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Through the Ear, to the Brain: How Cognitive Aging Impacts Veridical and False Hearing in the Presence of Misleading Context

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by
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ABSTRACT

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Professor Mitchell Sommers

A consistent finding in the literature (Benichov, Cox, Tun, & Wingfield, 2012; Dubno, Ahlstrom, & Horwitz, 2000; Hutchinson, 1989; Nittrouer & Boothroyd, 1990; Pichora-Fuller, Schneider & Daneman, 1995; Rogers, Jacoby, & Sommers, 2012; Sommers & Danielson, 1999; Wingfield, Aberdeen, & Stine, 1991) is that spoken word identification improves for both older and younger adults following the addition of a meaningful semantic context, but the improvements are typically greater for older adults. However, more recent findings (Jacoby, Rogers, Bishara, & Shimizu, 2012; Rogers, Jacoby, & Sommers, 2012) suggest that, especially under less favorable perceptual conditions, the increased benefits of semantic context for older compared with younger adults may reflect increased reliance on context as a basis for responding, rather than improved ability to use contextual information. This increased reliance on context makes older adults prone to context-based misperceptions – termed *false hearing* – when context is misleading. Although increased reliance on context by older adults has been described as a strategy for "filling in the blanks" caused by age-related declines in hearing acuity, few researchers have investigated the relationship between reliance on context and age-related changes in cognitive abilities. The present study examined the effects of working memory capacity, processing speed, and inhibitory control on veridical and false hearing in older and younger adults. We found that poor inhibitory control was related to increased susceptibility to false hearing among both older and younger adults. For older adults, slower processing speed was also related to increased susceptibility to false hearing, whereas higher working memory capacity and preserved inhibitory control corresponded to more accurate speech perception in the presence of misleading context. We propose that older adults' reliance on context may reflect a change in the relative weights assigned to contextual and sensory information during perception, wherein available contextual cues receive greater weight than sensory information. This reweighing of perceptual information may occur due to a combination of age-related hearing loss, which increases listening effort, and cognitive decline, which limits the resources available for effortful listening.

Chapter 1: Introduction

Hearing acuity declines naturally as we age, a process known as presbycusis. Presbycusic hearing loss is characterized by earlier and greater losses in the higher audiometric frequencies (Morrell, Gordon-Salant, Pearson, Brant, & Fozard, 1996; Sommers, Hale, Myerson, Rose, Tye-Murray, & Spehar, 2011). The detrimental effect of presbycusis on speech perception is especially noticeable for losses in audiometric frequencies between 500 and 3000 Hz, the frequency range encompassing most of the important acoustic features of speech signals (Committee on Hearing and Bioacoustics [CHABA], 1988).

The impact of hearing loss on older adults' ability to understand speech is exacerbated in unfavorable listening conditions, such as when listening to speech in background noise (Pichora-Fuller & Souza, 2003; Presacco, Simon, & Anderson, 2016; Schneider, Daneman, & Pichora-Fuller, 2002). Thus, both hearing loss and background noise reduce older listeners' access to acoustic features in speech. Age-related declines in temporal processing also limit older adults' ability to use temporal speech cues, which aid in word and talker identification, an effect that is exacerbated when speech is presented in noise (see Pichora-Fuller & Souza, 2003). In combination, hearing loss, greater effects of masking, and impaired temporal processing place older adults at a distinct disadvantage relative to younger adults when processing speech in noise.

In contrast to the substantial evidence for age-related declines in speech perception, listening comprehension – the ability to understand the meaning of spoken language – remains relatively stable until late adulthood. Sommers et al. (2011), for example, conducted a cross-sectional study in normal-hearing adults ages 20 through 89, testing both audiometric thresholds and listening comprehension. Participants were presented with spoken passages of approximately three to five minutes in duration, and were asked to answer comprehension questions about the content of the passages. The authors found that despite systematic age-related reductions in hearing acuity throughout adulthood, listening comprehension remained relatively stable until approximately age 65. Age did correlate negatively with listening comprehension for adults over age 65, but this relationship remained significant after controlling for hearing ability, suggesting that hearing acuity cannot fully account for changes in listening comprehension over time.

Sommers et al. (2011) suggested that comprehension may have been preserved despite declining hearing acuity in their study due to the availability of syntactic and semantic information in the spoken passages they used as stimuli: older adults may use these syntactic and semantic cues to infer what was missed due to hearing loss. This interpretation is corroborated by the findings of Sommers and Danielson (1999), who showed that older adults with normal hearing experienced deficits in word identification in noise relative to younger adults when there were no contextual cues to facilitate prediction (i.e., when the target word was presented alone or was preceded by a sentence providing no context), whereas there were no age differences when the target word was preceded by a highly predictive context. Indeed, there is a substantial literature showing that older adults obtain as much, if not more, benefit from supporting semantic contexts compared to younger adults for speech perception in the clear (i.e., without background noise; Wingfield, Aberdeen, & Stine, 1991) and in noise (Benichov, Cox, Tun, & Wingfield, 2012; Dubno, Ahlstrom, & Horwitz, 2000; Hutchinson, 1989; Nittrouer & Boothroyd, 1990; Pichora-Fuller, Schneider & Daneman, 1995; Rogers, Jacoby, & Sommers, 2012; Sommers & Danielson, 1999).

1.1 Impact of Context on Perception

Although the presence of valid contextual cues greatly benefits speech perception, Rogers et al. (2012) demonstrated that the presence of misleading contextual cues has the opposite effect, decreasing accuracy of word identification, particularly among older adults. In their experiments, Rogers et al. first established a meaningful semantic context by repeatedly presenting semantically related cue-target word pairs (e.g., BARN-HAY) during a training phase. Word pairs were presented orthographically on a computer screen and simultaneously over headphones to ensure that initial encoding was equivalent for younger and older adults. Additionally, a cued recall test after the training phase, in which participants saw the cue (e.g., BARN-?) and had to say aloud the paired target, was used to check that all participants could remember at least 80% of the cue-target pairs. Following the training phase, participants completed the test phase in which cue-target word pairs were presented aurally with the target in background noise for identification. The signal-to-noise ratio (SNR) used in the test phase was determined individually for each participant using a titration procedure (see American Speech-Language-Hearing Association [ASHA], 1988) that produced approximately 50% identification accuracy; this ensured that the audibility of stimuli was equated across participants. Stimuli in the test phase were either the cue-target pairs from the training phase (congruent condition; e.g., *barn-hay*), the cue from the training phase paired with a word differing from the learned target by a single phoneme, known as a phonological neighbor (incongruent condition; e.g., *barn-pay*), or an unlearned pair of words that were not semantically related (baseline condition; e.g., *cloud-fun*). After each identification, participants judged how confident they were that they had correctly identified the target word using a 0 to 100% scale. The authors found that when the cue provided a congruent context for the target, older adults correctly identified the target more frequently than did younger adults, a very rare occurrence of older adults outperforming their younger counterparts in a speech perception task when audibility is equated. However, when the target was a phonological neighbor of the contextually predicted word (e.g., *barn*-pay), older adults were more likely than younger adults to incorrectly report hearing the contextually predicted word (e.g., *hay*). Older adults also experienced greater confidence when their response was supported by context relative to when no context was available (i.e., in the baseline condition), and this was true both for correct identifications on congruent trials and for context-based misperceptions on incongruent trials, which the authors referred to as *false hearing*. Younger adults, on the other hand, experienced little change in confidence from baseline trials to those in which context was present. Finally, older adults were approximately four times more likely than younger adults to report 100% confidence in context-based misperceptions on incongruent trials, which the authors referred to as *dramatic false hearing*. The authors argued that the absolute certainty displayed in cases of dramatic false hearing demonstrates the ability of context to alter the subjective perceptual experience of listeners, particularly older adults.

Errors based on misleading contextual cues are not exclusive to speech perception. Jacoby, Rogers, Bishara, and Shimizu (2012) found that older adults are also particularly susceptible to context-based visual misperceptions. Participants were tasked with identifying a masked lowercase word briefly flashed on screen after reading aloud an uppercase prime word. The masked lowercase word could be the same word as the prime (congruent condition; e.g., DART, dart), a word differing from the prime by a single letter, known as an orthographic neighbor (incongruent condition; e.g., DART, dirt), or a non-orthographic neighbor of the prime (baseline condition; e.g., CHEW, dart). In a fourth condition, no lowercase word was presented (guessing condition; e.g., DIRT, _____). Trials began with presentation of the uppercase prime (e.g., DART) for 500 ms, followed by a blank screen for 1000 ms, a forward mask

(XQXQXQXQXQX) for 300 ms, the lowercase target (e.g., dirt) for either a short or long duration (described below), and finally after 14 ms of blank screen, a backward mask which was the same as the forward mask. The on-screen duration of the lowercase word was manipulated for each individual participant to equate identification performance in the baseline condition using a titration procedure analogous to that used by Rogers et al. (2012): Masked target words were presented at different durations until the duration at which the participant correctly identified approximately 60% of targets was found; this duration was used as the short duration in the test phase. The long duration in the test phase was determined by adding a constant to all short durations within each age group: long-duration targets were presented for 14 ms longer than short-duration targets for younger adults, and 28 ms longer for older adults to further equate performance between age groups. At the end of each trial, participants selected which of two words had appeared in lowercase (e.g., dart or dirt), and selected one of three options describing their basis for responding: 1) They saw the word or enough of the word to be confident in their response; 2) They did not see the word, but knew which word was presented; or 3) They had no idea what lowercase word was presented and guessed. Corroborating the findings of Rogers et al. (2012), older adults were more likely than younger adults to correctly identify words in the congruent condition, but were also more likely to incorrectly report seeing the lowercase version of the prime word in the incongruent condition, which the authors referred to as *false seeing*. Older adults were still more likely than younger adults to experience false seeing when comparing younger adults' performance in the short-duration condition to older adults' performance in the long-duration condition. Interestingly, older adults also reported seeing the lowercase version of the priming word in 20% of trials in which no lowercase word was presented (0% in the younger adult group), which was very similar to the 23% chance of false seeing observed for incongruent trials in older adults. The similarity in rates of false seeing when the target was an orthographic neighbor relative to when no target was actually presented suggests that false seeing in older adults is not exclusively a consequence of age-related reductions in the ability to distinguish between similar looking words, but rather may reflect an age-related increase in expectation-based responding. As was the case with false hearing in the study by Rogers et al. (2012), older adults were confident that they had correctly perceived the target word in cases of false seeing. When given the opportunity to withhold a response if they were unsure which word had been presented, older adults were less likely than younger adults to withhold responses in which they were misled by context, indicating that older adults had high confidence in the accuracy of their context-based visual misperceptions. Together, the findings of Rogers et al. (2012) and Jacoby et al. (2012) suggest that we become increasingly reliant on context as we age, to the extent that context can alter both subjective perception and our confidence in what we perceive.

1.2 Why does Context Use Increase with Age?

One explanation for older adults' increased use of contextual cues in speech perception is that age-related hearing loss motivates the use of context to fill gaps in the speech signal caused by impaired hearing (Sommers et al., 2011). However, evidence presented above suggests that sensory loss alone cannot account for increased reliance on context by older adults. Despite equating performance on baseline trials (i.e., trials with no context) by manipulating the amplitude of background noise and the on-screen duration of target words, older adults nevertheless demonstrated improved performance relative to younger adults when context was a valid cue for perception and increased susceptibility to false hearing and false seeing when context was misleading (Jacoby et al., 2012; Rogers et al., 2012). These findings led Jacoby, Rogers, and colleagues (2012) to suggest that declining cognitive ability may also contribute to overuse of context by older adults. Indeed, many cognitive abilities demonstrate age-related declines (Park, Lautenschlager, Hedden, Davidson, Smith, & Smith, 2002), introducing a potential confound into purely sensory-based accounts of older adults' increased use of contextual cues in speech perception. Because both hearing acuity and cognitive ability decline with age, many researchers have argued that explanations of age-related differences in speech perception are incomplete if they do not consider changes in both hearing acuity and cognitive ability (Benichov, Cox, Tun, & Wingfield, 2012; CHABA, 1988; Schneider, Daneman, & Pichora-Fuller, 2002).

1.3 Speech Perception and Cognitive Abilities

The role of cognitive abilities in speech perception has been studied extensively, although rarely under conditions differing in contextual constraint. In one such study, Benichov et al. (2012) presented sentences with no context, low-predictability contexts (cloze probability = .02 – .05; e.g., *The cigar burned a hole in the* <u>*floor*</u>), medium-predictability contexts (cloze probability = .09 – .21; e.g., *The boys helped Jane wax her* <u>*floor*</u>), and high-predictability contexts (cloze probability = .25 – .85; e.g., *Some of the ashes dropped on the* <u>*floor*</u>) with the final word in background noise to participants ages 19 through 89. Of interest was the SNR needed to correctly identify the sentence-final word under differing degrees of contextual constraint. The authors also measured hearing acuity, verbal ability, and cognitive ability (a composite of episodic memory, working memory, and processing speed). They found that chronological age, hearing, and cognitive ability were related to speech perception in the no, low, and medium context conditions. However, hearing acuity did not predict word identification performance in the high context condition, despite the continued roles of age and cognitive ability. The authors concluded that cognitive ability plays an important role in speech perception, and that the influence of cognitive ability increases relative to that of hearing acuity as the strength of contextual cues increases.

Although the study by Benichov et al. (2012) was informative regarding the relative contributions of hearing acuity and cognitive ability to speech perception across degrees of contextual constraint, the methods used do not permit conclusions regarding the contributions of individual cognitive abilities to speech perception. First, their measure of cognitive ability was a composite of measures targeting working memory capacity, episodic memory, and processing speed, so it is not possible to determine which specific cognitive abilities were related to speech perception across levels of contextual constraint. Second, although the sentences used in their study differed in degree of contextual support for the target word, the sentence contexts were never misleading, so we cannot determine the contributions of cognitive abilities to false hearing as described by Rogers et al. (2012). The present study was designed to address these questions.

As noted above, the relationships between individual cognitive abilities and speech perception have been studied extensively. Most research has focused on the relationship between speech perception and working memory – the system that allows us to maintain and manipulate information – due to the importance of working memory to speech comprehension. During a conversation, there are long streams of sounds that need to be held in memory, parsed into individual words, tied to meaning, integrated into the context of preceding words and sentences, and maintained for reference while formulating a response, all processes thought to rely, in part, on working memory.

One framework that has focused specifically on the role of working memory in speech perception is the Ease of Language Understanding model (ELU; Rönnberg, 2003; Rönnberg, Rudner, Foo, & Lunner, 2008). According to the ELU model of speech perception, the incoming auditory signal is matched to phonological representations in long-term memory. This matching process is assumed to be fast and automatic under optimal listening conditions, with little or no need to engage working memory. However, when conditions are sub-optimal, as is the case for those with hearing loss or when listening to stimuli in background noise, distortions are introduced into the speech signal, increasing the difficulty of matching the altered speech signals to stored representations. Under such conditions, explicit working memory processes are engaged to determine the best match between the incoming speech signal and stored lexical representations.

An important assumption regarding working memory is that the resources needed to process stimuli are limited, and that errors can occur when these resources are depleted (Kahneman, 1973). To test the contribution of working memory to speech perception, researchers have studied conditions that consume working memory's limited resources, typically targeting three cognitive abilities that affect memory performance: working memory capacity, processing speed, and inhibitory control. In the sections below, we review the literature pertaining to the roles of these three cognitive abilities in speech perception.

1.3.1 Working Memory Capacity

Working memory capacity is the term used to describe the amount of information that can be simultaneously maintained and manipulated in working memory. Working memory capacity is typically measured using one of several "span" tasks, in which stimuli (often lists of words, digits, or sentences) are presented to determine the maximum amount of information that can be held in memory for recall while simultaneously performing a manipulation of the stimuli (e.g., recalling the stimuli in the opposite order of presentation) or while performing a secondary task (e.g., solving simple math problems). Importantly, there are both individual and age differences in working memory capacity, with older adults typically demonstrating lower working memory capacities than younger adults (see Craik & Byrd, 1982; Wingfield, Stine, Lahar, & Aberdeen, 1988).

Within the domain of speech perception, working memory capacity has been studied primarily in relation to encoding effort. In a classic study, Rabbitt (1968) showed that increasing the effort required to accurately encode a set of stimuli reduces the amount of information that can be held in working memory. Participants were tasked with remembering spoken lists of digits presented in four conditions: completely in the clear, with only the first half of the list in background noise, with only the second half of the list in background noise, or with the full list in background noise. Rabbitt hypothesized that the increased effort required to hear stimuli in noise in the second half of a list could interfere with maintenance of previously presented stimuli, an idea now known as the effortfulness hypothesis (for a recent review of the role of effort in speech perception, see Pichora-Fuller & Kramer, 2016). Rabbitt's data supported his hypothesis: Digits in the first half of lists were better recalled when the second half was presented in the clear relative to when the second half was presented in noise, regardless of whether the first half was presented in the clear or in noise, suggesting that the increased effort needed to hear digits in noise in the second half of lists interfered with maintenance of digits from the first half.

More recently, Souza and Arehart (2015) found that working memory capacity was predictive of the SNR at which words could be correctly identified. In Souza and Arehart's study, older adults were tasked with repeating as many words as possible from low-context sentences presented in noise. Of interest was the SNR required to correctly repeat 50% of words from the sentences. Also measured were working memory capacity, hearing acuity, and reading comprehension. The authors found that older adults with lower, relative to higher, working memory capacities required more favorable SNRs to correctly repeat 50% of words from low-context sentences presented in noise. Additionally, the relationship between working memory capacity and SNR remained significant after controlling for age, hearing acuity, and reading comprehension. Corroborating Rabbitt's (1968) findings, these results suggest that more working memory resources must be expended as the effort required to process stimuli increases, such as when the SNR is made less favorable. Thus, individuals with higher working memory capacities may be better able to complete processing requiring more effort than those with lower working memory capacities.

The increased effort required to process speech that is degraded due to hearing loss may also affect working memory capacity (McCoy, Tun, Cox, Colangelo, Stewart, & Wingfield, 2005; Rabbitt, 1991). McCoy et al. (2005) presented spoken lists of words to older adults who either had good hearing (best ear pure-tone averages [PTA] ≤ 25 dB) or hearing loss (best ear PTA > 25 dB). The lists stopped randomly after five to 15 words, and each time the list was stopped, participants were asked to recall the last three words that had been presented. Lists differed in the degree of contextual constraint placed on each word by the preceding words. In low-context lists, words were unrelated to preceding words or were semantically related to only the immediately preceding word (e.g., *better write catch native evening bit position wish small proper grass*), whereas in high-context lists, words were semantically related to at least the two preceding words (e.g., *sun was nice dormitory is I like chocolate cake but I think that book is he wants to school there*; example taken from the source paper for the stimuli used by McCoy et al., Miller & Selfridge, 1950). Although both groups of older adults demonstrated nearly perfect recall for the three target words in high-context lists, performance by the hearing loss group declined disproportionately in low-context lists. The authors concluded that the extra effort required to process auditory stimuli with hearing loss was sufficient to impede maintenance of as few as three words. Additionally, the authors suggested that contextual support may reduce processing effort, freeing up more resources for encoding, and improving subsequent recall. Therefore, older adults' deficits in working memory performance could stem from added processing effort imposed by hearing loss, and reduction of processing effort could explain the mitigation or elimination of age differences in speech perception when contextual support is available.

Importantly, low working memory capacity may also impede comprehension of misleading sentences. To test the relationship between working memory capacity and language comprehension, Christianson, Williams, Zacks, and Ferreira (2006) had younger and older adults read unambiguous and garden-path sentences (i.e., ambiguous sentences in which an initial interpretation must be revised). Once the participant indicated that they had finished reading the sentence on screen, the sentence was replaced by a yes-or-no comprehension question. For example, for the garden-path sentence *While Anna dressed the baby that was small and cute played in the crib*, the comprehension question was *Did Anna dress the baby?* Christianson et al. found that older adults – who had lower working memory capacities on average relative to younger adults – were more likely to endorse the incorrect interpretation of garden-path sentences than were younger adults. Focusing on the older adult group, they found that individuals with lower working memory capacities were more likely to misinterpret garden-path sentences than were individuals with higher working memory capacities; no correlation between working memory capacity and endorsement of garden-path interpretations was found among the younger adults. The authors suggested that posing comprehension questions may cue participants to reanalyze the syntactic structure of sentences, and that reinstating the structure of a sentence may consume working memory resources. Therefore, older adults with lower working memory capacities may be less able to reinstate an accurate reproduction of the original sentence structure. Instead, older adults may rely on a “good-enough” representation based on their original, incorrect interpretation of the sentence, leading to more misinterpretations of garden-path sentences (see also Ferreira, Bailey, & Ferraro, 2002).

The negative impact of low working memory capacity on speech perception can be reduced if there are contextual cues to aid recall (McCoy et al., 2005; Meister, Schreitmüller, Ortmann, Rählmann, & Walger, 2016). As described in detail above, McCoy et al. (2005) found that increasing the relatedness of words in a list decreased the negative impact of hearing loss on memory for that list. A similar result was recently obtained using complete sentences as stimuli. Meister et al. (2016) superimposed two sentences, one in a male voice and the other in a female voice, to create stimuli with competing talkers. The superimposed sentences either both had low internal context (LC/LC), or consisted of one high- and one low-context sentence (LC/HC). An example of a low-context sentence used in this study is *Stefan buys seven wet shoes*, and an example of a high-context sentence is *eagles fly thousand meters high* (sentences translated from German). Older adults with normal hearing or hearing loss identified either as many words as possible from both talkers, or were cued to one talker prior to presentation. Working memory capacity was measured in a separate task, and was operationalized as the average number of words recalled from five lists of 15 words. To test the effects of hearing loss and working memory capacity on speech perception, the authors performed a median-split on working memory scores within their samples of normal hearing and hearing impaired older adults, yielding four separate groups: normal hearing – high working memory capacity, normal hearing – low working memory capacity, hearing-impaired – high working memory capacity, and hearing-impaired – low working memory capacity. Importantly, there were no significant differences in working memory capacity between hearing groups, and no differences in hearing between the high and low working memory groups. Although working memory capacity had little impact on the number of words recalled by the normal hearing group, lower working memory capacity was associated with fewer words recalled by the hearing-impaired group. The deficit experienced by hearing-impaired adults with lower working memory capacities was only evident in the LC/LC sentence condition, whereas working memory capacity had no effect in the LC/HC condition, which may have required less effortful processing due to the semantic consistency of the high-context sentence. These findings converge with those of McCoy et al. (2005) to support the contention that increased predictability of the to-be-recalled material decreases the amount of resources required for processing, improving performance for those whose working memory capacity would otherwise be exceeded.

Two limitations of the study by Meister et al. (2016) are worth noting. First, their sample size was small, yielding only seven participants in each of the four groups. Second, splitting data at the median is not a recommended practice. Although the median-split yielded groups that differed in their average working memory capacities, it does not guarantee that participants in either working memory group had what would be considered a high or low working memory capacity at the population level. Median-splitting is also problematic because participants close to either side of the median will be more similar in working memory capacity than those distant from the median. Because of these limitations, the results described by Meister et al. should be interpreted with caution.

The studies described above demonstrate that low working memory capacity may negatively impact speech perception in noise and interpretation of garden-path sentences, and suggest that increasing contextual support may improve speech perception by alleviating working memory load. Yet to be studied is the effect of working memory capacity on false hearing as described by Rogers et al. (2012). If Christianson et al. (2006) are correct in thinking that greater working memory capacity permits individuals to reinstate and re-evaluate the structure of misleading sentences, we might expect that greater working memory capacity would also be protective against false hearing due to better ability to re-evaluate incongruent stimuli. The present study tested the hypothesis that higher working memory capacity is related to lower susceptibility to false hearing.

1.3.2 Processing Speed

The argument has been put forth that deficits in working memory experienced by older adults are due, at least in part, to slowed information processing speed (Salthouse, 1996). According to this theory, the cognitive slowing that accompanies aging impedes completion of time-sensitive lower-level processing, with the effect that necessary processing at lower levels may be incomplete by the time the information is needed for subsequent operations. Thus, reduced information processing speed will impair functions – such as rehearsal – that are important for memory.

Experimental studies investigating the contributions of processing speed to memory have typically taken two approaches: altering the rate at which information is presented, or increasing the amount of time available for processing. Increasing the speaking rate of recorded passages decreases accuracy of recall in both younger and older adults, although this effect is exacerbated in older adults, who on average process information more slowly (Wingfield, Tun, Koh, &

Rosen, 1999; Wingfield, Tun, & Rosen, 1995). Wingfield et al. (1999) provided a useful analogy for understanding this effect:

> These effects of very rapid speech can be seen as analogous to a too-slow factory assembly-line worker who has fallen behind and who struggles more and more futilely to keep pace with the relentless influx of new material on his assembly line. For older adults, the experience of trying to process rapid speech may be similar, as the decrements that result from slowing at each step have a cumulative snowball effect that causes greater problems with each subsequent operation. (p. 387)

Although increasing the rate of speech negatively impacts recall, adding extra time for processing at syntactic boundaries counters this effect, allowing younger adults to fully recover to the performance obtained at normal speech rates, and older adults to fully recover in all but the fastest speech rates (Wingfield et al., 1999). Allowing extra processing time at syntactic boundaries also helps to offset performance deficits experienced by younger adults with hearing loss, which slows processing by increasing the effort necessary for initial encoding, relative to younger adults with normal hearing (Piquado, Bernichov, Brownwell, & Wingfield, 2012). Importantly, increasing processing time at random, non-syntactic locations (i.e., not at clause or sentence boundaries) disrupts performance relative to when processing time is added at syntactic boundaries, and is especially disruptive for older adults (Wingfield et al., 1999; Wingfield et al., 1995). Wingfield and colleagues (1999; 1995) suggested that segmenting speech at syntactic boundaries is beneficial because it maintains the passage's grammatical and semantic structure, and also preserves the prosody of speech, all factors shown to aid speech perception (Wingfield, Lahar, & Stine, 1989; Wingfield, Poon, Lombardi, & Lowe, 1985; Wingfield, Wayland, & Stine, 1992); segmenting speech at non-syntactic boundaries disrupts this natural structure. Returning to the assembly line analogy proposed by Wingfield et al. (1999), adding processing time at syntactic boundaries is analogous to stopping the quickly moving conveyor belt once all the necessary materials for one portion of the overall product has arrived, allowing the too-slow worker to catch up before the next wave of materials arrive. Adding processing time at random locations is akin to periodically stopping the conveyor belt, but the parts in front of the worker at any one time do not all fit together and some are missing, adding little improvement to efficiency. This analogy and the studies that support it corroborate the role of processing speed in speech perception, and the importance of maintaining semantic and syntactic context to improve efficiency of processing.

Since processing speed declines with age and affects speech perception, slowed processing may contribute to the greater frequency of false hearing experienced by older adults. Returning again to the assembly-line analogy, false hearing may occur when some quickly arriving pieces move past the too-slow worker while they are busy assembling preceding pieces. Because their focus is on assembling the previous pieces, the worker may only catch a brief glimpse of the passing pieces or may miss them altogether. However, upon inspecting the assembled pieces in their hands and using their many years of experience, the clever worker is able to figure out what pieces must be missing and picks them out of a pile of spare parts. Similarly, slower processors may not be able to devote their full attention to target stimuli if they have not completed processing earlier stimuli. If contextual cues are available, however, the missed target word can be inferred, resulting in accurate perception when contextual cues are valid, but increased context-based misperceptions when context is misleading. In the present study, we tested the hypothesis that slower processors would be more prone to false hearing than would faster processors.

1.3.3 Inhibitory Control and the Neighborhood Activation Model

The role of inhibitory control is to increase the efficiency of working memory by stopping irrelevant information from entering working memory and removing information that is no longer relevant (Hasher & Zacks, 1988; Stoltzfus, Hasher, & Zacks, 1996). While working memory capacity and processing speed may be especially important for maintaining and extracting meaning from useful information, inhibitory control allows us to disengage from misleading information.

Hsu and Novick (2016) provided compelling evidence that engaging inhibitory control before exposure to an ambiguous sentence can help to overcome an initial, incorrect interpretation. Participants heard ambiguous and unambiguous sentences instructing them to click and drag an object to a goal location. For example, participants heard the ambiguous sentence *Put the frog on the napkin onto the box* and were shown four pictures: a frog sitting on a napkin (i.e., the target object), a napkin with no frog (i.e., the incorrect goal location), a box (i.e., the correct goal location), and a horse (i.e., an irrelevant distractor). The correct interpretation of the sentence would lead the participant to drag the frog sitting on a napkin onto the box, whereas an incorrect interpretation would lead the participant to drag the frog sitting on a napkin onto the other napkin. The unambiguous version of the same sentence was *Put the frog that's on the napkin onto the box*. Prior to each sentence, participants completed either a congruent or an incongruent trial from the Stroop task (Stroop, 1935), in which the name of a color is presented in the same color ink (congruent; e.g., the word "red" in red ink) or in a different color ink (incongruent; e.g., the word "red" in yellow ink), and the participants are asked to say the color of the ink. Incongruent Stroop trials are thought to require inhibitory control to suppress activation from the written color name, so the authors reasoned that if inhibitory control is also necessary to suppress an initial, incorrect interpretation of an ambiguous sentence, prior completion of an incongruent Stroop trial may improve ambiguous sentence processing by pre-activating the necessary inhibitory control. In addition to measuring the accuracy of the participants' interpretations, the authors also used eyetracking to measure the duration of time participants spent looking at the correct and incorrect goal locations. They found that participants were less likely to misinterpret ambiguous sentences and spent more time looking at the correct goal location after completing an incongruent Stroop trial relative to a congruent Stroop trial. Additionally, gaze shifted from the goal location implied by the initial, incorrect interpretation to the correct goal location faster when ambiguous sentences were preceded by an incongruent, relative to a congruent, Stroop trial. The authors interpreted these findings as evidence that activation of inhibitory control from the preceding incongruent Stroop trial allowed participants to more quickly revise their interpretation of an ambiguous sentence.

Similar to working memory capacity and processing speed, inhibitory control declines with age. Older adults are less able to inhibit task-irrelevant information than are younger adults, yielding greater Stroop interference (West & Alain, 2000) and diminished ability to discard prepotent, but task-irrelevant, words from memory (Hartman & Hasher, 1991; Hasher, Quig, & May, 1997). Hasher et al. (1997, Experiment 1) had younger and older adults read high-cloze sentences missing the final word (e.g., *He mailed the letter without a* _____), which participants verbally completed with a word that followed from the sentence context. In a learning phase, one of two words appeared on screen once participants had verbally completed the sentence: the word predicted by the sentence (e.g., *stamp*), confirming the prediction, or a less predictable but semantically plausible alternative (e.g., *check*), disconfirming the prediction. Participants were instructed to remember the presented words for a later memory test. The memory test never actually occurred; the warning of an impending test was simply to encourage participants to hold the presented words in memory. After a short filler task, participants again read aloud and verbally completed a series of sentences missing the final word – we will refer to these as the test sentences. Half of the test sentences were constructed to elicit the presented low-predictability word from the learning phase (e.g., *check*) in 50% of responses, and the other half were constructed to elicit the disconfirmed high-predictability word from the learning phase (e.g., *stamp*) in 50% of responses. Of interest was whether participants would complete these sentences with the anticipated word in more than the expected 50% of cases (i.e., a priming effect). Participants should exhibit a priming effect for the low-predictability words presented in the learning phase because they were instructed to remember the presented words for a later test. The disconfirmed high-predictability words from the learning phase, however, were never actually presented, and thus should have been cleared from memory as they were irrelevant to the anticipated test; if participants exhibited a priming effect for the disconfirmed words from the learning phase, this would represent a failure of inhibitory control. The authors found that younger adults only exhibited a priming effect for the presented low-predictability words from the learning phase, whereas older adults exhibited a priming effect for both the presented low-predictability words and the unpresented high-predictability words. The authors interpreted these findings as evidence for an age-related decline in inhibitory control.

As was the case with working memory capacity and processing speed, deficits in inhibitory control can be reduced when contextual cues are present. In a follow-up to the study described above using the same paradigm, Hasher et al. (1997, Experiment 2) investigated whether increasing contextual support for the low-predictability words in the learning phase would facilitate elimination of disconfirmed high-predictability words from memory. To test this hypothesis, they presented the same learning phase sentences as in Experiment 1, but following presentation of the target word, a second sentence was presented on screen that increased the contextual support for the presented target word. For example, if the sentence *He mailed the letter without a* _____ is completed by the word *check* rather than the predicted word *stamp*, adding the elaborating sentence *He was expecting the money* may help older adults expel *stamp* from memory since the new information has retrospectively increased the predictability of *check*. Under these conditions, both younger and older adults completed test sentences with the presented word (e.g., *check*) in more than the expected 50% of cases, and neither group exhibited a priming effect for the initially predicted but disconfirmed word (e.g., *stamp*), evidence that contextual cues can help older adults overcome deficits in inhibitory control.

The results of Hasher and colleagues' (1997) experiments seem particularly useful for explaining older adults' increased susceptibility to false hearing relative to younger adults (Rogers et al., 2012). In each case, older adults seem to be less able to abandon a highly prepotent response when faced with disconfirming evidence than are younger adults. Since older adults are less able to clear disconfirmed, highly prepotent responses from memory than are younger adults, older adults in the study by Rogers et al. (2012) may have experienced increased competition for perception between the semantically incongruent target word and the contextually predicted phonological neighbor, resulting in more frequent cases of false hearing by older, relative to younger, adults.

The Neighborhood Activation Model (NAM; Luce & Pisoni, 1998) provides a framework for understanding the role of lexical competition in speech perception. According to the NAM, baseline activation of a word in the mental lexicon is determined by its frequency of occurrence in language. Hearing a word increases activation of both the word and similar sounding words in the mental lexicon. For example, hearing the word *sheet* activates both the target word *sheet* and phonological neighbors of the target word, such as *shear*, *cheat*, *meat*, and *beat*. These phonological neighbors compete with the presented word for activation, and the word that receives the greatest activation is perceived.

In a pair of papers, Sommers (1996) and Sommers and Danielson (1999) argued for the inclusion of two additional variables into the NAM framework: inhibitory control and availability of contextual cues. Sommers and Danielson (1999) had younger and older adults identify lexically easy words (i.e., words with fewer and lower frequency phonological neighbors) and lexically difficult words (i.e., words with more and higher frequency phonological neighbors) in background noise. Target words were either presented alone (e.g., *path*), were preceded by a low-predictability sentence (e.g., *She was thinking about the path*), or were preceded by a high-predictability sentence (e.g., *She was walking along the path*). As would be predicted by the NAM, lexically difficult words were harder to identify than were lexically easy words because having more high-frequency neighbors increases the amount of competition for perception (Luce & Pisoni, 1998). Older adults had lower identification rates than did younger adults for lexically difficult words presented alone or preceded by a low-predictability sentence; however, there were no differences in performance between age groups when lexically difficult words were preceded by a high-predictability sentence, supporting the proposition that older adults obtain greater benefit from context than do younger adults. Additionally, composite scores from three tests of inhibitory control (two versions of the Garner selective attention task [Garner, 1974], and an auditory Stroop task) were negatively correlated with identification of lexically difficult words, indicating that individuals with poorer inhibitory control were less likely to correctly identify lexically difficult words. Even after controlling for education, vocabulary, and age, the inhibitory control composite accounted for 36% of variance in identification of lexically difficult words preceded by low-predictability sentences. However, the inhibitory control composite only accounted for 20% of variance in identification of lexically difficult words preceded by high-predictability sentences. Interpreting their results within the framework of the NAM, Sommers and Danielson (1999) suggested that inhibition might be used to decrease the activation of competitors in the mental lexicon, thereby increasing the difference in activation between the target word and competitors. Context may benefit speech perception by selectively increasing activation of semantically congruent target words, thereby decreasing competition from semantically incongruent phonological neighbors, and diminishing the need to employ inhibition to achieve correct perception. Thus, the ability to correctly recognize spoken words is influenced by the number of phonological neighbors possessed by the target word (phonological neighborhood density), the frequencies with which the target word and its competitors appear in language, the ability of the listener to inhibit these competitors, and the congruence of activated words with available contextual cues.

These premises can be used to construct a convincing argument for the role of inhibitory control in false hearing as described by Rogers et al. (2012). If participants are tasked with identifying a target word that is not semantically related to the cue with which it is paired (e.g., *barn-pay*), the target word (e.g., *pay*) gains activation only by virtue of its phonological similarity to the auditory signal, whereas competing phonological neighbors that are predicted by context (e.g., *hay*) will gain activation both from the auditory signal – although this will be less than the activation allotted to the target word – and from the context, increasing the likelihood of a competitor being falsely heard. If the stimuli are played in noise, as in the study by Rogers et al. (2012), there is less information that can be obtained from the auditory signal, which increases the influence of context on perception, and in turn increases the likelihood of incorrectly perceiving a contextually predicted competitor. These premises also explain why older adults are more prone to false hearing than are younger adults. Since excitation has selectively increased the activation of contextually congruent competitors, inhibition must play a larger role if the presented, contextually incongruent, word is to be perceived. Older adults may be less able to inhibit contextually congruent competitors due to age-related deficits in inhibitory control (Hartman & Hasher, 1991; Hasher, Quig, & May, 1997; Hasher & Zacks, 1988; West & Alain, 2000), and thus must contend with more highly activated competitors than younger adults, yielding poorer identification rates of contextually incongruent stimuli, and a greater likelihood of false hearing.

The present study tested the hypothesis that false hearing occurs as result of failure to inhibit a highly prepotent response. To test this hypothesis, we analyzed the relation between frequency of false hearing and two measures of inhibitory control: the Stroop task and the frequency of memory intrusions in our test of working memory capacity, the Ospan.

1.4 Present Study

The present study was designed to elucidate the individual contributions of working memory capacity, processing speed, and inhibitory control to veridical and false hearing in younger and older adults. Participants identified sentence-final words in noise following high- and low-predictability sentences taken from the SPIN-R (Bilger et al., 1984), and provided confidence judgements for their perceptions. For 75% of high-predictability sentences, we substituted a phonological neighbor for the predicted word to create sentences in which the target word was incongruent with the context of the sentence (i.e., *She made the bed with a clean* <u>*cheat*</u>, for which the predicted word was *sheet*). Of particular interest in the present study was performance on these incongruent sentences: Correct identifications of the incongruent target words functioned as our measure of veridical hearing, and cases in which participants reported hearing the contextually predicted word with maximum confidence constituted our measure of false hearing.

Based on the findings of Rogers et al. (2012), we formulated several predictions for performance on the SPIN task. Because of older adults' increased reliance on contextual cues in speech perception, we expected older, relative to younger, adults to correctly identify as many or more target words preceded by a congruent context, and to correctly identify fewer target words preceded by an incongruent context. Also, we expected that older adults' increased reliance on context for speech perception would lead to higher confidence when responding their responses were supported by context relative to when context was unavailable, making them prone to false hearing.

We also generated specific hypotheses regarding each of our cognitive predictors based on the literature described above. Based on the findings from Christianson et al. (2006) showing that individuals with low working memory capacities rely on "good-enough" interpretations of sentences due to an inability to reinstate the structure of a sentence, we expected that individuals with high working memory capacity would be better able to re-evaluate incongruent sentences, essentially giving them a second opportunity to notice the incongruence between the sentence context and the target word. Thus, individuals with high working memory capacity should be more likely than those with low working memory capacity to correctly identify incongruent target words, and should also be less prone to false hearing.

Similarly, we expected participants with slower processing speeds to be more likely to fall behind in sentence processing and, as a result, devote insufficient attention to the sentence-final targets. Thus, we hypothesized that slower processors would be less likely to correctly identify incongruent targets and to be more prone to false hearing than faster processors.

However, since there was no time-limit for responding, and sentences were both short and spoken at a normal rate, we expected this effect to be small.

We expected that participants with poor inhibitory control would be more susceptible to false hearing than would those with better inhibitory control. This prediction was based on the findings of Hasher et al. (2007), who found that older adults' performance on a sentence completion task was influenced by highly predicted, but disconfirmed, words. Additionally, the revised NAM (Luce & Pisoni, 1998; Sommers, 1996) suggests that the semantically congruent phonological neighbors of a semantically incongruent target word should be highly competitive for perception, and that inhibition can be used to decrease activation of competitors. Therefore, individuals with better inhibitory control should be better able to disengage from the prepotent, context-based, response, improving perception of incongruent targets, and decreasing susceptibility to false hearing.

Finally, we believed that inhibitory control would be the best predictor of false hearing in our study. The strong contextual constraint characterizing our sentence stimuli should result in highly activated competitors for perception in incongruent sentences, increasing the importance of inhibitory control for achieving correct perception. The sentences used in this study were also short, spoken at a comfortable pace, and both semantically and syntactically sound until the final word, which means that the contributions of working memory capacity and processing speed to false hearing should be small in comparison to that of inhibitory control.

Chapter 2: Methods

2.1 Participants

Forty-seven younger adults (ages 18-22; *M* = 19.6; *SD* = 1.4) and 63 older adults (ages 61-83; *M* = 70.5; *SD* = 5.3) participated in this study. Younger participants were recruited from the Washington University in St. Louis Psychological & Brain Sciences participant pool. Older adults were recruited through Volunteers for Health, as well as from the Washington University in St. Louis Aging and Development participant pool. All participants were native English speakers, and none of our participants reported using hearing aids in daily life. Participants received either course credit (young adults) or $10/hr (older adults) for participating.

2.2 Hearing Acuity

Hearing thresholds were assessed for octave frequencies from 250 to 8000 Hz in a sound-attenuating booth using standard audiometry. Consistent with Benichov et al. (2012), high-frequency hearing was operationalized as the best-ear PTA across the 1000, 2000, and 4000 Hz frequencies, which are known to be important for speech perception (Humes, 1996).

2.3 Vocabulary Knowledge

Vocabulary knowledge was assessed using the Shipley Vocabulary Test (Shipley, 1940). Participants completed 40 trials, in which they decided which of four words was most similar in meaning to a target word, and indicated their responses by pressing the key corresponding to their answer. The target word was presented at the top of the screen in capital letters, and the four numbered response options were presented horizontally below. An interval of 1000 ms separated the input of a response and the onset of the next trial.

2.4 Speech Perception in Noise (SPIN) Test

2.4.1 Materials

Stimuli were 140 low-predictability sentences (hereafter referred to as baseline sentences; e.g., *She was thinking about the sheet*) and 80 high-predictability sentences (hereafter referred to as congruent sentences; e.g., *She made the bed with a clean sheet*) selected from the SPIN-R (Bilger et al., 1984). For each congruent sentence, an incongruent sentence was constructed by substituting the final word for one of its phonological neighbors (e.g., *She made the bed with a clean cheat*). All sentences were recorded at 48,000 Hz and 16-bit resolution, then were down-sampled to 11,025 Hz using Adobe Audition. Sentences were recorded in a double-walled, sound-attenuating booth, and were spoken at a normal rate by a male with a Midwestern American accent. All sentences were played at an average amplitude of 72 dB SPL.

2.4.2 Procedure

To ensure that stimulus audibility in the SPIN test was equated between younger and older adults, a modified version of ASHA's recommended procedure for determining speech reception thresholds (SRTs) was used (ASHA, 1988); SRT refers to the SNR at which a participant is able to correctly identify 50% of words in noise. To determine each participant's SRT, a random selection of sentences were chosen from a set of 100 possible baseline sentences. For each sentence, the final word was embedded in six-talker babble noise. The SNR began at +15 dB SPL and was increased or decreased by 2 dB SPL based on performance on the previous trial until the SNR at which the target word was correctly identified in approximately 50% of trials was determined. This SNR was used in the SPIN test. None of the baseline sentences used to determine the SRTs were used in the SPIN test.

Prior to beginning the SPIN test trials, participants completed six practice trials consisting of two baseline sentences, two congruent sentences, and two incongruent sentences, presented pseudo-randomly (i.e., in a predetermined random order). Participants did not receive feedback on practice trials, but were asked if they had questions prior to starting the test trials. Participants then completed 120 test trials consisting of 40 baseline sentences, 20 congruent sentences, and 60 incongruent sentences. Sentences were presented pseudo-randomly, and were counterbalanced across participants such that each non-baseline target word appeared equally often following a congruent sentence and an incongruent sentence, but only appeared once per experimental session. Trials began with a 500 Hz warning tone played for 500 ms, followed by 500 ms of silence before the onset of the sentence. Babble noise started 50 ms prior to the onset of the target word, and terminated 500 ms after offset of the target word.

Participants were instructed that they would hear complete sentences through headphones with the final word in background noise, and that their task was to identify the word in noise. Participants were not told that sentences would differ in contextual constraint, nor were they told that context could be misleading. After identifying the target word, they gave a confidence judgement on a 5-point Likert scale where 1 indicated absolute uncertainty (i.e., guessing) and 5 indicated absolute certainty that the word they reported hearing was presented.

2.5 Processing Speed Tasks

Participants completed two processing speed tasks. In the first task, which assessed verbal processing speed, the names of animals and food items were presented on screen sequentially, and participants made an animal/non-animal categorization by pressing the corresponding key. Participants completed 10 practice trials, followed by 40 test trials divided equally between animals and non-animals.

In the second task, which assessed visual-spatial processing speed, two colored dots were presented, one on each side of a central white dot. Participants indicated which of the two colored dots was closer to the central dot by pressing the corresponding key. Participants completed eight practice trials, followed by 20 test trials divided equally between left-dot-closer and right-dot-closer trials.

Participants were instructed in both tasks to respond as quickly as possible without sacrificing accuracy. Targets were presented randomly, and remained on screen until a response was provided. An interval of 250 ms separated the participant's response and the presentation of the next stimulus.

2.6 Working Memory Capacity Task

The Ospan was used to assess working memory capacity; this task was chosen because of its relation to reading comprehension (Turner & Engle, 1989). Participants completed simple math problems while remembering a series of words. Before each word was presented, a math problem appeared on screen with a provided solution (e.g., 2 + 5 = 7). Participants read each math problem aloud, then indicated whether the provided solution was correct by pressing the corresponding key; half of the provided solutions were correct. After an interval of 250 ms, a word appeared on screen for 1.5 seconds for later recall. At the end of each series, a tone was played through speakers and three question marks appeared on screen cueing participants to type the words they could recall from the current series in the order the words had appeared. Each series contained two to seven words for recall, and three series of each length were presented, resulting in 18 total series and 81 total words to recall.

Consistent with past studies (Engle, Tuholski, Laughlin, & Conway, 1999; Unsworth, Heitz, Schrock, & Engle, 2005), responses were scored by summing the number of words from all perfectly-recalled series (i.e., series in which all words were recalled in the correct order). For example, if a participant perfectly recalled three two-word series and one three-word series, they would receive a total score of nine. Ospan scores were only included in analyses if the participant correctly answered 85% of math problems.

2.7 Inhibitory Control Tasks

Inhibitory control was assessed using two tasks. The first task was the Stroop color naming task, in which the names of colors (red, blue, green, yellow) were presented on screen in either a congruent colored ink (e.g., the word "RED" in red ink) or an incongruent colored ink (e.g., the word "RED" in blue ink); baseline stimuli were strings of Xs (e.g., "XXXX" in red ink). Participants were tasked with saying aloud the color of the ink as quickly and accurately as possible. At the start of each trial, three plus signs (+++) appeared at the center of the screen for 500 ms to capture attention. After an interval of 50 ms, the stimulus word appeared on screen, and remained on screen until a verbal response was given. Responses were coded with a key press by a researcher present in the testing room. An interval of 750 ms separated the input of the response and the onset of the next trial. Participants completed 16 practice trials consisting of four congruent, four incongruent, and eight baseline trials, followed by 80 test trials consisting of 32 congruent, 24 incongruent, and 24 baseline trials. All trials were presented in random order. Stroop interference was calculated by subtracting mean reaction times on correctly answered baseline trials from mean reaction times on correctly answered incongruent trials.

Our second measure of inhibitory control was derived from our measure of working memory capacity, the Ospan. Recall that in the Ospan, participants are tasked with remembering a series of words while simultaneously solving simple math problems. An intrusion occurs when the participant reports remembering a word that was not present in the most recent series, representing a failure to stop irrelevant information from entering working memory, thus functioning as a second measure of inhibitory control. As in past studies (Unsworth, 2007;

Unsworth & Brewer, 2010), we divided intrusions into two categories: past-list (PL) intrusions, which were intrusions of words presented in earlier Ospan series, and extra-list (EL) intrusions, which were intrusions of words that were not presented in any previous series. Each category of intrusion was analyzed separately.

2.8 Additional Measures

We included a third measure of inhibitory control, which was an adaptation of the Hayling Sentence Completion Test from the Hayling and Brixton Tests (hereafter referred to as the Hayling test; Burgess & Shallice, 1997). The Hayling test is divided into two sections. In each section, a sentence was played through speakers with the final word missing, and participants were instructed to fill in the blank by saying a single word aloud as quickly and accurately as possible. In Section 1, participants were instructed to complete each sentence with a word that made sense given the context of the sentence (e.g., *The captain went down with the sinking* _____ could be completed with “ship”); this section yielded a measure of response initiation speed. In Section 2, participants were instructed to complete each sentence with a word that made no sense given the context of the sentence (e.g., *The captain went down with the sinking* _____ could be completed with “banana”); this section required subjects to inhibit the prepotent response before generating a nonsense ending, thus yielding a measure of inhibitory control. All sentence-final target words were nouns. Each section contained 15 sentences taken from Block and Baldwin (2010), with cloze probabilities ranging from .50 to .71. Sections were equated based on cloze probability and the probabilities of other frequently generated completions. Sentences were counterbalanced to appear equally in each section. Hayling test sessions were recorded using a handheld audio-recorder, and the time from the offset of the recorded sentence to the start of the participant’s response were determined using Adobe Audition.

Based on pilot testing and past research, we placed several constraints on Section 2 responses to ensure that participants attended to the content of the sentence; if participants ignored the content of the sentence, there would be no activation of a prepotent response, thus invalidating the measure. Participants were instructed to respond using only nouns, to not use vulgarity or antonyms, to not name objects present in the testing room, to not use the word predicted by the previous sentence, and to not repeat responses. Responses that violated any of these rules were omitted from analyses. To further ensure that participants attended to the content of the sentences in Section 2, participants were given a five-question comprehension test at the end of the section. For example, the question corresponding to the sentence *Billy hit his sister on the* _____ was "Who did Billy hit?" Participants were forewarned that this test would occur, and were provided an example question before they began Section 2. Data from participants who correctly answered fewer than three out of five comprehension questions were omitted from analyses.

Following data collection, we decided to omit the Hayling test data from analyses. We had several reasons for making this decision: First, data from 20 younger adults and 18 older adults (43% and 29% of respective age groups) had to be excluded because they failed to correctly answer at least three out of five comprehension questions; second, there was a high frequency of disallowed responses in Section 2 of the Hayling test due to incorrectly responding with a semantically related word, or repeating words that had been used as previous answers; third, we found that competing noises (e.g., coughing, shifting in the seat, filler words) often interfered with identifying the end of recorded sentences or the onset of participant responses, limiting our ability to accurately assess response time. Based on the low sample size after exclusions and the small number of valid trials remaining for those who were not excluded, we decided that data from the Hayling test would not be sufficiently reliable to draw meaningful conclusions.

2.9 Procedure

All participants completed the tasks in a set order: the audiogram to determine the participant's PTA, the SPIN test, the animal and dot processing speed tasks, the Ospan, the Stroop task, the Hayling test, and the Shipley Vocabulary Test. Each task was presented using E-Prime 2.0 software. Participants were informed that they could take breaks between each task, or between trials of any non-speeded task. The experiment took place during a single session, and lasted between 1.5 and two hours.

Chapter 3: Results

3.1 Data Analysis

To ensure that audibility of the SPIN trials was equated between age groups, data were excluded from analyses if the subject did not correctly identify 35 – 65% of baseline trials (recall that the SRT targets an accuracy of 50% correct). Because of the importance of SPIN data to our research questions, all data from participants not meeting this criteria were deleted in a list-wise fashion. This eliminated data from four younger adults and 14 older adults. The final sample size with usable SPIN data was 43 younger adults (29 female; ages 18 – 22; *M* = 19.74; *SD* = 1.42) and 49 older adults (37 female; ages 61 – 83; *M* = 69.84; *SD* = 5.43).

Within tasks measuring reaction time, trials were removed if they were three or more standard deviations above or below the participant's average. In the younger adult sample, 1.97% of trials were removed from the verbal processing speed task, 1.28% from the visual-spatial processing speed task, and 1.57% from the Stroop task. In the older adult sample, 2.18% of trials were removed from the verbal processing speed task, .95% from the visual-spatial processing speed task, and 1.13% from the Stroop task. Participant scores on individual tasks were removed if they were three or more standard deviations above or below the average within each age group; no more than three observations were removed as outliers from any task within each age group, aside from seven older adults whose low average confidence scores in the congruent condition of the SPIN task were deemed outliers (42 observations remained). The Shipley Vocabulary Test was added to the study after 10 younger and four older adults had participated, so data was only available for 33 younger and 45 older adults. Ospan scores were removed if accuracy on the secondary math task was lower than 85%, which excluded data from seven older adults. Additionally, data from the Ospan was missing for one younger adult due to a computer failure, and scores from three older adults were excluded because they did not consistently say the math problems aloud. Data from all tasks were available for 30 younger adults and 31 older adults; an additional eight younger adults and three older adults had data from all tasks excluding the Shipley Vocabulary Test. Sample sizes and descriptive statistics for each task are presented in Table 1.

Table 1
Descriptive statistics for variables related to hearing acuity, vocabulary knowledge, and cognitive ability within each age group.

	Younger adults		Older adults	
Variable	Mean (*SD*)	*N*	Mean (*SD*)	*N*
SNR (dB SPL)	-2.86 (2.02)	43	.33 (2.31)	48
PTA (dB HL)	.78 (4.20)	43	19.82 (10.97)	49
Shipley Vocabulary	32.15 (2.85)	33	34.38 (3.51)	45
Ospan	23.43 (11.23)	42	14.81 (6.77)	37
Verbal response speed (ms)	578.39 (64.85)	42	701.55 (117.39)	49
Visual-spatial response speed (ms)	661.81 (134.08)	43	949.34 (196.77)	46
Stroop (ms)				
Neutral trials	1145.73 (126.30)	40	1208.97 (159.14)	48
Congruent trials	1149.59 (135.03)	40	1234.64 (174.93)	48
Incongruent trials	1263.14 (161.08)	40	1453.11 (233.42)	48
Stroop interference (ms)	117.41 (68.34)	40	244.14 (124.65)	48
EL intrusions	3.56 (2.53)	41	2.77 (2.23)	39
PL intrusions	3.57 (3.16)	42	3.64 (2.79)	39

Note. SNR = signal-to-noise ratio used in the speech perception in noise task; PTA = best-ear pure-tone average; Ospan = operation span; EL = extra-list; PL = past-list

3.2 Group Comparisons

Welch's *t*-tests were used for all group comparisons to account for between-group differences in sample size and variance.

3.2.1 SPIN Task

Figure 1 displays the percent of trials in the congruent, baseline, and incongruent conditions in which a correct identification was made (hits), as well as percent of cases of false hearing in incongruent trials by age group. The addition of congruent context improved target word identification relative to the baseline condition for both younger adults, $t(74.05) = 25.51$, $p < .001$, and older adults, $t(79.77) = 32.68$, $p < .001$. The presence of incongruent context led to poorer target word identification relative to the baseline condition for both younger adults, $t(74.67) = 8.79$, $p < .001$, and older adults, $t(92.30) = 15.67$, $p < .001$. Younger and older adults did not differ in identification accuracy for target words preceded by baseline sentences, confirming that the titration procedure succeeded in equating audibility of stimuli between groups, $t(87.11) = .89$, $p = .38$. Despite both groups being near ceiling in terms of accuracy, older adults correctly identified more target words in the congruent sentence condition than did younger adults, $t(83.41) = 2.44$, $p = .02$. However, older adults were less likely than younger adults to correctly identify target words preceded by an incongruent sentence, $t(80.57) = 4.31$, $p < .001$. In cases where incongruent targets were misidentified, older adults were more likely to report the contextually predicted word than were younger adults, demonstrating an overreliance on contextual cues for determining the outcome of perception, $t(88.98) = 5.59$, $p < .001$. Older adults were also more likely to experience false hearing (i.e., context-based misperception with a confidence rating of 5 on Likert scale) than were younger adults, $t(79.83) = 6.39$, $p < .001$.

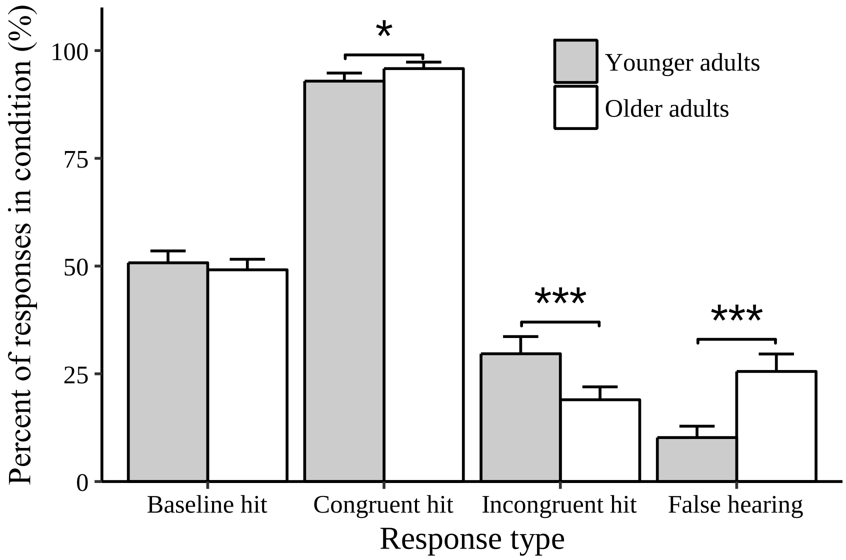

Figure 1. Percent of words correctly identified by each age group in the baseline, congruent, and incongruent conditions of the SPIN task, as well as percent of incongruent trials in which false hearing occurred.

Figure 2 shows group differences in confidence for correct identifications in the baseline, congruent, and incongruent conditions, as well as differences in confidence for context-based misperceptions in the incongruent condition. Older adults demonstrated greater confidence in their responses relative to younger adults when context supported their response. This was true both for correct identifications in the congruent sentence condition, $t(57.83) = 5.19$, $p < .001$,[1] and for misperceptions in the incongruent sentence condition, $t(85.75) = 3.52$, $p < .001$. Conversely, when context could not be used to achieve correct identification, older adults displayed lower confidence than younger adults: older adults were less confident in correct identifications in the baseline condition than were younger adults, $t(81.75) = 2.67$, $p < .01$, and

[1] Older adults' confidence in congruent hits remained significantly higher than that of younger adults when including the seven older adults whose low confidence on congruent trials qualified as outliers, $t(85.03) = -2.35$, $p = 02$.

had numerically lower confidence in correct identifications in the incongruent condition, $t(80.22) = 1.53$, $p = .13$.

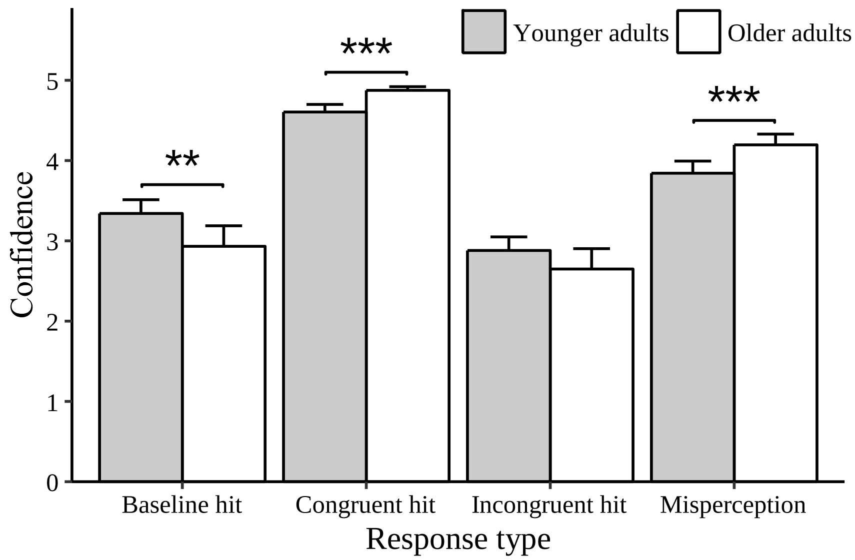

Figure 2. Confidence in identification for hits in the baseline, congruent, and incongruent conditions, as well as confidence in context-based misperceptions in the incongruent condition, by age group.

3.2.2 Hearing Acuity, Vocabulary Knowledge, and Cognitive Ability

Correlations between our measures of hearing acuity, vocabulary knowledge, and cognitive ability are presented in Table 2. Older adults had poorer hearing acuity than did younger adults, exemplified by both higher PTAs, $t(63.37) = 11.25$, $p < .001$, and the need for more favorable SNRs to achieve approximately 50% accuracy on baseline trials in the SPIN task, $t(88.95) = 7.04$, $p < .001$.

Older adults demonstrated better vocabulary knowledge on the Shipley Vocabulary Test than did younger adults, $t(75.15) = 3.09$, $p < .01$. This replicates the findings of Park et al. (2002), who showed age-related increases in vocabulary across three different measures, including the Shipley Vocabulary Test. This result also fits with Cattell’s (1963) theory of crystallized versus fluid intelligence, in which skills relying on prior knowledge improve with age (crystallized intelligence), whereas processing speed and the ability to apply skills to new situations decline with age (fluid intelligence).

Further supporting the distinction between crystallized and fluid intelligence, older adults demonstrated poorer performance across each of the cognitive tests in our study. Older adults demonstrated slower processing speed than younger adults on both the verbal task, $t(76.86) = 6.31$, $p < .001$, and the visual-spatial task, $t(79.73) = 8.10$, $p < .001$. Older adults also had lower working memory capacities than did younger adults, $t(68.51) = 4.19$, $p < .001$, and experienced greater Stroop interference than did younger adults, $t(75.23) = 6.04$, $p < .001$.[2] Interestingly, despite greater working memory capacity by younger relative to older adults, there were no age differences in number of PL intrusions, $t(78.79) = .11$, $p = .92$, or EL intrusions, $t(77.56) = 1.49$, $p = .14$, on the Ospan.

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[2] The age difference in Stroop interference remained significant when tested using the forced-entry hierarchical regression method described by Bugg, DeLosh, Davalos, and Davis (2007), which controls for age differences in response speed. Response time on incongruent Stroop trials was entered as the dependent variable, response time on baseline Stroop trials was entered as the lone predictor in the first regression model to partial out the effect of response speed, and age group was entered as a simultaneous predictor in the second model. The first model including only baseline response time was significant, $F(1, 88) = 208.40$, $p < .001$, and accounted for 69.97% of variance in incongruent Stroop trial response time. The second model including age group was also significant, $F(2, 87) = 122.70$, $p < .001$, and both baseline Stroop trial response speed and age group were significant within this model (both $p < .001$). This second model accounted for 73.22% of variance in incongruent Stroop trial response time, and subtracting the variance explained by the two models tells us that age group accounted for 3.25% of additional variance above and beyond the effect of age differences in response speed. Thus, although group differences in response speed were largely responsible for observed differences in incongruent Stroop trial response time, there were age differences in incongruent Stroop trial response time – and by extension, inhibitory control – even after controlling for response speed.

Table 2
Across-group correlations between hearing acuity, vocabulary knowledge, and cognitive abilities.

	PTA	*Shipley*	*Ospan*	*Processing speed*	*Stroop*	*EL intrusions*	*PL intrusions*
PTA							
Shipley	0.22*						
Ospan	-0.36**	-0.07					
Processing speed	0.48***	0.03	-0.32**				
Stroop	0.51***	0.07	-0.22+	0.55***			
EL intrusions	-0.16	-0.22	0.08	-0.06	0.06		
PL intrusions	-0.06	0.02	-0.14	0.06	0.02	0.25*	

*p < .10 = +; p < .05 = *; p < .01 = **; p < .001 = ****

Note. PTA = best-ear pure-tone average; Ospan = operation span; EL = extra-list; PL = past-list

3.3 Effects of Cognitive Abilities on Veridical and False Hearing

To determine the relationship between our cognitive measures (working memory capacity, processing speed, and inhibitory control) and both veridical and false hearing, we first conducted Pearson product-moment correlations between our predictor variables and our speech perception outcomes (incongruent trial hits, and cases of false hearing). Incongruent trial hits were used as our measure of veridical hearing due to lack of variability in congruent and baseline sentence performance: both younger and older adult groups achieved nearly perfect identification of congruent targets, and the SNR used in the SPIN task was set individually for each participant to obtain approximately 50% baseline accuracy (see Figure 1). Each variable that correlated significantly ($\alpha = .05$) or marginally significantly ($\alpha = .10$)[3] with one of the speech perception outcomes was entered into a simultaneous multiple regression model with either incongruent hits or false hearing as the dependent variable. This analysis procedure was first conducted across age groups (i.e., with both younger and older adults included in the sample), then was repeated within each age group to see whether the relations of individual cognitive abilities to veridical and false hearing differed between age groups.

Predictor variables (but not outcomes) used in regression models were converted to *z*-scores to facilitate comparison of effect sizes between predictors. For analyses including both younger and older adults, *z*-scores were calculated without consideration of age group. For within-group analyses, *z*-scores were calculated within each age group. Adjusted R^2 values are reported for each multiple regression model.

3.3.1 Across-Group Analyses

Because our measures of verbal and visual-spatial processing speed were highly correlated ($r = .60$, n = 88, $p < .01$), a composite processing speed measure was formed by *z*-scoring each variable, then taking the average of the two. Across group correlations between our predictors and speech perception outcomes are presented in Table 3.

[3] We chose to use a liberal criterion for marginal significance because we were primarily interested in effect sizes, and did not want to omit potentially informative measures from further analysis based solely on *p*-values, which are known to be influenced by other factors, such as sample size.

Table 3
Across-group correlations between predictor variables and SPIN outcomes.

	Incongruent hits	*False hearing*
Shipley Vocabulary	-0.17	0.03
Ospan	0.28*	-0.22+
Processing speed	-0.32**	0.50***
Stroop	-0.13	0.32**
EL intrusions	-0.13	0.15
PL intrusions	-0.13	0.21+

*p < .10 = +; p < .05 = *; p < .01 = **; p < .001 = ****

Note. Ospan = operation span; EL = extra-list; PL = past-list

There were two significant correlates of incongruent hits: working memory capacity (r = .28, n = 79, p = .01), and our processing speed composite (r = -.32, n = 88, p < .01). The multiple regression model containing both cognitive predictors was significant, $F(2, 74) = 5.87$, $p < .01$, accounting for 11.35% of variance in incongruent hits (see Table 4). Processing speed remained a significant predictor of incongruent hits when controlling for working memory capacity, with a one standard deviation increase in processing speed (i.e., slower processing) corresponding to a 3.80% decrease in incongruent hits. Working memory capacity was only a marginally significant predictor of incongruent hits after controlling for processing speed, with a one standard deviation increase in working memory capacity corresponding to a 2.60% increase in incongruent hits.

There were two significant correlates of false hearing – processing speed (r = .50, n = 86, p < .001) and Stroop inhibition (r = .32, n = 86, p < .01) – as well as two marginally significant correlates – working memory capacity (r = -.21, n = 77, p = .06) and PL intrusions on the Ospan

(r = .21, n = 79, p = .07). The multiple regression containing each correlate of false hearing was significant, $F(4, 67) = 7.46$, $p < .001$, accounting for 26.68% of variance in false hearing (see Table 5). Although the effects of working memory capacity and Stroop interference were not significant in the full model, processing speed remained a significant predictor of false hearing, and PL intrusions was a marginally significant predictor. After controlling for each other variable in the model, a one standard deviation increase in processing speed corresponded to an 8.55% increase in false hearing, and a one standard deviation increase in PL intrusions corresponded to a 2.71% increase in false hearing.

Table 4
Multiple regression of across-group correlates of incongruent hits.

	Incongruent Hits		
	B	*CI*	*p*
(Intercept)	25.00	22.26 – 27.75	**<.001**
Ospan	2.60	-0.26 – 5.46	.074
Processing speed	-3.80	-7.31 – -0.30	**.034**
Observations		77	
R^2 / adj. R^2		.137 / .114	

Note. Ospan = operation span

Table 5
Multiple regression of across-group correlates of false hearing.

	False Hearing		
	B	*CI*	*p*
(Intercept)	17.60	14.76 – 20.44	**<.001**
Ospan	-0.74	-3.95 – 2.46	.645
Processing speed	8.55	4.46 – 12.64	**<.001**
Stroop	-0.81	-4.20 – 2.57	.633
PL intrusions	2.71	-0.13 – 5.55	.061
Observations		72	
R^2 / adj. R^2		.308 / .267	

Note. Ospan = operation span; PL = past-list

3.3.2 Individual Group Analyses

3.3.2.1 Younger Adults

The correlation between verbal and visual-spatial processing speed was smaller, but still significant when constraining the sample to only younger adults (r = .37, n = 42, p = .02), so a composite processing speed measure was once again formed. Correlations between our predictor measures and speech perception outcomes within the younger adult group are presented in Table 6. No variables correlated with incongruent hits when looking only within the younger adult group. There was, however, one marginally significant predictor of false hearing: EL intrusions (r = .30, n = 39, p = .07). Because it was the only predictor of false hearing, we did not enter EL intrusions into a regression equation.

Table 6
Correlations between predictor variables and SPIN outcomes, within younger adult group.

	Incongruent hits	*False hearing*
Shipley Vocabulary	0.06	-0.29
Ospan	0.07	0.02
Processing speed	0.14	-0.23
Stroop	0.09	-0.02
EL intrusions	-0.16	0.30^{+}
PL intrusions	-0.19	0.24

$p < .10 = {}^{+}$; $p < .05 = *$; $p < .01 = **$; $p < .001 = ***$

Note. Ospan = operation span; EL = extra-list; PL = past-list

3.3.2.2 Older Adults

As in the previous analyses, our measures of verbal and visual-spatial processing speed were significantly correlated within the older adult group (r = .41, n = 46, p < .01), so we created a composite processing speed measure for our analyses. Correlations between our predictors and speech perception outcomes within the older adult group are presented in Table 7. In the older adult group, there were two correlates of incongruent hits: a significant correlation with EL intrusions (r = -.32, n = 39, p = .05), and a marginally significant correlation with working memory capacity (r = .31, n = 37, p = .06). The multiple regression model containing both predictors was significant, $F(2, 33) = 4.31$, p = .02, accounting for 15.90% of variance in incongruent hits (see Table 8). Within this model, both predictors were significant, with a one standard deviation increase in working memory capacity corresponding to a 3.34% increase in incongruent hits after controlling for EL intrusions, and a one standard deviation increase in EL intrusions corresponding to a 3.28% decrease in incongruent hits after controlling for working memory capacity.

Table 7
Correlations between predictor variables and SPIN outcomes, within older adult group.

	Incongruent hits	*False hearing*
Shipley Vocabulary	-0.15	-0.10
Ospan	0.33^{+}	-0.03
Processing speed	-0.17	0.37^{*}
Stroop	0.17	0.07
EL intrusions	-0.32^{*}	0.33^{*}
PL intrusions	-0.06	0.26

$p < .10 = {}^{+}$; $p < .05 = *$; $p < .01 = **$; $p < .001 = ***$

Note. Ospan = operation span; EL = extra-list; PL = past-list

Table 8
Multiple regression of significant correlates of incongruent hits, within older adult group.

	Incongruent hits		
	B	*CI*	*p*
(Intercept)	19.72	16.58 – 22.86	**<.001**
Ospan	3.34	0.19 – 6.49	**.038**
EL intrusions	-3.28	-6.44 – -0.11	**.043**
Observations		36	
R^2 / adj. R^2		.207 / .159	

Note. Ospan = operation span; EL = extra-list

There were also two correlates of false hearing in the older adult group: processing speed (r = .37, n = 46, p = .01) and EL intrusions (r = .33, n = 39, p = .04). The overall model with processing speed and EL intrusions entered as simultaneous predictors of false hearing was significant, $F(2, 35) = 6.26$, $p < .01$, accounting for 22.13% of variance in false hearing (see

Table 9). Both predictors within this model were significant, with a one standard deviation increase in processing speed corresponding to a 6.83% increase in false hearing after controlling for EL intrusions, and a one standard deviation increase in EL intrusions corresponding to a 4.50% increase in false hearing after controlling for processing speed.

Table 9
Multiple regression of significant correlates of false hearing, within older adult group.

	False hearing		
	B	*CI*	*p*
(Intercept)	25.66	21.59 – 29.74	**<.001**
Processing speed	6.83	1.49 – 12.17	**.014**
EL intrusions	4.50	0.52 – 8.48	**.028**
Observations		38	
R^2 / adj. R^2		.263 / .221	

Note. EL = extra-list

Chapter 4: Discussion

Our goal in the present study was to elucidate the relationships between individual cognitive abilities and both veridical and false hearing. In addition, we wanted to investigate whether these relationships differed between younger and older adults. To address these questions, we measured three cognitive abilities that have previously demonstrated relationships with speech perception – working memory capacity, processing speed, and inhibitory control – and examined their relationship to correct identifications and context-based misperceptions in the presence of highly predictive, but misleading, context. Similar to Benichov et al. (2012), we found that cognitive ability does indeed play a role in speech perception. However, this relationship was not observed across all cognitive abilities measured in this study, nor were the relationships between individual cognitive abilities and speech perception consistent across age groups. In the following sections, we summarize our findings and discuss some possible implications.

4.1 SPIN Task

Replicating the findings of Rogers et al. (2012), we found that the presence of a congruent semantic context improved word identification for both younger and older adults, and that the presence of an incongruent context was detrimental to performance for both groups. However, older adults received greater benefit from valid contextual cues than did younger adults, reflected in better performance on congruent trials. When context was misleading, however, older adults were less likely to correctly identify the target word and were more susceptible to false hearing than were younger adults. Older adults were also more confident than younger adults when their responses were supported by context, both for congruent hits and for context-based misperceptions on incongruent trials, and were less confident than younger adults on baseline trials, in which there was no context to support perception. Together, the accuracy and confidence data corroborate the conclusion tendered by Rogers et al. that older adults rely more heavily on contextual cues in speech perception than do younger adults, and remain confident in the accuracy of their perception even when misled by context.

An alternative explanation for age-related increases in context use described in previous studies (Hutchinson, 1989; Nittrouer & Boothroyd, 1990; Sommers & Danielson, 1999; see also Wingfield, Tun, & McCoy, 2005) is that increasing linguistic competency across the lifespan makes us better able to use contextual cues as we age. The idea that context use improves with linguistic experience is supported by the work of Nittrouer and Boothroyd (1990), who found that children (approximately age seven and younger) were less able to use semantic cues to facilitate perception than were adults ages 18 and older.

Although some background knowledge of the subject matter is necessary to be able to make predictions based on semantic context, we argue that increased language experience cannot fully account for the differences in context use between younger and older adults in this study. First, the sentences used in the present study were highly predictive, making it unlikely that younger and older adults differed in their ability to use the contextual cues to facilitate perception; this claim is supported by nearly perfect performance in both age groups when context was congruent with the target word. Second, despite older adults possessing greater vocabulary knowledge than younger adults, as indicated by higher scores on the Shipley Vocabulary Test (see Table 1), we observed no significant correlation between vocabulary knowledge and either incongruent hits or false hearing on the SPIN task, as one might predict if increasing linguistic experience was related to use of contextual cues. Similarly, Benichov et al. (2012) did not find a significant relationship between speech perception and their measure of verbal ability – a composite of the vocabulary subtest from the Wechsler Adult Intelligence Scale

III and the Wechsler Test of Adult Reading – after controlling for hearing acuity and cognitive ability. Finally, comparing the performance of younger and older adults in the incongruent condition of the SPIN task suggests that older adults are not necessarily better than younger adults at using context, but rather that older adults are simply more reliant on contextual cues in speech perception, as was suggested by Rogers et al. (2012). The incongruent sentence condition in this study is an example of an opposition procedure (Jacoby, 1991), in which the cues provided by context work in opposition to those provided by the sensory signal. Whereas using context on congruent trials will lead to improved perceptual accuracy, using context on incongruent trials, in which context is misleading, will reduce perceptual accuracy. Therefore, incongruent trials help us distinguish between automatic and controlled use of contextual cues. If increased language experience makes older adults better at using context, we might expect older adults to demonstrate increased control over context use, reflected in increased use of context when it provides a valid cue for perception, but maintained or improved ability to disengage from context when it provides an invalid cue for perception. What we observed, however, was greater automaticity in context use by older, relative to younger adults, reflected in increased use of contextual cues regardless of their validity, resulting in poor accuracy on incongruent trials and frequent cases of false hearing. Therefore, our findings suggest that context use does not improve with age, per se, but rather support the claim of Rogers et al. (2012) that aging adults become increasingly reliant on contextual cues for speech perception.

Given that older adults' increased reliance on context relative to younger adults transcends sensory modality, as suggested by higher rates of both false hearing (Rogers et al., 2012) and false seeing (Jacoby et al., 2012), Rogers et al. (2012) concluded that this increased contextual reliance must arise from a deficit in cognitive control as opposed to a deficit in sensation. The present study was the first to investigate potential cognitive correlates of older adults' increased reliance on context, specifically, age-related declines in working memory capacity, processing speed, and inhibitory control.

4.2 Effects of Cognitive Abilities

Collapsing across age groups, we found that greater working memory capacity and faster processing speed each increased the likelihood of accurate speech perception in the presence of misleading context. In contrast, more limited working memory capacity, slower processing speed, and poorer inhibitory control, as indicated by greater Stroop interference and more PL intrusions, each were related to increased susceptibility to false hearing. For the most part, these effects remained consistent when dividing the sample into younger and older age groups, although effects were primarily confined to the older adult group: Greater working memory capacity and better inhibitory control, as indicated by fewer EL intrusions, were each related to improved veridical speech perception in older adults, whereas slower processing speeds and poorer inhibitory control, as indicated by more EL intrusions, were each related to increased susceptibility to false hearing, the latter effect appearing in both age groups.

It is unsurprising that group-level effects were confined predominantly to the older adult group. If Rogers et al. (2012) are correct that increased contextual reliance in speech perception arises as a consequence of cognitive deficits, we should expect to observe this relationship more readily in our sample of older adults, who as a group demonstrated poorer and more variable performance on our cognitive tasks than the younger adult group (see Table 1). It is likely that our group of healthy, university-age younger adults was simply too homogeneous in terms of most of the cognitive abilities measured in this study for effects to emerge.

The only cognitive variable for which there were no age differences was the frequency of working memory intrusions, one of our measures of inhibitory control. Greater frequency of EL intrusions (i.e., poorer inhibitory control) corresponded to greater susceptibility to false hearing among both younger and older adults. Additionally, lower frequency of EL intrusions (i.e., better inhibitory control) was related to improved incongruent trial accuracy for older adults. Although inhibitory control was not the best predictor of false hearing as we had hypothesized – processing speed was a better predictor in both the across-group and older adult group analyses – these findings support the role of inhibitory control in false hearing, and suggest that inhibitory control may be primarily responsible for false hearing experienced by younger adults.

Our hypothesis regarding the relationship between inhibitory control and false hearing was based on premises from the revised NAM (Luce & Pisoni, 1998; Sommers, 1996), which proposes that words in the mental lexicon gain activation based on their phonological similarity to the presented word, and that inhibition is used to dampen activation of competitors, thereby facilitating perception of the target word. Similarly, context is thought to improve perception by selectively increasing activation of words that fit within the preceding semantic structure (Sommers & Danielson, 1999). As long as context is predictive of the presented word – which is the case in the vast majority of real-world scenarios – context should facilitate correct perception by increasing the difference in activation between the target word and semantically incongruent competitors. The context provided by incongruent sentences in our study, however, should have had the opposite effect: Rather than lending further activation to the semantically-incongruent target, the highly predictive context supported a competitor, which should decrease the difference in activation between the target word and the competitor, potentially to the extent that the activation of the competitor surpasses that of the target. Additionally, playing target words in noise decreased the amount of information that could be obtained from the auditory signal, meaning that there should be little difference in activation between the target word and similar-sounding competitors in the absence of context, increasing the likelihood that context will determine which word is perceived. This set of conditions should increase the influence of inhibitory control on perception. Better inhibitory control should increase the difference in activation between the target word and contextually-congruent competitors, thus improving the likelihood of correct perception, whereas poor inhibitory control should result in less difference in activation between the target and contextually-congruent competitors, increasing the likelihood of context-based misperceptions.

Although intrusions on the Ospan consistently predicted false hearing, the type of intrusion that predicted false hearing differed in the across-group and within-group analyses. The across-group analyses suggested that PL intrusions were related to false hearing, whereas the within-group analyses suggested that EL intrusions were related to false hearing. The absence of a relationship between PL intrusions and false hearing within each age group is most likely a consequence of insufficient statistical power to detect an effect that was only marginally significant in the across-group analysis. The null effect of EL intrusions in the across-group analyses, on the other hand, appears to be a consequence of differences in the distributions of EL intrusions and the frequency of false hearing between the age groups (see Figure 3). Because older adults experienced false hearing more frequently than did younger adults, collapsing across groups increased the *y*-intercept of the regression line relative to when focusing only on the younger adult group. This, in combination with the weaker relationship between EL intrusions and false hearing among younger, relative to older, adults, and the greater concentration of younger adults at the upper end of the distribution of intrusions, caused the regression line describing the relationship between EL intrusions and false hearing to flatten when collapsing across age groups. Therefore, although there was a relationship between EL intrusions and false hearing for both younger and older adults, differences in the distributions of scores in each age group obscured this relationship when collapsing across groups.

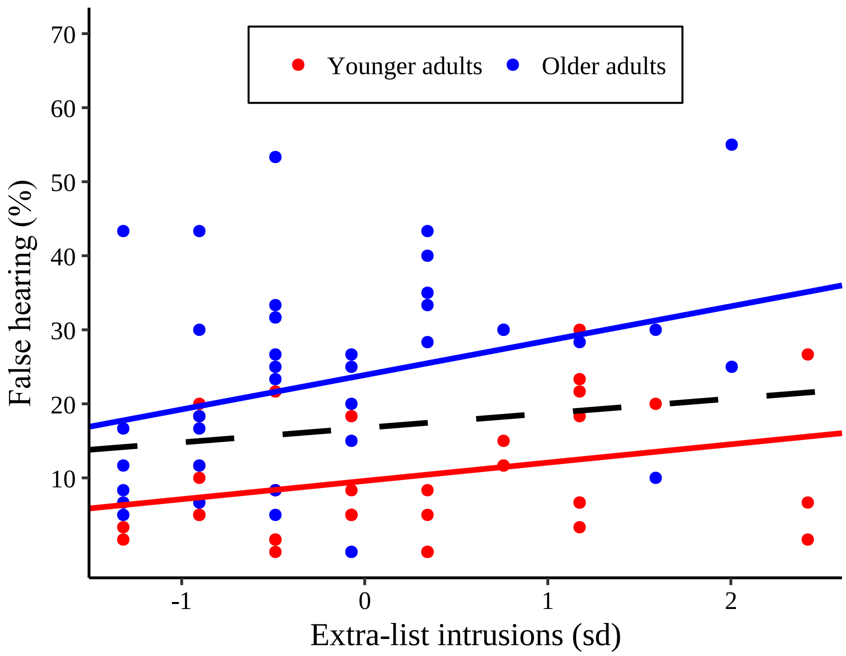

Figure 3. Relationship between false hearing and extra-list (EL) intrusions on the Ospan within and across age groups. The three lines represent three different regression equations: the red line represents the relationship between EL intrusions and false hearing for younger adults, the blue line represents the same relationship for older adults, and the dashed black line represents the same relationship when collapsing across age groups.

Interestingly, although older adults experienced false hearing more frequently than did younger adults, there were no age differences in intrusions – PL or EL – on the Ospan. If we are to argue that both intrusions and false hearing stem from deficits in inhibitory control, these results seem to indicate that older adults experienced a deficit in inhibitory control relative to younger adults in the SPIN task, but not in the Ospan. There is one key difference between the classification of intrusions on the Ospan and false hearing that may help to explain this discrepancy. False hearing was defined as a context-based misperception with maximum confidence. However, no confidence judgements were obtained for words recalled on the Ospan. Therefore, intrusions on the Ospan could represent either a lower-confidence guess or a high-confidence false memory. To examine this possibility, we correlated PL and EL intrusions with both false hearing and context-based misperceptions regardless of confidence (lower-confidence misperceptions) within each age group (see Table 10). We found that EL intrusions were more strongly related to false hearing than lower-confidence misperceptions for older adults, whereas the opposite was true for younger adults, with EL intrusions being more strongly related to lower-confidence misperceptions than to false hearing. These findings suggest that, while younger and older adults may be equally likely to recall an unpresented word on the Ospan, intrusions on the Ospan may reflect different processes depending on age group: predominantly false memory for older adults, and predominantly guessing for younger adults. Thus, comparing age groups based on Ospan intrusions may not be equivalent to comparing age groups based on false hearing. To test the validity of this explanation, future studies should collect confidence ratings for each word recalled in the Ospan, and compare maximum confidence intrusions to false hearing.

Table 10
Correlation of PL and EL intrusions to lower-confidence misperceptions and false hearing, by age group.

	Younger adults		*Older adults*	
	Lower-confidence misperceptions	*False hearing*	*Lower-confidence misperceptions*	*False hearing*
EL intrusions	0.38^{*}	0.30^{+}	0.25	0.33^{*}
PL intrusions	0.12	0.24	-0.01	0.26

$p < .10 = {}^{+}$; $p < .05 = *$; $p < .01 = **$; $p < .001 = ***$

Note. EL = extra-list; PL = past-list

Although a relationship between our other measure of inhibitory control – the Stroop task – and false hearing was found when collapsing across groups (see Table 3), this relationship disappeared in the within-group analyses. The observed relationship between Stroop interference and false hearing when collapsing across groups appears to be a consequence of age differences in Stroop interference, and greater variability in Stroop interference among older adults (see Figure 4). The differences in the distribution of Stroop interference scores between younger and older adults made it appear as though there was a relationship between Stroop interference and false hearing when collapsing across groups, when there was in fact no relationship in either age group. Due to the conflicting findings between the across-group and within-group analyses, we cannot determine whether there is in fact a relationship between Stroop interference and false hearing. Future research should explore this potential relationship in a sample including adults of all ages to examine the effect continuously rather than with discrete age groups.

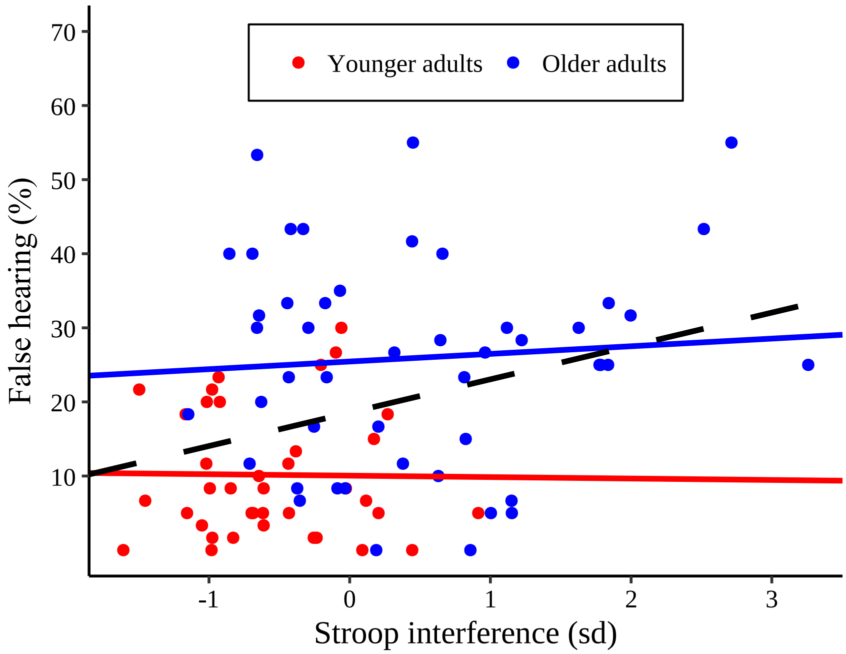

Figure 4. Relationship between false hearing and Stroop interference within and across age groups. The three lines represent three different regression equations: the red line represents the relationship between Stroop interference and false hearing for younger adults, the blue line represents the same relationship for older adults, and the dashed black line represents the same relationship when collapsing across age groups.

We found no significant correlation between Stroop interference and either PL or EL intrusions (see Table 2), which suggests that our measures of inhibitory control may tap different constructs. To discount the possibility that the absence of a relationship between Stroop interference and Ospan intrusions was due to the different bases for intrusions (guessing vs. false memory) between younger and older adults described above, we correlated Stroop interference with both EL and PL intrusions within each age group. There were no significant correlations between Stroop interference and EL or PL intrusions in either age group (see Table 11). Despite being a commonly used test of inhibitory control, inconsistent findings in the literature have led some researchers to question whether the Stroop test is a pure test of inhibition. For example, while some studies report that Stroop tests in different modalities (visual vs. auditory) correlate with one another (Roberts & Hall, 2008), others find no correlation (Shilling, Chetwynd, & Rabbitt, 2002). Additionally, while some studies find a relationship between Stroop interference and speech perception in noise (Janse, 2012; Sommers & Danielson, 1999), other studies do not find this relationship (Gilbert, Tamati, & Pisoni, 2013; Helfer & Freyman, 2014). Knight and Heinrich (2017) measured the correlations between visual and auditory Stroop interference scores calculated using several previously used formulae, and tested their relation to speech perception in noise. They found that the different methods of calculating Stroop interference scores were highly correlated within a given modality, but there were no significant correlations across modalities, suggesting that visual and auditory Stroop tasks may not measure the same construct. Additionally, the relation of Stroop interference to speech perception in noise differed based on a variety of methodological factors, such as the nature of the stimuli to be perceived (single words vs. sentences), the contextual constraint of sentence stimuli, the SNR, and the formula used to derive the Stroop interference score. These findings suggest that Stroop interference effects are largely dependent on the nature of the task, and led Knight and Heinrich (2017) to conclude that the Stroop test may not be a reliable measure of inhibitory control. This could explain why we found no relationship between the Stroop test and intrusions on the Ospan.

Table 11
Correlation of PL and EL intrusions to Stroop interference, by age group.

	Younger adults		Older adults	
	EL intrusions	*PL intrusions*	*EL intrusions*	*PL intrusions*
Stroop	0.13	0.06	0.21	0.01

$p < .10 = ^{+}$; $p < .05 = *$; $p < .01 = **$; $p < .001 = ***$

Note. EL = extra-list; PL = past-list

Although inhibitory control, as measured by frequency of EL intrusions, was the only consistent predictor of false hearing across age groups, and was the best predictor of false hearing among younger adults, it was not the best predictor of false hearing when collapsing across age groups or within the older adult group, as we had predicted. Slowed processing speed emerged as the strongest predictor of false hearing in these samples, and remained a significant predictor of false hearing after controlling for differences in inhibitory control. Slowed processing speed was also the best predictor of incongruent hits when collapsing across groups, although this relationship disappeared when dividing the sample by age group. Above, we expanded upon the factory-worker analogy put forth by Wingfield et al. (1999) to describe how slowed processing may contribute to false hearing. Just as a slow factory worker may miss a piece on the conveyer belt while busy assembling the pieces in their hands, slow information processors may not finish processing words earlier in the sentence by the time the target word is presented, causing them to either completely miss the target word, or to devote insufficient resources to processing it. In this hypothetical scenario, the clever factory worker is able to figure out what piece they missed by inspecting the assembled pieces in their hand. Similarly, slow information processors may infer the missed target word using the semantic context provided by the preceding sentence, which would account for the increased rates of false hearing observed among slower, relative to faster, information processors.

As stated in our hypotheses, we believed that the effect of processing speed would be small in our study because sentences were short and spoken at a normal rate. What we observed, however, was a moderate-to-strong relationship between processing speed and our speech perception outcomes. When collapsing across age groups, processing speed demonstrated the strongest correlation with both incongruent hits ($r = -.32$) and false hearing ($r = .50$) of any cognitive ability measured in this study, and was also the best predictor of false hearing among older adults (r = .37). Additionally, the observed relationships between processing speed and veridical and false hearing remained significant even when controlling for all other significant and marginally significant correlates. Thus, our results suggest that processing speed may play an important role in both veridical and false hearing in the presence of misleading context. We suggest that future studies manipulate sentence length and speaking rate to see if these relationships becomes even stronger as processing demands increase.

The final notable correlation observed in our study was between working memory capacity and incongruent hits. Greater working memory capacity corresponded to improved accuracy on incongruent trials both when collapsing across age groups and when constraining the sample to only older adults. This effect is in line with the work of Christianson et al. (2006), who suggested that greater working memory capacity facilitates the ability to reinstate and re-analyze ambiguous sentences, improving sentence comprehension. In the context of the present study, it could be the case that greater working memory capacity helped older adults discount initial, context-based predictions by allowing them to accurately reinstate both the sentence context and the target word, giving them a second opportunity to achieve correct perception. A second possibility is that greater working memory capacity could increase the likelihood of correctly perceiving the target word the first time, with no need for re-analysis. Above, we reviewed Rabbitt’s (1968) effortfulness hypothesis, which states that more working memory resources are consumed by processing that requires more effort, such as processing speech stimuli that are degraded due to background noise (Rabbitt, 1968; Souza & Arehart, 2015) or hearing loss (McCoy et al., 2005; Rabbitt, 1991). Therefore, it is possible that individuals with low working memory capacity had insufficient resources to fully process the target word in noise, producing a lower fidelity representation of the target word, and resulting in lower accuracy in incongruent sentences relative to individuals with greater working memory capacity. This effect might be exacerbated in older adults, whose hearing acuity was, on average, poorer than that of younger adults (see Table 1). Like presenting speech in noise, hearing loss distorts the auditory signal. Therefore, older adults may be required to exert greater effort, and by consequence expend more working memory resources, to accurately perceive both the sentence contexts and the target words in the SPIN task. This increase in processing effort would account for the stronger relationship between working memory capacity and incongruent hits in older, relative to younger, adults.

4.3 Revised Explanation of Age-Related Changes in Context Use

Rogers et al. (2012) suggested that older adults' increased reliance on context results from deficits in cognitive control. Our finding of a negative relationship between inhibitory control, as measured by intrusions on the Ospan, and false hearing is consistent with this interpretation. However, the additional relationships we observed between working memory capacity, processing speed, and our speech perception outcomes suggests that deficits in inhibitory control are only partially responsible for older adults' increased reliance on contextual cues in speech perception.

We suggest that there are, in fact, two separate factors that result in older adults' increased reliance on context. The first factor, as proposed by Rogers et al. (2012), is an age-related decline in inhibitory control, which decreases the ability to disengage from highly prepotent responses (Hasher, Quig, & May, 1997). The second factor is a change in the relative weights provided to sensory and contextual information for determining the outcome of perception, wherein the weight afforded to contextual cues is increased relative to that of the sensory signal in older adults. We argue that this reweighting occurs to compensate for declining hearing acuity and cognitive ability. Age-related hearing loss increases the cognitive effort necessary for accurate perception (McCoy et al., 2005; Rabbitt, 1968; Rabbitt, 1991), and this effort becomes less manageable due to age-related declines in working memory capacity (see Craik & Byrd, 1982; Wingfield, Stine, Lahar, & Aberdeen, 1988) and processing speed (Wingfield, Tun, Koh, & Rosen, 1999; Wingfield, Tun, & Rosen, 1995).

Increasing the weight afforded to contextual cues alleviates some of the cognitive effort necessary for correct perception, but also increases the likelihood of false hearing in cases where context is misleading. Within the NAM framework, increasing the weight afforded to contextual cues relative to the auditory signal in speech perception would correspond to an increase in the amount of activation allotted to words in the mental lexicon based on semantic consistency relative to the amount of activation allotted based on phonetic similarity to the auditory signal. In cases where context is misleading, allotting extra activation to contextually congruent words would increase the likelihood of false hearing by increasing the activation of contextually congruent competitors relative to the contextually incongruent target word. This effect is exacerbated by age-related declines in inhibitory control. Within the NAM, inhibitory control serves to reduce the activation of competitors in order to increase the likelihood of perceiving the target word (Sommers, 1996; Sommers & Danielson, 1999). Thus, age-related declines in inhibitory control make it harder to counteract the increased activation allotted to contextually congruent competitors, further increasing the likelihood that false hearing will occur when context is misleading.

This reweighting hypothesis is supported by unpublished work from our lab, which showed that older adults' word identification accuracy was unaffected by an 8 dB change in SNR in the presence of congruent context, whereas younger adults' accuracy increased monotonically as SNR became more favorable. This finding suggests that, contrary to the clear importance of stimulus audibility to word-in-noise identification for younger adults, audibility plays a more limited role in speech perception for older adults when contextual cues are present.

4.4 Limitations and Future Directions

It is important to recognize that this study was purely correlational. The goal of this study was simply to identify potential relationships between individual cognitive abilities and speech perception when faced with misleading context. We recommend that future studies test the relationships observed in this study experimentally. To experimentally test the relationship between working memory capacity and veridical speech perception, future research could manipulate the length of sentences or add a secondary task that must be accomplished while simultaneously completing the SPIN task. The relationship between processing speed and false hearing could be tested by manipulating the presentation rate of sentences in the SPIN task, as was done by Wingfield and colleagues (1995; 1999). Finally, the relationship between inhibitory control and false hearing could be tested by manipulating characteristics of the target words in the SPIN task. Sommers (1996) argued that inhibition is especially important for perception of lexically difficult words (i.e., words that have many high frequency phonological neighbors). Therefore, choosing target words differing in lexical difficulty would permit assessment of the effect of inhibition on false hearing: increasing lexical difficulty should correspond to increasing susceptibility to false hearing.

A second important limitation of the present study was that the roles of individual cognitive abilities in speech perception could only be assessed in the presence of misleading context. This was due to near-ceiling performance in the congruent condition, and our use of the baseline condition to ensure that audibility was equated between age groups. Including contexts of varying strength should increase variability in performance on congruent sentences, permitting assessment of the roles of cognitive abilities in speech perception with valid contextual cues. Also, because we controlled for audibility by manipulating the SNR, we could not assess how hearing acuity and cognitive ability interact to influence speech perception. The reweighting hypothesis proposed above includes the effects of hearing loss, cognitive decline, and the interaction between the two; therefore, future studies should either keep SNR consistent across all participants or include multiple SNRs in each experimental session to assess the concurrent roles of hearing acuity and cognitive ability in speech perception.

The final limitation of our study that we will discuss here stems from our use of an extreme-groups design (i.e., including younger and older adults in our study, but no adults whose ages fell between the two extremes). Because extreme-groups designs are known to inflate effect sizes (Preacher, Rucker, MacCallum, & Nicewander, 2005), we included analyses within each age group to determine whether the relationships observed in the full sample would remain when constraining the sample to either younger or older adults. Although the convergence of findings between the across-group analyses and those within the older adult group increased our confidence in the observed relationships, future studies should include adults of all ages to assess these effects continuously across the lifespan. Better yet, participants should be tested longitudinally to see how changes in hearing and cognitive ability affect speech perception across the lifespan. This would be the best test of our proposed reweighting hypothesis, as we could see how changes in hearing acuity and cognitive ability interact, and how they relate to context use at the level of the individual, rather than at the group level.

4.5 Conclusions

Contextual cues provide useful information that aids speech perception for both younger and older adults. Context is rarely misleading outside of the laboratory, making context-based inference an effective strategy to compensate for age-related hearing loss and cognitive decline. The results of the present study, however, show that older adults fail to use context judiciously, relying on contextual cues even when they are consistently misleading, which resulted in frequent context-based misperceptions. Additionally, replicating the findings of Rogers et al. (2012), we found that older adults often exhibited absolute confidence in these misperceptions, which we referred to as false hearing. Like Rogers et al., we believe that failures of inhibitory control are primarily responsible for false hearing, as this relationship emerged in both younger and older adults. However, we observed that deficits in other cognitive abilities, specifically working memory capacity and processing speed, also play a role in older adults' increased reliance on context. We suggest that the increased effort required to process speech due to age-related hearing loss and cognitive decline motivates a reweighting of perceptual cues, wherein the influence of context over perception increases relative to that of the sensory signal, to alleviate cognitive effort.

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