Text captioning buffers against the effects of background noise and
hearing loss on memory for speech

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Abstract

Objectives. Everyday speech understanding frequently occurs in perceptually demanding environments, for example due to background noise and normal age-related hearing loss. The resulting degraded speech signals increase listening effort, which gives rise to negative downstream effects on subsequent memory and comprehension, even when speech is intelligible. In two experiments, we explored whether the presentation of realistic assistive text captioned speech offsets the negative effects of background noise and hearing impairment on multiple measures of speech memory.

Design. In Experiment 1, young normal hearing adults ($N = 48$) listened to sentences for immediate recall and delayed recognition memory. Speech was presented in quiet or in two levels of background noise. Sentences were either presented as speech only or as text captioned speech. Thus, the experiment followed a 2 (caption vs no caption) $\times$ 3 (no noise, +7 dB SNR, +3 dB SNR) within-subjects design. In Experiment 2, a group of older adults (age range : 61 – 80, $N = 31$), with varying levels of hearing acuity completed the same experimental task as in Experiment 1. For both experiments, immediate recall, recognition memory accuracy, and recognition memory confidence were analyzed via general(ized) linear mixed effects models. In addition, we examined individual differences as a function of hearing acuity in Experiment 2.

Results. In Experiment 1, we found that the presentation of realistic text-captioned speech in young normal-hearing listeners improved immediate recall, delayed recognition memory accuracy, and memory confidence compared to speech alone. Moreover, text captions attenuated the negative effects of background noise on all speech memory outcomes. In Experiment 2, we replicated the same pattern of results in a sample of older adults with varying levels of hearing

acuity. Moreover, we showed that the negative effects of hearing loss on speech memory in older adulthood were attenuated by the presentation of text captions.

Conclusion. Collectively, these findings suggest that listeners can rapidly integrate text and speech, and that the simultaneous presentation of text can offset the negative effects of effortful listening on speech memory.

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Introduction

Age-related changes in sensory and cognitive functioning can have a profoundly negative effect on comprehension and memory for language. One of the most striking examples of this is the negative effect of age-related sensorineural hearing loss (i.e., presbycusis) on speech understanding. By some estimates, sensorineural hearing loss is the third-most-prevalent chronic medical condition in older adults (after arthritis and hypertension), afflicting approximately 50% of adults over 65 and over 80% of adults over the age of 70 (Cruickshanks et al., 1998). At the same time, typical audiometric tests do not explain the full range of difficulties that adults with hearing loss report in speech listening. Even when adults can successfully perceive speech, the additional cognitive effort required to extract meaning from degraded sensory input has a substantially negative impact on comprehension and subsequent memory for speech (Wingfield et al., 2005; Peelle, 2017; Pichora-Fuller et al., 2016). This increased *listening effort* is an oft-cited hidden effect of hearing loss and is crucially important in understanding the challenges listeners face in high-level speech understanding.

The visual presentation of captioned speech is a promising route that may reduce the cognitive burden of auditory perceptual decoding in the face of age-related hearing loss. For example, text captioning has been shown to improve perceived speech intelligibility, word perception, and accuracy of word recognition in sentences (Gordon-Salant & Callahan, 2009; Krull & Humes, 2016). In the current study, we report the results of two experiments examining the effects of realistic text captioning on multiple measures of auditory sentence memory under listening conditions intended to impose different degrees of listening effort. In Experiment 1, we

introduce a novel cumulative moving window paradigm to study the effects of text captioning on immediate speech recall and delayed recognition memory in young adults with normal hearing. In Experiment 2, we extend this paradigm to a sample of healthy older adults with a wide range of hearing acuity.

Speech Memory, Listening Effort, and Aging

Everyday listening commonly occurs in environments that present challenges to speech perception. Even when listeners can successfully identify perceptually degraded speech, the additional effort allocated to decoding the noisy signal interferes with downstream cognitive processes such as successful memory encoding (Rabbitt, 1968; Rabbitt, 1991; Wingfield et al., 2005). This general finding has been observed across a large number of experiments, dating back to the 1960s. Rabbitt (1968) first presented evidence that sensory processing draws on cognitive resources from higher-order and domain-general systems to support perceptual decoding. He presented young normal-hearing adults with lists of spoken digits. The first block of each list contained unprocessed speech, while the second block was presented in background noise. Critically, memory for early list items—which themselves were not degraded—was poorer when items in the later part of the list were degraded, suggesting that understanding speech in noise interfered with cognitive processes required for memory encoding. Similar effortfulness effects have been replicated in word lists (Cousins et al., 2014; Piquado et al., 2010) and in running memory for speech (McCoy et al., 2005). Indeed, the consequences of effortful listening extend beyond memory impairments, impacting high-level sentence and discourse comprehension as well (Rabbitt, 1991; Surprenant, 1999; Pichora-Fuller, 2003; McCoy et al., 2005; Cousins et al., 2014).

For example, sentence comprehension interacts with perceptual demands in hearing-impaired adults, particularly when the sentences are more linguistically complex. Wingfield and

colleagues (2006) presented younger adults with normal hearing and older adults with and without hearing impairment sentences that varied in syntactic complexity (i.e., subject- versus object-relative clauses), and perceptual intelligibility (via time-compressed speech). Older adults with hearing impairment showed a differential disruption in comprehension accuracy for the more demanding object-relative sentences when they were presented at fast speech rates, despite the fact that all participants could still accurately perceive the speeded speech. Similarly, Stine-Morrow and colleagues (Gao et al., 2011; Stine et al., 1986; Stine & Hindman, 1994; Stine & Wingfield, 1990; Stine-Morrow, et al., 2008) have demonstrated across multiple experiments that older adults show differentially worse memory for propositionally-dense speech and text compared to younger adults, with effects that are exaggerated under increased perceptual demand. Related findings have been reported in auditory discourse comprehension, where adults with hearing loss show reduced memory for detailed semantic features in short narrative discourses, despite having high intelligibility (Piquado et al., 2012). These studies present compelling evidence that acoustic challenge interacts with linguistic cognitive demand, pointing toward the involvement of domain-general cognitive resources in understanding degraded speech.

Assistive Text Captioning

Although few studies have directly examined the effects of text captioning on speech memory, several complementary literatures exist examining the effects of audio-visual integration in speech processing, supplemental text on speech reception thresholds, comprehension of captioned television and newscasts, and the effects of captioning on the perception of ambiguous speech. These literatures provide complementary findings supporting the claim that text captioning may offset the costs of effortful listening. These findings are briefly summarized below.

An oft-cited finding in the speech processing literature is that speech reception thresholds and speech comprehension in background noise are improved when adults are able to view the articulatory expressions of the speaker (e.g., audiovisual speech or “speech-reading”). These findings suggest that integrating cues from visual and auditory sensory channels can provide a benefit to intelligibility when speech is degraded, with an effect equivalent to an improvement in the speech-to-noise ratio of as much as 15 dB (Sumby & Pollack, 1954; Sommers & Phelps, 2016; Grant, 2002). This is critical, as studies have shown that a 1-dB improvement in signal-to-noise ratio (SNR) can correspond to upwards of a 10% increase in listener intelligibility performance (Grant & Braida, 1991). At the same time, the extant research on the integration of visual and auditory speech cues suggests that aging may be associated with a reduced capacity to rapidly integrate multiple sensory inputs (e.g., Tye-Murray et al., 2010; Sommers & Phelps, 2016).

Are there more robust visual cues that could be used to supplement speech, besides the speaker’s facial movements? Orthographic cues from simultaneously presented text would arguably provide much less ambiguous information relative to the subtle phonetic cues defined by facial articulation. There are a number of reasons to believe that text can be rapidly integrated with speech. For example, functional neuroimaging studies show heteromodal activation of auditory cortex to presentation of speech sounds and of corresponding letters representing those same speech sounds in literate adults, suggesting that the processing of shared orthographic and acoustic representations relies on similar underlying neural mechanisms (van Atteveldt et al., 2004).

To date, there is limited literature directly examining the simultaneous processing of text and speech. Early studies aimed to test whether speech perception could be biased by presenting simultaneous text cues. For example, Frost and Katz (1989) presented individual bi-syllabic words in noise with accompanying visual word presentation. Critically, the words either matched or did

not match the speech, and speech sounds were either presented in background noise, or were noise bursts only (no speech was presented). Using signal detection methods, Frost and Katz found a strong bias effect, such that visual input appeared to make amplitude-modulated noise sound more like speech, but it did not improve the detectability of the speech. At the same time, however, reaction times to correct detections were reliably shorter when text and speech matched, suggesting some evidence of a benefit to perception in audio-visual word recognition. Later work (e.g., Grant & Seitz, 2000) showed that presenting matched orthographic text with speech in noise improved auditory word detection and provided masking release in sentences. More recently, studies have shown that text cues can directly recalibrate the perception of ambiguous phonetic information for individual speech sounds. Keetels et al. (2016), for example, showed that when participants were presented with ambiguous speech sounds halfway between /b/ and /d/ that were combined with the presentation of the letter *b* or *d*, participants were more likely to categorize the test sounds in accordance with the visually presented letter. These results suggest that listeners adjust their phonetic boundaries during speech perception in accordance with the disambiguating orthographic information.

Beyond word recognition, a small number of studies have begun exploring the added benefits of text captioning to the perceived clarity of degraded speech. Gordon-Salant and Callahan (2009) have shown that real-time closed captioning of speech in television improves speech intelligibility in adults with hearing impairment. Additionally, this study compared the benefits of hearing aids to speech recognition with and without captioning. Strikingly, although identification of words in sentences was improved with the hearing aid, the effects of captioning were much larger. In fact, hearing aids provided no appreciable benefit to word recognition when text captioning was available.

Similar results have been found in studies examining the benefits of text captioning for improving word recognition in varying levels of background auditory noise (Zekveld et al., 2008; Krull & Humes, 2016; Wild et al., 2012). Some studies, however, have provided less robust evidence for benefits of text captioning to perceived intelligibility (Sohoglu et al., 2014; Stine & Wingfield, 1990). For example, Sohoglu et al. (2014) examined the effects of written text on listeners ratings of clarity of noise-vocoded speech in young normal-hearing adults. They showed that perceived clarity was highest when text was presented before rather than after speech onset. In their study, intelligibility benefits of text were lost after a short stimulus-onset asynchrony (i.e., if text was presented even 200 ms after speech onset). However, it is important to note that the spectral vocoding used in this study resulted in a massive reduction in intelligibility relative to what is observed in noise-masked speech, making the task much more difficult than normal listening situations.

As reviewed above, a number of previous studies have shown that text cues may modulate the perception of degraded or ambiguous speech. Nevertheless, it is not clear what downstream benefits this improved clarity has on adults' subsequent speech memory. Two studies to date are most relevant to addressing this question. First, Grossman and Rajan (2017) showed that the simultaneous presentation of congruent (but not incongruent) text benefitted word recall of noise-degraded speech in young adults with normal hearing. Second, Krull and Humes (2016) tested whether the presentation of partially accurate visual text from an automatic speech recognizer could be used to successfully supplement word recognition in noise among young normal-hearing adults and older adults with normal hearing or moderate hearing loss. They found that combining degraded speech with partially correct text increased the percent of speech keywords accurately

repeated by both young and older adults, relative to a condition with either auditory-only or text-only performance.

As seen in the above review, the extant literature provides some evidence supporting the idea that text captioning may offset demands of perceptual processing and reduce effects of effortful listening. Importantly, the text presentation methods used in prior studies have not been ecologically-valid and have not approximated real-world text captioning systems as currently implemented in most technology (e.g., captioned television or assistive hearing telephones). In Krull and Humes (2016), for example, presented the text word-by-word via rapid serial visual presentation, thus precluding the natural ability to read and re-read which is critical for effective comprehension (see e.g., Schotter & Payne, 2019; Payne & Silcox, 2019). Grossman and Rajan (2017) in contrast, used a whole-sentence presentation in which the entire sentence appeared on the screen at the onset of the speech. This method allows readers to preview text prior to its onset in speech, which is not possible in real-world assistive text captioning. Finally, prior studies have largely used short, simple, and non-naturalistic speech stimuli. Given that the effects of hearing loss and perceptual demand are more apparent when the cognitive demand of the language is more taxing (see Wingfield & Stine-Morrow, 2000; Payne & Silcox, 2019 for reviews), it is important to examine the assistive effects of text captioning for more demanding, naturalistic speech.

The Current Study

We conducted two experiments aimed at directly testing the effects of realistic assistive text captioning on immediate recall, delayed recognition memory, and recognition confidence for real-world, propositionally-dense sentences. In Experiment 1, we examined the effects of background noise and text captioning on memory for speech in young normal-hearing listeners.

Consistent with prior work, we predicted an effortfulness effect: i.e., that increasing background noise, even modestly, would result in poorer downstream speech memory. However, we predicted that these effortfulness effects would be attenuated when speech was presented with text captioning. In Experiment 2, we replicated Experiment 1 in a cohort of older adults with a wide range of hearing acuity. Here, we expected that effects of background noise would be larger overall and exaggerated among older adults with poorer hearing acuity. However, if audiovisual integration of text and speech is preserved in aging, we expected text captioning to buffer against both the effects of poorer hearing and the increased effects of background noise on speech memory, resulting in a larger caption benefit when hearing thresholds were elevated and when SNR was lower.

Experiment 1

The aim of the first experiment was to examine the impact of real-world assistive text captioning on memory for informationally-dense speech in variable levels of background noise. Toward this goal, we presented real-world, propositionally-dense sentences (adapted from Stine-Morrow et al., 2008) in background noise at varying levels to manipulate perceptual challenge. Speech was either presented alone (speech-only) or with cumulative text captioning (text-captioned speech). This was accomplished via a novel multi-word cumulative text presentation paradigm, described below in more detail.

Method

Participants. Forty-eight young adults gave written informed consent. Participants' mean age was 22.89 years old (range: 18 – 34). The sample was 81% Caucasian, 12% ($N = 6$) Asian, and 2% ($N = 1$) African American. All participants completed high school; 78% had at least some

college experience, and 4% had completed some post-graduate education. Participants reported normal or corrected-to-normal vision and reported no hearing loss, use of a hearing aid, or any history of ear or hearing-related disorders. From this sample, two participants were excluded from further analysis because they did not complete the entire protocol. All procedures were approved by the University of Utah Institutional Review Board.

Stimulus Materials and Design. Participants were presented with a total of 90 propositionally-dense sentences drawn from prior work on sentence memory and aging (Stine-Morrow, et al., 2001; Payne & Stine-Morrow, 2017). Stimulus sentences were each 18 words long and dealt with diverse topics in science, nature, and history, with many adapted from popular magazines like *National Geographic*. Table 1 presents example sentences. Sentences were recorded by a single female native English speaker in a quiet room via a cardioid USB microphone. Audio was recorded and digitized at a sampling rate of 44.1 kHz. Individual sentences were existed and then trimmed to eliminate silent periods preceding and following each sentence. Sound files were then scaled to the same root-mean-square amplitude. The noise masker was a stationary speech-shaped noise with the long-term frequency spectrum of the speech.

Sentences were presented in two blocks of 45 sentences each, one without text captioning (auditory-only) and one with text captioning, with block order counterbalanced across subjects. Sentences were presented in quiet or at one of two different SNRs, +7 and +3 dB. These levels were chosen based on pilot testing to increase reported listening effort while maintaining high levels of subjective intelligibility. Despite the stimuli being rated as highly intelligible, we nevertheless expected the increased effort required for perceptual decoding in background noise to increase listening effort, yielding subsequent deficits in immediate recall and delayed

recognition memory. The noise manipulation was randomized across items, resulting in a 2 (caption vs no caption) x 3 (no noise, +7 dB SNR, +3 dB SNR) within-subjects design.

Procedure and Apparatus.

Participants were tested in a quiet sound-attenuated testing room. Speech stimuli were presented through the sound card of the stimulus presentation computer and routed to a MAICO MA-41 audiometer via the auxiliary channel, allowing for direct control of stimulus intensity. The audiometer routed the speech to the participant via RadioEar IP-30 insert air-conduction earphones. Stimuli were presented at 60 dB HL for all participants. All hardware was calibrated to standard in our testing room by a NASED (National Association of Special Equipment Distributors) certified technician. Stimuli were presented diotically.

For the text-captioned speech conditions, we developed a novel multi-word cumulative text segmentation technique to present captions. This method, a modification of the moving-window paradigm commonly used in reading research (see Haberlandt, 1994), was used because it closely approximates the real-time captioning of automated speech recognition systems like those used in captioned telephone conversations. In order to maintain control over the timing of stimulus delivery, we fixed the offset between speech and text and maintained a fixed number of words per presentation interval. Text was presented cumulatively on the screen in fixed-interval 3-word “chunks” with the previous text segments remaining on the screen until the end of the sentence. The presentation rate was yoked to the speech stimuli on a single-trial basis, with the constraint that the text could not precede the auditory signal, similar to real-word text captioning (i.e., the intermodal asynchrony with respect to auditory input could not be negative). We implemented this by coordinating the visual presentation onset of each 3-word text chunk with the auditory offset of the third word of that chunk. This was accomplished by creating a video file of each audio-visual

stimulus and editing the text onsets and offsets manually via Adobe Premiere Pro video editing software.

On each trial, the audio or audio-visual sentence was first presented. To ensure that participants read and listened simultaneously for the audio-visual trials, the whole sentence disappeared from the screen 1000 ms after the offset of the final word of the sentence. Following the sentence offset, a fixation cross ('+') appeared on the screen for a 5000-ms retention interval. After 5000 ms, a visual recall visual cue ('???') was presented, at which point participants were instructed to say aloud as much of the sentence as they could remember. After participants finished recalling the sentence, they pressed a button on a response box to initiate the next trial. Recalled sentences were recorded for later transcription and scoring. Recall was scored for each sentence as the proportion of individual words correctly recalled (e.g., Potter & Lombardi, 1998; Gilchrist et al., 2008), which for single sentences correlates very strongly with gist-based propositional scoring (typically above $r = .9$; Kintsch & van Dijk, 1978; Stine-Morrow et al., 2008; Payne & Stine-Morrow, 2017)¹.

After the end of each block of 45 sentences, a delayed recognition memory task was administered (see Payne et al., 2016; Payne & Federmeier, 2017). In each memory task, participants were presented with a set of 42 sentences. For each sentence, participants were asked to indicate whether or not they saw the sentence in the study (recognition accuracy), and then rate their confidence in their response (retrospective confidence) on a Likert scale from 1-5, where 1 indicated no confidence and 5 indicated complete confidence (e.g., Busey et al., 2000). In each task, half of the items were previously viewed/heard and half of the items were foil sentences that shared some features with previously presented sentences but were not identical. For example, if the (previously heard) target sentence was: "*Swordfish and marlins have muscles behind their eyes*

which adjust the temperatures of their brains in colder waters”, the foil sentence was: “Swordfish heat up their eyes to above ambient ocean temperature in order to improve their tracking of prey”.

Foil and target sentences were matched for sentence length and propositional density. Koeritzer and colleagues (2018) recently showed that the inclusion of foils reduces ceiling effects, resulting in better sensitivity in recognition memory for spoken sentences. Moreover, the inclusion of foils that are yoked to specific items allows for the measurement of accuracy rates across stimulus conditions (i.e., background noise; see Koeritzer et al., 2018 for more detail).

Statistical Analysis. Generalized linear mixed-effects models (GLMMs) were fit to the sentence recall and recognition memory data. Completely crossed random intercepts were defined for participants and items, and a maximal random-effects structure for all within-subject effects was included in the models (Barr, 2013; Barr et al., 2013; Bates et al., 2015; Matuschek et al., 2017) with a variance-components structure for the random slopes (excluding covariance terms between the random slopes to improve convergence; see Barr, 2013). Statistical inference on the fixed effects was conducted via separate likelihood ratio tests for each fixed-effects parameter. For follow-up tests decomposing higher-order interactions, unstandardized contrast estimates (*est.*) are presented with 95% confidence intervals. Approximate degrees of freedom are calculated via a Satterthwaite approximation. For recognition memory accuracy, a binary outcome at the single-trial level, a logit link function was used and the model was fit based on maximum likelihood estimation through the Laplace approximation. Follow-up tests for the logit models present estimates on a log odds scale.

Results and Discussion

Immediate Speech Recall. Figure 1 (left panel) plots correct word recall proportion as a function of text captioning and noise. Error bars represent within-subject standard errors. A 2

(Caption: Caption vs. No Caption) by 3 (Noise: quiet, +7 dB SNR, +3 dB SNR) linear mixed-effects model was fit to the recall data. This model revealed statistically significant main effects of Caption ($\chi^2(1) = 22.08, p < .0001$) and Noise ($\chi^2(1) = 14.89, p < .001$). Importantly, we observed a significant Caption x Noise interaction ($\chi^2(2) = 9.40, p < .01$) as well. Follow-up contrasts revealed that, in the no-captioning condition, recall was worse for sentences presented at +3 dB SNR compared to both the +7 dB SNR ($est. = -.03, 95\% CI [-.05, -.01]$) and quiet conditions ($est. = -.04, 95\% CI [-.06, -.02]$). There was no reliable difference in recall between the +7 dB and quiet conditions. In contrast, in the text-captioning condition, there was no significant difference between Noise conditions. These findings thus replicated the listening effort effect—that speech recall is hindered by increasing background noise. More importantly, the simultaneous delivery of assistive text captioning offsets the negative effects of signal degradation, resulting in improved speech recall.

Delayed Recognition Memory Accuracy. Figure 1 (middle panel) plots sentence recognition accuracy as a function of text captioning and noise. Error bars represent within-subject standard errors. A 2 (Caption: Caption vs. No Caption) by 3 (Noise: quiet, +7 dB SNR, +3 dB SNR) logit mixed-effects model was fit to the accuracy data. This model revealed a statistically significant main effect of Caption ($\chi^2(1) = 20.28, p < .001$) such that recognition memory was higher in the presence of text captions compared to trials without text captions. In addition, we observed a significant Caption x Noise interaction ($\chi^2(1) = 16.68, p < .001$). Follow-up tests revealed that, in the no-captioning condition (listening only), recognition accuracy was worse for sentences presented at +3 dB SNR compared to both the +7 dB SNR ($est. = -1.38, 95\% CI: [-2.18, -.58]$) and quiet conditions ($est. = -.91, 95\% CI [-1.52, -.30]$). There was no reliable difference in recognition memory between the +7 dB and quiet conditions. These findings indicate that

increased noise reduced recognition memory accuracy when listening to speech alone. In the text captioning condition, there was no significant difference in recognition memory as a function of listening condition. Overall these findings indicate that text captioning improves delayed sentence recognition memory and offsets the negative effects of background noise on speech memory, even in young normal-hearing adults.

Recognition Memory Confidence. Figure 1 (right panel) plots sentence recognition confidence ratings as a function of text captioning and noise. Error bars represent within-subject standard errors. A 2 (Caption: Caption vs. No Caption) by 3 (Noise: quiet, +7 dB SNR, +3 dB SNR) linear mixed-effects model was fit to the ratings data. This model revealed a statistically significant main effect of Caption ($\chi^2(1) = 13.43, p < .001$), such that responses to test items that were previously paired with text captions were more confidently rated than items presented without text captions. In addition, we observed a significant Caption x Noise interaction ($\chi^2(2) = 6.85, p < .05$), suggesting that text captioning moderated the effects of noise on recognition confidence. In the no-caption condition, subsequent recognition confidence was lower for trials presented at a +3 dB SNR compared to items presented in quiet ($est. = -.10, 95\% CI: [-.19, -.002]$). However, with text captions, there were no effects of background noise on subsequent recognition confidence. Thus, consistent with the recognition accuracy data, text captioning appeared to improve subsequent recognition confidence and offset the negative effects of background noise.

Collectively, the findings from the first experiment are clear. First, effects of background noise were apparent in immediate recall, recognition memory, and retrospective recognition confidence. Replicating past work in young normal-hearing listeners (see Peelle, 2018 for a recent review), even subtle increases in acoustic perceptual challenge during speech processing can result in negative downstream consequences for subsequent speech memory. More importantly, we

showed that the presentation of simultaneous assistive text captions offset the negative effects of background noise on all three speech memory measures in the current study, eliminating the effects of background noise on immediate free recall, delayed recognition memory, and retrospective recognition confidence. Thus, even in young adults with normal hearing, who would not be expected to be very susceptible to the negative effects of background noise, we still observe a benefit of assistive text captioning. In Experiment 2, we examined whether text captions yielded beneficial effects on speech memory in older adults with and without hearing loss.

Experiment 2

Method

Participants. Thirty-one older adults gave written informed consent. Participants' mean age was 71 years old (range: 61 – 80). The sample was 100% Caucasian. 87% of participants reported a high school education and at least some college experience, and 48% had completed at least some post-graduate education. One participant reported using a hearing aid (though not at the time of study), and 23% self-reported some degree of hearing loss or hearing problem. One participant reported deafness in the left ear and thus was only tested in the right ear. All procedures were approved by the University of Utah Institutional Review Board.

Hearing Assessment and Vision Screening. Two hearing tests were conducted. The stimuli were presented through MA-41 audiometer via RadioEar IP-30 insert air-conduction earphones. First, pure-tone thresholds were measured using the modified Hughson-Westlake at octave frequencies from 250 to 8000 Hz for each ear. Inter-octaves 750, 1500, and 3000 Hz were included if a 20-dB or greater difference was found between the respective octave frequencies. In addition, we tested speech recognition thresholds (SRTs) using a recorded Central Institute for the Deaf

(CID) W-1 spondee word list (Auditec, St. Louis, MO). Spondees were presented beginning at 30 dB HL and participants were asked to repeat the words they heard. The modified Hughson-Westlake method was then used to identify the participant's SRT in each ear. Near visual acuity was also tested for both the right and left eye using the Rosenbaum visual acuity test.

Cognitive Assessment. Participants completed a brief battery of cognitive assessments. Participants completed the Mini Mental State Exam (MMSE; Folstein et al., 1975), a brief 30-item cognitive impairment assessment often used in clinical settings to assess general cognitive function and risk for Alzheimer's dementia. A score below 24 often indicates some risk for clinically relevant cognitive impairment. Participants also completed the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005), which has been used as a clinical instrument to assess the presence of mild cognitive impairment (MCI). Moreover, the MoCA has been used to predict amnesic MCI-related language comprehension difficulties (Payne & Stine-Morrow, 2016). Although the appropriate cut-off score for cognitive impairment in the MoCA is variable across samples (e.g., Waldron-Perrine & Axelrod, 2012), individuals scoring below 20 are generally considered to be at increased risk for MCI.

Participants also completed the phonemic fluency task as a measure of verbal fluency (Benton et al., 1994). In this task, participants were given a letter cue (phonemic: e.g., "F") and asked to produce as many words that they could think of that begin with that letter in 60 s. A total score is calculated as the sum of accurate unique words correctly produced across the trials.

Verbal working memory capacity was measured via the short-form computerized version of the reading span task, as in Oswald et al. (2015). Participants were presented with a set of sentences of approximately 10–15 words in length and were asked to judge whether or not each sentence was sensible (approximately half were sensible). After each sentence, participants were

presented with a letter for recall at the end of the set. Sets of sentences and letters ranged in size from 4 to 6, with three administrations for each set size. Participants' absolute scores are the number of trials in which the participant recalled all elements in the correct order without error. Higher scores reflect larger working memory capacity.

Finally, verbal ability was assessed via the extended range vocabulary tests from the ETS Kit of Factor Referenced Cognitive Tests (Ekstrom, 1976). The test is timed such that participants must finish within 6 minutes. For each item, participants are asked to choose a correct synonym of a target word from a list of five possible words. The total score is the number of correct answers minus a fraction of incorrect answers. Higher scores reflect greater verbal ability.

Apparatus, Design, and Stimulus Materials. The apparatus, design, and stimulus materials were identical to Experiment 1, with the exception that stimuli were presented monaurally at 65 dB HL to the participant's better-hearing ear (based on average pure-tone thresholds at 1-4 kHz).

Audibility Control Task

An audibility control task was conducted to ensure that the speech-in-noise conditions were sufficiently audible to the participants at the target SNRs. Participants heard a total of six test sentences (5 to 7 words long, e.g., "Mary chose not to join the army"), three at +3 dB SNR and three at +7 dB SNR, all at the presentation level (65 dB HL) used in the primary experiment. The participants were asked to "shadow" the speech by repeating out loud each word as it was heard, therefore minimizing any memory component to the task. Word shadowing accuracy was 97%. Therefore, the memory analyses presented below cannot be explained simply by a lack of audibility, but rather by the increased cognitive effort for perceptual decoding as a function of SNR and hearing level.

Procedure. Participants first completed the cognitive test battery. They then completed hearing assessments and a vision screening. Participants then completed the audibility control task, followed by the primary experiment. The experimental paradigm and procedure were identical to Experiment 1.

Results

Hearing Testing. All participants successfully completed both hearing evaluations. Figure 2 shows the average audiogram for the left and right ears from 250-8000 Hz. The audiogram shows the characteristic sloping configuration associated with typical age-related hearing loss. Using a better-ear PTA (1, 2, 4kHz) of < 25 dB HL as a criterion for normal hearing (Hall & Mueller, 1997), $N = 12$ of the participants had clinically relevant hearing loss. Analyses reported below use a continuous measure of PTA. Average speech recognition thresholds were 25 dB HL ($SD = 7.54$) 24.84 dB HL ($SD = 8.21$) for the left and right ears, respectively. SRTs were correlated with average 1-4 kHz PTAs (right ear: $r = .76$, left ear: $r = .57$).

Cognitive Test Battery. Table 2 provides means and standard deviations for the measures in the cognitive test battery. All participants in the current study scored in the normal range on the MMSE (range 25–30), and the MoCA (range 24–30), indicating that none of the participants showed clinically relevant cognitive impairment. Fluency and verbal ability scores are comparable to performance of age and education matched samples (Tombaugh et al., 1999). Although normative data are not available for the verbal working memory assessment, Oswald et al. (2015) reported an average score of 23.25 ($SD = 4.78$) on the same computerized reading span assessment among $N = 172$ younger adults (mean age = 19.4). The older adult sample in the current study performed below the younger adults in Oswald et al. (2015) ($M = 17.45$, $t(201) = 5.87$, $p < .0001$),

consistent with the well-reported age-related decline in verbal working memory (e.g., Bopp & Verhaeghen, 2005).

Speech Recall. Figure 3 (left panel) plots recall percentage as a function of text captioning and noise. A 2 (Caption: Caption vs. No Caption) by 3 (Noise: quiet, +7 dB SNR, +3 dB SNR) linear mixed-effects model was fit to the recall data. This model revealed a statistically significant main effect of Caption ($\chi^2(1) = 23.39, p < .001$) such that sentence recall was higher among trials with text captions compared to trials without text captions. In addition, there was a main effect of noise ($\chi^2(1) = 41.63, p < .001$), such that recall was lower for +3 dB than +7 dB (*est.* = -.06, 95% CI: [-.07, -.04]) and quiet (*est.* = -.10, 95% CI: [-.12, -.08]). Moreover, sentence recall was worse for +7 dB than quiet (*est.* = -.04, 95% CI: [-.06, -.02]).

Finally, we observed a significant Caption x Noise interaction ($\chi^2(2) = 36.99, p < .001$), indicating that text captioning moderated the effects of background noise on recall. Follow-up tests revealed that, in the no-captioning condition (listening only), recall was worse for sentences presented at +3 dB SNR compared to both the +7 dB (*est.* = -.10, 95% CI: [-.12, -.08]) and quiet conditions (*est.* = -.15, 95% CI: [-.18, -.12]). Moreover, recall was worse at an SNR of +7 dB than in quiet (*est.* = -.05, 95% CI [-.08, -.02]). In contrast, in the text captioning condition, effects of noise were reduced in magnitude, as can be seen in Figure 2. With text captions, there was no significant difference in recall between the +3 and +7 dB conditions (*est.* = -.01, 95% CI [-.03, .01]). Although recall was modestly worse in the +3 dB (*est.* = -.04, 95% CI [-.07, -.02]) and +7 dB (*est.* = -.04, 95% CI [-.06, -.01]) SNR conditions relative to quiet, effect sizes were substantially reduced in magnitude relative to the trials without text captioning. The effect size of the captioning benefit (difference between text captioned and non-text captioned block) was .15 (95% CI [.11, .18]) in the +3 dB noise condition, .05 (95% CI [.02, .09]) in the +7 dB condition, and .04

(95% CI [-.001,.08]) in the quiet condition. Overall then, these findings indicate that there were reliable improvements in immediate recall with text captioning among older adults with hearing impairment, and that the presence of text captioning helped to buffer against (but not completely eliminate) the negative impacts of increased background noise on speech memory.

Recognition Memory. Figure 3 (middle panel) plots delayed sentence recognition memory accuracy as a function of text captioning and noise. A 2 (Caption: Caption vs. No Caption) by 3 (Noise: quiet, +7 dB SNR, +3 dB SNR) logit mixed-effects model was fit to the accuracy data. This model revealed a statistically significant main effect of Caption ($\chi^2(1) = 28.45, p < .0001$) such that, on average, the presence of adaptive text captioning improved sentence recognition accuracy compared to trials with speech only ($est. = .81, 95\% CI: [.44, 1.17]$). In addition, we observed a significant Caption x Noise interaction ($\chi^2(2) = 6.86, p < .05$), indicating that text captioning moderated the effects of noise on delayed recognition accuracy.

Follow-up tests revealed that, in the no-captioning condition (listening only), delayed recognition accuracy was worse for sentences presented at +3 dB SNR compared to both the +7 dB ($est. = -1.21, 95\% CI: [-2.05, -.38]$) and quiet conditions ($est. = -1.67, 95\% CI [-2.56, -.79]$). There was no reliable difference in recognition memory between the +7 dB and quiet conditions. These findings replicated those in Experiment 1 with younger adults in indicating that increased noise reduced recognition memory accuracy when listening to speech alone. In the text captioning condition, there were no significant differences in recognition memory as a function of acoustic clarity. As in Experiment 1 with younger adults, the overall findings indicated that text captioning improved delayed sentence recognition memory accuracy in older adults and, additionally, offset the negative effects of background noise on sentence recognition memory.

Recognition Memory Confidence. Figure 3 (right panel) plots sentence recognition confidence ratings as a function of text captioning and noise. Error bars represent within-subject standard errors. A 2 (Caption: Caption vs. No Caption) by 3 (Noise: quiet, +7 dB SNR, +3 dB SNR) linear mixed-effects model was fit to the ratings data. This model revealed a statistically significant main effect of Caption ($\chi^2(1) = 27.29, p < .0001$), such that responses to test items that were previously paired with text captions had higher recognition confidence ratings than items presented without text captions. In addition, we observed a significant Caption x Noise interaction ($\chi^2(2) = 9.04, p < .01$), suggesting that text captioning moderated the effects of noise on recognition confidence. In the no-caption condition, subsequent recognition confidence was lower for trials presented in noise at a +3 dB SNR compared to items presented at +7 dB SNR (*est.* = -.13; 95% CI: [-.24, -.02]) and in quiet (*est.* = -.21, 95% CI: [-.32, -.11]). However, with text captions, there were no effects of background noise on subsequent recognition confidence. Thus, consistent with the results from Experiment 1, text captioning appeared to improve subsequent recognition confidence and offset the negative effects of background noise in older adults.

Interactions with Hearing Level. Exploratory follow-up analyses were conducted in order to test whether individual differences in hearing level moderated the effects of text captioning and background noise on speech recall and recognition memory accuracy and confidence. For these analyses, hearing level was included as a covariate in the models fit above and treated as a moderator of the effects of text captioning, noise, and the Caption x Noise interaction (i.e., a 3-way interaction Hearing Level x Caption x Noise). This model is presented graphically in Figure 4 (left panel) and summarized in the top panel of Table 3. The Caption x Noise x Hearing Level interaction was significant, indicating that the text captioning attenuated the effects of hearing loss on speech recall in more acoustically challenging situations. As can be seen in Figure 4, in the no-

text-captioning condition, there was a negative relationship between hearing threshold and speech recall, an effect that was stronger in conditions with higher background noise. This was confirmed by a significant Noise x Hearing Level interaction in the block with no text captions ($\chi^2 (2) = 10.00, p < .01$). However, in the text caption block, there were no reliable effects of noise ($\chi^2 (2) = 1.19, p > .05$) or hearing level ($\chi^2 (1) = .19, p > .05$), nor was there an interaction between noise and hearing level ($\chi^2 (2) = 1.71, p > .05$). Thus, text captioning appeared to lead to improvements in speech recall among older adults with lower hearing acuity, attenuating the effects of background noise and hearing level on recall.

Similar follow-up analyses were conducted for recognition memory accuracy and confidence. Results of these analyses are presented graphically in Figure 4 (middle and right panels for accuracy and confidence, respectively). Likelihood ratio tests are presented in the middle and bottom panels of Table 3. We observed a significant interaction between text captioning and hearing acuity on recognition accuracy. This effect was driven by a reliable negative effect of hearing level on recognition memory accuracy without text captioning ($\chi^2 (1) = 6.25, p < .05$), whereas hearing level did not affect recognition accuracy in text-captioned speech ($\chi^2 (1) = .40, p > .05$). A similar pattern was observed for recognition confidence, where a significant Caption x Hearing Level interaction was observed, which was driven by a stronger relationship between hearing level and memory confidence in the block without text captions than in the block with text captions (see Fig 4).

General Discussion

Across two experiments, we examined the effects of assistive text captioning on memory for degraded speech. In our first experiment, we examined young adults with self-reported normal hearing, and in the second experiment, we examined older adults with a range of hearing acuity. To approximate real-world text captions, we developed a novel cumulative text-captioning presentation that presented captions simultaneously with speech and examined effects of text captioning relative to listening alone for immediate speech recall, delayed recognition memory accuracy, and delayed recognition confidence ratings. Importantly, under a listening effort model (Peelle, 2018; Pichora-Fuller et al., 2016), even small increases in background noise should draw attentional resources away from memory encoding, even when speech is still intelligible (Piquado et al., 2012; McCoy et al., 2005). If text captions can be used as a compensatory tool to reduce the effects of effortful listening, then the negative effects of noise degradation on speech memory outcomes should be attenuated in text captioned speech. Across both experiments, our findings were clear: the audiovisual benefit provided by text captions improved all memory outcomes in both younger (Experiment 1) and older adults (Experiment 2) and attenuated both the effects of increased background noise (in both experiments) and hearing loss (in Experiment 2). In the following, we discuss specific findings in detail and discuss the implications of these findings for our understanding of listening effort, audiovisual integration, and the potential real-world benefit of text captioned speech.

Listening Effort and Speech Memory. In both experiments, we observed that in the listening-only conditions, adding noise to speech negatively impacted immediate recall memory, delayed recognition memory accuracy, and recognition confidence relative to speech presented in quiet. The detrimental effects of background noise were observed in both younger and older

listeners. Moreover, we found in Experiment 2 that hearing acuity modulated these effects, such that older adults with poorer hearing acuity were more negatively affected by the presence of background noise when listening to speech alone. These findings are consistent with a number of prior studies (Cousins et al., 2014; McCoy et al., 2005; Piquado et al., 2010; Rabbitt, 1968; Rabbitt, 1991; Wingfield et al., 2005), in showing that when listening is more perceptually effortful, it interferes with memory encoding. Some (e.g., Rabbitt, 1968; Pichora-Fuller et al., 2016) have argued that increases in listening effort increase demand on a limited reserve of cognitive resources. The listener's speech processing system prioritizes correct perception of the speech signal, and thus increasing the effort at leaves fewer resources available for higher-level processes such as memory encoding and retention. In Experiment 2, we presented participants with a short speech shadowing task using the same SNR in the primary task and observed that participants performed near ceiling on this task, suggesting that they were able to correctly perceive the speech presented to them. Note, also, that the SNRs used were on par with those found in everyday listening scenarios (Wu et al., 2018). Thus, the effects found were present in normal SNRs experienced in everyday effortful listening. Collectively, our findings support effort-based theories that suggest that increased perceptual effort consumes resources that would otherwise be available for memory encoding and maintenance.

Importantly, this study extends prior research by showing robust effects of listening effort across multiple memory outcomes in the same study. Although increases in listening effort have been reported for immediate recall (e.g., Cousins et al., 2014; McCoy et al., 2005), only very few studies have systematically examined how acoustic properties of the speech affect delayed recognition memory of spoken sentences. Van Engen and colleagues (2012) examined differences between clear and conversational speech on recognition memory. They observed improved

recognition memory for clear speech relative to conversational speech presented in quiet, suggesting that the improvement in clarity with clear speech can benefit subsequent memory. Similarly, Gilbert and colleagues (2014) showed that subsequent recognition memory for clear speech in noise was improved relative to conversational speech in noise. Finally, Koeritzer and colleagues (2018) showed that sentence recognition memory was poorer for acoustically challenging sentences that contained lexically ambiguous words, suggesting that linguistic complexity can interact with perceptual difficulty in negatively influencing subsequent memory. Importantly, the current study is the first, to our knowledge, to simultaneously examine listening effort effects on recall, recognition accuracy, and confidence. Such a simultaneous investigation is important, as dissociations between recall and recognition and between recognition accuracy and confidence have shown that these measures, while highly overlapping, reflect partially dissociable memory mechanisms (Balota & Neely, 1980; Benjamin et al., 1998; Weidemann & Kahana, 2016; Yonelinas & Jacoby, 2012).

Text Captioning Benefit to Memory. Although we found that listening to degraded speech generally had a negative impact on memory in both older and younger listeners, simultaneously presenting text captions with the speech dramatically reduced these negative effects for both groups. We found that when captions were presented, changes in background noise had little or no effect on a listener's ability to remember sentences that they heard. This is in line with previous work that has shown that text captions are beneficial to word intelligibility and recognition (Zekveld et al., 2008; Krull & Humes, 2016; Wild et al., 2012). However, our findings extend those found previously, in that we found broad benefits to multiple memory outcomes. Taken in line with prior research, our results suggest that text captions may not only benefit perceptual

processes (e.g., improving intelligibility) but that the addition of the text input may directly reduce listening effort, freeing up available cognitive resources, and leading to improved memory.

It is also important to highlight how ubiquitous the benefits from captions were on memory outcomes. Although younger listeners in Experiment 1 reported normal hearing acuity, we still observed a benefit from text captions across all of their memory performance measures. In our exploratory analysis of the effects of hearing acuity in older adults, we found a significant interaction such that, when no captions were present and the signal was degraded, older listeners performed worse on all outcome measures as hearing acuity declined. But, when captions were present, these hearing impairment effects were largely eliminated. Taken together, our results suggest that captions can provide a benefit to all adult listeners regardless of age or hearing acuity, but the benefit from captions is largest for older adults with hearing impairment. These findings parallel the literature on video captioning, which shows that captioning videos improves comprehension and memory for the video across all populations, from young children to older adults (see Gernsbacher, 2015 for a review).

Another important dimension that the current study investigated was the use of real-world text captions. We used a novel multi-word cumulative text segmentation technique to present captions. This method was designed to simulate current real-time captioning systems. The captions were cumulatively presented in 3-word segments which remained on the screen until the end of a sentence. While Krull and Humes (2016) added a degree of realism by using automatic speech recognition (ASR) technology to create their stimuli, they used a single-word RSVP technique to present their sentences (see also Wild et al., 2012). This allowed the audio and visual information to be presented synchronously but is not used in real-world text captioning and would not allow for participants to read in a natural way. Zekveld and colleagues (2008) likewise used ASR to

create their stimuli but they presented whole sentences at the onset of the audio. This would allow for naturalistic reading of the visual information but is not how text captions are commonly presented in natural settings. The advantage of our novel presentation method over those used previously is that it simulates real-world caption presentations, which allow for listeners to use naturalistic reading techniques (e.g., regressive eye-movements, etc.) to help clear up ambiguities that may have been present in the audio signal.

Integration of Text and Speech. As the literature on text-captioned speech has begun to grow, one open question in the literature concerns the degree to which audiovisual integration (AVI) of text and speech operates similarly to the traditional AVI literature on speech and facial articulatory cues. Previous research suggests that speech recognition performance is increased and subjective ratings of listening effort are decreased when a degraded speech signal is simultaneously presented with a speaker's face (e.g., Fraser et al., 2010), suggesting that speech facial cues are rapidly integrated with the acoustic signal to aid in word recognition. Notably, even when the facial information is also degraded, there is still a benefit in speech recognition for younger listeners (Munhall et al., 2004). Other work has recently examined how coarse visual cues to speech acoustic features (e.g., onset, amplitude envelope) can impact listening effort. Strand and colleagues (2020) for example tested whether a visual cue of a 'ball' that dynamically increased and decreased in size along with the amplitude envelope of the speech would moderate listening effort in speech recognition. Interestingly, they actually found evidence for increases in listening effort (operationalized as reaction time) with the visual task, despite subjective reports that the task was easier. In contrast, our results fit with the prior literature on assistive text captioning which suggest that visual text cues can provide a substantial benefit to speech processing (e.g., Krull & Humes, 2016; Gordon-Salant & Callahan, 2009; Grossman & Rajan, 2017).

Some prior studies have reported that older adults do not show a robust benefit to speech perception from visual facial cues, suggesting that audiovisual integration of speech and facial cues may be impaired in aging. For example, Picou et al. (2013) found that older adults with bilateral sensorineural hearing loss on average did not gain any benefit to speech perception in noise when they could view facial articulatory cues. However, individual differences in speechreading ability did moderate this effect (see also Sommers et al., 2005; Tye-Murray et al., 2007). More recently, Sommers and Phelps (2016) directly compared younger and older listeners on a serial recall task using lists presented in noise and found that younger listeners performed better on the recall task when they could both see and hear the speaker compared to when they could only hear the speaker. However, in older adults, there was no benefit in serial recall performance with visual support. Similarly, Gosselin and Gagne (2011) showed evidence that older adults expend more listening effort with AV speech compared to younger adults. In contrast to these findings, our study showed a robust AV benefit in older adults for text captions relative to listening only. Such findings suggest that AVI deficits in aging may not be general but may vary depending on the type of visual stimulus being integrated with the speech as well as the task.

While facial cues provide information on place of articulation that can translate to fine phonetic detail (Erber, 1969; Sumby & Pollack, 1954; Grant & Walden, 1996), text provides orthographic access to lexical semantic features and corresponding phonological representations that can provide rich information to guide auditory word recognition. Moreover, in our study (in which text captions were completely accurate, a point we return to later), there was no ambiguity or uncertainty in the visual cue, making it a highly reliable signal. There is also a temporal aspect to processing facial cues which may make it difficult for older adults to gain a benefit from using both audio and visual facial cues simultaneously. As someone is listening to a speaker face-to-

face, they do not have the ability to visually revisit past information provided by facial gestures except for that which is available in visual working memory. On the other hand, persistent text captions allow for re-reading, which is beneficial to comprehension and memory (Schotter et al., 2014; Schotter & Payne, 2019). Although we did not present a whole sentence simultaneously at the onset of the speech, once a three-word segment was revealed on the screen it stayed there until the end of the trial. This would provide listeners with more time to process the text and perhaps revisit words they had trouble hearing to ensure that they had the correct representation. Future work would benefit by conducting direct comparisons of the benefits provided by multiple visual cues (e.g., text, faces) in the same study.

Limitations and Future Research Directions. Although our findings clearly showed evidence of captioning benefits to multiple speech memory outcomes, there are a number of important limitations and areas for future research that need to be discussed. First, these initial experiments were conducted largely as a proof-of-concept to establish the magnitude of the benefit provided by real-world text captions. As such, these experiments do not speak directly to the exact mechanism by which text captions yield improvements in speech memory. We argue above that the text captions may act to reduce the cognitive workload of listening effort by providing a supplementary sensory modality in which to process the language. Future research should consider on-line methods (e.g., event-related brain potentials, pupillometry) to assess real-time speech-text processing to determine how sensory and higher-level language processes are impacted by presenting simultaneous text. Moreover, studies could combine our text-captioning paradigm with the real-time measurement of eye movements to study text captioned speech reading strategies, an area that to our knowledge has not yet been explored.

One related concern is whether listeners may adopt a strategy by which they ‘ignore’ the speech and switch to relying on text alone. However, there are a number of reasons why we believe this alone cannot account for the current findings. First, while readers can shift attention across multiple modalities, it is not clear that speech input can be completely inhibited (Conway et al., 2001; Strauß et al., 2014). Second, although the effects of noise were attenuated with text captions, consistent with the effortful listening model, it is not the case that all effortfulness effects were completely eliminated. In Experiment 2, noise effects on recall were still statistically significant in the text caption condition, and there remained a modest (but not statistically significant) trend for increased hearing thresholds to predict recall in the +3 dB SNR noise condition with text captions (see Figure 4). If readers were relying only on the text input, then acoustic challenge should not impact memory. To fully tease this apart however, studies would need to present conflicting information between the text and speech modalities. One such study has been conducted in younger adults that can speak directly to this modality-switching hypothesis. Grossman and Rajan (2017) tasked participants with recalling sentences that were presented visually, auditorily, or both simultaneously. Importantly, they varied whether the text and speech were congruent or incongruent and whether the participants were to recall the speech or the text. They found that when the speech signal was degraded, participants’ performance in recalling the speech increased when the text was congruent with the speech but was unaffected when the text was completely incongruent. This might suggest that participants were switching modalities to rely on the one that would be most beneficial to the task at hand. To help rule this out, Grossman and Rajan (2017) ran a follow up experiment which included a condition where the text and audio would mismatch on only a single keyword near the end of the sentence, so that participants would not know at the sentence onset which modality would be better to rely on. They found that the

participants' performance on recalling the keyword in these partially-incongruent sentences was intermediate between the congruent and completely incongruent conditions. In addition, when the participants were tasked to recall the text instead of the speech, performance decreased when the speech was incongruent with the text. Grossman and Rajan (2017) argued that taken together, these results cannot be explained by participants simply switching to using only a single modality.

Although we argue above that our realistic caption presentation technique was a major improvement relative to prior work on assistive text captioning, one important limitation is that our text captions were “ideal-world” captions that contained no errors. Real-world captions tend to have errors. One recent paper estimated that some popular ASR systems have word error rates between 9 and 34% (Kěpuska & Bohouta, 2017). As noted previously, both Krull and Humes (2016) and Zekveld and colleagues (2008) used ASR technology to generate the text that accompanied the speech, which would allow for the introduction of realistic captioning errors. While Krull and Humes (2016) did not report the type of errors nor the error rate in their various experimental conditions, they categorized text captions made using degraded speech as “poor” in quality and text made with speech in quiet as “more accurate”, and also had a condition in which they created captions without error. Zekveld and colleagues (2008) reported the types of errors and the rate at which each error type occurred, but summed all of these together to systematically evaluate the effects that total error rates per sentence had on the processing of the speech. More research is needed that not only looks at the effects of error rates in text captioning on speech processing but also systematically studies the effects of the different types of errors that can occur when using ASR technology.

Another way in which our text presentation method is “ideal-world” is in the rate at which the text captions were presented. As explained in detail above, each 3-word text segment appeared

on screen immediately after the corresponding speech segment had been heard. Thus, the captions were presented much faster than they would be in a more natural setting. Real-world text captioning voice-to-text technology typically has a high degree of variability in the latency at which the captions are presented, but the auditory input always leads the text, as speech-to-text transcription occurs in real-time. Several studies have found that benefits from text captions occur when the text precedes the speech rather than when it follows (Davis et al., 2005; Jones & Freyman, 2012; Sohoglu et al., 2014). Likewise, when there is asynchrony between visual facial cues and speech, it has been found that successful integration can occur with a much larger asynchrony when the visual information leads the audio information than when the speech leads the facial cues (Grant & Greensberg, 2001; Grant et al., 2004). In contrast, however, we have found that realistic text captions with the audio leading the text input yielded a benefit to immediate recall and delayed recognition memory. Given this, we encourage a systematic study of intermodal asynchrony on the benefits provided by text captions in the future.

Conclusion. The findings from the current study suggest that text captions provide a clear benefit to memory of degraded speech. Findings from Experiment 1 and Experiment 2 converged in showing reliable improvements in multiple measures of speech memory with text captions. The benefits of text captioning were strongest in cases where acoustic challenge was high (i.e., high background noise) and among older adults with lower hearing acuity. However, although effect sizes were largest among older adults with hearing loss, the benefits of text captioning for subsequent memory were even apparent in young normal-hearing listeners, suggesting that assistive text captions can not only improve speech memory outcomes in older adults with hearing impairment, but that they may yield some benefit for all adult listeners.

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Footnotes

¹For the first 18 participants in Experiment 1, recall for one item was lost due to a programming error, leaving 89 intact recall samples for these participants.

Table 1. Example stimulus sentences

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1. The Central Georgia Railroad used to be the most complete and elegant railroad complex in the United States.
 2. Every morning housewives in Bali put some rice on small pieces of banana leaves to ward off spirits.
 3. The innermost layer of fur on a Husky which is as soft as goose down keeps it warm.
 4. In many species it is the females who shape evolution through their subtle exercise of choice in mating.
 5. Most Turkish peddlers pool their meager funds in order to travel to big cities in tired old buses.
 6. The white-backed night heron hides by day in reed beds and does not venture out until after twilight.
 7. As a boy Norman Rockwell drew pictures of sailing ships copying them from packs of American Fleet cigarettes.
-

Table 2. Descriptive statistics of cognitive test battery performance among participants in Exp 2

Measure	Mean	SD	Min	Max
1. MMSE	28.81	1.67	25	30
2. MoCA	27.68	1.72	24	30
3. Phonemic Fluency	38.48	10.76	20	57
4. Reading Span	17.45	6.44	3	26
5. Vocabulary	16.73	3.89	6	24

Table 3. Likelihood ratio tests for hearing level, caption, and noise effects on immediate recall accuracy (top panel), delayed recognition memory (middle panel), and delayed recognition confidence (bottom panel).

Immediate Recall Accuracy			
Effect	df	χ^2	p-value
Caption	1	10.82	<.01
Noise	2	.85	.65
Hearing Level	1	2.84	.09
Caption x Noise	2	3.37	.19
Caption x Hearing Level	1	43.45	<.0001
Noise x Hearing Level	2	15.34	<.001
Caption x Noise x Hearing Level	2	7.39	.02
Recognition Memory Accuracy			
Effect	df	χ^2	p-value
Caption	1	22.87	<.0001
Noise	2	20.15	<.0001
Hearing Level	1	0.75	.39
Caption x Noise	2	6.7	.04
Caption x Hearing Level	1	7.43	.01
Noise x Hearing Level	2	0.5	.78
Caption x Noise x Hearing Level	2	3.43	.18
Recognition Memory Confidence			
Effect	df	χ^2	p-value
Caption	1	21.96	<.0001
Noise	2	8.87	.01
Hearing Level	1	0.15	.70
Caption x Noise	2	5.6	.06
Caption x Hearing Level	1	7.97	.01
Noise x Hearing Level	2	5.04	.08
Caption x Noise x Hearing Level	2	1.82	.40

Figure Captions

Figure 1. Sentence memory as a function of background noise and text captioning in Experiment

1. Left panel: Immediate recall accuracy; Middle panel: Delayed recognition memory; Right panel: Recognition memory confidence. Standard errors reflect within-subject 95% confidence intervals.

Figure 2. Pure tone audiogram for better hearing ear for the older adult participants in Experiment

2.

Figure 3. Sentence memory as a function of background noise and text captioning in Experiment

2. Left panel: Immediate recall accuracy; Middle panel: Delayed recognition memory accuracy; Right panel: Delayed recognition memory confidence. Standard errors reflect within-subject 95% confidence intervals.

Figure 4. Effects of hearing level (PTA = pure tone average), background noise, and text captioning on immediate recall accuracy (left panel), delayed recognition memory accuracy (middle panel), and delayed recognition confidence (right panel).

Experiment 1: Young Adults

Experiment 2: Older Adults