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Age-Related Changes in Listening Effort for Various Types of Masker Noises

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ABSTRACT

It is well established that older listeners have more difficulty understanding speech in background noise than younger listeners (e.g. Dubno et. al., 1984). Some have attributed this increased difficulty to peripheral hearing loss, while others suggest that older listeners may perceive listening in noise as difficult and effortful because it requires them to exert more cognitive resources (Desjardins et. al., 2009). The purpose of the present study was to directly evaluate the relationship between cognitive function, listening effort and speech recognition for a group of younger and older normal hearing adults, and a group of older adults with hearing impairment, in various types of background noise.

A dual-task paradigm was used to objectively evaluate listening effort. The primary task required participants to repeat sentences presented in three different background noise masker conditions (e.g. Two-Talker (TT), Six-Talker (SIX), Speech-Shaped Noise (SSN)). The secondary task was a digital visual pursuit rotor tracking test (DPRT), for which participants were instructed to use a computer mouse to track a moving target around an ellipse that was displayed on a computer screen. Each task was presented separately and concurrently at a fixed speech recognition performance level of 76% correct. In addition, participants' subjectively rated how easy it was to listen to the sentences in each masker condition on a scale from 0 (e.g. very difficult) to 100 (e.g. very easy). Last, participants completed a battery of cognitive tests which measured working memory (Reading Span test), processing speed (DSST) and selective attention (Stroop test) ability.

Results revealed that participants' working memory and processing speed ability were significantly related to their speech recognition performance in noise in all three background noise masker conditions. Both groups of older participants expended significantly more listening effort than younger participants in the SSN and TT masker conditions. For each group of participants, there were no significant differences in listening effort measured across the masker conditions, with the exception of the younger participants who expended more effort listening in the SIX masker condition compared to the SSN condition. All participants' listening effort expended on the TT and SSN masker conditions was significantly correlated with their working memory and processing speed performance. Participants' subjective ratings of listening effort did not correlate with their objective measures of listening effort on any of the listening conditions. Findings from the present study indicate that older adults, independent of peripheral hearing loss, require more cognitive resources than younger adults to understand speech in background noise.

AGE-RELATED CHANGES IN LISTENING EFFORT FOR VARIOUS TYPES OF MASKER NOISES

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To my wonderful husband Jeff and two beautiful daughters Hannah and Rebekah, thank you for all your love and support. I am truly grateful and blessed to have you in my life.

LITERATURE REVIEW

Sensorineural hearing loss is the third most prevalent chronic condition affecting seniors in the United States. Specifically, 1 in 3 adults over the age of 60 years, and approximately 1 in 2 adults over the age of 75 years have a significant hearing loss (NIH, 2009). Presbycusis, sensorineural hearing loss due to aging, has been linked to degenerative changes in the peripheral auditory nervous system and is associated with speech understanding difficulties among older individuals (CHABA, 1988). However, many older participants have poorer speech understanding than would be expected based on their audiometric thresholds, especially in background noise (Dubno & Ahlstrom, 1997). In fact, older participants with and without hearing impairment have little difficulty understanding speech in quiet listening conditions, but often have considerable difficulty understanding speech in noisy listening conditions. This difficulty increases when the background noise is speech (Plomp, 1978; Kochkin, 2000). For example, Desjardins and Doherty (2008) examined speech understanding in noise in older and younger participants with normal hearing. They reported that older participants with normal hearing use the same listening strategy in quiet, but different listening strategies when processing fast speech in noise compared to younger participants. Listening in noise has also been reported to be more effortful and tiresome for older adults with normal or near normal hearing thresholds even when they are able to understand what is being said (CHABA, 1988).

Speech communication is a complex process that involves both peripheral and cognitive functions. For example, a participant must have an intact or aided peripheral auditory system for sound to be audible. Then, the participant must have the cognitive function to be able to selectively attend to the sound source, store the information in memory, use context cues to resolve ambiguities, and generate responses quickly. Any kind of distortion or limitation of an incoming speech stimulus, such as background noise, makes processing speech more cognitively demanding (Gordon-Salant & Fitzgibbons, 1997; Wingfield, 2000). Numerous studies have reported that three aspects of cognitive function; working memory, processing speed, and selective attention, are necessary for effective speech-communication in noise (e.g. Akeroyd, 2008; Humes and Coughlin, 2006; Pichora-Fuller, Schneider, and Daneman, 1995). Unfortunately, these aspects of cognitive function have been shown to decline with increasing age (Park, 1999; Salthouse, 1985). Thus, listening in noise may be more difficult and effortful for older participants because they must exert more cognitive resources in order to maintain listening performance comparable to younger normal-hearing participants (Desjardins, et. al. 2008; Downs, 1982; Rabbitt, 1968).

Desjardins et. al. (2009) examined cortical activity on a speech understanding task in younger and older participants with normal hearing using functional magnetic resonance imaging (fMRI). Results revealed greater fMRI neural activity in the inferior and mid frontal cortices, bilaterally, in older normal-hearing participants compared to younger participants regardless of the fact that the two groups obtained similar speech recognition scores on the listening task. Interestingly, the older participant who obtained the lowest behavioral performance score did not recruit these additional neural regions. It was concluded that these findings are consistent with the theory of compensatory neural recruitment. That is, the differences in neural activity observed between younger and older participants with similar speech recognition scores may reflect increased cognitive compensatory effort by older participants in order to maintain behavioral performance levels similar to younger participants. This suggests that the observed age-related changes in listening effort may be due to age-related changes in cognitive processing.

The increase in cognitive load required for listening in background noise may come at the cost of using cognitive processing resources that could have been available for other tasks (Tun, O'Kane & Wingfield, 2002). This can be problematic, because in everyday situations, older participants are expected to communicate in noisy listening conditions (CHABA, 1988), while performing other tasks. For example, an older adult's ability to drive a car or walk on uneven ground may become impaired while they are responding to conversational inquires in the presence of a background noise (Li, Lindenberger, Freund & Baltes, 2001; Strayer & Johnson, 2001).

Speech Recognition in the Presence of Background Noise

Speech is seldom transmitted in a completely quiet environment. In fact, most listening situations have some level of background noise that can distort a speech signal by making the less intense portions of the stimulus inaudible (Houtgast & Steeneken, 1973). Although young normal-hearing adults can tolerate moderate amounts of noise with only minimal degradation of their speech recognition abilities (Olsen, Noffsinger & Kurdziel, 1975), older individuals with and without sensorineural hearing loss are more susceptible to these distortions (Humes, Dirks, Bell, Ahlstrom, & Kincaid, 1987).

To date, a considerable research base has emerged examining the factors that contribute to the speech recognition in noise problems that are experienced by older people (e.g. Dubno, Dirks, & Morgan, 1984; Frisina & Frisina, 1997; Humes & Roberts, 1990; Souza & Turner, 1994). A number of these studies have concluded that the main factor is deterioration of the peripheral auditory system (e.g. elevated thresholds) which can degrade the speech signal available for cognitive processing (e.g. Humes & Roberts, 1990; Souza & Turner, 1994; Van Rooij & Plomp, 1992). For example, Humes and Roberts (1990) examined monaural and binaural speech identification of young normal-hearing participants (YNH), elderly hearing impaired participants (EHI), and young participants with simulated hearing loss using a noise masker (YHI). The participants were presented nonsense syllables in background noise with and without reverberation. Results revealed that the EHI and YHI participants performed similarly on the speech identification tasks, but the YNH participants' performed better than both the hearing impaired groups. There was a significant correlation between the elderly participants' average pure-tone threshold levels and their speech identification scores. Thus, these results suggest that the speech understanding difficulties of older participants in noise is, at least partially, attributed to peripheral hearing impairment.

Souza and Turner (1994) reported similar findings in their study of the effects of spectrum noise, a modulated speech spectrum noise, and a 12 multi-talker babble masker on the recognition of monosyllabic words for 10 younger normal-hearing participants (20-40 years of age) and 10 younger (22-35 years of age) and 10 older (64-77 years of age) participants with mild to moderate sensorineural hearing loss. They found that the older and younger participants with hearing impairment performed similarly, but more poorly than the young normal-hearing participants, on all the background noise conditions. They concluded that sensorineural hearing loss, not age, accounted for the older participants' performance on the speech recognition in noise tasks.

However, others contend that pure-tone thresholds alone cannot account for the variance in speech understanding in noise among older participants (Dubno, Dirks, & Morgan, 1984; Frisina & Frisina, 1997). They suggest that the speech understanding difficulties of older participants in background noise are due to age-related changes in cognitive processing, or to a combination of age-related changes in cognitive processing and a decline in peripheral auditory function. For instance, Dubno, et. al. (1984) examined age-related speech recognition performance in quiet and background noise in a group of older and younger participants with normal hearing and a group of older and younger participants with matched mild sensorineural hearing loss. They used an adaptive procedure to measure the signal-to-noise ratio (SNR) needed to achieve 50% recognition for spondaic words, and sentences from the Revised Speech Perception in Noise Test (R-SPIN) (Bilger, Neutzel, Rabinowitz & Rzeckzkowski, 1984). They presented the speech stimuli at soft to loud conversational speech levels. Results revealed that all participants with hearing loss performed significantly poorer than their normal hearing counterparts in all listening conditions. Also, the normal hearing and hearing impaired older participants in the study performed significantly poorer than their younger counterparts in the noise conditions despite equivalent performance in quiet. These results suggest that both age and peripheral auditory function contribute to a participant's ability to understand speech in background noise.

Consistent with these results, Frisina and Frisina (1997) reported that older participants with and without hearing impairment performed differently than younger normal-hearing participants on a sentence in multi-talker noise recognition task. They concluded that both peripheral and central auditory function contribute to the speech understanding difficulties of older participants. Further support for these findings comes from the Gordon-Salant and Fitzgibbons (1997) study that examined age-related performance on a low context R-SPIN sentence recognition task. They tested a group of older and younger participants with normal hearing and a group of older and younger participants with matched sensorineural hearing loss. They found that older participants' performed poorer on the sentence recall tasks, independent of peripheral hearing impairment, compared to the younger participants. These results suggest that age, not peripheral hearing loss, accounted for the older participants' lower scores on the sentence recognition in noise task.

Thus, while it is widely accepted that speech understanding in noise is more difficult for older participants compared to younger participants, there is less of a consensus as to *why* older participants have more difficulty understanding speech in background noise. In other words, is it more of a cognitive aging effect, a peripheral hearing limitation, or a combination of both? We hypothesize that the answer to this question may depend on the *type* of background noise that is interfering with the target speech signal.

Certain types of background noises may be more likely to reveal differences in speech recognition as a function of age. Specifically, it is more difficult for older participants to understand speech in a background noise of competing talkers than in a Gaussian noise (e.g. "white noise") (Helfer & Freyman, 2008). It is likely that older adults have more difficulty understanding speech in *this type* of noise because while all types of background noise produce interference at the auditory periphery, known as energetic masking, meaningful sound sources, such as competing talkers, can interfere with the processing of the target speech signal at both the auditory peripheral level, due to energetic masking effects, and at the cognitive level due to informational masking effects (e.g. Arbogast, Mason, and Kidd, 2005; Brungart, Simpson, Ericson and Scott, 2001; Brungart, 2001; Carhart, Tillman and Greetis, 1969; Oh and Lufti, 1998; Freyman, Helfer, McCall and Clifton, 1999; Freyman, Balakrishnan, and Helfer, 2004; Helfer and Freyman, 2008). Because older individuals are more likely to have age-related declines in cognitive function, they may be more susceptible to the effects of informational masking compared to younger participants.

Informational Maskers

In theory, because speech fluctuates over time in spectral composition and amplitude, a masker consisting of competing talkers should produce less masking of a target signal than a steady state noise (e.g. air conditioner) (Feston & Plomp, 1990). Specifically, speech contains pauses in the signal and silence during the beginning of stop consonants, as well as very weak consonants such as /f/ and /th/ all which will reduce energetic masking. In addition, the spectrum of the competing speech masker fluctuates independently from the spectrum of the target speech such that a low energy high-frequency /s/ sound in the interfering speech may be present simultaneously with a high energy low frequency vowel in the target speech. Thus, these spectral and amplitude fluctuations in the speech masker seemingly provide the participant with brief, but numerous, moments of clarity of the target speech signal. Although speech maskers have spectral and temporal fluctuations that can reduce energetic masking, they have been shown to be more detrimental to a participant's speech understanding than steady state interference (e.g. Arbogast, Mason, and Kidd, 2005; Brungart, Simpson, Ericson and Scott, 2001; Brungart, 2001; Carhart, Tillman and Greetis, 1969; Oh and Lufti, 1998;

Freyman, Helfer, McCall and Clifton, 1999; Freyman, Balakrishnan, and Helfer, 2004; Helfer and Freyman, 2008).

Carhart, Tillman, and Greetis (1969) examined speech intelligibility in young normal hearing adults using a speech masker, and non-meaningful modulated noises. Results revealed that the speech masker produced more masking than the modulated noise masker. They concluded that the excess masking caused by the speech masker was due to the participants' difficulty extracting the target speech from the complex masker of voices. They used the term "perceptual masking" to describe this phenomena, which is typically now referred to as informational masking.

Informational masking of a target speech signal is more likely to occur when the target and masker are similar to one another. For example, there should be more informational masking when both the target talker and the masker talker are of the same gender (e.g. they are both female voices). This is primarily because the amount of informational masking increases when there is confusion about which of two or more talkers is actually the "target". Brungart (2001) measured the speech intelligibility of young normal-hearing participants using target phrases masked by a single competing masker phrase that was either the same-talker, same-sex of the talker, or different-sex of the talker. The results revealed that the amount of informational masking increased as the target and masker voices became more similar. In a follow up study, Brungart, Simpson, Ericson, and Scott (2001) examined young normal hearing participants' ability to understand a target phrase masked by a 3-talker or 4-talker masker phrase with the same-talker, same-sex talker, and different-sex target and masker talkers. Consistent with the previous results, the target phrase was least intelligible when the target and masker phrases were spoken by the same talker. The authors concluded that auditory factors such as, the vocal characteristics of the target and masker talkers, play an important role in the segregation of speech signals in multi-talker environments.

In addition to the vocal similarity between target and masker talkers, the number of talkers in a speech masker has also been shown to affect the amount of informational masking. Freyman, Balakrishnan, and Helfer (2004) investigated the number of talkers that produce maximum informational masking in young normal-hearing participants' recognition of nonsense sentences. Participants were presented nonsense sentences, spoken by a female talker, in the presence of 1, 2, 4, 6, and 10 female talkers reciting similar nonsense sentences. Results revealed that the two-talker masker was the most effective masker. The authors contend that a two-talker masker caused more competition for attention of the target speech signal than the one talker masker. However, as the number of talkers in the masker increased beyond two, the masker became more like general babble, and the similarity of the masker and target decreased, thus decreasing the amount of informational masking. This result is consistent with several other studies which reported that two-talker maskers produced the greatest amount of informational masking compared to one and three-talker maskers, respectively (e.g. Brungart et. al., 2001; Freyman et. al., 1999; 2001; Hall et. al., 2002).

Informational Masking and Hearing Loss

Informational masking effects have been shown to differ among normal hearing and hearing impaired participants (Arbogast, Mason, and Kidd, 2005; Hornsby, Ricketts and Johnson, 2006). Specifically, informational masking has *less* of a negative effect on hearing impaired participants than age-matched normal-hearing participants. Arbogast, Mason, and Kidd (2005) investigated informational and energetic maskers in age matched normal-hearing and hearing impaired participants between the ages of 21 to 79 years on a closed-set sentence recognition task. Results revealed that masking effects were greatest for all participants with the informational masker compared to the energetic masker, but that informational masking was less for the group of hearing impaired participants. The authors stated that the results could have been partially attributed to the differences in masker sensation level (SL) between the normal hearing and hearing impaired participants. Specifically, the hearing impaired group of participants was, on average, tested at a lower SL than the normal hearing group of participants.

Alexander and Lutfi (2004) examined informational and energetic masking effects using non speech stimuli in normal hearing and hearing impaired participants. Participants' thresholds for a 2000 Hz pure-tone were measured in the presence of a masker designed to produce varying amounts of informational masking. Results revealed that informational masking decreased when the 2000 Hz tone was presented at lower sensation levels. When tested at equal SLs, informational masking had a similar effect on participants with normal hearing and participants with hearing impairment. However, in many studies the speech signals are presented at fixed overall intensity levels. As a result, the SL is typically lower for the hearing impaired participants, which may decrease the amount of informational masking.

Informational Masking and Age

In listening environments containing multiple talkers, age-related changes may be caused by increased sensitivity to energetic masking, increased susceptibility to informational masking (e.g. confusion between the target voice and masking voices) and/or cognitive deficits. To better understand the contributions of these factors, Li, Daneman, Qi, and Schneider (2004) examined energetic and informational masking in younger (19-22 years old) and older (63 to 75 years old) adults with normal hearing. They measured participants' ability to understand nonsense sentences spoken by a female talker in the presence of a female two-talker masker of nonsense sentences and a speech shaped noise. Results revealed that speech recognition performance was poorer for all participants in the two-talker masker than the speech shaped noise condition. Equivalent amounts of informational masking effects were observed in both the younger and older groups. Thus, they concluded that cognitive interference from a two-talker informational masker was the same for both younger and older adults.

Recently, Agus, Akeroyd, Gatehouse, and Warden (2009) measured the effects of age on informational masking of speech in 8 young normal-hearing participants and 20 older (51-80 years of age) participants with pure-tone thresholds varying from normal hearing to a moderate high frequency hearing loss. Participants' speech recognition for sentences spoken by a male talker was measured in the presence of sentences spoken by the same male talker and a white noise. Results revealed equal amounts of informational masking for both older and younger participants, but smaller informational masking effects for the older participants with poorer audiometric thresholds. The authors concluded that younger and older participants are equally susceptible to informational masking.

Helfer and Freyman (2008) examined informational masking effects in a group of 12 younger normal hearing participants (mean age 22.67 years) and 12 older participants (61-81 years old) with pure tone thresholds varying from normal hearing to a moderate high frequency hearing loss. Participants' speech recognition was measured using topic based sentences spoken by a female talker in the presence of a female two-talker masker, a male two-talker masker, and a speech shaped noise. Results revealed that older participants' speech recognition performance was significantly poorer in all three masker conditions, with the largest difference in the male two-talker condition compared to the younger participants. The authors suggest that the older participants' poorer performance may be due, at least partially, to age-related changes in cognitive function.

Tillman, Carhart, and Nicholls (1973) studied the effect of age on informational masking in 10 normal hearing younger participants and 45 older participants (age 63-85 years) with normal or near normal (i.e. spondee thresholds $\leq$ 30 dB HL in the poorer ear) hearing thresholds. Participants' speech recognition for spondee words spoken by a male talker was measured in the presence of sentences spoken by a male talker (e.g. informational masker), and a modulated white noise (e.g. energetic masker). They found that all participants' speech recognition performance was poorer in the presence of the informational masker than the energetic masker. However, the older participants' performance was poorer for the informational masking condition compared to the younger participants. Thus, the authors concluded that older participants were more susceptible to informational masking of speech than younger participants. Results from this study suggest that older participants are able to preserve their speech recognition performance in simple background noise (e.g. white noise) listening conditions, but as the listening situation becomes more complex (e.g. cognitively demanding) older participants perform poorer than younger participants.

One limitation in the studies discussed above is that only overall percent correct scores on speech recognition tasks were reported. Unfortunately this type of assessment provides only a general measure of the differences in participants' speech perception abilities, offering little insight into the underlying mechanisms that may contribute to differences in participants' performance scores. For example, it has been previously shown that participants' can obtain the same overall speech recognition scores but use different listening strategies from each other to perform the same listening task (Doherty & Lutfi, 1996). Furthermore, some masking studies discussed above did not carefully control for differences in hearing threshold levels and none of the studies directly assessed any aspect of the participants' cognitive function, which is believed to play a strong role in informational masking.

Cognition and Speech Perception in Older Adults

Speech understanding is a complex process that involves not only the perception and identification of individual speech sounds and words, but also the integration of successively heard words, phrases, and sentences in order for a participant to arrive at a coherent and accurate representation of the message communicated. Thus, it is highly likely that age-related changes in cognitive function could affect the speech understanding of older adults in background noise. In fact, some specific cognitive abilities have been shown to be inherently involved in the processing of speech (Wingfield, 2000), which have also been shown to decline with age (Park, 1999; Salthouse, 1985). Specifically, the cognitive processes of working memory, perceptual processing speed, and selective attention have all been shown to contribute to participants' speech understanding performance (Akeroyd, 2008; Cleary, Pisoni & Geers, 2001; Larsby, Hallgren, Lyxell, 2008; Pichora-Fuller, Schneider, Daneman, 1995; Salthouse, 1985). Unfortunately, these three cognitive skills have also been shown to deteriorate with age (e.g. Li et al, 2001; Salthouse, 1996; Wingfield & Tun, 2001).

Thus, in the current study we will examine how these three aspects of cognitive function (i.e. working memory, processing speed, and selective attention) affect speech understanding in noise for a group of older and younger participants. Although, all of these cognitive functions are needed for processing speech in any noise (e.g. energetic or informational), they are likely to play a greater role when listening in background noises that have more informational masking.

Working Memory

Working memory is a system for the temporary storage, management, and manipulation of information required for carrying out complex cognitive tasks such as language comprehension (Baddeley & Hitch, 1974). For example, working memory is used in language comprehension to retain earlier parts of a spoken message until they can be integrated with the later parts. Thus, working memory is needed to hold new information that has been given to us, but also to integrate it with the old information (Salthouse, 1985). Models of working memory assume that when the capacity limits of working memory are exceeded due to processing demands, either comprehension will become slowed or errors will occur. Thus, when older adults hear short sentences with reasonably simple syntax, their comprehension of the speech content is quite good. However, as the length and complexity of sentences increase, older adults have significantly more difficulty comprehending sentences than younger adults (Gordon-

Salant & Fitzgibbons, 1997; Wingfield, 2000). That is, added memory demands have a detrimental effect on elderly participants' sentence recall abilities.

When an incoming speech stimulus is distorted or limited, such as from a background noise, speech processing becomes more cognitively demanding. Thus, listening to speech in background noise could have a detrimental effect on a participant's working memory performance. Pichora-Fuller, Schneider, and Daneman (1995) examined the contribution of working memory on speech understanding in noise for 16 younger (19-23) and 16 older (64-77) participants with normal hearing. Participants were presented R-SPIN sentences in quiet and in 12-talker babble noise at multiple SNRs. They were asked to repeat the final word in the sentence, as well as maintain a number of final words in memory so that they could be recalled at the end of a fixed number of sentences. In half of the sentences, the final word was predictable from the context of the sentence (high context), and in half of the sentences the final word was unpredictable (low context). Results revealed that both younger and older participants recalled fewer final words in noise, but the older participants recalled even fewer final words than younger participants. Older participants derived more benefit from context cues to understand the signal in noise than younger participants, as evidenced by differences between psychometric functions for high and low context sentences. The authors concluded that the results from this study suggest that older participants require additional processing resources when listening becomes difficult (e.g. due to noise).

Consistent with these results, Murphy, Craik, Li and Schneider (2000) examined the effects of aging and background noise (e.g. 12 talker babble noise) on working memory performance in younger participants with normal hearing and older participants with a moderate high frequency hearing loss on a paired associate recall task. They found that the performance of older adults in *quiet* was nearly equivalent to that of the younger adults' performance in *noise*. They concluded that both aging and noise impair encoding in memory. Unfortunately, because the authors did not control for differences in hearing threshold between the younger and older groups of participants, it remains unclear whether working memory performance was impaired by a degraded sensory representation (e.g. high-frequency hearing loss), or as a function of reduced cognitive processing resources.

Working memory performance can be assessed by a variety of tasks including span tests, and object re-ordering tasks. However, age-effects in working memory performance have been shown to be most prominent on complex working memory tasks such as The Reading Span test (Daneman and Carpentar, 1980; Ronnberg, 1989). The Reading Span test is a measure of working memory that taxes the combined processing and storage capacity of working memory. On the Reading Span test, participants are presented with sentences and asked to simultaneously comprehend them and store the final word in the sentence for retrieval after a specified block of sentences are presented. Performance on the Reading Span test has been shown to be significantly correlated with a participant's ability to understand spoken discourse (Akeryod, 2008). In addition, the Reading Span test has been widely used in behavioral cognitive aging (Verhaeghen & Salthouse, 1997) and speech perception (e.g. Lunner et. al., 2007) studies. Thus, a digital version of The Reading Span test (Ronnberg, 1989) was used in the current study.

Perceptual Processing Speed

Perceptual processing speed refers to the rate at which necessary cognitive processing operations must be performed for the accurate perception of an incoming signal. Speech comprehension is based on a transient acoustic signal whose rate is largely controlled by the talker, not the participant. In order for a participant to effectively comprehend a message, the incoming auditory input must be analyzed, segmented, and processed for structure and meaning, all while new information continues to arrive. These cognitive processes must occur quickly because conversational speaking rates often exceed 200 words per minute (Miller, Grosjean & Lomanto, 1984).

In general, many studies contend that a slowing of processing speed is the primary reason for age-related decline in cognitive function (Cerella, 1985; Myerson, Ferraro, Hale, & Lima, 1992). Furthermore, it has been hypothesized that overall cognitive performance is degraded when processing is slow because relevant operations cannot be successfully executed and the products of early processing may no longer be available when later processing is complete (Salthouse, 1985). In addition, it is thought that as a task becomes more difficult or complex, requiring an individual to expend more cognitive resources, older adults' speed of processing will be slowed.

Several studies have investigated the relationship between slower speed of information processing and speech recognition (e.g. Gordon-Salant & Fitzgibbons, 1997; 1999; 2001; Wingfield et. al., 1985). Wingfield et. al. (1985) hypothesized than an age-related decline in processing speed would be detrimental to the rapid decoding and construction of meaning required for on-line processing of fluent speech. They conducted several experiments using time-compressed speech. Time compressing speech is an effective method of temporally degrading a speech signal without affecting the pitch and prosody of the original signal. In addition, time-compression reduces the redundancy of acoustic cues in speech and causes the acoustic cues for consonant identification to become more transient (Letowski & Poch 1996). Wingfield et. al. (1985) concluded that time-compression has its effect more from removing normally available processing time than by degrading the speech signal itself. In contrast, Gordon-Salant and Fitzgibbons (2001) suggested that older participants have difficulty in recognizing fast speech due to trouble in processing the brief, limited acoustic cues for consonants inherent in rapid speech. Overall, however, both suggest that there is an age-related decline in the rate of information processing in older participants. In addition, further evidence for age-related slow down in processing comes from several auditory evoked potential (AEP) studies. These studies have shown age-related prolongations in latency measures of cortical evoked potentials (e.g. P300, AMLR, and ALR) (Pfefferbaum, 1980; Goodin, 1978; Vander Werff & Burns, 2009).

While processing speed can be assessed using a variety of tasks, one of the most widely used behavioral instruments is the Digit Symbol Substitution Test (DSST) from the Wechsler Adult Intelligence Scale-III (Wechsler, 1981). Strong correlations have been reported in the literature for performance scores on the DSST and age (Birren, 1965; Salthouse, 1992) and with other measures that involve perceptual speed of processing (Salthouse, 2000; Sliwinski & Buschke, 1999). For example, Hoyer, Stawski, Wasylysshyn, and Verhaeghen (2004) found that in an analysis of effect sizes for age reported in 141 studies, age accounted for 86% of the variance in DSST scores. In addition, the DSST is easy and quick to administer. Thus, we used the DSST in the current study to measure perceptual processing speed.

Selective Attention

Selective attention is an essential component of day-to-day functioning that enables individuals to preferentially process high priority signals at the expense of less task-relevant information. In other words, when an individual selectively attends, they actively filter stimulus information in order to select only relevant information for processing. Selective attention is required when listening to speech in the presence of background noise in order for a participant to attend to the target signal and ignore or suppress the background noise. In fact, the classic example of selective attention is the "cocktail party problem" originally described by Cherry (1953) who wrote, "How do we recognize what one person is saying when others are speaking at the same time (the "cocktail party problem")?

Several studies have shown that the ability to selectively attend to visual or auditory stimuli is impaired by the aging process (e.g., Alain, Ogawa, & Woods, 1996; Allen, Weber, & Madden, 1994; Barr & Giambra, 1990; Karayanidis, Andrews, Ward, & Michie, 1995; Madden, 1990; McCalley, Bouwhuis, & Juola, 1995). It has been hypothesized that this age-related decrease in selective attention is due to a decrease in inhibitory processing with aging (e.g. Hartman & Hasher, 1991; McDowd & Shaw, 2000; Troyer, Leach, & Strauss, 2006). In other words, older adults are not as effective in filtering irrelevant stimuli. For example, it has been shown that older adults have more difficulty in detecting infrequent auditory targets embedded in a sequence of distracters than younger adults (Alain et al., 1996; Karayanidis et al., 1995).

Humes, Lee, and Coughlin (2006) examined auditory attention in 10 young normal-hearing participants (21 to 34 years old) and 13 older hearing impaired participants (61 to 81 years old) on a sentence recognition task where the target sentences were spoken by one talker and a second talker produced a very similar competing sentence. Results revealed that the older participants performed significantly worse than the younger participants on all measures of auditory attention. Interestingly, correlational analysis suggested that the individual differences in attention performance were strongly associated with individual differences in working memory performance on the digit span subtest of the WAIS-III (Wechsler, 1981).

Age-related changes in selective attention are frequently evaluated in the cognitive aging literature using the Stroop test (Stroop, 1935). In fact, the Stroop test (Stroop, 1935) has been one of the most widely used behavioral measures of selective attention for the past 70 years (MacLeod, 1991). The Stroop effect was first described in 1935 by J. Ridley Stroop. In his experiment, Stroop had people read aloud color words (e.g., “red”, “blue”, “green”, etc...) that were presented in different colored fonts (e.g. the word “red” was printed in blue ink). The main finding from his study was that when people had to say the name of the font color, they were faster to respond when the color of the word matched the color of the font, and slower when these mismatched. The slowed responding is considered by many to be evidence of *interference* between cognitive processes. Many studies have shown that Stroop test is sensitive to identifying age related differences in selective attention (see review by McDowd & Shaw, 2000). Thus, the Stroop test was used in the current study to measure selective attention in older and younger adults.

In summary, the interference of background noise on a participant’s ability to understand speech may be related to the degree of cognitive load in the task. That is, listening in unfavorable listening conditions (e.g. noise) may require a participant to use more cognitive resources (e.g. working memory, processing speed, and selective attention) than when listening in quiet. When a participant must expend more cognitive resources in order to understand speech in the presence of a background noise, the listening task will become more effortful.

Listening Effort

Listening effort refers to the cognitive resource requirements necessary for an individual to understand speech (Broadbent, 1958; Downs, 1982; Feuerstein, 1988). Listening to speech in the presence of background noise may require participants to use more cognitive resources because when a signal is noisy, the participant must remove ambiguity and recover the information in the signal that has been degraded by the noise.

The most common behavioral method used for assessing listening effort is a dual-task paradigm (Broadbent, 1958). This method is based on the theory that the brain has a limited capacity to respond to all sensory systems and this capacity is allocated across systems on an as needed basis (Kahneman, 1973). As the cognitive demands for one task increase, so does its share of cognitive resources. This in turn reduces the resources available for an individual to simultaneously perform a second task (Downs & Crum, 1978; Rabbitt, 1968).

The decrease in secondary task performance is interpreted as evidence of increased cognitive effort (Downs & Crum, 1978; Rabbitt, 1968) which is referred to as listening effort when the primary task is an auditory task. Thus, the dual-task method uses two-tasks; a primary task and a secondary task (Rabbitt, 1968). Performance on the primary task is presumed to use the majority of mental capacity and the remaining mental capacity is used to perform the secondary task. When the primary task is made more difficult, less mental capacity remains for completion of the secondary task, which hinders performance on the secondary task. This decrease in secondary task performance is interpreted as increased listening effort (Broadbent, 1958; Downs & Crum, 1978; Rabbitt, 1968).

In a classic experiment of listening effort, Broadbent (1958) used a dual-task paradigm to examine speech discrimination performance under different listening conditions (e.g. quiet and background noise). Young normal-hearing participants were presented speech in background noise at multiple SNRs. Results revealed that participants' speech intelligibility scores remained unchanged across SNR conditions. However, the changes in SNR resulted in changes in performance on a concurrent measure of effort, a high speed tracking task. He concluded that speech intelligibility scores across conditions were obtained at the expense of unequal amounts of effort exerted by the participant. Thus, when the listening condition was more difficult, the participant exerted more effort to maintain their speech intelligibility performance. Broadbent concluded that the results from this experiment stress the importance of using multiple measures to assess speech understanding. In other words, assessing participants' speech understanding solely using speech intelligibility scores may be misleading.

Rabbitt (1968) hypothesized that the extra effort expended by a participant to discriminate speech in the presence of background noise can reduce "cognitive effort reserves" required to perform cognitive operations on an incoming speech signal, such as storing information into memory. Thus, he hypothesized that the increased difficulty of speech recognition in noise may interfere with participants' cognitive processing. Results from his study revealed that an individual's ability to remember words was impaired in noisy listening conditions, even when the noise did not interfere with their speech recognition performance.

In recent years, dual-task paradigms have been used in several auditory (e.g. Sarampalis, Kalluri, Edwards, Hafter, 2009; Downs, 1982; Feuerstein, 1992; Hicks and Tharpe, 2002; Rakerd, Seitz, Whearty, 1996; Tun, McCoy & Wingfield, 2009) and speech production (e.g. Kemper, Schmalzried, Herman, Leedahl and Mohankumar, 2009) studies. For example, Sarampalis et. al. (2009) used a dual-task experiment to examine the benefit of a digital noise-reduction algorithm (NR) in hearing aids for a group of normal-hearing young participants. Participants were asked to perform two dual-task experiments with and without NR. In the first experiment, the participants' primary task was to repeat R-SPIN sentences that were played to them in the presence of a 12 talker babble noise at various SNRs, and the secondary task was to repeat back the final words of a block of eight R-SPIN sentences after all eight sentences were presented. In the second experiment, the participants' primary task was to repeat back words presented at various SNRs, and the secondary task was to perform a visual reaction time task in which the participant was instructed to press an arrow button that pointed towards a number when it was an even numbered digit, and to press an arrow button that pointed away when it was an odd numbered digit. Results revealed that participants' recognition of R-SPIN sentences (e.g. the primary task) decreased as the SNR decreased (making the primary task more difficult). Participants' recognition performance on the primary task stayed constant across SNRs with and without NR, but performance on the secondary task (e.g. memory recall task) was different. That is, when tested with NR, the participants' performance on the secondary task was significantly improved in the difficult SNR conditions than without NR. This suggests that NR reduced listening effort which freed up cognitive processing resources the participant could use for performing other tasks, in this case a working memory task. The authors contend that future hearing aid research should include objective measures of listening effort. If speech recognition performance were the only measure used to assess this NR algorithm, one would have concluded that NR has no affect on participants' performance in background noise when in fact it reduced listening effort.

Downs (1982) examined the effects of hearing aid use on measures of speech discrimination and listening effort in hearing-impaired individuals using a dual-task paradigm procedure. Participants were presented lists of CNC words in a multi-talker babble at 0 dB SNR with and without their hearing aids on, while simultaneously responding to a visual probe reaction time task. Results revealed that hearing impaired participants had faster reaction times on the visual probe task when they wore their hearing aids. The author concluded that hearing aids can reduce listening effort for hearing impaired individuals. Hicks and Tharpe (2002) used the same dual task paradigm as Downs (1982) to determine if children with hearing loss expend more effort than children with normal-hearing when listening under adverse conditions than when listening under more favorable conditions. The children with hearing loss expended more effort than the children with normal hearing on the speech in noise task even though they obtained similar speech discrimination scores.

Rakerd et. al. (1996) also examined effortful listening using a dual-task paradigm in a group of normal hearing and a group of hearing impaired participants. Participants were required to listen to passages of speech while memorizing a list of digits to be recalled after the entire speech passage was presented. Results revealed that participants with hearing loss demonstrated significantly more effort listening to passages than normal hearing participants, as indicated by their poorer performance on the digit memorization task. The authors concluded that peripheral hearing loss increases the demand for cognitive resources thus increasing listening effort. Consistent with these results, Tun et. al. (2009) reported that listening effort increased for a group of hearing impaired participants when recalling word lists at a sound intensity level that ensured audibility.

Recently, Kemper, et. al. (2009) introduced a visual rotor tracking task, as a secondary task in a dual-task paradigm to measure effort in younger and older adults. The visual tracking task is a Digital Pursuit Rotor Tracking task (DPRT) developed by the Digital Electronics and Engineering Core in the Center for Biobehavioral Neurosciences in Communication Disorders at the University of Kansas (Kieweg, 2009). The DPRT is a digital version of the classic pursuit rotor tracking task (McNemar & Biel, 1939) and consists of an elliptical track, and a circular target that rotates along the track, digitally displayed on a computer monitor. Participants are instructed to use the computer mouse to position a pair of cross-hairs over the target. Once the target begins to move around the ellipse, the participant must track the moving target on the computer screen by using the mouse to keep the cross-hairs superimposed on the target. The amount of time the participants' moved off the target and the distance they were off from the target are stored in a data file for each participant.

In the current study, we used a dual-task paradigm to assess listening effort in younger and older participants on a speech understanding in noise task. Specifically, we used the DPRT as the secondary task and sentence recognition in noise as the primary task of a dual-task paradigm. We selected the DPRT to use as the secondary task in this study because 1) it has been successfully used in dual-task paradigms with younger and older adults (e.g. Kemper et. al., 2009), 2) performance on the task can be time-locked to performance on a speech discrimination test, 3) participants can be trained in a few minutes to perform the DPRT and 4) scoring of the task allows the examiner to control for baseline differences in individual performance.

In the above discussion of listening effort, the focus has been on studies that have reported objective measures of listening effort. However, there have been several other studies which have reported subjective measures of listening effort, referred to as "ease of listening" (Feuerstein, 1992; Hicks & Tharpe, 2002). Ease of listening is the perceived difficulty of a listening situation by the participant, and is typically measured using subjective magnitude estimation scales (Feuerstein, 1992). Magnitude estimations are made by exposing subjects to various conditions of the stimulus and having them provide a number, of their choosing, which best describes the level of the stimulus on the dimension being scaled (e.g. ease of listening, loudness, clarity, etc.). Unfortunately, a drawback to this procedure is that different subjects may use highly disparate number systems for their judgments. For example, some subjects may choose to limit their responses to a 1 to 5 range, others may use 0 to 1,000, and some may choose to use both positive and negative values. Such disparities can complicate comparison of data across subjects. Geller and Margolis (1984) suggested that restricted magnitude estimation

(RME) should be used for subjective judgments. Specifically, they suggested using a scale from 0 to 100 with the upper and lower limits defined in terms of the scaling dimension. They speculated that this type of scale would provide subjects with sufficient freedom of choice while at the same time keeping the rating values manageable.

Feuerstein (1992) used restricted magnitude estimation (RME) procedure to examine perceived ease of listening in 48 young normal-hearing participants on a speech in noise task under binaural and two simulated unilateral conductive hearing loss (monaural) conditions. The subjects were required to rate ease of listening for each R-SPIN sentence list (e.g. 50 sentences) using a scale of 0 to 100, with 0 being defined as very, very easy and 100 being defined as very, very difficult. Results revealed that there was a significant decrease in perceived ease of listening for both simulated conductive hearing loss conditions compared to the binaural hearing condition.

In the current study, we were interested in using the RME procedure to assess perceived ease of listening in younger and older participants in order to determine if there is an association between subjective (e.g. RME) and objective (dual-task paradigm) measures of listening effort. Currently, measuring listening effort is difficult and relatively non-existent in clinical audiological practice. If the RME procedure is highly correlated with participants' performance on the proposed dual-task paradigm, this procedure could potentially be used clinically to assess listening effort.

In summary, the difficulty older participants have understanding speech in background noise has received considerable attention in the literature in terms of the types of noises that are most detrimental to speech recognition (Helfer & Freyman, 2008), and the differences in signal-to-noise-ratios that are required for older and younger participants to obtain similar speech recognition scores (Pichora-Fuller et. al., 1995). However, the effect of noise on *listening effort* has received less attention, and is typically discussed more subjectively as self reports (Benter et. al., 2008). Thus, few auditory studies have objectively examined age-related effects on listening effort, and to date, no studies have directly examined the effect of different background noise maskers on listening effort.

SPECIFIC OBJECTIVES

The purpose of the present study was: 1) to directly evaluate the relationship between measures of cognitive function and speech understanding in background noise, and 2) to objectively and subjectively measure the listening effort young normal-hearing, old normal-hearing, and old hearing-impaired participants expend on a speech and noise listening task using background noises that represent a continuum of difficulty ranging from most difficult (TT) to least difficult (SSN). Specifically, the following hypotheses were tested:

Hypothesis 1. There is a significant association between participants' performance on a speech recognition in noise test and the Reading Span test, the DSST, and the Stroop test.

Hypothesis 2. As the masker condition becomes more difficult (SSN,SIX, TT) listening effort will increase, but the increase will be greater for older participants than younger participants.

Hypothesis 3. Listening effort will be significantly correlated with participants' performance on the Reading Span test, the DSST, and the Stroop test.

Hypothesis 4. There is a significant association between objective and subjective measures of listening effort.

EXPERIMENTAL DESIGN AND METHODS

Participants

Forty six adults participated in this study: 15 young normal-hearing (YNH) 18-25 years of age (Mean (M) = 21.66, Standard Deviation (SD) = 2.66), 15 older normal hearing (ONH) 55-77 years of age (M = 66.86, SD = 6.7), and 16 older hearing impaired (OHI) 59-76 years of age (M = 68.18, SD = 4.62). The sample size for this study was based on an a priori power analysis of an ANOVA (difference in means =10, standard deviation = 8.5 (Kemper et. al., 2009) using alpha = .05 and power = .8 (Cohen, 1988). YNH and ONH participants had hearing thresholds $\leq$ 25 dB HL from 250 Hz through 4000 Hz (ANSI, 2003), bilaterally. Older hearing impaired participants had bilateral sensorineural hearing loss with hearing thresholds $\leq$75 dB HL at all octave audiometric test frequencies and no more than a 15 dB difference in thresholds between ears at any test frequency. In addition, all OHI participants were experienced hearing aid users and wore hearing aids, bilaterally, for at least six months prior to participation. Figure 1. shows mean pure-tone thresholds of the YNH and ONH participants, and mean unaided and aided pure-tone thresholds of the OHI participants averaged across the left and right ears, respectively.

All participants in this study were native speakers of English, had normal or corrected normal vision (e.g. 20/40 acuity) according to the Snellen eye chart, and had good to excellent sentence recognition scores (>80%) in quiet. Older participants were

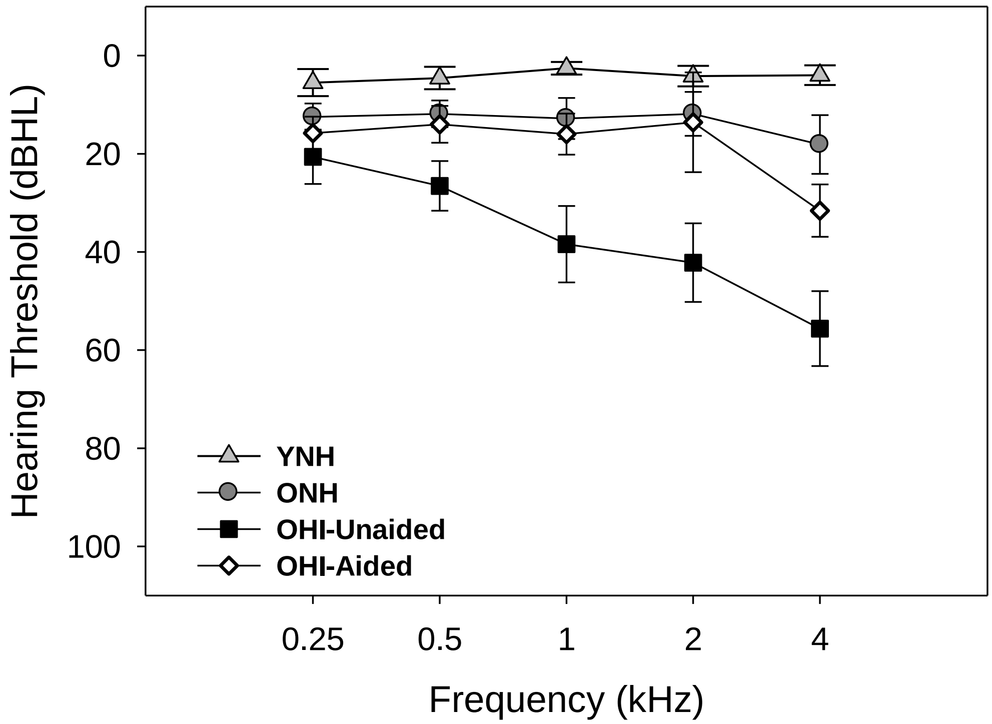

Figure 1. Mean pure-tone thresholds (in dB HL) averaged across the right and left ears for 15 YNH (triangles) and 15 ONH (circles), and unaided (squares) and aided (triangles) thresholds for 16 OHI (squares, unaided) participants, respectively. Error bars represent ±1 SD.

recruited from Syracuse University's Gebbie Hearing Clinic, senior centers in the Syracuse area and the Hearing Science Lab Database. Younger participants were recruited from the university community. Participants were paid an hourly wage for their participation in the study.

Listening Materials

Speech Stimuli

The Revised Speech Perception in Noise (R-SPIN) Test (Bilger, Neutzel, Rabinowitz, and Rzeczkowski, 1984) spoken by a *female* talker was used as the speech recognition material for this study. The sentences were recorded and digitized using the Computerized Speech Lab, CSL-4500 (Kay Elemetrics, 2008) at a 44,100 Hz sampling rate. The R-SPIN was chosen for use in this study because it contains both high and low context sentences which are more representative of the types of speech in noise people encounter in "real life" situations.

The R-SPIN consists of eight lists of 50 sentences (400 total sentences). Each 50 sentence list contains 25 high context sentences where the sentence final-word is predictable from the sentence context (e.g. I cut my finger with a knife) and 25 low context sentences where the sentence final-word is not predictable (e.g. I am thinking about the knife). The lists have been reported to be equivalent in difficulty and have high test re-test reliability (Bilger et. al., 1984). The high and low context sentences are presented in a fixed pseudorandom order. The target word is always the final word in the sentence. Scores are reported as the percent of target words the participant identified correctly.

Background Noise

The R-SPIN sentences were presented to participants in three background noises: female two-talker babble (TT), female six-talker babble (SIX), and a speech spectrum shaped noise (SSN). All three noises were spectrally shaped using Adobe Audition 3.0 (Adobe Systems Incorporated, 2007) to be equal to the Long Term Average Speech Spectrum (LTASS) of the 400 R-SPIN sentences (see figure 2.). Thus, these noises are spectrally similar but represent a continuum of masking difficulty, from most difficult (e.g. female two-talker babble), to least difficult (e.g. speech shaped noise). The R-SPIN sentences and the three noise maskers (e.g. SSN, SIX, TT) were normalized to the same root-mean-square (RMS) pressure level using Praat computer software (Praat Language Lab ©2006).

Female two-talker babble (TT)

A babble of two female voices reciting nonsense sentences was used as the background noise for the TT condition. The TT noise was created by Freyman, Helfer, and Balakrishnan (2007). They individually recorded two different female talkers reciting discrete nonsense sentences in a 16 bit format at a 22 kHz sampling rate. The sentences were then edited to create continuous 35 second streams of speech for each talker. The RMS outputs of the individual speech streams were equated with one another and then combined together to generate the two-talker masker. The 35 second stream of two-talker babble was then concatenated using Praat (Praat Language Lab ©2006) to produce a 5 minute stream of babble. The two-talker babble and the R-SPIN were then combined together and recorded on CD using Adobe Audition 3.0 (Adobe Systems Incorporated, 2007) in a 16 bit format at a 22 kHz sampling rate. A two-talker female masker was chosen for this study because it has been shown to produce a large amount of

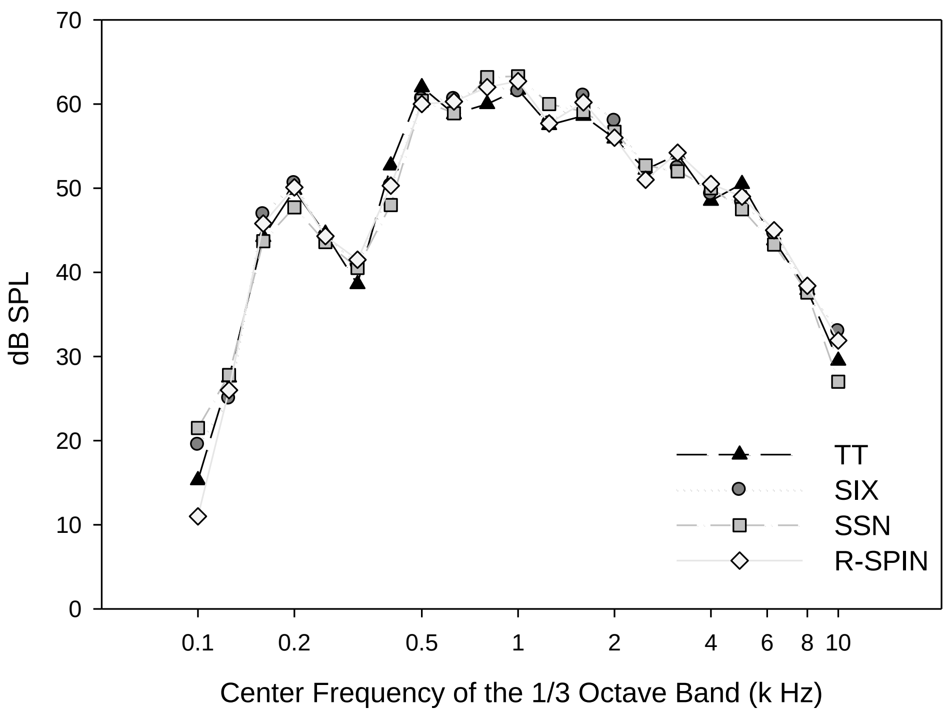

Figure 2. Long Term Average Speech Spectrum (LTASS) of the TT (triangle), SIX (circle), and SSN (square) maskers, and R-SPIN sentences (diamond).

informational masking when the target speech is also a female talker (e.g. Freyman et. al., 2004; Helfer and Freyman, 2008).

Female six-talker babble (SIX)

A babble of six female voices reciting sentences was used as the background noise for the SIX condition. The SIX babble was recorded and edited by Freyman et. al. (2007) and recorded onto a CD in the same manner as described above. A six-talker female masker was chosen because several studies have shown that when the speech in the masker cannot be clearly understood (e.g. six talker masker), it is easier for a participant to recognize the target signal than if the speech masker could be understood clearly (e.g. two talker masker) (e.g. Freyman, et. al., 2001; Freyman et. al., 2004). The six individual talkers create mutual masking of one another, thus appearing less like individual streams of speech, because the additional masker waveforms fill in temporal and spectral gaps in the signal.

Speech Spectrum Noise (SSN)

A spectrally shaped noise was generated in MATLAB using a 16 bit, 44. 1 kHz sampling rate, by passing a Gaussian noise through an FIR filter with a magnitude response equal to the Long Term Average Speech Spectrum (LTASS) of the 400 R-SPIN sentences. The SSN and the R-SPIN were then combined together and recorded on CD using a 16 bit format at a 22 kHz sampling rate using Adobe Audition 3.0 (Adobe Systems Incorporated, 2007). The SSN masker should produce the least amount of informational masking in this study.

Visual Tracking

The Digital Pursuit Rotor Tracking (DPRT) program (Digital Electronics and

Engineering Core, University of Kansas, 2009) was used to measure visual motor tracking. The DPRT is a digital version of the classic pursuit rotor tracking task (McNemar & Biel, 1939). The DPRT was developed using LAB VIEW software (National Instruments, 2009) and consists of an elliptical track with a circle shaped target that rotates along the track and is displayed on a computer monitor. On a given trial, a participant used a cordless laser computer mouse to position a cursor over the target. When positioned completely over the target, the target color changed from red to green and began to move along the elliptical track. As the target moved along the elliptical track, the participant tracked the moving target by keeping the cursor placed directly over the target. The DPRT program sampled the location of the cursor and recorded if the participant was on the target, or off the target, and computed the distance they were off the target. Thus, a score for time on target (%), and tracking error (the distance in pixels from the target to the cursor) for each sentence was stored in a data file for each participant.

The speed at which the target rotated around the ellipse (revolutions per minute) was determined prior to experimental testing for each participant during a DPRT practice test session. Participants practiced the DPRT to determine the tracking speed that was required for them to stay on target approximately 80% of the time (Kemper et. al., 2009). This level of baseline tracking performance was selected based on previously reported results using the DPRT with younger and older participants (Kemper et. al., 2009). In addition, establishing a baseline level of 80% time on target equated the difficulty of the secondary task across the three groups of participants, as well as avoided any floor and ceiling effects on performance.

During the practice session participants initially performed the DPRT for 30 seconds and then received feedback on their tracking performance. A 2 up/1 down staircase training procedure was used to manipulate the tracking speed on successive 30-second trials. For each successive trial, the tracking speed was increased by 10% if the average time on target was 80% or better for the previous trial. If the average time on target was less than 80%, the tracking speed was decreased by 5% on the next successive trial. The staircase procedure continued until the tracking speed remained relatively constant around the same value, moving up and down past this value three times.

Subjective Listening Effort

A restricted magnitude estimation scale (Geller and Margolis, 1984) was used to measure subjective listening effort. Participants were instructed to rate how easy it was to listen to R-SPIN sentences presented in the three background noise maskers (SSN, SIX, TT). Specifically, they rated listening ease from 0, representing ‘very, very difficult’ to 100 representing ‘very, very easy listening’(Feuerstein, 1990; Geller and Margolis, 1984), Once they assigned a value, participants were asked to write the value on a 3 x5 index card and turn the card face down before the next block of R-SPIN sentences was presented. A separate card was used for each list of sentences presented.

Cognitive Assessment

Working Memory

The digital version of The Reading Span Test (Daneman and Carpenter, 1980; Rönnberg et al., 1989) was used to assess participants’ working memory function. In the Reading Span Test, participants were presented sentences one word at a time, at a rate of one word per 0.80 seconds, on a computer screen. All sentences consisted of a noun, a verb, and an object. Half of the sentences presented were nonsense (e.g., “The train sang a song”), and half were meaningful sentences (e.g. “The girl brushed her teeth”). After each sentence, the participant was required to respond “yes” verbally for a meaningful sentence and “no” verbally for a nonsense sentence, during a 1.75-sec interval after each sentence. The “yes and no” responses are not formally scored as correct or incorrect, but are meant to ensure that the participant is attending to the entire sentence, not just the initial and final words.

Blocks of three, four, five, and six sentences were presented to participants. Each block was presented three times to each participant for a total of 54 test sentences (e.g. 3 blocks of 3 sentences = 9 sentences; 3 blocks of 4 sentences =12 sentences; 3 blocks of 5 sentences = 15 sentences; 3 blocks of 6 sentences = 18 sentences). When all of the sentences in a single block were presented, the software paused and the word “RECALL” was displayed on the computer screen. The experimenter said either “First” or “Last” in a randomized manner and the participant recalled as many first or last words as possible in any order. After the participant recalled as many words as possible, the experimenter continued the test with a new sequence of sentences. Performance was determined by the percent of correctly recalled words.

Processing Speed

The Digit Symbol Substitution test (DSST) from the Wechsler Adult Intelligence Scale-III (WAIS-III; Wechsler, 1981) was used to assess participants’ perceptual speed of processing. In the DSST, participants were presented with a sheet of paper that has a code table displaying pairs of digits (1-9) and symbols. Beneath the code table are rows of double boxes with the digit in the top box and nothing in the bottom box (see figure 3).

The participants were asked to use the code table to determine which symbols were associated with each digit and to write as many symbols as possible in the empty boxes in a 120-s period. The number of correct symbols is the score for this task. The DSST was administered to participants in a paper and pencil format following the standardized test instructions for administration. The DSST was chosen because scores on the DSST have been shown to exhibit strong correlations with measures that involve perceptual speed of processing (Salthouse, 2000; Sliwinski & Buschke, 1999).

Selective Attention

The Stroop test (Stroop, 1935) was used to assess participants' selective attention. Participants were presented a paper version of the Stroop test which consists of a list of words that are the names of colors printed in a color of ink different from the color name they represent (e.g. the word RED printed in GREEN ink), and a list of " * 's" printed in different color ink. Participants were given 45 seconds to name the color of ink of the series of *'s, and an additional 45 seconds to name the color of ink of the printed words, as quickly as they could. If the participant made an error, the examiner said "No", and the participant corrected the error and then continued with the test. Scores were calculated based on the number of words, and the number of *'s correctly named. An interference score was calculated using the following formula: Interference = (number of *'s – number of color names) /number of *'s x 100 (adapted from Kemper et. al., 2009).

Procedure

The Snellen vision screening test was administered first. For participants who

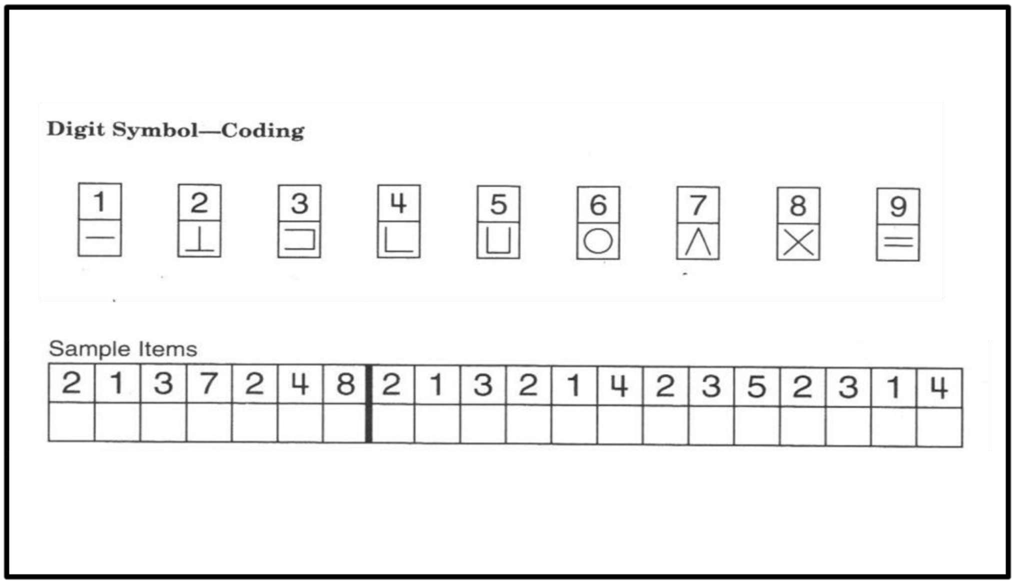

Figure 3. Example of a portion of the DSST score sheet

passed the vision screening, air-conduction thresholds at octave frequencies between 0.25 kHz and 8 kHz and bone conduction thresholds at octave frequencies between .5 kHz and 2000 k Hz were measured in a double-walled, sound-proof booth using a GSI-16 audiometer with TDH-50 supra-aural earphones (American National Standards Institute, 2004). Sentence recognition testing in quiet was then conducted at 70 dB SPL using 25 sentences from the Connected Speech Test (Cox et. al., 1988) presented through a speaker located 1 meter directly in front of the participant (0 degree azimuth). Participants were then seated in a quiet room and administered the three cognitive test measures (e.g. The Reading Span test, The DSST, and the Stroop test) in a randomized order.

Prior to dual-task testing, primary and secondary task baseline test measures were obtained. The primary-task baseline measure, which consisted of sentence recognition in noise performance, was obtained first. Lists of R-SPIN sentences were presented to participants in the presence of a background noise masker (SSN, SIX, TT) in a randomized order at 70 dBSPL via a Sony multi-disc CD changer (Sony electronics Inc., 2011) routed through a GSI-16 audiometer to GSI loudspeakers located 1 meter, at ear level, to the left and right of the participant's head (45 degrees azimuth). Participants were required to repeat back each sentence they heard during a 4 second silent interval that followed the presentation of each sentence. Performance was scored as the percent of final sentence words the participant repeated correctly.

During a practice primary-task test session, the level of the masker noise was adjusted by the examiner to determine the SNR required for each participant to obtain approximately 76% correct on the speech recognition in noise task. A fixed overall percent correct performance level was chosen to equate the difficulty of the primary task across the three groups of participants, and to avoid any potential floor and ceiling effects. All further sentence recognition in noise testing in this study was conducted for each participant using these SNR values. After practice primary task testing, participants were presented one list of 50 R-SPIN sentences at 70 dB SPL in each speech noise masker condition (e.g. SSN, SIX, TT) at the SNR determined in the practice test session. Presentation order of the background noise conditions and sentence lists were randomly selected for each participant. Percentage correct was considered the baseline speech recognition in noise score. After each list of 50 R-SPIN sentences was presented, participants were asked to rate on a scale of 0 to 100 how easy it was for them to listen to the sentences as described in the subjective listening effort section above.

The secondary-task baseline was then obtained. The secondary task baseline was participants' performance on the DPRT measured in quiet. Participants completed the DPRT practice test session first, and then completed a 5 minute DPRT baseline test session as described in the DPRT section above. The DPRT was displayed on a 20" Dell high-definition flat screen monitor placed in front of the participant on a small table. The participants' average time on target (TOT, %), and distance off the target (pixels) was recorded, and considered the baseline DPRT scores.

Following baseline measurements, the dual-task paradigm was explained and administered to participants. Participants were instructed that repeating the sentences was their *main* task, but that they should also continue tracking the moving target on the computer monitor as best they could (Downs, 1982; Feuerstein, 1988; Hicks and Tharpe, 2002). During a practice dual-task session, participants repeated 10 R-SPIN sentences in the presence of the SSN and simultaneously tracked the moving target on the ellipse displayed on the computer screen. Upon completion of the practice session, participants were presented 1 list (e.g. 50 sentences) of the R-SPIN sentences in each of the three background noise conditions (TT, SIX, SSN) with no one list repeated during any of the testing. Presentation order of the background noise conditions and sentence lists were randomly selected for each participant. Participants were required to repeat back each sentence during the 4 second silent interval that followed the presentation of each sentence. Listening and repeating the sentence were done while continuously tracking the moving target on the computer screen. Percentage correct scores, time on target (%) and distance from target (pixels) were recorded for each list of R-SPIN sentences presented. These scores were considered the dual-task performance scores. All testing was completed in two two-hour test sessions.

OHI participants performed the procedure described above with Audiosync Now NT behind-the-ear (BTE) hearing aids coupled to disposable canal earmolds with no venting, bilaterally. Noise reduction algorithms and directional microphones were disabled in the hearing aids during all testing. The gain of the hearing aids was determined based on the Desired Sensation Level (DSL) prescriptive method (Scollie et. al., 2005). The DSL targets were generated using the Starkey Inspire 2009 software in NOAH, and verified with the Audioscan Verifit VF-1 real ear system (Dorchester, Ontario Canada). The frequency response of the hearing aids was adjusted as necessary so that the insertion gain was within 5 dB across the prescribed values for 250, 500, 1000, 2000 Hz, and within 10 dB for 4000 Hz and 6000 Hz at an input signal of 70 dB SPL for each OHI participant.

Mean aided and unaided audiometric thresholds for the OHI participants and mean unaided thresholds for the YNH and ONH participants from 250 Hz through 4000 Hz averaged across the right and left ears are shown in figure 1. OHI participants' mean aided thresholds were compared to the mean unaided thresholds of the YNH and ONH participants using a univariate GLM analysis. Results revealed significant [F (2, 45) = 31.8, p = .001] differences in hearing thresholds among the three groups of participants. Specifically, post-hoc multiple comparisons, using a Bonferroni adjusted critical alpha level, showed that YNH participants had significantly (p =.001) better (e.g. lower) audiometric thresholds than both groups of older participants from 250 Hz through 4000 Hz. However, there were no significant (p > .05) differences between the ONH participants' thresholds and the OHI participants' mean aided thresholds except at 4000 Hz, where the OHI participants had significantly (p = .001) poorer (e.g. higher) thresholds than the ONH participants.

In this study, the purpose of the hearing aids was to ensure that the speech presented during testing was audible to the OHI participants. Audibility was calculated using the Speech Intelligibility Index (SII). The SII, is a measure, ranging between 0.0 and 1.0 that is highly correlated with the intelligibility of speech (ANSI, S3.5, 1997), and can be used to predict speech recognition scores for specific speech materials (Sherbecoe and Studebaker 2003). In this study, SII scores were computed for all participants using the online calculation procedure based on the ANSI S3.5-1997 (Methods for Calculation of the Speech Intelligibility Index, ANSI, 1997). SII scores ranged from 0.64 to 0.84 (M= .7314, SD = .05) for the OHI participants, from .8214 to .8468 for the ONH participants (M = .8382, SD = .009) and from .8466 to .8468 for the YNH participants

(M= .8467, SD = .00007). These SII scores correspond to 99% speech intelligibility for the OHI participants and 100% speech intelligibility for the YNH and ONH participants for R-SPIN sentences presented in quiet (Sherbecoe and Studebaker 2003). Thus, despite significant differences in hearing threshold levels between the participant groups, speech was audible for all participants in this study.

Data Analysis

Statistical Analysis of the data was performed using the SAS v9.1.3 (SAS, Cary, North Carolina) and SPSS v16. (SPSS Inc.,Chicago Ill.) software. Listening effort was analyzed using a split-plot Analysis of Variance (ANOVA) with masker condition (TT, SIX, SSN), as the nested subplot factor, and group (YNH, ONH, OHI) as the whole plot factor. Cognitive function was analyzed using a one-way ANOVA with the cognitive test score (Reading Span test, DSST, Stroop Test) as the dependent variable and group as the factor. The relationship between cognitive function and listening effort was assessed using Pearson Correlations. A 0.05 significance level was used for all analyses.

RESULTS

Cognitive Measures

Participants in this study were given a battery of cognitive tests designed to measure working memory (Reading Span test), processing speed (DSST) and selective attention (Stroop test). Mean scores and standard deviations on the three cognitive tests are shown for the three groups of participants in Table 1.

Table 1. Means and standard deviations on the cognitive test measures for the young normal hearing (YNH), older normal hearing (ONH), and older hearing impaired (OHI) groups.

	Group					
	YNH		ONH		OHI	
Measure	M	SD	M	SD	M	SD
Reading Span Test	54.8	9.14	49.4	11.2	41.8	10.5
DSST	61.7	9.7	47.8	8.7	40.2	7.0
Stroop Test						
Non-Word	75.2	8.5	63.1	17.1	47.8	9.8
Color-Word	51.7	7.9	37.4	6.7	33.8	6.5
Interference	30.6	10.3	39.1	10.9	28.5	9.9

Note. M= mean; SD = standard deviation

On all three tests the YNH participants performed better than the ONH and/or the OHI participants, except on the interference measure of the Stroop test. The group means for the cognitive measures were compared using a series of one-way analysis of variance (ANOVA) analyses with group as the between subjects factor. The ANOVAs showed significant differences among the three groups of participants for the Reading Span test [F (2, 46) = 6.16, p = .004], the DSST [F (2, 46) = 25.18, p = .001], and the non-word [F (2, 46) = 18.73 p = .001], color-word [F (2, 46) = 37.35, p = .001] and interference scores [F (2, 46) = 4.5, p = .016] on the Stroop test.

Post hoc multiple comparisons using a Bonferroni adjusted critical alpha level were performed to further examine the effect of group. Results revealed a significant difference ($p = .003$) in Reading Span scores between the YNH and OHI groups. Specifically, the OHI participants recalled fewer words correctly on the Reading Span Test compared to the YNH participants in the study. However, there were no significant differences ($p > .05$) in Reading Span scores between the two older groups (e.g. ONH and OHI) or between the ONH and the YNH participants.

The YNH group of participants scored significantly higher ($p = .001$) on the DSST (i.e. indicating faster perceptual processing speed) compared to both groups of older participants (e.g. ONH and OHI). Also, ONH participants scored significantly ($p = .043$) higher on the DSST compared to OHI participants.

YNH participants named significantly more blocks of non-words ($p < .05$) and color-words ($p < .05$) (i.e. indicating better performance) on the Stroop test compared to ONH and OHI participants. OHI participants named significantly ($p = .003$) fewer blocks of non-words than the ONH participants. The only significant difference in interference scores on the Stroop test was between the two groups of older participants. Specifically, ONH participants had significantly ($p = .02$) higher interference scores (i.e. a higher score indicates poorer performance) compared to the OHI participants.

Baseline Measures

Primary Task Performance

The SNR was adjusted so that participants' performance on the primary task baseline condition, sentence recognition in background noise, was approximately 76% in each of the three background noise masker conditions. Mean percent correct scores on the sentence recognition task are shown for the three masker conditions in Table 2.

Table 2. Means and standard deviations on the sentence recognition task for the young normal hearing (YNH), older normal hearing (ONH), and older hearing impaired (OHI) groups for the three masker conditions.

	Group					
	YNH		ONH		OHI	
Masker Condition	M	SD	M	SD	M	SD
SSN	76.8%	3.6	77.5%	2.9	77.8%	2.9
SIX	76.6%	3.4	75.7%	3.9	77.4%	2.4
TT	76.13%	3.2	75.5%	4.22	76.13%	2.7

Note. M= mean; SD = standard deviation

A two-way ANOVA using the factors group and masker revealed no significant ($p > .05$) differences in primary task speech recognition scores within or between the three groups of participants. Thus, equivalent performance on the task by the three groups of participants was successfully achieved.

The mean SNRs for each group of participants needed to obtain the ~76% correct scores on the sentence recognition in noise task are shown in Figure 4. The SNR group means were compared using a split-plot ANOVA with group as the whole plot factor and background noise masker and as the sub-plot factor. Results revealed significant main effects of background noise masker [$F(2, 129) = 82.4$, $p = .001$] and group [$F(2, 129) = 90.647$, $p = .001$], but there was no significant ($p > .05$) interaction between group and background noise masker. To further examine the effect of masker and group, post hoc pair-wise comparisons using a Bonferroni adjusted critical alpha level were performed. Results indicated that all participants needed significantly ($p = .001$) more favorable SNRs

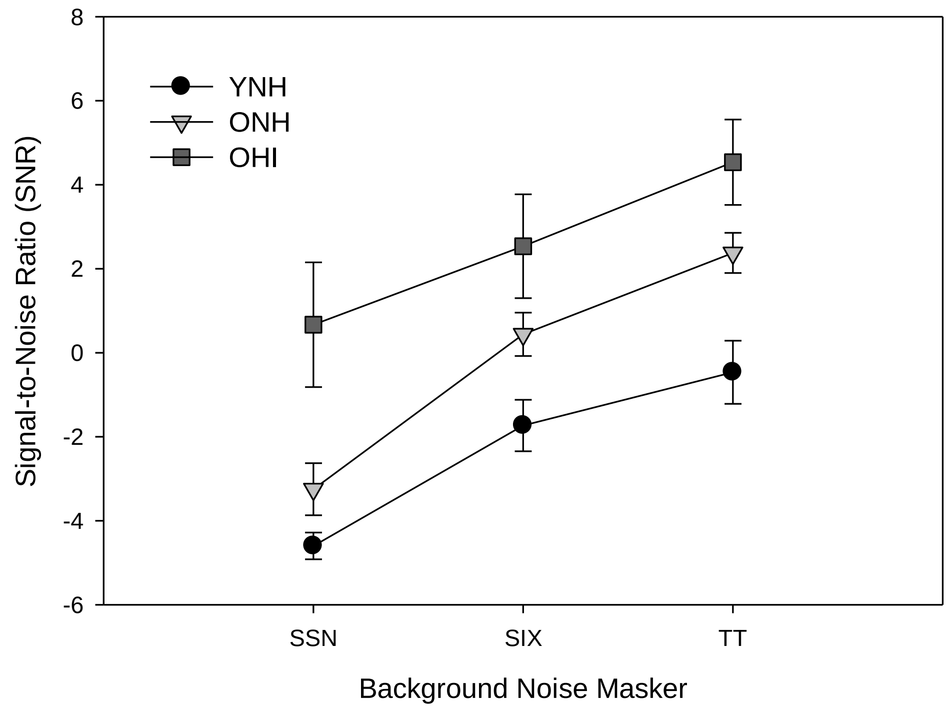

Figure 4. Mean signal-to-noise ratios (SNR) for 15 YNH (circles), 15 ONH (triangles), and 16 OHI (squares) for the three background noise masker conditions. Error bars represent +/- one standard error from the mean.

to obtain 76% on the R-SPIN in the TT and SIX masker conditions compared to the SSN condition, but the most favorable SNRs were required for the TT condition. This indicates that the TT condition was the most difficult for all the participants. Compared to the YNH participants, both groups of older participants needed significantly (p = .000) more favorable SNRs in all three masker conditions to achieve ~76% sentence recognition score. The OHI participants required the most favorable SNRs (p = .000) in all masker conditions compared to YNH and ONH participants.

The relationship between participants' cognitive function and speech understanding performance (e.g. SNRs) in background noise was evaluated using a series of Pearson correlations. See table 3. for the Pearson correlations and p-values in this analysis.

Table 3. Pearson correlations (r), and p-values (p) of the variables in the analysis.

		Cognitive Function				
		Reading Span	**DSST**	**Stroop Test** Non-word	Color-word	Interference
Speech Understanding						
SSN	*r=*	-.452**	-.470**	-.521**	-.526**	-.069
	p=	.001	.000	.000	.000	.324
SIX	*r=*	-.518**	-.494**	-.505**	-.563**	-.002
	p=	.000	.000	.000	.000	.494
TT	*r=*	-.546**	-.578**	-.567**	-.644**	.002
	p=	.000	.000	.000	.000	.494

Note. n=46
** Correlation is significant at the 0.01 level
* Correlation is significant at the 0.05 level

There was a significant relationship between SNRs in the three background noise masker conditions and participants' performance on the Reading Span test, the DSST, and the non-word and color-word measures of the Stroop test. However, there was no significant (p > .05) relationship between participants' speech understanding in background noise and the interference measure of the Stroop test.

During primary-task baseline testing, participants were asked to subjectively rate the difficulty of the sentence recognition in noise task from 100 (“very, very easy”) to 0 (“very, very difficult”) in each background noise masker condition (SSN, SIX, TT). Mean perceived ease of listening rating scores for the TT, SIX, and SSN maskers for the three groups of participants are plotted in Figure 5. Group means for perceived ease of listening ratings were compared using a split-plot ANOVA analysis with the whole plot factor of group and the sub-plot factor background noise masker. Results revealed significant main effects of background noise masker [$F (2, 129) = 27.4$, $p = .000$] and group [$F (2, 129) = 7.45$, $p = .001$]. There was no significant ($p > .05$) interaction between group and background noise

Secondary Task Performance

Participants initially practiced the DPRT to determine the tracking speed that was required for them to achieve a time on target score of approximately 80% in the secondary-task baseline DPRT condition (e.g. performing the DPRT in silence). Mean tracking speeds were 1.85 (SD = .67), 0.88 (SD = .17), and 1.29 (SD = .37) for the YNH, ONH, and OHI groups, respectively. There was a significant difference [one-way ANOVA; $F (2, 44) = 16.9$, $p = .001$] in tracking speeds across the three groups of participants. Post hoc multiple comparisons using a Bonferroni adjusted critical alpha level revealed that the YNH participants’ tracking speed was significantly faster ($p = .001$) than both groups of older participants. However, there was no significant difference ($p > .05$) in tracking speed between the two older groups.

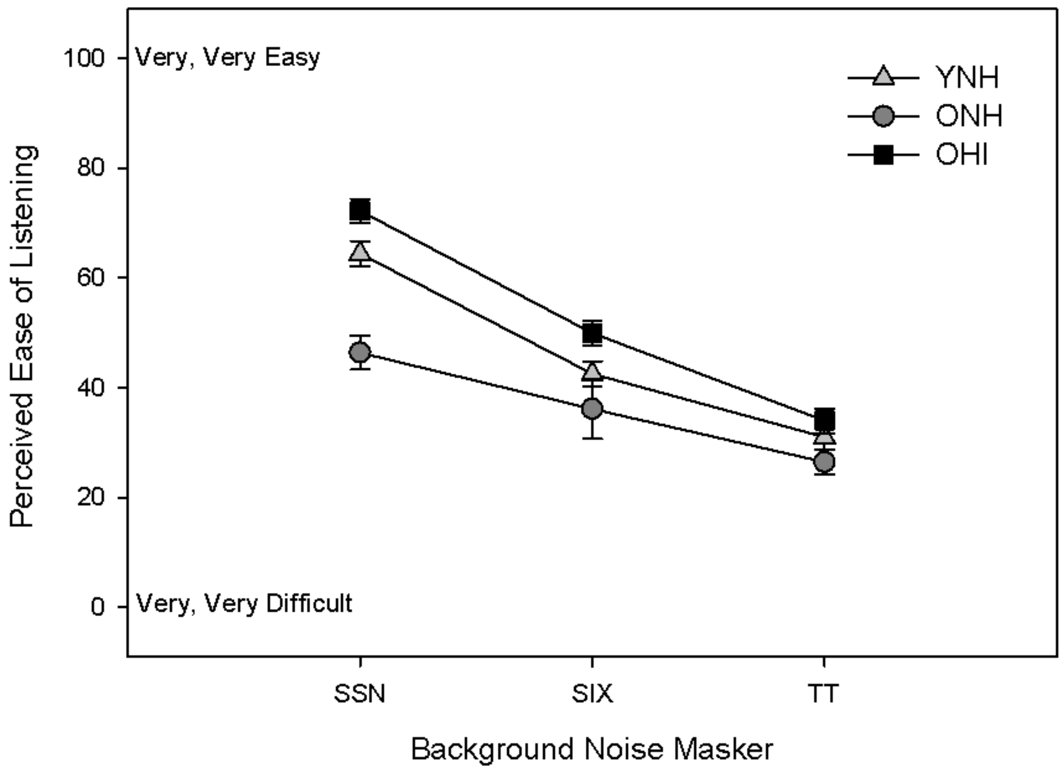

Figure 5. Mean perceived ease of listening rating scores for 15 YNH (triangles), 15 ONH (circles), and 16 OHI (squares) for the three background noise masker conditions. Error bars represent +/- one standard error from the mean.

Baseline time on target scores were 77.6% (SD = 4.1), 82.3% (SD = 2.1), and 80.03% (SD = 4.5) for the YNH, ONH, and OHI groups, respectively. A one-way ANOVA [F (2, 44) = 5.8, p = .004] showed a significant difference in baseline time on target scores between the groups. Specifically, post hoc multiple comparisons using a Bonferroni adjusted critical alpha level, revealed that time on target scores were significantly different between the younger and older normal hearing participants. Baseline tracking error scores (distance from target measured in pixels) were 12.8 (SD = 1.6), 26.7 (SD = 9.9) and 24 (SD = 8.8) for the YNH, ONH, and OHI groups, respectively. Tracking error for the younger participants was significantly lower than that of the two groups of older participants but, there was no difference in tracking error scores between the two groups of older adults [one-way ANOVA; F (2,44) = 13.5, p = .001; post-hoc multiple comparison using Bonferroni adjusted critical alpha level, p= .001]. Thus, when the participants were off the target during baseline testing, older participants were off by a significantly greater distance than younger participants.

Experimental Measures

Dual-Task Performance

In a dual-task paradigm it is critical that a participant's performance on the primary task (e.g. speech recognition in noise) remains stable throughout the experiment. This is because listening effort is calculated as the *change* in a participant's performance on the secondary task (e.g. DPRT) from the baseline to the dual-task condition, while their performance on the primary task remains constant. To ensure the participants in this study maintained their performance on the primary task, we compared their speech recognition scores obtained on the baseline primary task and dual-task conditions (see

Figure 6). A series of paired samples t-tests were used to compare baseline primary task sentence recognition scores in each background noise condition to participants' sentence recognition scores in three background noises in the dual-task condition. Results revealed no significant ($p > .05$) differences in sentence recognition scores between the primary task and dual-task scores in the SSN ($t = -1.979$), SIX ($t = -1.86$) and TT ($t = -.047$) masker conditions. Using a split-plot ANOVA, group means for sentence recognition scores in the dual-task condition were compared using the whole plot factor group and the sub-plot factor background noise masker. Results revealed that there were no significant ($p > .05$) differences in sentence recognition scores on the dual-task within or between the three groups of participants. Thus, there were no significant differences between speech recognition scores within or between the three groups of participants.

Listening effort in this study was calculated as the change in DPRT performance from the secondary baseline task (e.g. DPRT performance obtained quiet without any speech signal) to the dual-task condition. To control for differences in baseline DPRT performance among individual participants, listening effort was computed using the formula:

Listening effort = 100 * (Baseline – Dual Task) / Baseline (Adapted from Kemper et. al., 2009).

Initially, listening effort was computed individually for both measures of tracking performance (time on target (%) and distance from target (pixels)). However, no significant ($p > .05$) changes in the distance from target scores were observed between the dual-task and secondary-task baseline conditions and therefore not given any further

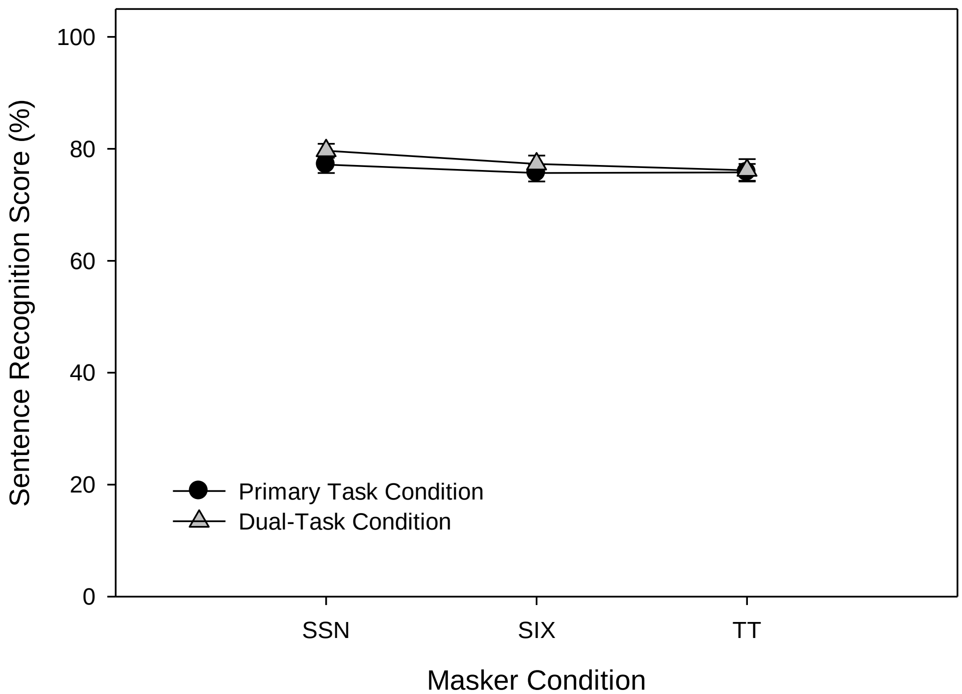

Figure 6. Mean sentence recognition scores in the primary-task (circles) and the dual-task (triangles) conditions for all 46 participants for the three background noise maskers. Error bars represent +/- one standard deviation from the mean.

consideration.

Mean listening effort scores for the TT, SIX, and SSN maskers for the three groups of participants are plotted in Figure 7. To compare differences in listening effort across the three groups of participants, a 3x3x2x2 split-plot ANOVA was performed on the factors background noise masker (e.g. TT, SIX, SSN), linguistic context cues (high context and low context), response type (listening and verbal repeating) and group (e.g. YNH, ONH, OHI). Results indicated a significant interaction of masker x group [F (4, 473) = 7.21, $p < .001$] and significant main effects of group [F (2, 43) = 4.29, $p = .0201$] and response type [F (1, 473 = 34.87, $p < .0001$].

Post-hoc pair wise comparisons using a Tukey's adjusted critical alpha level to control for experimentwise error indicated that YNH participants exerted significantly ($p = .018$) more effort in the SIX masker condition compared to the SSN and TT conditions. ONH and OHI participants' expended significantly ($p< .05$) more effort than YNH participants when processing speech in background noise in the TT and SSN masker conditions relative to the SIX condition. However, there was no significant difference in listening effort between the two groups of older participants and the YNH participants in the SIX masker condition, or between the ONH and OHI groups for any of the masker conditions. This suggests that aging is the primary reason why the older participants exerted more listening effort than the younger participants.

On any sentence recognition task, participants must listen to the sentence presented and then verbally repeat the sentence. To compare the listening effort expended on the sentence recognition in noise task when the participant listened to the sentence to when they verbally repeated the sentence, listening effort was calculated

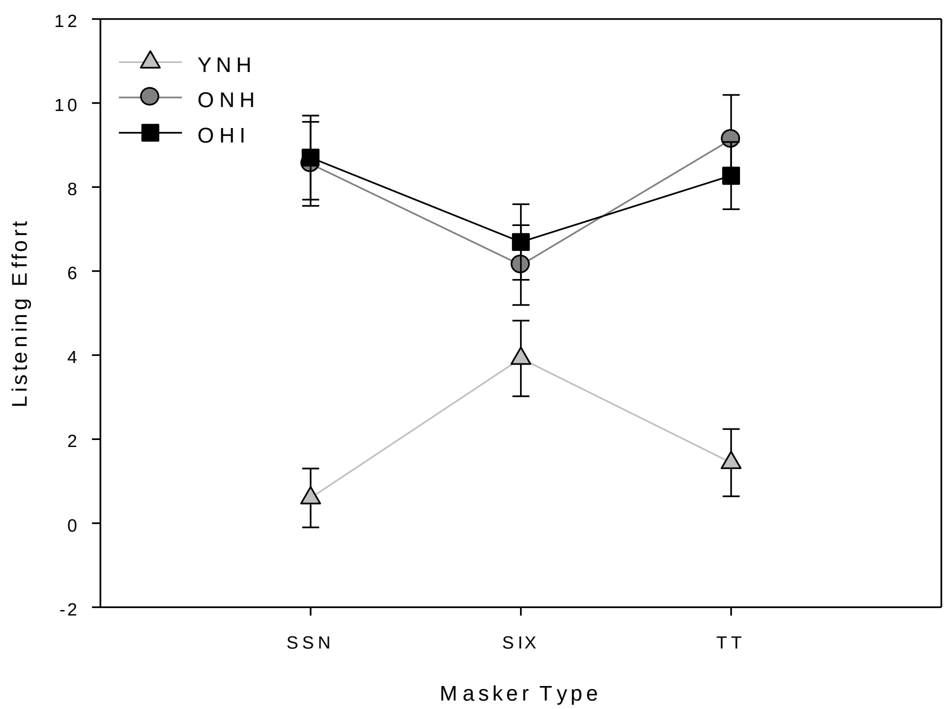

Figure 7. Mean objective listening effort scores for the 15 YNH (triangles), 15 ONH (circles) and the 16 OHI (squares) participants for the three background noise masker conditions. Error bars represent +/- one standard error from the mean.

separately for each. These measures were included in the analysis above as the factor "response type". All three groups of participants expended significantly more listening effort, across the three masker conditions, when *listening* to sentences compared to when they verbally repeated the sentences (see figure 8).

To compare participants' speech recognition performance for high verses low context sentences, percent correct scores were calculated separately for the high and low context subsets of each R-SPIN sentence list. All three groups of participants in this study scored better on the high context compared to the low context sentences. Specifically, the differences in percent correct scores for the high and low context sentences were 17.71 (SD= 12.25), 8 (SD = 11. 59) and 22 (SD = 10.01) for the YNH group, 24.31 (SD = 9.7), 27.07 (SD = 10.3), and 28.30 (SD = 6.8) for the ONH group, and 24.92 (SD = 9.95), 22.42 (SD = 8.45) and 25.14 (SD = 7.59) for the OHI group on the TT, SIX, and SSN masker conditions, respectively.

The group means for the difference in sentence recognition scores for the high and low context conditions were compared using a split-plot ANOVA with the factors whole plot factor group and sub-plot factor background noise masker. Results revealed significant main effects for masker [$F(2, 113) = 3.83$, $p = .025$] and group [$F(2, 113) = 13.386$, $p = .001$]. The interaction between group and masker was not significant ($p > .05$). Post-hoc pair wise comparisons using a Bonferroni adjusted critical alpha level indicated that the difference between high and low context performance scores was significantly ($p = .020$) less for the SIX masker condition compared to the SSN condition. However, there were no significant ($p > .05$) difference between the TT and SIX or the TT

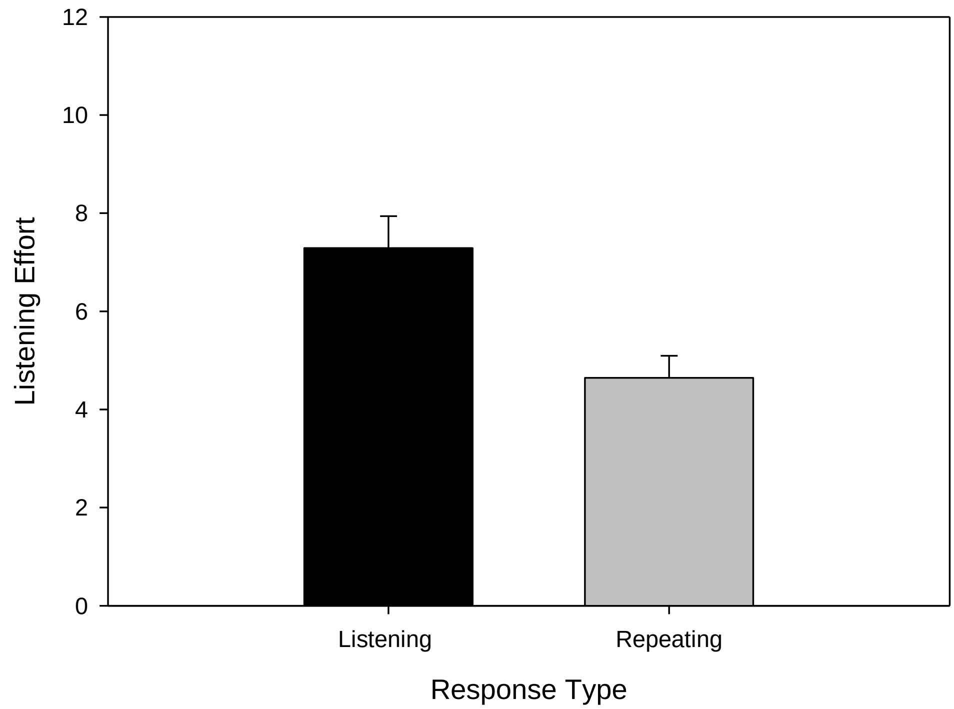

Figure 8. Mean listening effort scores collapsed across all three masker conditions for all 46 participants when listening and verbally repeating R-Spin sentences. Error bars represent +/- 1 standard error of the mean.

and SSN masker conditions. Both groups of older participants (ONH and OHI) had significantly (p = .000) greater differences in performance scores between the high and low context conditions compared to the YNH participants. However, there was no significant (p > .05) differences in scores between the two older groups. This suggests that the older participants, independent of peripheral hearing impairment, benefited more from the contextual cues in the sentences than the younger participants.

Despite significant differences in percent correct scores for the high and low context conditions, there were no differences in the amount of listening effort participants' expended on the high and low context sentences of the R-SPIN across masker conditions for all three groups of participants (see figure 9).

To examine how individual differences in cognitive ability affect listening effort, a series of Pearson correlations were used to determine the strength of association between the variables listening effort and participants' performance on the three cognitive tests, the Reading Span, the DSST, and the Stroop (see Table 4).

Table 4. Pearson correlations (r), and p-values (p) of the variables in the analysis.

		Cognitive Function				
		Reading Span	**DSST**	**Stroop Test** Non-word	Color-word	Interference
Listening Effort						
SSN	*r=*	-.304*	-.332*	-.366**	-.345**	-.031
	p=	.020	.012	.006	.009	.420
SIX	*r=*	-.047	-.072	-.133	-.050	-.099
	p=	.379	.318	.190	.371	.257
TT	*r=*	-.253*	-.202	-.280*	-.240	.075
	p=	.045	.089	.030	.054	.310

Note. n=46.
** Correlation is significant at the 0.01 level
* Correlation is significant at the 0.05 level

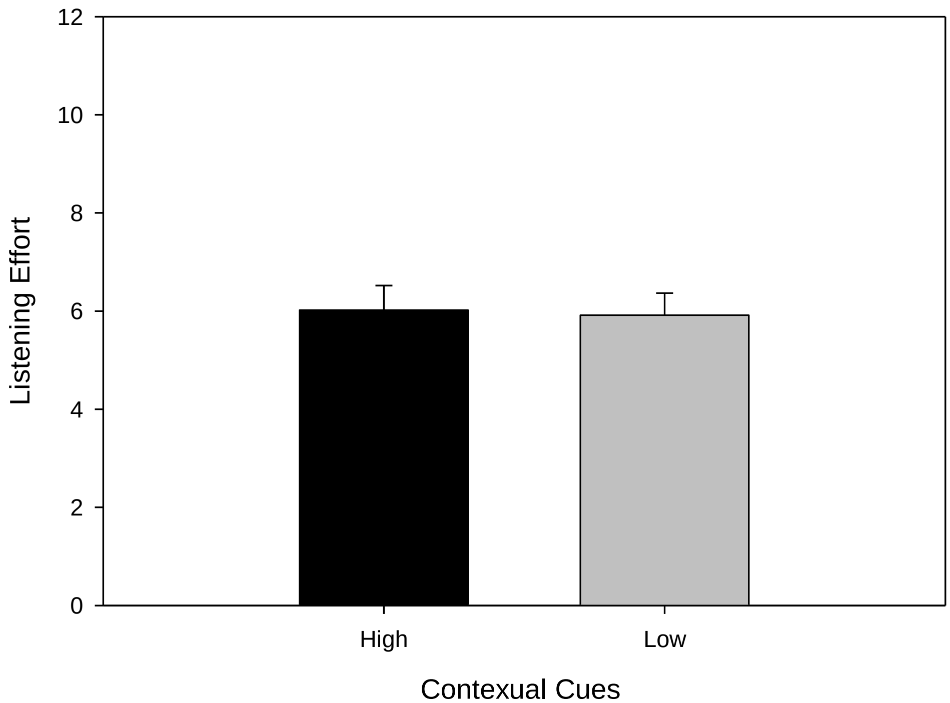

Figure 9. Mean listening effort scores collapsed across all three masker conditions for all 46 participants for high and low context R-Spin sentences. Error bars represent +/- 1 standard error of the mean.

Results revealed that listening effort in the SSN condition was significantly ($p< .05$) negatively correlated with participants' performance on the Reading Span test, the DSST, and the non-word and color-word measures of the Stroop test. In addition, listening effort in the TT condition was significantly ($p < .05$) negatively correlated with participants' performance on the Reading span test, and the non-word measure of the Stroop test. There were no significant ($p > .05$) correlations observed between listening effort in the SIX condition and participants' performance on any of the cognitive measures in this study.

YNH participants perceived, based on their subjective ratings, the listening tasks to be more difficult than was objectively measured using the dual-task paradigm, and ONH and OHI participants perceived the listening tasks to be less difficult than was objectively measured. The relationship between objective and subjective measures of listening effort was examined using a Pearson correlation. Results revealed there were no significant ($p >.05$) correlations between subjective ease of listening rating scores and objective listening effort scores in any of the three background noise masker conditions.

DISCUSSION

In the present study we examined the association between cognitive function, listening effort and speech recognition in background noise in younger and older listeners with normal hearing and older listeners with hearing impairment. To better understand this complex relationship, we used traditional speech recognition in noise tasks, cognitive measures, and measures of subjective and objective listening effort.

Speech Recognition in Noise

Findings from the present study support the complaint often cited by older adults that understanding speech in noisy listening situations can be challenging. Specifically, both groups of older individuals in this study (e.g. ONH, OHI) had more difficulty understanding sentences in non-speech (SSN) and speech (SIX, TT) background noise maskers compared to younger individuals. Specifically, the older participants' required significantly more favorable SNRs in all three background noise masker conditions compared to the younger participants to obtain the same recognition score. As was expected, the older participants with hearing loss had the most difficulty across all the listening conditions, and thus required the most favorable SNRs of the three groups.

The connection between age and speech understanding in noise has been reported in several studies (e.g. CHABA, 1988; Frisina & Frisina, 1997; Dubno et. al. (1984); Gordon-Salant & Fitzgibbons, 1999). In general, these studies suggest an individual's ability to understand speech in background noise decreases with age because cognitive function declines with age (Baltes & Lindenberger, 1997). For example, Gordon-Salant & Fitzgibbons (1999) found that older listeners, independent of peripheral hearing impairment, performed more poorly on a sentence recognition in noise task than younger listeners. They concluded that age-related changes in speech recognition performance were most likely associated with deterioration of cognitive processing mechanisms due to age. Other studies, however, have not found a significant relationship between age and speech understanding (e.g. Humes & Roberts, 1990; Souza & Turner, 1994). These studies contend that older listeners' difficulty understanding speech in noise is due to elevated peripheral hearing thresholds. Thus, while it is widely cited in the literature that speech recognition in noise is more difficult for older participants compared to their younger counterparts (e.g. CHABA, 1988; Frisina & Frisina, 1997; Dubno et. al., 1984; Gordon-Salant & Fitzgibbons, 1997; Humes & Roberts, 1990; Souza & Turner, 1994), there is less of a consensus among researchers as to *why* older participants have more difficulty understanding speech in background noise.

In the current study we found that older listeners, in general, had more difficulty understanding speech in noise than younger listeners, but the older listeners with hearing loss had the most difficulty understanding speech across all listening conditions. This suggests that a combination of peripheral hearing loss *and* age-related cognitive changes contribute to older listeners' difficulty understanding speech in noise. If older listeners' increased difficulty understanding speech in noise could be accounted for entirely by peripheral hearing loss, then we should not have observed any differences in speech in noise performance between the younger and older normal hearing groups. However, this was not the case.

Background Noise Maskers

In the current study, we assessed speech understanding in noise using three different background noise maskers (e.g. SSN, SIX, TT) that represent a continuum of masking difficulty from the least difficult non-speech masker (e.g. SSN) to most difficult two- talker masker (e.g. TT). Other studies using similar background noise maskers (e.g. Freyman et. al., 1999; 2007) have also shown that a two-talker female masker will create the most difficult listening condition when the target is a female talker due to the addition of informational masking (e.g. Freyman et. al., 2004; Helfer and Freyman, 2008; Yost, Dye, & Sheft, 1996). For example, when speech is presented in a competing speech environment (e.g. TT), masking processes exist beyond those normally attributable to traditional energetic masking. This additional informational masking is thought to interfere with the processing of the target signal at more of a cognitive level.

The greatest amount of informational masking occurs when confusion between the target and masker voices is greatest (Freyman et. al., 1999). This is consistent with our finding that all three groups of participants (e.g. YNH, ONH, OHI) required the most favorable SNRs in the TT masker condition and the least favorable SNRs in the SSN masker condition, to achieve the same overall performance score (e.g. 76% correct). In fact, our results are consistent with numerous studies (e.g. Arbogast, Mason, and Kidd, 2005; Brungart, Simpson, Ericson and Scott, 2001; Brungart, 2001; Carhart, Tillman and Greetis, 1969; Oh and Lufti, 1998; Freyman, Helfer, McCall and Clifton, 1999; Freyman, Balakrishnan, and Helfer, 2004; Helfer and Freyman, 2008) that have shown listeners experience more difficulty understanding a target speech signal when it is presented in a background noise of two competing talkers compared to more than two-talkers (e.g. SIX) and non-speech noises (e.g. SSN).

To evaluate the role informational masking may have played in the present study, we compared the difference in SNRs between the two-talker (TT) and speech-shaped noise (SSN) listening conditions for each participant. We selected these two conditions because the TT masker has been shown to have the most informational masking and the SSN masker the least (Freyman et. al., 2007). A one-Way ANOVA revealed a significant [$F(2, 45) = 5.334$, $p = .009$] difference across the three participant groups. Post hoc multiple comparisons, using a Bonferroni adjusted critical alpha level, showed that the ONH participants had a greater difference in SNRs (5.63 dB, SD = 1.31) between the TT and SSN conditions compared to the YNH (4.13 dB, SD= 1.72), and the OHI (3.86 dB, SD = 1.8) participants. There was no significant ($p>.05$) difference between informational masking effects for the YNH and OHI groups. This suggests that the ONH participants in our study were most susceptible to the effects of informational masking. This finding is consistent with Tillman, Carhart, and Nicholls (1973) who found that older participants with normal hearing are more susceptible to informational masking of speech than younger participants.

Several studies have shown that hearing impaired listeners, independent of age, are *less* susceptible to the effects of informational masking than listeners with normal hearing (e.g. Alexander and Lutfi, 2004; Arbogast, Mason, and Kidd, 2005; Hornsby, Ricketts and Johnson, 2006). It has been suggested that differences in masker sensation levels (SL) may account for these differences (Alexander and Lutfi, 2004; Arbogast, Mason, and Kidd, 2005). Specifically, the smaller the SL (i.e. the range between a participant's hearing threshold and the presentation level of the signal), the smaller the informational masking effects. This may account for why the hearing impaired participants in the current study obtained the smallest difference in SNRs between the TT and SSN masker conditions. Thus, although the OHI participants in our study wore bilateral hearing aids to ensure audibility, their aided hearing thresholds above 2000 Hz were poorer than the hearing thresholds of the other two groups of participants (See figure 1). Given that we used a fixed presentation level, it is possible that differences in SL may have influenced our results.

We did not specifically measure or control for SLs in this study, because our primary purpose was to examine the relationship between speech recognition and cognition among older and younger listeners, not to explicitly measure the effects of informational masking. Thus, rather than equating SLs between groups, we were more interested in maximizing the audibility of speech presented at a normal conversational level.

Cognitive Function

In the current study, we measured three aspects of cognitive function, working memory, processing speed and selective attention, all of which have been shown to be important for understanding speech as well as to deteriorate with age (CHABA, 1988). Consistent with other studies (e.g. Hoyer et. al., 2004; Kemper et. al., 2008; Salthouse, 1985), the older participants in our study showed reduced working memory, processing speed and selective attention abilities compared to the younger participants. Most interestingly, the results from our study confirm that there is a significant relationship between participants' cognitive function (i.e working memory and processing speed) and speech recognition performance in non-speech *and* speech background noise maskers. Our finding is consistent with studies that have shown a significant correlation between speech recognition in noise and working memory (e.g. Akeroyd, 2008; Foo et. al., 2007; Lunner, 2003; Rudner et. al., 2007; Rudner et. al., 2008) and perceptual processing speed (e.g. Wingfield et. al., 1985).

Somewhat surprising was the lack of a relationship between participants' selective attention, as measured by the interference score on the Stroop test, and their speech recognition performance in noise score. One exception, was the significant relationship between OHI participants' speech understanding performance in the SSN condition and their interference score on the Stroop test ($r = -.657$, $p = .004$). Intuitively, proficiency in being able to selectively attend to a target should be important for *all* listeners in discriminating between a target voice and a background noise masker. However, our results suggests that participants' working memory and processing speed abilities are more predictive of speech understanding performance in noise than selective attention.

Objective Listening Effort

In the current study, we used a dual-task paradigm to assess objective listening effort in younger and older participants on a speech recognition in noise task. Specifically, we used a visual rotor tracking task (i.e DPRT) as the secondary task, and a sentence recognition in noise test as the primary task. Listening effort was calculated as the *change* in a participant's performance on the secondary task (DPRT) from the baseline to the dual-task condition, while performance on the primary task remained constant. We found that the older participants' (ONH, OHI) expended significantly more listening effort to understand speech in the TT and SSN background noise masker conditions than the younger participants. Thus, older adults needed to expend more effort than younger adults to obtain similar speech recognition scores (e.g. ~76%) on the TT and SSN masker conditions. This finding is consistent with fMRI studies that have shown increased neural activation in the cognitive brain regions (e.g. prefrontal cortex) of older adults' who are able to obtain similar performance scores on a speech recognition in noise task as younger adults (Desjardins et. al., 2009; Wong et. al., 2009). Interestingly, no significant difference in listening effort was observed between the ONH and OHI participants in this study. This suggests that the older adults, independent of peripheral hearing loss, required more cognitive resources to understand speech in background noise, which left them with fewer resources to perform the secondary task (e.g. DPRT), than younger adults.

The listening effort results from this study demonstrate that overall percent correct scores on speech recognition tasks provide only a general measure of listeners' speech perception abilities. They do not provide insight into the factors that contribute to a listener's performance score (e.g. listening effort). For example, the older and younger listeners in this study achieved the same percent correct scores (~76%) on the sentence recognition in noise tasks. Based on speech recognition scores alone, one would conclude that there was no difference in these participants' ability to understand speech in background noise. However, the older participants' in this study expended approximately eight times more effort than the younger participants to obtain a 76% correct score on the SSN masker condition. If this were a real life listening situation, one could imagine the older person would fatigue sooner than the younger listener and stop engaging in the listening situation.

Thus, this finding highlights the importance of instituting multiple measures of speech recognition performance (e.g. speech recognition and listening effort) into clinical and research audiological practice. Currently, speech recognition testing is an integral part of a hearing evaluation however, assessing listening effort is not. When speech recognition ability is based solely on a listener's speech recognition score, it could mislead the clinician or researcher to assume an individual has little difficulty understanding speech in noise, when in fact it could be very challenging for the individual.

Several listening effort and speech recognition in noise studies have reported similar decrements on secondary task performance (e.g. Sarampalis, Kalluri, Edwards, Hafter, 2009; Downs, 1982; Gosselin and Gagne, 2010). Most recently, Gosselin and

Gagne (2010) used a dual-task paradigm to investigate listening effort and speech recognition in noise for younger and older adults. The primary task was a closed set sentence recognition test presented in a pink noise masker at a fixed SNR (e.g. -12 SNR) and at an equated performance level of 80%. The secondary task was a vibro-tactile pattern recognition test on which participants were asked to identify pulse combinations (e.g. long-short-long) emanating from a vibrating device that they held in their hand. Listening effort was defined as the change in the participant's performance from the baseline to the dual-task condition on the secondary vibro-tactile test. They found that older adults expended more listening effort than younger adults in both the fixed SNR and equated performance conditions. They concluded that this increased listening effort was *likely* due to a combination of age-related changes in sensory and cognitive function. However, such an interpretation is difficult because the authors did not control for sensory function (i.e. hearing threshold level were only screened at 25 dBHL from 250 to 2000 Hz). In addition, they did not employ any formal measures of cognitive function, they only screened for gross cognitive impairment.

The general trend reported by Gosselin and Gagne (2010) that older adults expend more listening effort than younger adults when understanding speech in a non-speech background noise is consistent with our results. It would be interesting to compare the *amount* of listening effort expended by the younger and older adults in the two studies however, because the methods were different across studies it is not possible. Although both studies used a dual-task paradigm and quantified listening effort as the difference between the baseline secondary task and dual-task conditions, the secondary tasks used in the two studies were very different. Specifically, in our study we used a visual tracking task (DPRT), and Gosselin and Gagne used a tactile task. Unfortunately, because objectively measuring listening effort is relatively new in audiology, standard methods of measurement do not exist. Thus, it is challenging and often impossible to make direct comparisons across studies.

Although only assumed in many studies, we directly measured a relationship between listening effort on a speech recognition in noise task and cognitive ability. Specifically, the listening effort participants' expended on the sentence recognition in noise task in SSN and TT masker conditions was significantly associated with their working memory, and processing speed performance. This result is consistent with the many studies that have suggested listening in noise is more difficult and effortful for older participants because they must exert more cognitive resources to maintain listening performance similar to younger normal-hearing participants (Desjardins, et. al. 2009; Hallgren, Larsby, Lyxell & Arlinger, 2005; Humes, 2007).

Further support for our finding comes from a recent MRI study (Wong et. al., 2010) which reported a strong relationship between speech recognition in noise and cognitive function. Specifically, Wong et. al. (2010) examined speech recognition in noise in a group of older and younger adults with normal hearing thresholds using behavioral and MRI measures. They found that older adults who performed poorest on the behavioral speech understanding in noise task had a smaller prefrontal cortex volume and thickness compared to younger and older listeners who performed best on the speech recognition in noise task. They describe their results as consistent with the neural compensation hypothesis, which states that some older adults are able to compensate for declines in performance by recruiting more general cognitive areas of the brain (e.g.

prefrontal cortex).

It was surprising that the only significant difference in listening effort across the three masker conditions, despite significant differences in SNRs, was between the SSN and SIX masker conditions for the YNH group of participants. Specifically, the YNH group expended more listening effort on the SIX masker condition than the SSN condition. We expected that all participants would expend more effort on the most "difficult" masker condition (e.g. TT). One explanation may be that the DPRT baseline of 80% time-on-target was too easy for participants, and therefore, not sensitive enough to detect differences in effort across the masker conditions. For example, if the baseline level was too easy, it is likely that changes in DPRT performance (e.g. listening effort) would occur only if there were very large differences in the difficulty between conditions. In the current study, however, there were relatively small differences (e.g. only 2-5 dB SNR) in difficulty between the conditions.

We chose to use a DPRT baseline level of 80% time-on-target performance in this study based on previously reported DPRT results from younger and older participants (Kemper et. al., 2009). Our study, however, was the first to use the DPRT to measure effort on a *listening* task and the first to measure listening effort across different masker conditions. By using this baseline level, we were able to equate the difficulty of the secondary task across the three groups of participants, and avoid floor and ceiling effects on performance. However, in future studies, it may be beneficial to perform more extensive pilot testing of DPRT baseline performance levels in order to determine the best level for detecting small changes in listening effort across masker conditions.

Another possible reason why we did not find significant differences in listening effort across the three masker conditions was because we equated the participants' performance (76%) on the primary speech recognition in noise task. Specifically, the examiner adjusted the SNRs for each participant in each masker condition to generate approximately 76% correct scores on the task. We chose to equate performance across the three groups of participants and the three masker conditions to make the primary task equally difficult, and to avoid any potential floor and ceiling effects. However, if we had used a fixed SNR across the masker conditions, simulating more real world listening conditions, the TT listening condition would have been more difficult compared to the SSN condition, and more difficult for the OHI group compared to the YNH group. For example, one OHI participant in this study required the SNR to be adjusted 5 dB between the SSN and TT masker conditions. In theory, if we had used a fixed SNR in this study, the difference in performance between these two masker conditions could have been as much as 50% (Duquesnoy, 1983). Thus, by using a fixed SNR, we would have expected to observe greater differences in listening effort across the masker conditions, but at the same time we would have likely encountered floor effects.

Listening vs. Repeating Sentences

To better understand how listeners' process speech in noise we measured listening effort while they were listening to the sentence and when they were verbally repeating the sentence (e.g. responding). We found that all listeners expended more effort when listening to the sentences compared to when they verbally repeated the sentences. This was consistent across participant groups and masker type for high and low context sentences. Thus, the participants' general processing strategy was to expend more processing resources when the sentences were initially presented and fewer resources when they repeated the sentences back. Thus, participants were able to expend the majority of processing resources to decipher rather than to produce the sentence. If the listeners in this study had neurological impairments or articulation disorders then this strategy may have been different.

Contextual Cues

To compare participants' speech recognition performance for high verses low context sentences, percent correct scores were calculated separately for the high and low context subsets of each R-SPIN sentence list. Results showed that all three groups of participants in this study scored significantly better on the high context compared to the low context sentences. However, the difference between high and low context scores was significantly greater for both groups of older participants compared to the younger participants. This suggests that the older participants, independent of peripheral hearing impairment, benefited more from the contextual cues in the sentences than the younger participants.

That is, the older adults with and without hearing impairment derived more benefit from the contextual cues in the sentences than the younger adults. Pichora-Fuller et. al. (1995) reported a similar result regarding younger and older listeners' ability to process high and low context sentences in background noise. Specifically, they found a significant difference in the psychometric functions for high and low context SPIN sentences in younger and older adults. They concluded that in difficult listening situations, older listeners must rely more on the context in sentences to decipher the target signal than younger listeners. Furthermore, they state that older adults' reliance on contextual cues requires them to expend greater listening effort to understand speech in background noise compared to younger adults.

If this assumption is true, we would have expected to observe a significant difference in listening effort between the older and younger participant groups, which we did. However, we did not observe any difference when we measured listening effort separately for the high and low context sentences across or within the participant groups.

Initially, we assumed that the low context sentences, which were significantly more difficult to recognize than the high context sentences, would require participants' to expend more listening effort to process. However, based on Pichora-Fuller et. al. 's (1995) assumption, the high context sentences should have required participants to expend more listening effort to process the contextual information. Although we did observe a difference in overall listening effort across the younger and older participant groups, that is both groups of older participants expended significantly more listening effort understanding speech in background noise compared to the younger participants, the listening effort for the high and low context sentences was the same. Again this may be because the relatively high baseline performance (e.g. 80% TOT) we selected for the DPRT was not sensitive enough to pick up a difference in listening effort between the high and low context sentence conditions.

Subjective Listening Effort

We asked participants' to subjectively rate how easy it was to listen to sentences in each of the three background noise masker conditions using a scale of 0 to 100, with 0 being defined as very, very difficult and 100 being defined as very, very easy. All three participant groups rated the SSN masker condition the easiest and TT masker condition to be the most difficult. Thus, the participants' ratings were consistent with the continuum of difficulty across the masker conditions. Interestingly, the OHI group rated listening to be relatively easier across all three masker conditions compared to the ONH and YNH groups. We assumed that the OHI group would rate the three listening tasks to be the most difficult compared to the ONH and YNH groups, because they required the most favorable SNRs across the masker conditions. However, perhaps because the OHI participants find noisy everyday listening situations to be extremely challenging, our SNR adjustment to make speech recognition 76% correct was easier for them than they are typically used to when listening in noise in “real life”..

We found no significant relationship between objective measures of listening effort (e.g. changes in DPRT performance) and subjective ease of listening ratings regardless of masker condition or participant group. Specifically, the YNH participants subjectively rated the listening in noise task to be more effortful in all three masker conditions, compared to their objective listening effort scores. Conversely, the older participants (ONH and OHI) subjectively rated the listening in noise task to be *less* effortful across the three masker conditions compared to their respective objective listening effort scores. This finding is consistent with several studies which have examined objective and subjective measures of listening effort in adults (e.g. Downs & Crum, 1978; Feuerstein, 1992; Gosslein & Gagne, 2010). For example, Feurerstein (1992) used a subjective rating scale ranging from difficult (e.g. 0) to easy (e.g. 100) to examine perceived ease of listening, and a reaction time task to measure objective listening effort. He found that while the ease of listening ratings were correlated with performance accuracy on the primary speech task, objective measures of listening effort were not correlated with subjective ratings. He suggested that while subjective ease of listening ratings may provide an indication of one's perception of effort or ease of listening in a listening situation, they do not appear to reflect the availability or demand on processing resources (Wickens, 1992). In other words, although listeners may expend more resources to recognize speech in noise they may not always be able to perceive this increase.

CONCLUSIONS

In summary, the primary findings from this study are:

1) Older listeners with and without hearing loss expend significantly more objective listening effort than younger listeners to obtain the same speech recognition score in a TT and SSN background noise.
2) Older listeners, regardless of peripheral hearing impairment, expend the same objective listening effort to understand speech spoken in both speech and non-speech background noise maskers.
3) Working memory and processing speed are significantly associated with speech recognition performance in noise (speech and non-speech) for both younger and older listeners.
4) Working memory and processing speed are significantly correlated with objective listening effort on speech in noise recognition tasks (two-talker and speech-shaped noise maskers).
5) The amount of listening effort adults expend on a speech in noise task differs based on whether it is quantified using a subjective or objective measure of

listening effort.

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