether they are online or offline. Memory measures, including both those in list-learning paradigms, recognition memory, and the current study, are necessarily offline. Thus, having observed a difference in memory performance, we can reasonably conclude that cognitive processing differed at time of encoding. However, a lack of a difference is not strong evidence for an absence of cognitive challenge during encoding, given the numerous possible compensatory mechanisms available to listeners. Compensatory neural activity during challenging listening situations is commonplace (Davis & Johnsrude, 2003; Erb et al., 2013; Hervais-Adelman et al., 2012; Wild et al., 2012), and older adults frequently show increased recruitment of large-scale neural networks during sentence comprehension relative to young adults (Peelle, Troiani, Wingfield, & Grossman, 2010; Wingfield & Grossman, 2006). Thus, we anticipate that online measures of the task reported here would show increased cognitive demand during degraded speech relative to normal speech, which would be required for listeners to maintain the same high level of performance. It is not unreasonable to think that older adults may show greater compensatory activity than young adults, although this remains an open question.

We found that reading span, intended to measure verbal working memory, was significantly correlated with overall recall levels for both young and older adults. (It is notable that, although older adults in general had lower reading span scores, there was substantial overlap in young and older adults' performance, as seen in Figure 2.) These results suggest that listeners' encoding of narrative structure—and not just items in unrelated lists—relies in part on verbal working memory. Our results are consistent with evidence that verbal working memory can affect listeners' speech perception, particularly in noise (Ng, Rudner, Lunner, Pedersen, & Rönnerberg, 2013; Rudner, Rönnerberg, & Lunner, 2011; Zekveld et al., 2011). Neuroanatomically, this would be consistent with a distributed verbal working memory system (Chein & Fiez, 2010) that relies in part on premotor cortex (Szenkovits, Peelle, Norris, & Davis, 2012). Interestingly, these conclusions are supported by a previous study in which left-lateralized motor cortex activity (influenced by participants' performing a motor task) interfered with narrative recall more than right-lateralized activity (Wingfield, Milstein, & Blumberg, 1984). In our case, although older adults had poorer verbal working memory than the young

adults, individual differences in capacity impacted behavioral performance similarly for young and older adults.

Finally, we did not find a significant relationship between hearing ability and recall performance. This may be because the overall hearing of our older adults was relatively good (most PTAs  $\leq 25$  dB HL [hearing level]); we would expect listeners with worse hearing to be differentially affected by external acoustic degradation (for example, in Piquado et al., 2012 the mean PTA was 41.0 dB HL).

In conclusion, we found that acoustically degraded (but intelligible) spoken stories were recalled more poorly than unprocessed stories by both young and older adult listeners. We interpret these results as being consistent with a framework in which the additional cognitive demands caused by a degraded acoustic signal use resources that would otherwise be available for memory encoding for both young and older adults.

### **ACKNOWLEDGMENTS**

We are extremely grateful to Sheridan Frank, Tyler Frank, Carol Iskiwitch, Hunter Patterson, Vivian Tao, Katie Vogel, and Rebecca Yang for help with data collection and scoring, and our volunteers for their participation.

### **FUNDING**

Research reported here was supported by the Dana Foundation and the National Institute on Aging of the National Institutes of Health under award number R01AG038490.

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**APPENDIX A*****The Lion and the Boar***

In the heat of a summer day, a lion and a boar became thirsty and stopped to take a drink from a small well. The two beasts fought for the opportunity to drink first, each prepared to take down the other. During a break in the fight, they saw some vultures waiting in the distance for the first victim. The lion and the boar immediately stopped quarreling to befriend one another so that neither became a meal for the birds.

**APPENDIX B**

Below we provide an example of idea unit scoring for a single sentence.

To be recalled:

“In the heat of a summer day, a lion and a boar became thirsty and stopped to take a drink from a small well.”

Actual recall:

“A lion and a boar got thirsty, and stopped to drink from a small watering hole.”

Idea unit scoring scheme:

First order	Second order	Third order	Fourth order	Level code	Recalled?
A lion and boar became				1	Yes
	became thirsty			2	Yes
	on a day (during the daytime)			2	No
		on a hot day		3+	No
		on a summer day		3+	No
A lion and a boar stopped				1	Yes
	to drink			2	Yes
		from a well		3+	No
			a small well	3+	Yes