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Hearing Loss And Verbal Memory Assessment In Older Adults

Christina G. Wong
Wayne State University,

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HEARING LOSS AND VERBAL MEMORY ASSESSMENT IN OLDER ADULTS

by

CHRISTINA G. WONG

DISSERTATION

Submitted to the Graduate School

of Wayne State University,

Detroit, Michigan

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for the degree of

DOCTOR OF PHILOSOPHY

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MAJOR: PSYCHOLOGY (Clinical)

Approved By:

Advisor Date

DEDICATION

I dedicate this dissertation to my family and friends. To my parents, Elaine Gerhardstein and Christopher Wong, thank you for your unwavering support and encouragement. From helping with science fair projects to proofreading essays, you helped me get to this point in so many ways. To my brother, Alexander Wong, thank you for always cheering me on.

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CHAPTER 1 INTRODUCTION

Age-related hearing loss, also known as presbycusis, is one of the most common chronic health conditions among older adults (Collins, 1997; Lethbridge-Cejku, Schiller, & Bernadel, 2004). In the United States, hearing loss is prevalent in nearly two thirds of adults age 70 years and older (Lin, Thorpe, Gordon-Salant, & Ferrucci, 2011). Despite the high prevalence of hearing loss, treatment via hearing aid use is consistently low: Approximately 22.9 million older Americans with hearing loss do not use hearing aids (Chien & Lin, 2012). Many factors contribute to low hearing aid use including cost, stigma, and competing chronic health conditions (Barnett et al., 2016). Even if hearing aids are obtained, they do not fully alleviate communication difficulties, especially under degraded listening conditions (Gordon-Salant, 2005).

Presbycusis is typically characterized by high-frequency sensitivity loss, which is especially impairing, as the ability to hear high-frequency sound is crucial for speech perception. Figure 1 illustrates the sloping pattern of age-related hearing loss in average adults.

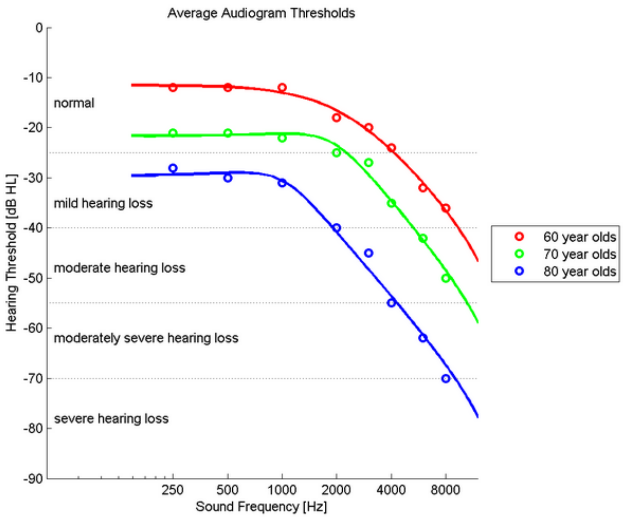


Figure 1. Average Age-Related Hearing Loss in 60-, 70-, and 80-Year Old Adults.

High-frequency loss affects one-to-one communication and can cause substantial difficulties in group conversations (Oberg, Marcusson, Nagga, & Wressle, 2012). Diminished ability to hear is related to adverse consequences such as reduced quality of life, depression, and functional decline in older adults (Carabellese et al., 1993).

Hearing is a complex process that involves both peripheral structures (e.g., eardrum, cochlea, etc.) and the central nervous system (e.g., auditory cortex). In the inner ear, the cochlea converts the mechanical energy of sound into electrical signals that are passed along the auditory nerve to the brain. The auditory cortex interprets this information as sound. Age-related hearing loss is most commonly due to sensorineural hearing loss, which involves changes in the inner ear. Noise exposure and health conditions such as high blood pressure and diabetes can also contribute to hearing loss (Frisina, 2009).

Previous research has found that hearing impairment is associated with low cognitive functioning (Anstey, Luszcz, & Sanchez, 2001a; Gates et al., 1996; Lin, 2011; Lindenberger & Baltes, 1994; Uhlmann, Larson, Rees, Koepsell, & Duckert, 1989; van Boxtel et al., 2000); however, many cognitive domains, particularly verbal memory, are assessed using neuropsychological tests that involve auditory stimuli. One of the most common ways to assess memory is by using multi-trial word learning tests read aloud to an examinee who is asked to recall the words immediately after presentation and after a delay period (Lezak, Howieson, Bigler, & Tranel, 2012). The detrimental effects of reduced sensory sensitivity on cognitive test performance are generally overlooked, which could potentially result in overdiagnosis of memory problems in individuals with hearing loss. Inaccurate diagnosis of cognitive impairment could have serious implications for patients, their families, and the overall healthcare system.

Seminal population studies demonstrated the association between sensory sensitivity and cognitive abilities, and showed that the strength of this association increases with age (Lindenberger & Baltes, 1994, 1997). Since then, a growing body of research has examined the link between sensory loss, cognitive functioning, and aging (for reviews, see Fortunato et al., 2016; Gallacher, 2004; Wayne & Johnsrude, 2015). Several hypotheses have been proposed to explain the relationship between hearing loss and performance on cognitive tests in older adults:

1. **Common cause hypothesis**: Widespread neural decline related to common factors results in reduced hearing sensitivity, auditory processing, and cognitive abilities.
2. **Deprivation hypothesis:** Adverse consequences of age-based reductions in sensory input accumulate over time and lead to structural and/or functional changes in the brain.
3. **Resource allocation hypothesis:** Increased listening effort taxes allocation of cognitive resources for understanding speech, which in turn, depletes cognitive resources normally dedicated to the task at hand.
4. **Perceptual degradation hypothesis:** Poor performance on neuropsychological tests simply reflects an auditory disadvantage due to hearing loss (i.e., stimuli are not heard or they are misperceived during auditory presentation).
5. **Social isolation hypothesis:** Individuals with hearing loss have reduced social engagement, which in turn, negatively affects cognitive functioning.

A review of the literature shows that there is mixed support for these hypotheses. Many studies tend to support one of two main pairs of hypotheses: The common cause and deprivation hypotheses versus the perceptual degradation and resource allocation hypotheses. Due to their nature, it is difficult to delineate support for the hypotheses within each pair. For example, a study that finds support for the common cause hypothesis cannot rule out the deprivation hypothesis unless it employed a longitudinal design that follows individuals prior to the onset of cognitive and sensory decline. Of course, this kind of longitudinal design involving multiple time points is methodologically challenging. Similarly, establishing support for the perceptual degradation hypothesis, by showing that improving hearing sensitivity by use of hearing aids or sound amplification results in improved cognitive test performance, also supports the resource allocation hypothesis. Improving hearing sensitivity would reduce the amount of cognitive resources needed for speech perception and would, in turn, theoretically result in improved cognitive test performance. In sum, the two hypotheses are inextricably confounded.

Common cause/deprivation hypothesis

Support for the common cause hypothesis has been demonstrated in a number of ways. One line of support comes from research showing that performance on auditory and *visual* cognitive tests is impaired in individuals with hearing loss (Dupuis et al., 2014; Gates et al., 2010; Granick, Kleban, & Weiss, 1976; Harrison Bush, Lister, Lin, Betz, & Edwards, 2015; Lin, Ferrucci, et al., 2011; Uhlmann, Teri, Rees, Mozlowski, & Larson, 1989; Valentijn et al., 2005). Such results indicate that poor test performance in older adults with hearing loss is not limited to tests that involve auditory presentation of stimuli. Theoretically, use of visual neuropsychological tests rules out the possibility that test performance below expectation is due to solely to misperception of auditory stimuli (perceptual degradation hypothesis) or increased dedication of cognitive resources to perceptual processing during testing (resource allocation hypothesis). These findings are consistent with the idea that a common underlying neurological factor might be driving both reductions in hearing and cognitive abilities across sensory modalities. Overall, findings related to hearing loss and performance on visual cognitive tests are mixed.

Additional support for the common cause hypothesis comes from findings that show a significant association between hearing loss and increased prevalence of dementia (Gold, Lightfoot, & Hnath-Chisolm, 1996; Gurgel et al., 2014; Lin & Albert, 2014). In addition, higher prevalence of hearing loss has been found among individuals with Alzheimer's disease compared to demographically-matched, non-demented controls (Uhlmann, Larson, et al., 1989). Longitudinal studies have also shown that baseline-hearing status is predictive of which individuals will go on to develop dementia (Gallacher et al., 2012; Gates et al., 1996; Lin et al., 2013). For example, Lin et al. (2013) demonstrated that hearing loss at baseline is independently associated with a 30 – 40% rate of accelerated cognitive decline over a 6-year period. Accelerated cognitive decline among individuals with hearing loss was not limited to performance on auditory cognitive tests. Although the common cause hypothesis is a possible explanation, the authors noted that the measure of hearing loss used (pure tone audiometry) reflects peripheral hearing loss, which has not been found to be related to Alzheimer's disease neuropathology.

Neuroimaging studies have revealed that hearing impairment is associated with reduced cortical volume in the auditory cortex (Peelle, Troiani, Grossman, & Wingfield, 2011) as well as accelerated rates of lateral temporal lobe and whole brain atrophy (Lin et al., 2014). In addition, functional neuroimaging studies have demonstrated compensatory recruitment of frontal and temporoparietal regions for auditory speech processing in older adults (Wingfield & Grossman, 2006) and that older adults have less overall temporal and occipital cortical activation compared to younger adults when presented with auditory stimuli (Cliff et al., 2013). These findings suggest that not only deficits at the peripheral level might interfere with performance on memory testing, but rather that reduced auditory cortex activation during perception of auditory stimuli in older adults could negatively affect the quality of information available to higher-order cognitive processes such as memory.

There is some support uniquely for the deprivation hypothesis. Animal models of hearing impairment show that degraded auditory signals and reduced stimulation from an impaired cochlea may *precipitate* changes in cortical reorganization and brain morphometry (Fetoni et al., 2013). Findings from longitudinal human studies are inconclusive. Valentijn et al. (2005) found that a decline in auditory sensitivity predicted a decline in memory performance; however, the study did not find convincing evidence for a time lag between reduced hearing sensitivity and cognitive functioning.

Perceptual degradation/resource allocation hypothesis

One form of support for the perceptual degradation hypothesis comes from studies that show that the association between hearing impairment and cognitive decline is *not* retained when *visual* cognitive tests are used (Granick et al., 1976; Gussekloo, de Craen, Oduber, van Boxtel, & Westendorp, 2005; Wong, Yu, Chan, & Tong, 2014; Zekveld, Deijen, Goverts, & Kramer, 2007). Such results indicate that cognitive ability is preserved in the context of hearing loss; thus, findings that hearing loss is related to cognitive decline could be due to reliance on auditory cognitive tests. One study actually found that severity of hearing loss was *positively* associated with performance on a spatial working memory task (Zekveld et al., 2007). The authors suggested that individuals with hearing loss might use working memory as a compensatory mechanism.

Some research examining the perceptual degradation hypothesis has utilized experimental simulations of reduced hearing sensitivity designed to resemble age-related hearing loss (Lindenberger, Scherer, & Baltes, 2001; Murphy, Craik, Li, & Schneider, 2000; Rabbitt, 1968). For example, Lindenberger et al. (2001) simulated reduced auditory sensitivity in middle-aged adults with normal hearing by using noise-protector headphones. Unexpectedly, participants with simulated sensory impairment showed slightly higher levels of performance in reasoning and knowledge than controls. The authors suggested that the unexpected finding might have been due to redundancy between visually and auditorily presented information as well as a reactive increase in attention and effort to compensate for the simulated losses. The finding of improved cognitive performance under unfavorable listening conditions has also been shown in young adults with normal hearing (Neidleman, Wambacq, Besing, Spitzer, & Koehnke, 2015). Lindenberger et al. (2001) also reported that experimentally-induced auditory sensitivity reductions resulted in worse performance on an auditory working memory task (which was unimodal in presentation). Although the authors concluded that their findings do not provide support for the perceptual degradation hypothesis, the study only included middle-aged adults and hearing loss was simulated by use of noise protectors, which likely did not fully capture the complexity of age-related hearing loss.

Results from other simulated hearing loss studies have demonstrated support for the perceptual degradation/resource allocation hypothesis (Baldwin & Ash, 2011; Jorgensen, Palmer, Pratt, Erickson, & Moncrieff, 2016; Murphy et al., 2000; Rabbitt, 1968; Tun, McCoy, & Wingfield, 2009). Jorgensen et al. (2016) examined the effect of reduced audibility via hearing loss simulation on a global screening measure (Mini Mental State Exam; MMSE) among young adult participants with normal hearing. They found that the majority of participants who completed the MMSE with reduced audibility would have been classified as having dementia, despite being cognitively intact, and that as the amount of simulated hearing loss increased, MMSE performance decreased. Murphy et al. (2000) found that word list recall of young adults tested in noise was equivalent to word list recall of older adults with normal to mild hearing loss tested in quiet. The results are consistent with predictions that age-related performance on memory tests reflect concomitant sensory losses. The authors proposed that the resource allocation hypothesis is a possible explanation of these findings and stated that aging and testing in noise are similar in that they are both associated with a reduction in processing resources. Overall, the authors conclude that both age-related sensory loss and an age-related reduction in cognitive resources influence performance on memory tests.

Rather than simulate hearing loss in young or middle-aged adults, Verhaegen, Collette, and Majerus (2014) compared performance on verbal short-term memory tests between older adults and young adults with hearing loss matched for hearing threshold (average pure-tone audiometry thresholds for 500, 1000, and 2000 Hz were 17.13 dB HL and 17.24 dB HL, respectively). A group of young adults with normal hearing was included as well. Results indicated that elderly and hearing-matched young adults showed equal levels of performance on all verbal short-term memory tasks, and both groups performed lower than normal-hearing young control participants. The authors interpreted these findings to suggest that deficits seen on cognitive testing are due to reduced auditory sensitivity and not cognitive impairment, as young adults with mild hearing loss performed similarly to older adults. Explanation of these findings also included the resource allocation hypothesis.

Other research has examined the effect of improved hearing via hearing aids on cognitive test performance. Per the degradation hypothesis, improving hearing sensitivity should theoretically lead to improved test performance on auditory cognitive tests because difficulty related to perceiving stimuli is reduced. Alternatively, in the long term, hearing aid use may also address reduced sensory input due to hearing loss that could lead to functional and structural brain changes (deprivation hypothesis). Results from studies on this topic are variable. A 25-

year, longitudinal study found that self-reported hearing loss at baseline was associated with accelerated cognitive decline but that hearing aid use attenuated this relationship (Amieva et al., 2015). Because of lack of randomization though, differences between groups may have been related to unmeasured participant characteristics. Hearing aid use has been associated with better performance on *visual* cognitive tests, suggesting that the benefit of hearing aid use on cognitive performance is not solely due to improved audibility of test stimuli (Dawes et al., 2015). On the other hand, other studies have found that intervention with hearing aids did not result in better cognitive performance compared to testing done prior to receiving hearing aids (Allen et al., 2003; Valentijn et al., 2005; van Hooren et al., 2005) or only found a small effect (Mulrow et al., 1990). Wong et al. (2014) found that hearing aid users had worse cognitive performance compared to a normative sample of older adults but did not include a group of individuals with hearing loss who did not use hearing aids. Of note, results showing that hearing aids do not improve neuropsychological test performance might reflect that hearing aids do not fully correcting hearing (Wong et al., 2014). In addition, people often have hearing loss for many years before they seek treatment; thus, hearing aids might not address irreversible changes due to years of reduced sensory input (Wong et al., 2014). Many of these studies are limited due to small sample sizes, which limits power to detect differences across the conditions, as well as reliance on self-report of hearing loss and hearing aid use.

Combined Models

A number of these explanatory pathways co-exist and may jointly contribute to cognitive impairment in individuals with hearing loss (Lin, Ferrucci, et al., 2011). In a conceptual model by Lin and Albert (2014), hearing impairment might simultaneously lead to increased allocation of cognitive resources to hearing perception, changes in brain structure and function, and reduced social engagement, all of which contribute to impaired cognitive functioning. At the same time, there could be common etiology that is contributing to hearing impairment, the mediating variables, and cognitive decline.

A multi-level model by Li and Lindenberger (2002) suggests that the onset of age-related sensory decline is possibly earlier than the onset of age-related cognitive decline. Adaptation to hearing loss may occur in multiple ways including changes in neural structure and function, and in terms of modifications to attentional allocation, all of which may co-occur with neuropathological changes associated with cognitive impairment.

In a review of the effects of adult-onset hearing loss on cortical auditory regions, Cardin (2016) concludes that the combination of atrophy of cortical auditory regions in hearing loss and older age and degraded auditory input because of peripheral damage results in increased reliance on cognitive resources for accurate auditory perception. In turn, all listening is effortful and cognitive capacity for other tasks is reduced, both of which may be factors that contribute to accelerated cognitive decline in older adults with hearing loss (Cardin, 2016).

Ronnberg (2003) proposed the *ease of language understanding* (ELU) model to examine the association between hearing loss and cognitive decline. According to the ELU model, under optimal conditions, information processing involves “rapid, automatic, and multimodal binding of phonological information (RAMBPHO).” The process produces phonological information that “unlocks the lexicon” by matching phonological input with stored phonological representations in semantic long-term memory. Under suboptimal conditions (e.g., hearing impairment or noisy conditions), the likelihood of a mismatch between input and stored phonological representations increases. The mismatch triggers recruitment of resources to infer the meaning of the message based on both information retrieved from long-term memory and actual information being held in working memory. This model places working memory as a crucial component for compensating for hearing loss. With a mismatch, less information encoded into episodic long-term memory, and over an extended period, leads to "disuse" of episodic long-term memory and a subsequent decline in episodic long-term memory ability. Ronnberg et al. (2011) examined the relationship between sensory sensitivity and cognition among 160 hearing aid users without dementia and found that hearing loss was negatively related to long-term memory but not short-term memory, as predicted by the ELU model.

Although the theoretical concepts regarding the relationship between hearing loss and cognitive functioning have been expounded, research has not demonstrated compelling and consistent support for a particular model. Interest in this topic has been growing in recent years, especially in the field of audiology and otolaryngology, which will likely help to provide clarity regarding the underlying mechanisms. Psychologists are well positioned to contribute to understanding the association between hearing loss and cognition, and may bring new perspectives to the table. There remains much to be learned and interdisciplinary collaborations will be crucial for advancing knowledge in this area. At this point, however, it is clear that hearing loss has the strong potential to diminish auditory cognitive test performance.

Possible Solutions

As researchers have begun to consider that cognitive tests that utilize auditory stimuli may be invalid in the context of hearing loss, different approaches for addressing this problem have been proposed. One possibility is to use alternative scoring procedures that eliminate or reduce the weight of auditory items. For example, Dupuis et al. (2014) created and examined new scoring procedures for the Montreal Cognitive Assessment (MoCA) that removed different combinations of language-based items. Using the normal scoring procedures, only 38% of older adults with hearing loss scored above the cutoff for passing, which is lower than expected based on MCI prevalence rates. Using the alternative scoring procedures, both individuals with and without hearing loss were more likely to pass the MoCA, but the discrepancy between the groups was reduced. Of course, deviating from standard administration and scoring procedures may affect the validity of tests and reduce sensitivity for identifying genuine problems with cognition. Additional research in this area is needed before alternative procedures to accommodate hearing loss can be used clinically.

Another possible solution might be to utilize visual presentation modalities to assess cognitive domains normally evaluated using auditory cognitive tests such as verbal memory. Research specifically examining visual-verbal memory measures as alternatives to auditory-verbal memory measures in the context of hearing loss is limited; however, some studies have compared performance on auditory versus visual formats of the same test (Brand & Jolles, 1985; Dupuis et al., 2014; Rabbitt, 1990). For example, Rabbitt (1990) demonstrated that younger adults had better free-recall performance when words were presented aurally rather than visually, whereas older adults with mild hearing loss performed better when the words were presented visually compared to aurally. The degradation and resource allocation hypotheses were proposed as explanations for these findings.

An early study comparing auditory and visual multi-trial verbal free recall among healthy young adults found that there were no differential effects of presentation format on a number of performance variables and supported the clinical application of visual-verbal memory tests (Brand & Jolles, 1985). Valentijn et al. (2005) examined the effect of sensory sensitivity on performance on the Visual Verbal Learning Test (VVLT) created by Brand and Jolles (1985) and found that auditory sensitivity *change* from baseline to 6-year follow up was predictive of decline in VVLT. Baseline auditory sensitivity was not significantly related to any cognitive variables after controlling for age, educational attainment, and sex. Of note, the VVLT uses Dutch words and an equivalent English version does not exist.

Rationale

In summary, many studies find that hearing loss is adversely related to performance on cognitive testing (Harrison Bush et al., 2015; Lin et al., 2013); still, others find no association between hearing sensitivity and cognitive ability (Anstey, Luszcz, & Sanchez, 2001b; Gennis, Garry, Haaland, Yeo, & Goodwin, 1991; Hofer, Berg, & Era, 2003; Jones, Victor, & Vetter, 1984; Shahidipour, Geshani, Jafari, Jalaie, & Khosravifard, 2013; Vesterager, Salomon, & Jagd, 1988). Given mixed findings regarding the link between hearing loss and cognitive functioning and no conspicuous explanation regarding this relationship, additional research on this topic is needed. Studies utilizing experimental designs are limited and most research has sacrificed ecological validity for high internal validity.

Improving our understanding of the association between hearing loss and auditory-verbal memory assessment potentially has direct clinical implications regarding neuropsychological assessment and patient recommendations. Support for the perceptual degradation/resource allocation hypothesis would suggest that assessing verbal memory in an auditory modality would be invalid for individuals with hearing loss and could result in overdiagnosis of memory impairment in this population. A modified administration format, such as visual presentation of verbal stimuli, could potentially resolve this problem. On the other hand, if the common cause/deprivation hypothesis were supported, hearing loss in older adults might be a useful as a marker of cognitive dysfunction and continued use of auditory verbal memory tests would be substantiated.

With prevalence rates of dementia expected to double every 20 years resulting in an estimated 115.4 million individuals with dementia worldwide by 2050 (Ferri, Sousa, Albanese, Ribeiro, & Honyashiki, 2009), accurate assessment of memory ability is exceedingly crucial. Despite support that auditory and visual versions of word-learning tests are equivalent (Brand & Jolles, 1985), clinical neuropsychological assessment continues to rely on auditory-verbal memory tests for the assessment of verbal memory. One possible reason for the establishment of this practice is noted by Brand and Jolles (1985) who suggest that "most word-learning tests used in clinical neuropsychology are presented auditorily because visual presentation necessitates the use of a sophisticated apparatus such as slide projectors and/or computers" (p. 202) if precise control of presentation rate is desired. Although use of computers in neuropsychological testing is now commonplace, there is already a large body of literature surrounding auditory word-learning tests. Understandably, there is hesitancy to deviate from the "gold standard" method of verbal memory assessment; however, the questionable validity of using auditory cognitive tests with individuals with hearing loss motivates the need to challenge this practice.

The current study aimed to determine whether auditory-verbal memory tests are a valid way to assess memory in older adults with hearing loss and to examine the effect of different hearing conditions (optimal vs. non-optimal) on auditory-verbal memory performance in older adults with and without hearing loss. For individuals with hearing loss, optimal conditions were achieved via artificially boosted auditory input, whereas non-optimal conditions were status quo (i.e., auditory presentation at a normal speaking volume); for normal hearing adults, optimal conditions were status quo, whereas non-optimal conditions were achieved via a simulated hearing loss condition. The purpose of this study was also to examine the validity and utility of a *visual*-verbal memory test in older adults, which tests verbal memory without necessitating auditory processing. In addition, the current study examined the relationship between hearing ability, auditory-verbal memory, and other cognitive variables in older adults with and without hearing loss.

Specific Aims and Hypotheses

Although there is evidence to support both pairs of explanatory hypotheses (common cause/deprivation vs. perceptual degradation/resource allocation), a review of the literature provides compelling support for the perceptual degradation/resource allocation hypothesis. Thus, the specific hypotheses were made following the assumptions of the perceptual degradation/resource allocation hypothesis: (a) Poor performance on auditory cognitive tests in individuals with hearing loss is due to auditory disadvantage during testing (i.e., auditory stimuli are limited or distorted resulting in degraded information available for higher cognitive processes); and (b) increased listening effort taxes allocation of cognitive resources for understanding speech, which in turn, depletes cognitive resources normally dedicated to the task at hand.

Aim 1: Examine the Effect of Different Presentation Conditions on Verbal Memory Performance.

Hypothesis 1(a): As previous research has demonstrated that even mild hearing loss can result in reduced auditory-verbal memory performance (van Boxtel et al., 2000), it was expected that older adults with hearing loss would have worse auditory-verbal memory performance compared to older adults with normal hearing under a *natural auditory condition* (status quo presentation; i.e., normal speaking volume).

Hypothesis 1(b): A *crossed auditory condition*, in which adults with hearing loss completed a version of the auditory-memory test with amplified volume (optimal) and adults with normal hearing completed it under a simulated hearing loss presentation (non-optimal), was also examined. It was expected that performance on an auditory-verbal memory test administered under these conditions would yield worse performance among adults with normal hearing compared to adults with hearing loss.

Hypothesis 1(c): Between groups, visual-verbal memory performance would not differ meaningfully between older adults with hearing loss and older adults with normal hearing.

Hypothesis 1(d): Within groups, for both groups, auditory-verbal memory performance was expected to be better under an optimal hearing condition as compared to a non-optimal hearing condition. Among adults with normal hearing, auditory-verbal memory and visual-verbal memory would not meaningfully differ (Brand & Jolles, 1985). In contrast, among adults with hearing loss, visual-verbal memory performance was expected to be better than auditory-verbal memory performance (Rabbitt, 1990).

Aim 2: Compare Performance Between Groups on Neuropsychological Tests Across Other Domains.

Hypothesis 2(a): It was hypothesized that older adults with hearing loss would perform worse on other auditory cognitive tests compared to older adults with normal hearing.

Hypothesis 2(b): Performance on visual cognitive tests would not differ meaningfully between groups.

Aim 3: Determine the Extent to Which Other Cognitive Abilities are Related to Auditory- and Visual-Verbal Memory.

Hypothesis 3: For both groups, it was expected that working memory would be related to auditory-verbal memory performance, as it has been shown to be important for speech perception (Vaughan, Storzbach, & Furukawa, 2008; Waters & Caplan, 2001).

CHAPTER 2 METHOD

Participants

Participants were recruited from Henry Ford Health System (HFHS) Audiology Department and the community. Inclusion criteria for participants with hearing loss: (1) 55 – 85 years old; (2) moderate-to-severe hearing loss defined as a pure tone average (PTA) of 40-70 dB HL for one of two sets of frequencies: 1. .5k, 1k, and 2k Hz, or 2. 1k, 2k, and 4k Hz for the better ear; (3) hearing loss that is sensorineural in nature. Inclusion criteria for participants without hearing loss: (1) 55 – 85 years old; (2) normal to minimal hearing loss (PTA 0-25 dB HL). Exclusion criteria for participants in both groups: (1) non-English speaking participants; (2) less than 23/30 on mental screening test; (3) vision worse than 20/40 after correction with glasses or contact lenses; (4) documented stroke, brain injury, or other neurologic condition that could invalidate testing data; (5) current psychiatric or medical condition that could interfere with cognitive testing; (6) conductive or eighth nerve disorders or middle ear dysfunction.

The total sample collected included 130 participants. Participants with thresholds < 25 dB at .5k, 1k, 2k, and 4k Hz were classified as passing the criteria for normal hearing. Six participants who tested with one frequency in one ear > 25dB also were classified as passing and included in normal hearing group. Of the 69 individuals recruited for the NH group, 20 did not meet the hearing screen criteria. Eight individuals were excluded because they did not meet other inclusion criteria (e.g., current psychiatric or medical condition that would interfere with cognitive testing), resulting in 41 included participants in the NH group. In the HL group, 61 individuals were recruited and 6 were excluded for not fully meeting the inclusion criteria, resulting in 55 eligible participants. Preliminary analysis indicated that there was a significant age difference between the groups. Because age is associated with cognitive test performance, the systematic confounding of age and group was resolved via matching the two groups on age. Thus, 41 participants from the HL group were matched on age ($\pm$ 3 years) to the 41 participants in the NH group. The resulting groups were not significantly different in age, $t(80) = 1.88$, $p = .06$, or gender proportion, X^2 $(1, N = 82) = 0.78$, $p = .37$. Power analyses confirmed that a medium effect size could be detected with this sample size; with parameters alpha = .05 and $N = 82$, power is .80 to detect an effect size Cohen's d = 0.55.

Measures

Sensory Testing

Audiometric Evaluation: Results of standard clinical audiometric testing were obtained for participants with hearing loss recruited from HFHS Audiology. Audiometric threshold measurement was evaluated with a Grason-Stadler model 61 (GSI 61) audiometer calibrated to American National Standards Institute (ANSI) 1996 standards. Pure-tone air conduction thresholds are obtained with EAR 3A insert earphones for test frequencies of 0.5, 1, 2, 3, 4, and 8 kHz. For each test frequency, the initial presentation level is 30 dB HL, after which intensity is decreased in 10 dB steps until the participant fails to respond. Presentation levels are then increased by in 5 dB steps following each no-response presentation until a response is observed. Levels are then decreased by 10 dB until the subject no longer responds. Ascending trials are repeated three times, and threshold is operationally defined as the lowest level at which responses are obtained on two of three ascending trials.

Word-recognition scores are obtained with recordings (Auditec Ordered by Difficulty Version II) of the Northwestern University Auditory Test #6 (NU-6). Words are presented from a computer through the GSI 61 at 80 dB HL. Scores are expressed as the percentage correct of the 25 words presented.

Middle-ear function is assessed with a Grason-Stadler immittance meter (GSI TympStar) calibrated to ANSI 1989 standards. Vector tympanograms are obtained with a 226 Hz probe tone. Ear-canal air pressure is varied from +200 to -200 daPa as acoustic admittance is measured. Ipsilateral acoustic reflex thresholds are obtained at 1 and 2 kHz; contralateral reflex thresholds were obtained at 0.5, 1, and 2 kHz.

For participants with hearing loss recruited from the community, free hearing evaluations were completed at the Wayne State University Audiology Clinic using similar procedures as described for the HFHS hearing test. For participants with hearing in the normal range recruited from the community, audiometric evaluations were conducted with a portable audiometer and consisted of a standard audiometric screening.

Both groups completed the following measures:

<u>Rosenbaum Pocket Vision Screener:</u> The Rosenbaum Pocket Vision Screener is a brief measure of visual sensitivity. A chart with 10 lines of block numbers is presented 14 inches from the participant. The first line consists of two large numbers and each subsequent line consists of numbers that gradually decrease in size. The examinee covers one eye and reads each line aloud, then repeats the process with the other eye.

Neuropsychological Measures

Each of the participants completed a comprehensive neuropsychological battery that included employed widely used and well validated clinical tests, each of which has been shown to meet contemporary psychometric standards for reliability and validity (Lezak et al., 2012; Strauss, Sherman, & Spreen, 2006).

<u>Mini-Mental State Exam (MMSE; Folstein, Folstein, & McHugh, 1975):</u> The MMSE is a 30-point global cognitive screening measure, which is often used to screen gross cognitive

functioning and dementia (Tombaugh & McIntyre, 1992). Scores less than 23 are considered impaired. It takes 5-10 minutes to administer the test, which includes measures of registration, attention and calculation, delayed recall, language, ability to follow commands, and orientation.

Test of Premorbid Functioning (TOPF; Wechsler, 2009): Recognition vocabulary is relatively robust to brain insult and it is a useful estimate of general intellectual ability (Green et al., 2008). The TOPF is a widely used word reading test that utilizes atypical grapheme-phoneme translation to provide an estimate of IQ. It is normed for ages 16:0 – 90.11 years.

Hopkins Verbal Learning Test-Revised (HVLT-R; Brandt & Benedict, 2001): The HVLT-R is a brief auditory-verbal list learning and memory test (immediate recall, delayed recall, and delayed recognition) with six alternate forms. The test is widely used in research and clinical settings with older adults. A list of 12 words is auditorily presented three times. After each presentation, the participant is asked to recall as many words as possible in any order. The three trials provide an estimate of learning/encoding, and scores for each trial are summed to produce a total immediate recall score (Total Recall). Following a 20- to 25-minute delay after the third trial, participants are asked to recall as many words as possible (Delayed Recall). The percent of information retained (Retention) is calculated by dividing the Delayed Recall score by the higher score of Trials 2 and 3, then multiplying by 100. Last, a recognition portion of the test is administered in which 24 words (12 targets and 12 foils) are read to the participant. Participants are instructed to respond "yes" if the word was on the list or "no" if the word was not on the list. Recognition Discriminability is determined by subtracting false positive errors from recognition hits. Norms are available for adults aged 16 to 92 years.

Three alternate forms were used in the present study. The two forms selected for the auditory presentation format (Forms 4 and Form 6) were chosen because they are similar on average number of syllables, as monosyllabic words are more difficult to perceive than multisyllabic words (Kirk, Hay-McCutcheon, Sehgal, & Miyamoto, 2000). Video recordings of an examiner presenting the HVLT-R were created at Wayne State University and Detroit Public Television Midtown TV Studio. The videos were presented to participants over noise-canceling headphones via a portable computer to control for administration differences. Video recordings also provided ecologically valid lipreading cues, which have shown to be important in previous research (Jesse & Janse, 2012), unlike an auditory-only presentation format. Information regarding the nature of the task was provided to participants prior to viewing the videos and standardized test instructions were included in the videos.

Form 1 of the HVLT-R was used in a visual-verbal memory presentation paradigm. A visual version of the HVLT-R was created for computerized presentation via Microsoft PowerPoint. Participants were shown printed words presented at the rate of one per 2 seconds on a computer screen, rather than words presented in the standard auditory format. The word font was a commonly used, easy to read font (Times New Roman, 60-point). White text with a black background was presented. As with the standard format, participants provided their answers orally and the examiner recorded their responses on a test form.

<u>Brief Visuospatial Memory Test-Revised (BVMT-R; Benedict, 1997):</u> The BVMT-R is a measure of visuospatial memory that involves three Learning Trials, a Delayed Recall Trial, and a Recognition Trial. For each learning trial, the participant views the stimulus page for 10 seconds and then is asked to draw as many of the figures in their correct location as possible. After a 25-minute delay, the participant is asked to draw the figures again from memory. The Recognition Trial, in which the participant is presented with 12 figures and asked to identify the six target figures, is administered last. The test is normed for ages 18 to 79 years.

Wechsler Adult Intelligence Scale-4th Edition (WAIS-IV; Wechsler, 2008) Digit Span: Digit Span is measure of auditory attention and working memory, in which a series of numbers are read aloud by an examiner. It consists of three sections: Forward, Backward, and Sequencing. For the Forward trials, the participant is instructed to repeat back the numbers in the same order. For the Backward trials, the participant is instructed to repeat the numbers in the reverse order. For the Sequencing trials, the participant is instructed to repeat the numbers in order from lowest to highest. Scores for the three sections are totaled to yield a Total Digit Span score. Reliable Digit Span was calculated as a measure of task engagement by summing the forward and backward span length for the highest completely correct (2-point) items.

eCorsi Block Tapping Test (Brunetti, Del Gatto, & Delogu, 2014): This test provides an index of visuospatial working memory. The task is administered using an iPad. Examinees are required to mimic a sequence of spatially separated blocks in the same order in which they light up for the Forward condition; they must respond in the reverse order of presentation for the Backward condition. Trial lengths range from two to nine blocks. The longest span for the Forward and Backward conditions were used for this study. According to the test authors, error rates for this computerized version are essentially analogous to errors rates for the original, physical version of the Corsi test (Brunetti et al., 2014).

Wechsler Adult Intelligence Scale-4th Edition (WAIS-IV; Wechsler, 2008) Coding: This test is a widely-used index of processing speed. The examinee copies symbols that are paired with numbers within a specified time limit of 120 seconds.

Wechsler Adult Intelligence Scale-4th Edition (WAIS-IV; Wechsler, 2008) Symbol Search: This test is a measure of processing speed for which examinees have to quickly identify whether visual stimuli match target symbols.

Trail Making Test (Reitan & Wolfson, 1993): This timed paper-and-pencil test consists of two parts. Part A (TMT-A) requires numerical sequencing, visual search, and perceptual-motor speed. Examinees are instructed to draw a continuous line to connect circled numbers from 1 to 25 in sequential order, with speed and accuracy. Part B (TMT-B) adds to the TMT-A task the component of letter sequencing and introduces a demand for cognitive flexibility and shifting of perceptual set. Examinees are instructed to connect numbers (1 – 13) and letters (A – L) in order, alternating between the two.

Judgment of Line Orientation (Benton, Hamsher, Varney, & Spreen, 1983): The Judgment of Line Orientation task is a measure of visuospatial judgment. The short-form (15-item version) was used (Woodard et al., 1996).

Apparatus

Portable audiometer: Individuals with normal hearing were screened using a Beltone Special Instruments 120 Audiometer Model 120. Air conduction screening testing were done using TDH-50 Earphones (noise-excluding headphones).

Headphones: Bose QuietComfort 25 Headphones are full-size, over-the-ear noise-canceling headphones were used for presentation of auditory-verbal memory stimuli.

Computer: A MacBook Air laptop computer (13.3-inch diagonal; LED-backlit glossy widescreen display, 1440-by-900 resolution; 4GB memory; 128GB flash storage) was used to present audiovisual test stimuli.

Video stimuli program: Two forms of the HVLT-R were videotaped in a professional audiovisual recording studio. The recordings were filmed as “talking head videos,” framed as a medium close-up with the examiner speaking directly to the camera. Special attention was paid to ensure adequate lighting to illuminate the face with minimal shadowing (e.g., standard three-point lighting; key, fill, and back lighting), and sound quality controlled by a sound engineer. Post-production audio editing yield two versions of each HVLT-R form: one with intact (unedited) audio and one with audio edited to mimic a common age-related hearing loss pattern. Figure 2 illustrates the pattern of hearing loss simulated for the video stimuli, which parallels average dB and frequency loss observed in moderate age-related impairment.

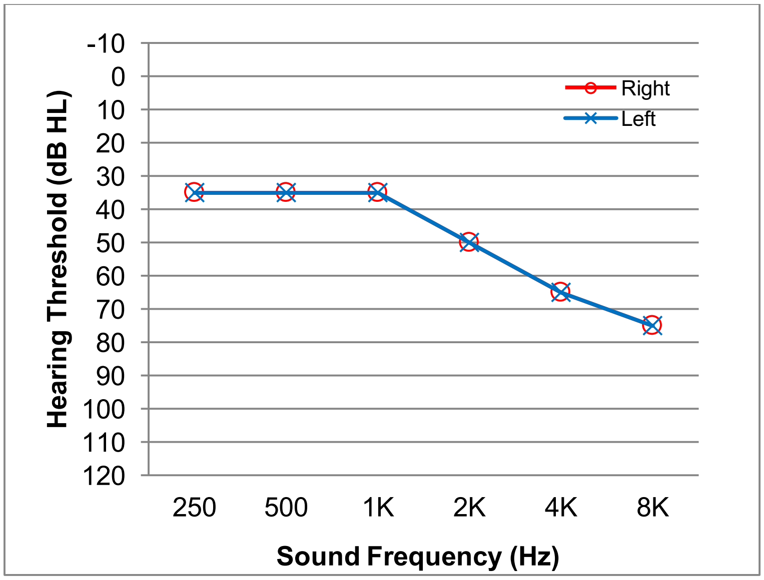


Figure 2. Simulated Age-related Hearing Loss for HVLT-R Non-optimal Condition

Procedure

Hearing Loss (HL) Group. Most participants with hearing loss were recruited through the HFHS Audiology Department. Individuals with moderate-to-severe hearing loss who were identified as meeting the hearing and age criteria were provided information about the study following their hearing evaluations or hearing aid consultations. Individuals who were interested in participating were contact to answer additional screening questions and discuss scheduling. Other participants with hearing loss were recruited through community organization such as the

Hearing Loss Association of America and the Healthier Black Elders Participant Research Pool.

Normal Hearing (NH) Group. Older adults with normal hearing were recruited from HFHS Audiology as well, including significant others of participants in the HL group. Participants who did not have an audiometric evaluation completed the hearing screen to confirm that they did not have hearing loss that is greater than 25 dB HL. Individuals with normal hearing were also recruited from the Healthier Black Elders Participant Research Pool and Wayne State University Institute of Gerontology events.

Following informed consent procedures, vision screening and global cognitive screening (MMSE) were completed. Participants recruited for the NH group completed the audiometry screening at that time as well. All participants then completed the assessment battery.

HVLT-R procedure. Both groups completed the HVLT-R in two presentation modalities (standard audiovisual and written visual); moreover, the audiovisual HVLT-R was presented in two auditory conditions (Natural Auditory and Crossed Auditory). Thus, presentation condition was a within-subject variable with three levels: Natural Auditory, Crossed Auditory, and Visual.

- For the *Natural Auditory condition*, both groups completed the HVLT-R while wearing noise-canceling headphones with the volume set to a normal speaking volume (~40 dB HL). This condition was the optimal condition for the NH group and the non-optimal condition for the HL group.
- For the *Crossed Auditory condition*, participants in the HL group completed the HVLT-R while wearing noise-canceling headphones with the volume set to ~80 dB HL (optimal condition). Participants in the NH group completed the HVLT-R while wearing noise-canceling headphones using stimuli that were modified to simulate moderate-to-severe

hearing loss (non-optimal condition). Simulated loss mimicked an audiogram of moderate age-related hearing loss equivalent to 50 dB, with greater proportionate loss in high frequency ranges (> 1K Hz) as compared to lower frequencies (250 to 1K Hz).

- All auditory-verbal HVLT-R administrations were done using noise-canceling headphones. This helped to minimize background noise and control the distance of the listener from the source (which varies when auditory stimuli are presented over a speaker). Among individuals with hearing loss, hearing aids were not used in either condition.

To control for version effects, the HVLT-R alternate forms were counterbalanced to the optimal and non-optimal conditions (i.e., the simulated hearing loss video was produced for both versions of the HVLT-R). To control for order effects, administration of the auditory-verbal HVLT-R in the optimal and non-optimal conditions were counterbalanced. The Visual Condition employed a single version (HVLT-R Form 1) and was administered first, so that preliminary normative data could be gathered. The rest of the battery was completed in a standardized order. Administration time for the full battery (not including the hearing evaluation) was ~2 hours and 15 minutes.

CHAPTER 3 RESULTS

Preliminary Analyses

The data were screened for violations of univariate and multivariate assumptions as recommended by Tabachnick and Fidell (2007). The following raw score variables were winsorized by changing the outlying scores to one unit greater than the next highest/lowest score: HVLT Natural Recognition Discrimination for the NH group, HVLT Visual Retention for the HL group, and Trails B for HL group. No variable required more than one data point winsorized. BVMT Recognition Discriminability was significantly skewed and found to have multiple outliers in the HL group; therefore, nonparametric tests were used for this variable.

The entire sample completed the full neuropsychological battery. For 2 individuals in the HL group, HVLT Retention scores under the Natural (non-optimal) Auditory condition could not be calculated because they did not recall any words during the presentation trials. One HL participant is missing a Digit Span Total score because one section of the test was not administered. There is 1 missing case in each group for eCorsi Forward, 2 missing cases in the HL group for eCorsi Backward, and 4 missing cases in the NH group for eCorsi Backward due to technical errors.

Demographic Characteristics. Descriptive statistics for the HL and NH groups are summarized in Table 1. The sample of 82 adults (36 men, 46 women) ranged in age from 55 to 80 years (*M* = 66.7, *SD* = 6.5) and ranged in education from 9 to 20 years (*M* = 15.2, *SD* = 2.6). Consistent with inclusion criteria, all individuals had MMSE scores of ≥23 (*M* = 27.5, *SD* = 2.0). The sample ranged in estimated IQ based on single-word reading from 67 to 127 (*M* = 99.4, *SD* = 13.8). Forty-nine percent of the sample identified themselves as Caucasian, 48% identified as Black/African American, 2% identified as Latino/Latina, and 1% identified as other ethnicities.

The groups were not significantly different on age, education, MMSE, estimated IQ, gender, or race.

Verbal Memory Performance

Aim 1: Examine the effect of different presentation conditions on verbal memory performance. The HVLT raw score data were analyzed using 2 x 3 mixed-model analysis of variance (ANOVA), with group (HL, NH) as the between-subjects factor and condition (Natural Auditory, Crossed Auditory, Visual) as the within-subject factor. Four HVLT variables were examined for each condition: Total Recall, Delayed Recall, Retention, and Recognition Discriminability. Results of the main effects and interactions for the ANOVAs are presented in Table 2. In overview, all four mixed-model ANOVAs indicated significant main effects of condition, with large effect sizes (η_p^2 =.41 to .62). All four mixed-model ANOVAs also showed significant group by condition interactions ($p < .001$ to .05) with large effect sizes for Total Recall, Delayed Recall, and Recognition Discriminability (η_p^2 = .41 to .68) and a medium effect size for Retention ($\eta_p^2 = .07$). Specific results for the four analyses, including the marginal means, are presented below. Descriptive statistics and group comparisons for verbal memory (HVLT) performance are summarized as a function of group membership (HL and NH) in Table 3. The interactions for Total Recall and Delayed Recall are depicted in Figures 3 and 4, respectively.

For Total Recall, the main effect of condition was significant, $F(2, 79) = 50.41$, $\eta_p^2 = .56$, which reflected that participants in the groups combined scored significantly higher in the Visual condition ($M = 24.27$, $SE = 0.58$) than the Natural ($M = 18.27$, $SE = 0.79$) and Crossed ($M = 18.01$, $SE = 0.70$) conditions, which did not differ significantly from each other. The main effect of group was not significant, $F(1, 80) = 0.30$, $p = .587$, $\eta^2 = .00$. The group x condition interaction was significant, *F*(2, 79) = 83.25, $\eta_p^2 = .68$.

For Delayed Recall, the main effect of condition was significant, *F*(2, 79) = 64.65, $\eta_p^2 = .62$, which again reflected that participants in the groups combined scored significantly higher in the Visual condition (*M* = 8.82, *SE* = 0.30) than the Natural (*M* = 5.56, *SE* = 0.41) and Crossed (*M* = 5.66, *SE* = 0.36) conditions, which did not differ significantly from each other. The main effect of group was not significant, *F*(1, 80) = 0.46, *p* = .491, $\eta^2 = .01$. The group x condition interaction was significant, *F*(2, 79) = 27.56, $\eta_p^2 = .41$.

For Retention, the same pattern was observed: The main effect of condition was significant, *F*(2, 77) = 26.66, $\eta_p^2 = .41$; participants in the groups combined scored significantly higher in the Visual condition (*M* = 91.02, *SE* = 1.94) than the Natural (*M* = 66.40, *SE* = 4.21) and Crossed (*M* = 68.33, *SE* = 3.72) conditions, which did not differ significantly from each other. The main effect of group was not significant, *F*(1, 78) = 0.09, *p* = .768, $\eta^2 = .00$. The group x condition interaction was significant, *F*(2, 77) = 3.15, $\eta_p^2 = .08$.

Recognition Discriminability also showed the same pattern of results for main effects and interaction. The main effect of condition was significant, *F*(2, 79) = 64.79, $\eta_p^2 = .62$; participants scored significantly higher in the Visual condition (*M* = 11.02, *SE* = 0.12) than the Natural (*M* = 8.3, *SE* = 0.32) and Crossed (*M* = 8.71, *SE* = 0.28) conditions, which did not differ significantly from each other. The main effect of group was not significant, *F*(1, 80) = 0.93, *p* = .338, $\eta^2 = .01$. The group x condition interaction was significant, *F*(2, 79) = 39.00, $\eta_p^2 = .50$.

Post hoc analyses: between groups – independent t tests. The Natural Auditory condition (HVLT-R presented at normal speaking volume) was the NH group's optimal presentation condition and the HL group's non-optimal presentation condition. For the Natural Auditory condition, post hoc contrasts showed that the HL group performed significantly worse than the NH group ($p < .001$) on Total Recall, Delayed Recall, and Recognition Discriminability with large effect sizes ($d = 0.97$ to 1.43). In the Crossed Auditory condition, for which the HL group had a boosted volume presentation (optimal) and the NH group had a hearing loss simulation (non-optimal), the NH group performed significantly worse than the HL group ($p < .001$) on Total Recall, Delayed Recall, and Recognition Discriminability, with similarly large effect sizes ($d = 0.84$ to 1.52). For both auditory conditions, the groups did not differ significantly on Retention, which showed small effect sizes ($d = 0.05$ to 0.38). Notably, the groups did not differ significantly on the Visual condition for any of the HLVT variables and showed small effect sizes ($d = 0.05$ to 0.21).

Post hoc analyses: within groups – paired t tests. The HL group had significantly worse performance on the Natural (non-optimal) Auditory condition than the Crossed (optimal) Auditory condition ($p < .001$) for Total Recall, Delayed Recall, and Recognition Discriminability with large effect sizes ($d = 0.74$ to 1.17). Retention did not significantly differ between the Natural and Crossed Auditory conditions for the HL group. Performance on the Visual condition was significantly better than the Natural (non-optimal) Auditory condition ($p < .001$) for all HVLT variables with large effect sizes ($d = 0.79$ to 1.33). Performance on the Crossed (optimal) Auditory condition was closer to performance on the Visual condition compared to the Natural (non-optimal) Auditory condition, as Total Recall was not significantly different between the Crossed Auditory and Visual conditions ($d = 0.18$). Delayed Recall was significantly better in the Visual than the Crossed (optimal) Auditory condition ($p < .01$) with a medium effect size ($d = 0.46$). Retention and Recognition Discriminability were significantly better in the Visual than the Crossed (optimal) Auditory condition ($p < .001$) with large effect sizes ($d = 0.61$ to 0.62).

For the NH group, performance on the Natural (optimal) Auditory condition was significantly better than the Crossed (non-optimal) Auditory condition ($p < .001$) for Total Recall, Delayed Recall, and Recognition Discriminability with large effect sizes ($d = 0.96$ to 1.77). As in the HL group, Retention did not significantly differ between the Natural and Crossed Auditory conditions ($d = 0.27$). Verbal memory performance on the Natural (optimal) Auditory condition was significantly worse than the Visual condition ($p < .05$); however, effect sizes were in the small to medium range ($d = 0.35$ to 0.59), compared to the large effects observed between these conditions for the HL group. Performance on the Crossed (non-optimal) Auditory condition was significantly worse than the Visual condition ($p <.001$) for Total Recall, Delayed Recall, and Recognition Discriminability with large effect sizes ($d = 1.33$ to 1.67), whereas Retention showed a medium effect size ($d = 0.69$).

Correlations between presentation conditions. Correlations among the different verbal memory conditions are presented in Table 4a for the HL group and Table 4b for the NH group. As seen in Table 4a, among the HL group, the different conditions are not consistently correlated with each other, despite the task being the same. The Natural (non-optimal) condition showed a generally weak pattern of correlation to the Crossed and Visual conditions. For example, Natural (non-optimal) Auditory Total Recall was weakly correlated with Crossed (optimal) Auditory Total Recall ($r = .35$) and not significantly related to Visual Total Recall ($r = .19$). On the other hand, Crossed (optimal) Auditory Total Recall showed a significant, moderate correlation with Visual Total Recall ($r = .58$). Fisher's r-to-z comparisons testing dependent correlations from a single sample (Cohen & Cohen, 1983) indicated that the correlation between Natural (non-optimal) Auditory Total Recall and Visual Total Recall ($r = .19$) was significantly different than the correlation between Crossed (optimal) Auditory Total Recall and Visual Recall ($r = .58$; $Z = -2.38$, $p = .008$). The correlations between the Visual condition with Natural and Crossed conditions for Delayed Recall were not significantly different for the HL group.

Table 4b illustrates that the different conditions were highly intercorrelated among the NH group. Although Total Recall was significantly correlated between each condition, the correlation between the Crossed (non-optimal) Auditory and Visual conditions (r = .40) was significantly weaker than the correlations between the Natural (optimal) Auditory and Visual conditions (r = .71, Z = 2.88, p = .002) and between the Crossed (non-optimal) Auditory and Natural (optimal) Auditory conditions (r = .64, Z = 2.36, p = .009). Consistent with the HL group, the correlations between the different conditions for Delayed Recall were not significantly different.

Standardized verbal memory scores. Standardized T scores adjusted for age were obtained for the HVLT variables from the HVLT-R Professional Manual (Brandt & Benedict, 2001) and are presented in Table 5. Under each group's respective optimal auditory conditions (i.e., Natural Auditory for the NH group and Crossed Auditory for the HL group), age-adjusted mean T scores for each group were within a standard deviation of the normative sample. For example, under the Natural Auditory condition, the NH group had a mean Total Recall T score of 44.9 (*SD* = 12.5) and only 22.0% of the NH group score more than 1.5 Z below the normative mean (*M* = -0.51, *SD* = 1.25 Z). Under the Crossed Auditory condition, the HL group had a mean Total Recall T score of 45.3 (*SD* = 10.8); 14.6% of the HL group scored more than 1.5 Z below the normative mean (*M* = -0.47, *SD* = 1.08 Z).

Under non-optimal auditory conditions (i.e., Crossed Auditory for the NH group and Natural Auditory of the HL group), age-adjusted mean T scores for each group were impaired ($\geq$ 1.5 Z below the normative mean). For example, under the Natural Auditory condition, the HL group had a mean Total Recall T score of 24.9 (*SD* = 18.6), which is -2.5 Z below the normative mean. Under the Crossed Auditory condition, the NH group had a mean Total Recall T score of 23.7 (*SD* = 16.8), which is -2.6 Z below the normative mean. On non-optimal Total Recall, 68.3% of the HL group scored more than 1.5 Z below the normative mean (*M* = -2.51, *SD* = 1.86 Z); similarly, under the non-optimal condition, 75.6% of the NH group score more than 1.5 Z below the normative mean (*M* = -2.63, *SD* = 1.67 Z).

In contrast, for the Visual condition, both groups scored within a standard deviation of the normative sample on Total Recall (HL *M* = 46.8, *SD* = 12.2; NH *M* = 47.7, *SD* = 11.8); 17.1% of HL and 19.5% of NH scored more than 1.5 Z below the normative mean. Results for Delayed Recall, Retention, and Recognition Discriminability were similar to those observed for Total Recall for each presentation condition.

Other Neuropsychological Test Performance

Aim 2. Compare Performance Between Groups on Neuropsychological Tests Across Other Domains. Independent *t* tests compared individuals with and without hearing loss across other cognitive domains including attention/working memory, processing speed, executive function, visual perception, and visual memory. Results are presented in Table 6, including *p* values, 95% confidence intervals, and effect sizes in Cohen's d (Cohen, 1966). The groups did not significantly differ on any of the other neuropsychological variables and showed small effect sizes (*d* = 0.06 to 0.39).

Aim 3. Determine the Extent to Which Other Cognitive Abilities are Related to Auditory- and Visual-Verbal Memory.

Correlations between the HVLT Natural Auditory and HVLT Visual conditions and the other neuropsychological variables are presented in Table 7a for the HL group and Table 7b for the NH group. For the HL group, the Natural (non-optimal) Auditory condition showed few significant correlations with the other cognitive variables. Total Recall under the Natural condition, which is likely most affected by a non-optimal presentation format, was not significantly related to any of the neuropsychological variables. In contrast, Total Recall under the Visual condition was significantly correlated ($p < .05$) to most the other neuropsychological variables. The other HVLT variables showed a similar pattern of relation to the neuropsychological variables. In general, measures of attention/working memory (Digit Span, eCorsi) were not highly related to HVLT performance. Processing speed measures were significantly related to Retention in the Natural (non-optimal) Auditory condition (r = .35 and .37) and significantly related to most HVLT variables in the Visual condition (r = .38 to .53). Executive functioning (Trails B time) was not significantly related to HVLT performance under the Natural (non-optimal) condition, but showed significant inverse relation to Total Recall and Delayed Recall in the Visual condition (r = -.42 and -.27, respectively). Visual perception (JOLO) was not significantly related HVLT variables in either condition. Figural memory (BVMT-R) was not significantly correlated with HVLT performance in the Natural (non-optimal) Auditory condition but was significantly correlated with HVLT performance in the Visual condition.

For the NH group, the Natural (optimal) Auditory condition was significantly correlated ($p < .05$) to several of the other neuropsychological variables; however, the Visual condition generally showed more and stronger correlations to the other neuropsychological variables than the Natural condition. Unlike the HL group, auditory attention/working memory (Digit Span) was significantly correlated with HVLT performance in both conditions (r = .36 to .63). Visual attention (eCorsi Forward) was significantly related to HVLT Visual performance (r = .33 to .47). Like the HL group, processing speed showed several significant correlations with HVLT performance in both conditions. Also, consistent with the HL group, executive functioning (Trails B) was not significantly related to the HVLT Natural (optimal) Auditory condition, but was significantly related to the HVLT Visual condition (*r* = -.28 to -.39). Figural memory (BVMT) was generally significantly correlated with HVLT performance in both conditions.

For both groups, the relationships between age, education, and estimated IQ and verbal memory performance were examined. Results are reported in Table 7a for the HL group and Table 7b for the NH group. Age was not significantly related to HLVT performance in either condition for both groups. In the HL group, education and estimated IQ were significantly related to Delayed Recall and Retention for the Natural (non-optimal) Auditory condition (*r* = .27 to .35) and significantly related to Total Recall and Delayed Recall for the Visual condition (*r* = .39 to .48). In the NH group, education and estimated IQ were significantly related to Total Recall and Recognition Discriminability for the Natural (optimal) Auditory condition (*r* = .28 to .35) and significantly related to Total Recall and Delayed Recall for the Visual condition (*r* = .30 to .40).

CHAPTER 4 DISCUSSION

As hypothesized, unaided, moderate-to-severe sensorineural hearing loss negatively affected auditory-verbal memory (HVLT-R) performance among older adults. Furthermore, when older adults with normal hearing completed the HVLT-R under a simulated hearing loss condition, their performance was similarly impaired as the participants with hearing loss. Performance on a *visual* version of the HVLT-R was equivalent between individuals with and without hearing loss, as was performance on other neuropsychological tests. These findings suggest that poor performance on auditory-verbal memory tests among these older adults with hearing loss is not primarily a reflection of cognitive impairment, but rather measurement error, independent of verbal learning and memory. Visual versions of verbal memory tests can likely provide a valid alternative for individuals with impaired hearing.

Older adults with hearing loss performed significantly worse with large effect sizes on the auditory HVLT-R under natural presentation conditions (normal speaking volume) compared to older adults with normal hearing. These results are consistent with previous findings of low performance on auditory cognitive tests among individuals with hearing loss (Harrison Bush et al., 2015; Lin, Ferrucci, et al., 2011; van Boxtel et al., 2000). Previous research by van Boxtel et al. (2000) demonstrated that even a mild-to-moderate hearing loss is predictive of low verbal memory performance, even after accounting for age, sex, educational level, and processing speed. They found that delayed recall in a 60-year-old with a 30-dB pure-tone hearing loss was statistically comparable to that of an 85-year-old with normal hearing. Considering these findings, it would be expected that a moderate-to-severe hearing loss would be even more detrimental to verbal memory performance, which is supported by the present results. Participants with moderate-to-severe hearing loss had severely impaired immediate recall and moderately impaired delayed recall compared to age-based normative data under a natural auditory presentation condition.

The present study is the first to examine the effect of simulated hearing loss on cognitive test performance among older adults. In the Crossed Auditory condition, older adults with normal hearing completed the HVLT-R under a simulated hearing loss condition, whereas older adults with normal hearing completed the HVLT-R with amplified volume. Under these conditions, adults with hearing loss outperformed individuals with normal hearing at nearly the magnitude of effect size observed in the natural auditory condition. This finding is consistent with those of Jorgensen et al. (2016), who found that cognitively intact, young adults with normal hearing had impaired performance on a dementia screener under simulated hearing loss conditions. The present findings are also consistent with other studies that examined effects of reduced audibility on verbal memory performance via added background noise (Murphy et al., 2000; Pichora-Fuller, Schneider, & Daneman, 1995; Rabbitt, 1968). Conversely, Lindenberger et al. (2001) found that reduced hearing sensitivity via the use of noise-protector headphones did not impair cognitive performance among middle-aged adults with normal hearing. Both the present study and the study by Jorgensen et al. (2016) manipulated the auditory stimuli to reflect typical age-related hearing loss (i.e., greater loss at high frequencies compared to low frequencies), which is particularly impairing for speech comprehension. Reducing hearing sensitivity via noise protectors likely does not capture the full complexity of sensorineural hearing loss. Thus, findings from studies that use audio-engineered hearing loss simulations likely generalize better to real hearing loss populations compared to those that do not. Overall, there is strong evidence that auditory-verbal memory performance is negatively affected by reduced audibility, be it from simulated or real hearing loss.

The negative effect of impaired hearing on auditory cognitive tests underscores the importance of examining the validity and utility of alternative neuropsychological measures for assessment of individuals with hearing loss. A visual version of the HVLT-R was created for this study. The wordlist was presented as written words on a computer screen at a rate of one word per 2 seconds, which parallels the format of the standard auditory-verbal HVLT-R. As predicted, individuals with hearing loss had equivalent performance on the visual version of the HVLT-R compared to individuals with normal hearing. In addition, both groups performed better on the visual version of the HVLT-R compared to the auditory versions; this effect was particularly pronounced when the visual version was compared to the non-optimal auditory condition. Previous research has supported the use of visual multi-trial word learning tests (Brand & Jolles, 1985), and has found better performance on visual-verbal memory tests compared to auditory-verbal memory tests among older adults (Rabbitt, 1990).

Additional support for the validity of the visual version of the HVLT-R comes from the current findings regarding within group correlations between the different presentation conditions. Among individuals with normal hearing, the two auditory conditions and the visual version were significantly related, indicating that the same construct was being measured between the different conditions, as would be expected, given that it is the same task (i.e., verbal learning). For individuals with hearing loss, however, the expected pattern of correlations between the conditions was not observed: The optimal and non-optimal auditory versions were not significantly correlated with each other and the visual version showed few correlations with the auditory versions. These findings suggest that using auditory-verbal memory tests, particularly under non-optimal hearing conditions among individuals with hearing loss, does not accurately measure memory functioning.

Regarding the relationship between verbal memory and other cognitive domains, the visual version of the HVLT-R showed more and stronger relationships with performance on the other neuropsychological tests compared to the natural auditory version. For both individuals with and without hearing loss, processing speed was related to verbal memory, which has been demonstrated previously (Brebion et al., 2013), and this relationship was especially pronounced in the visual condition. Of note, all the processing speed measures were visually based; therefore, being able to process visual information quickly is likely to benefit performance on a visual-verbal memory test. Attention and working memory were not highly related to verbal memory in either presentation condition among individuals with hearing loss, which was inconsistent with predictions and previous research (Vaughan et al., 2008; Waters & Caplan, 2001). On the other hand, among individuals with normal hearing, auditory attention was significantly associated with verbal memory performance in both the visual and natural auditory condition, and visual attention was related to visual-verbal memory performance. Figural memory was associated with verbal memory performance in both conditions for individuals with normal hearing, but only related to visual-verbal memory performance among individuals with hearing loss. Overall, the natural auditory version of the HVLT-R did not show expected associations with other neuropsychological indices among individuals with hearing loss, whereas the visual version did, again supporting the use of a visual-verbal memory test over an auditory-verbal memory test.

The groups were equivalent on age, years of education, gender proportions, estimated IQ, and MMSE performance. For both individuals with and without hearing loss, age was not related to HVLT-R performance, which is consistent with some previous research (Kuslansky et al., 2004), but not others (Vanderploeg et al., 2000). The relatively restricted age range (55-80 years), which included only older adults, likely constrained the magnitude of the relationship between age and verbal memory performance. Among individuals with normal hearing, education and estimated IQ were associated with immediate recall on the HVLT-R for both auditory and visual presentation conditions. Individuals with hearing loss showed similar patterns for the associations between education and estimated IQ with immediate recall for the visual condition, but not the auditory condition. These findings further support that the auditory-verbal memory test under non-optimal auditory conditions for individuals with hearing loss may not be validly measuring the target construct of memory.

Although there are currently few visual-verbal memory tests being used clinically, the Word List Memory test from the Consortium to Establish a Registry for Alzheimer's Disease (CERAD) – Neuropsychological Assessment Battery (NAB) is an exception. For the Word List Memory test, 10 unrelated words are presented on printed cards and examinees are instructed to read each word aloud as it is presented. Like the HVLT-R, the test includes immediate recall after each of the three learning trials, delayed free recall after 15 minutes, and a recognition trial for which 10 target and 10 distractor words are visually presented (Welsh et al., 1994). The CERAD battery has been found to be psychometrically sound, and performance on the word list recall distinguishes patients with Alzheimer's disease from normal controls (Morris, Mohs, Rogers, Fillenbaum, & Heyman, 1988; Welsh, Butters, Hughes, Mohs, & Heyman, 1992).

Despite its demonstrated utility, the CERAD is used much less frequently than auditory-verbal memory tests. A survey of assessment practices among clinical neuropsychologists showed that the Wechsler Memory Scale and the California Verbal Learning Test (CVLT) are the most frequently used memory instruments, both of which involve auditory presentation of verbal stimuli (Rabin, Barr, & Burton, 2005). The CERAD was ranked 35 out the top 40 neuropsychological assessment instruments, demonstrating that use of auditory-verbal memory tests largely prevails in clinical practice. One issue with the CERAD Word List Memory test is that is less challenging than the CVLT and, therefore, is not as sensitive to detecting mild declines in memory (Beck, Gagneux-Zurbriggen, Berres, Taylor, & Monsch, 2012). For the purposes of this study, the HVLT-R was chosen because three alternate forms were needed for the three different presentation conditions (the CVLT only has standard form and one alternate form). Future research aims to examine the validity and utility of a visual version of the CVLT.

Contrary to hypotheses, participants with hearing loss did not perform worse on the auditory attention/working memory measure (WAIS-IV Digit Span) compared to participants with normal hearing. Further consideration of this task, however, indicates that performance on Digit Span may not be as affected by hearing loss compared to a verbal memory test. The set of stimuli is limited to the numbers zero through nine, which allows for increased ease in comprehending what is being said, and the numbers used do not sound like each other, which reduces the chance of mishearing information. Visual input from lipreading this restricted set of words also facilitates accuracy (Feld & Sommers, 2009). In addition, the auditory attention/working memory task was presented by an examiner rather than video/audio recording presentation; therefore, volume of presentation may have varied and/or tended to be louder than the verbal memory presentations. Participants who had hearing aids could use them during this task, whereas they did not wear them during any of the verbal memory administrations.

The current study found intact performance on measures of cognitive domains other than verbal memory among individuals with hearing loss. Previous research on this topic has yielded mixed findings. Several studies have shown that hearing loss is predictive of poor performance on measures of global cognition, working memory, processing speed, and executive function (Dupuis et al., 2015; Gallacher et al., 2012; Harrison Bush et al., 2015; Lin, Ferrucci, et al., 2011), whereas other do not find a relationship between hearing loss and these cognitive domains (Anstey et al., 2001b; Bucks et al., 2016; Gennis et al., 1991; Hong, Mitchell, Burlutsky, Liew, & Wang, 2016; van Boxtel et al., 2000). One reason for the discrepancy between studies on this topic is differences in inclusion of individuals with or without dementia and variability in defining cognitive impairment. Also, some studies have statistically significant findings, but have large sample sizes and small effect sizes; it is unclear whether these differences are clinically significant. Importantly, these studies did not systematically account for disadvantage and disruption of test performance due to use of auditory stimuli during instruction and/or administration of test items. Findings from the present study indicate that poor performance by adults with hearing loss on tests of other cognitive domains may reflect, at least in part, measurement error associated with administration modality versus valid reflection of impairment in those domains. Overall, the present study provides evidence that cognitively intact older adults with hearing loss have equivalent performance on neuropsychological tests compared to aged-peers with normal hearing, apart from tests that have a high auditory demand.

Of the four verbal memory indexes examined (Total Learning, Delayed Recall, Retention, and Recognition Discriminability), Retention was less affected by non-optimal auditory conditions compared to the other memory indexes. Total Learning is detrimentally affected by reduced audibility because performance on it is dependent on being able to hear the stimuli accurately. Limited encoding of information during learning trials constrains ability to recall the information later (i.e., Delayed Recall). The recognition memory stimuli were also presented under non-optimal auditory conditions and were similarly vulnerable to the effects of reduced audibility as Total Learning performance. Additionally, foil words that are phonemically similar to target words may have resulted in increased false positive errors, which reduces recognition discriminability. The finding that Retention was relatively better compared to the other variables indicates that individuals with hearing loss were generally retaining the information that was encoded during the learning trials, even if it was a small amount. They did not demonstrate rapid forgetting of information that is associated with medial-temporal lobe dysfunction (Scheltens & Korf, 2000). This finding further supports that the link between hearing loss and low neuropsychological performance is because of difficulty hearing stimuli rather than true cognitive impairment.

Findings from the present study support the *resource allocation/degradation hypotheses* (Schneider & Pichora-Fuller, 2000; Tun et al., 2009; Valentijn et al., 2005). In other words, poor performance on cognitive tests among these adults with moderate-to-severe hearing loss appears primarily due to difficulty with auditory stimuli and increased allocation of cognitive resources to listening rather than true cognitive impairment. Only auditory-verbal memory performance was significantly worse among individuals with hearing loss compared to individuals with normal hearing. The groups were equivalent on measures of attention, working memory, processing speed, executive function, visual perception, and figural memory. The *common cause hypothesis* predicts that common, underlying factors contribute to both reduced hearing sensitivity and cognitive functioning (Lindenberger & Baltes, 1994); it would be expected that hearing loss and cognitive decline would occur simultaneously, which is inconsistent with current findings. The *deprivation hypothesis* states that reduced audibility over time results in structural and functional changes in the brain (Lin et al., 2013; Lindenberger & Baltes, 1994). It is unclear how long individuals need to be exposed to reduced sensory input for it to cause cognitive changes, as proposed by the deprivation hypothesis. Although older adults with hearing loss were cognitively intact at the time of the current study, it may be that they are more likely to develop dementia compared to individuals with normal hearing. Longitudinal studies are needed to address whether hearing loss is related to increased risk of cognitive decline.

Limitations and Future Research

A limitation of this study was the specific nature of the sample: participants were older adults with moderate-to-severe sensorineural hearing loss, which limits generalizability to other populations. Additional research focusing on mild hearing loss is especially important, as it is the most prevalent type of hearing loss (Timmer, Hickson, & Launer, 2015). Furthermore, individuals who are deaf or have profound hearing loss were not included in the present study, as they likely would not have been able to hear the non-optimal auditory condition well enough to engage meaningfully in the tasks. Limited research regarding cognitive assessment of individuals who are deaf or have profound hearing loss is available, and studies have generally focused on administering tests in sign language (Denmark et al., 2016). Research on the psychometric properties of visual-verbal memory assessment among this population is needed.

The prevalence of hearing loss is higher in men compared to women, and men tend to have greater high frequency loss (2k Hz and above) compared to women (Moscicki, Elkins, Baum, & McNamara, 1985). In addition, women typically perform better than men on verbal memory tests, and this advantage in verbal memory might represent a form of cognitive reserve (Sundermann et al., 2016). It is possible that the combination of worse hearing loss and worse verbal memory test performance in men compared to women may put men at a relative disadvantage on auditory-verbal memory tests. The sample size of this study limited statistical examination of groups separated by demographic characteristics; however, it should be examined in future studies.

This study examined a particular auditory-verbal memory test, the HVLT-R. It is expected that results would generalize well to other multi-trial word list memory tasks such as the CVLT, but it is unclear if hearing loss would similarly affect performance on structured auditory-verbal memory tests such as Logical Memory from the Wechsler Memory Scale. Logical Memory involves auditory presentation of short stories, which provides context that can aid both memory and speech comprehension (Swinney & Love, 2002). Structured verbal memory tests may be less susceptible to the negative effects of hearing loss compared to unstructured (word list) memory tasks; future research should compare these types of memory tests among older adults with hearing loss. Visual versions of structured verbal memory tests should also be explored.

This study differed from other studies of auditory comprehension and memory because it presented *videos* of an examiner administering the verbal memory test rather than only audio recordings. This difference may limit comparisons to previous research; however, it likely increases external validity and generalizability because it provided visual information from lipreading cues that is normally available in a real assessment. Future research should compare audio and video presentations of verbal memory assessments under non-optimal auditory conditions to determine whether lipreading cues benefit performance on these tests.

A limitation of this study was the lack of information regarding hearing aid use history. Hearing aids vary in quality, and length of hearing aid use differed between participants; therefore, hearing aids were not used during auditory-verbal memory testing to control for those factors. However, the effect of hearing aid use on auditory-verbal memory performance is a clinically important question and is a target for future research. History of hearing aid use is particularly important to consider for the deprivation hypothesis, as it would predict that mitigating some of the sensory deprivation due to hearing loss via hearing aids could reduce the likelihood of cognitive changes. Results from previous research about the effect of hearing aid use on cognition is mixed (Amieva et al., 2015; van Hooren et al., 2005). The effect of cochlear implants on cognition is also an area that warrants additional research (Castiglione et al., 2016).

One issue that this study encountered was that several older adults who reported that they had normal hearing and were recruited for the normal hearing group had some degree of hearing loss upon completion of a hearing screen. Hearing loss is often unrecognized because of its gradual onset. This issue reinforces the importance of clinicians and researchers not relying on patients' report of hearing status and instead having information from a formal audiological exam. To increase study feasibility, most participants with normal hearing were evaluated with a portable audiometer hearing screen rather than a full audiological evaluation. Information about the specific hearing thresholds of the normal hearing group would have been helpful to characterize the sample comprehensively. In addition, previous research has found a relationship between central auditory processing deficits and incidence of cognitive impairment and Alzheimer's disease (Gates, Anderson, Feeney, McCurry, & Larson, 2008). Only peripheral hearing loss was assessed in the current study.

This study found support for the resource allocation/degradation hypotheses, rather than the common cause/deprivation hypotheses. However, to address the multiple hypotheses regarding the link between hearing loss comprehensively, future research should utilize longitudinal designs starting prior to cognitive decline and hearing loss. Many previous longitudinal studies were lacking in measurement of hearing ability and/or cognition (i.e., relying on self-report of hearing loss or cognitive impairment, using only screening measures to assess for cognitive impairment). Monitoring health factors that can be related to both increased prevalence of hearing loss and cognitive dysfunction, as well as audiological rehabilitation history, will also be important. Future studies that incorporate neuroimaging to examine potential structural and functional brain changes related to hearing loss would also be valuable. Intervention studies that track whether improvement on neuropsychological test performance occurs after fitting older adults with hearing aids would be helpful for evaluating the explanatory hypotheses as well.

Conclusions and Clinical Implications

Increased risk of overdiagnosing memory problems among individuals with hearing loss should be considered by clinicians and researchers. This study demonstrated that cognitively intact older adults with hearing loss appeared impaired on an auditory-verbal word list memory test under typical administration conditions. Auditory-verbal memory tests are among the most commonly used neuropsychological measures and have extensive research support; however, visual versions of verbal memory tests are promising alternatives for assessment of older adults with hearing loss.

As seen in prior research and the current study, hearing loss often goes unrecognized and relying on patients' self-report of hearing ability is not sufficient. Clinical neuropsychologists should ensure that older adult patients complete an audiological exam prior to cognitive testing. As part of neuropsychological assessment is providing feedback and recommendations, neuropsychologists are well positioned to provide psychoeducation to older patients about hearing loss, the importance getting hearing screenings, and the benefits of hearing aids. They could also be involved in educating the public and family members who help care for older adults with hearing loss about these issues. Facilitating the early detection and treatment of hearing loss could help avoid potential long-term effects sensory deprivation and social isolation associated with hearing loss. Audiologists could also intervene by communicating with other medical providers if they see a patient for whom hearing loss might be contributing to misdiagnosis of dementia.

If auditory-verbal memory tests are used with individuals with hearing loss, they should be interpreted with caution, and follow-up tests that limit auditory demand should be added to the evaluation battery. Efforts to improve audibility during cognitive testing should be taken. Older adults with hearing loss performed better on the auditory-verbal memory test with amplified volume compared to when it was presented at a normal speaking volume. Although the effect of hearing aid use was not a focus of this study, hearing aids improve speech comprehension. It is recommended that patients wear their hearing aids during testing to optimize audibility, and clinicians should encourage patients without hearing aids to receive a hearing aid consultation if warranted. It is important to consider that even if hearing aids are obtained, they do not fully correct hearing. Additional research is needed regarding the effect of hearing aids on cognition. Background noise (i.e., noise from the hallway or from fans/HVAC systems) should be addressed when doing cognitive testing, and examiners should face the patient when speaking and enunciate clearly. Use of visual-verbal memory tests would help to reduce the influence of these factors that could invalidate testing, and create a more enjoyable testing experience for examiners and patients with hearing loss compared to when auditory stimuli are used. Providing written instructions for tests would also likely be beneficial, as individuals with hearing loss could miss important elements of instructions that are provided auditorily. Reading ability and vision need to be considered when using visual-verbal memory tests.

Understanding the relationship between hearing loss and cognition is a highly pressing issue. Replication of current findings is needed. Future research should aim to conduct longitudinal studies starting prior to onset of hearing loss and cognitive decline. Rigorous measurement of hearing loss and cognition, as well as factors that can be related to both (e.g., smoking and diabetes), will be crucial. Increased interdisciplinary collaboration will facilitate these goals and advance knowledge that has direct clinical implications. As auditory-verbal memory assessments are the “gold standard” format for assessment verbal memory, research on understanding their limitations is particularly important to initiate changes toward developing and embracing alternate measures. There is increasing movement toward computerized administration of neuropsychological tests, and use of a computerized visual-verbal memory test is highly compatible with this trend. This study lends support to using visual-verbal memory tests among individuals with hearing loss. It highlights the importance of considering individual characteristics of patients that may affect the validity of testing and continuing to refine and develop measures to provide reliable and valid assessment.

APPENDIX A

Table 1. *Descriptive Statistics for Hearing Loss (HL) and Normal Hearing (NH) Groups.*

	HL (*n* = 41)		NH (*n* = 41)		Total (*N* = 82)				
Variable	*M*	*(SD)*	*M*	*(SD)*	*M*	*(SD)*	*Range*	*p*[1]	*Cohen's d*
Age (years)	68.0	(6.3)	65.4	(6.6)	66.7	(6.5)	55 – 80	.063	0.4
Education (years)	15.3	(2.6)	15.2	(2.7)	15.2	(2.6)	9 – 20	.771	0.0
MMSE	27.8	(2.0)	27.4	(1.9)	27.6	(2.0)	23 – 30	.431	0.2
Estimated IQ (TOPF)	100.0	(13.8)	98.8	(13.9)	99.4	(13.8)	67 – 127	.715	0.1
Percent men	48.8		39.0		43.9			.373	0.2

Note. MMSE = Mini Mental State Examination; TOPF = Test of Premorbid Functioning.

[1] Independent *t* (80), except Percent men, χ^2(1).

Table 2. *Mixed-model Analyses of Variance for HVLT-R Indices: Groups (Hearing Loss, Normal Hearing) by Condition (Natural, Crossed, Visual).*

Variable	*F*	*df*	*p*	η^2
Total Recall				
Hearing Group	0.30	1, 80	.587	.00
Condition[1]	50.41	2, 79	< .001	.56
Group x Condition	83.25	2, 79	< .001	.68
Delayed Recall				
Hearing Group	0.46	1, 80	.491	.01
Condition[1]	64.65	2, 79	< .001	.62
Group x Condition	27.56	2, 79	< .001	.41
Retention (%)				
Hearing Group	0.09	1, 78	.768	.00
Condition[1]	26.66	2, 77	< .001	.41
Group x Condition	3.15	2, 77	.048	.08
Recognition Discriminability				
Hearing Group	0.93	1, 80	.338	.01
Condition[1]	64.79	2, 79	< .001	.62
Group x Condition	39.00	2, 79	< .001	.50

Note. Natural Condition = standard HVLT-R auditory administration. Crossed Conditions = simulated age-related hearing loss audio (normal hearing group); volume-boosted audio (hearing loss group). Visual Condition = visual presentation of HVLT-R words.

1. Main effect of condition, post hoc marginal means: Visual > (Natural = Crossed).

Table 3. *Descriptive Statistics and Group Comparisons of HVLT-R Raw Scores for HL (n = 41) and NH (n = 41) Groups.*

	HL		NH				
Variable	*M*	*SD*	*M*	*SD*	*p*	*d*	*95% CI of the difference*
HVLT Natural							
Total Recall	13.1	(8.6)	23.4	(5.4)	<.001	1.43	[-13.45, -7.13]
Delayed Recall	3.7	(3.8)	7.3	(3.6)	<.001	0.97	[-3.66, 0.81]
Retention (%)	59.4	(42.6)	73.4	(30.4)	.091	0.38	[-30.48, 2.31]
Recognition Dis.	6.4	(3.6)	10.2	(2.0)	<.001	1.30	[-5.09, -2.52]
HVLT Crossed							
Total Recall	22.8	(5.0)	13.2	(7.4)	<.001	1.52	[6.86, 12.41]
Delayed Recall	7.0	(2.9)	4.3	(3.5)	<.001	0.84	[2.78, 0.71]
Retention (%)	72.5	(23.8)	63.7	(40.9)	.237	0.26	[-5.90, 23.50]
Recognition Dis.	10.0	(1.8)	7.4	(3.0)	<.001	1.05	[1.53, 3.74]
HVLT Visual							
Total Recall	23.7	(5.5)	24.8	(5.0)	.339	0.21	[-3.45, 1.20]
Delayed Recall	8.7	(2.8)	9.0	(2.6)	.656	0.11	[-0.27, 0.60]
Retention (%)	91.5	(17.7)	90.7	(16.5)	.832	0.05	[-6.72, 8.33]
Recognition Dis.	11.1	(0.8)	11.0	(1.2)	.528	0.10	[-0.31, 0.61]

Note. HVLT = Hopkins Verbal Learning Test; Recognition Dis. = Recognition Discriminability; *d* = Cohen's d. Natural Condition = standard HVLT-R auditory administration. Crossed Conditions = simulated age-related hearing loss audio (normal hearing group); volume-boosted audio (hearing loss group). Visual Condition = visual presentation of HVLT-R words.

Table 4a. *Pearson Correlations for HVLT-R Verbal Memory Performance: Hearing Loss Group (n = 41).*

	1	2	3	4	5	6	7	8	9	10	11	12
1. Natural Total Recall	--											
2. Natural Delayed Recall	$.86^{**}$	--										
3. Natural Retention	$.43^{**}$	$.75^{**}$	--									
4. Natural Recognition Dis.	$.81^{**}$	$.67^{**}$	.24	--								
5. Crossed Total Recall	$.35^{*}$	$.51^{**}$	$.55^{**}$	.19	--							
6. Crossed Delayed Recall	.03	.12	.23	.03	$.59^{**}$	--						
7. Crossed Retention	-.04	-.05	.02	.01	$.29^{*}$	$.91^{**}$	--					
8. Crossed Recognition Dis.	.10	.21	.19	.08	$.50^{**}$	$.36^{**}$	.21	--				
9. Visual Total Recall	.19	$.38^{**}$	$.49^{**}$	.01	$.58^{**}$	$.38^{**}$	.16	$.34^{*}$	--			
10. Visual Delayed Recall	.17	$.39^{**}$	$.56^{**}$	.07	$.52^{**}$	.23	-.03	$.49^{**}$	$.71^{**}$	--		
11. Visual Retention	.14	.24	$.31^{*}$	.16	.18	.04	-.12	$.36^{*}$	.20	$.72^{**}$	--	
12. Visual Recognition Dis.	-.03	.08	.18	-.04	.18	.10	.00	$.35^{*}$	$.35^{*}$	$.51^{**}$	$.40^{**}$	--

Note. HVLT = Hopkins Verbal Learning Test; Recognition Dis. = Recognition Discriminability. Natural Condition = standard HVLT-R auditory administration. Crossed Conditions = simulated age-related hearing loss audio (normal hearing group); volume-boosted audio (hearing loss group). Visual Condition = visual presentation of HVLT-R words.

${}^{*}p < .05$, ${}^{**}p < .01$.

Table 4b. *Pearson Correlations for HVLT-R Verbal Memory Performance: Normal Hearing Group (n = 41).*

	1	2	3	4	5	6	7	8	9	10	11	12
1. Natural Total Recall	--											
2. Natural Delayed Recall	.77**	--										
3. Natural Retention	.63**	.95**	--									
4. Natural Recognition Dis.	.71**	.74**	.70**	--								
5. Crossed Total Recall	.64**	.45**	.33*	.54**	--							
6. Crossed Delayed Recall	.71**	.58**	.46**	.60**	.86**	--						
7. Crossed Retention	.61**	.57**	.53**	.58**	.51**	.79**	--					
8. Crossed Recognition Dis.	.72**	.57**	.44**	.56**	.74**	.79**	.69**	--				
9. Visual Total Recall	.71**	.69**	.64**	.71**	.40**	.56**	.70**	.57**	--			
10. Visual Delayed Recall	.74**	.68**	.59**	.70**	.48**	.62**	.65**	.61**	.88**	--		
11. Visual Retention	.42**	.34*	.27*	.43**	.24	.29*	.30*	.23	.40**	.71**	--	
12. Visual Recognition Dis.	.60**	.48**	.38**	.50**	.42**	.47**	.48**	.48**	.71**	.63**	.26	--

Note. HVLT = Hopkins Verbal Learning Test; Recognition Dis. = Recognition Discriminability. Natural Condition = standard HVLT-R auditory administration. Crossed Conditions = simulated age-related hearing loss audio (normal hearing group); volume-boosted audio (hearing loss group). Visual Condition = visual presentation of HVLT-R words.

$^{*}p < .05$, $^{**}p < .01$.

Table 5. *Descriptive Statistics and Group Comparisons of Age-Adjusted HVLT-R T Scores for HL (n = 41) and NH (n = 41) Groups.*

	HL		NH				
Variable	*M*	*SD*	*M*	*SD*	*p*	*d*	*95% CI of the difference*
HVLT Natural							
Total Recall	24.9	(18.6)	44.9	(12.5)	<.001	1.26	[-27.00, -13.05]
Delayed Recall	27.3	(17.9)	41.1	(17.5)	.001	0.78	[-21.60, -6.05]
Retention	33.2	(25.3)	38.9	(19.3)	.262	0.25	[-15.80, 4.36]
Recognition Dis.	20.9	(24.2)	45.4	(14.7)	<.001	1.22	[-33.28, -15.65]
HVLT Crossed							
Total Recall	45.3	(10.8)	23.7	(16.8)	<.001	1.53	[15.42, 27.81]
Delayed Recall	41.1	(14.6)	27.8	(16.7)	<.001	0.85	[6.45, 20.23]
Retention	40.1	(14.3)	36.3	(21.1)	.345	0.21	[-4.13, 11.69]
Recognition Dis.	45.6	(11.1)	25.3	(22.5)	<.001	1.11	[12.45, 28.04]
HVLT Visual							
Total Recall	46.8	(12.2)	47.7	(11.8)	.741	0.07	[-6.15, 4.39]
Delayed Recall	49.1	(11.8)	48.7	(12.1)	.890	0.03	[-4.90, 6.63]
Retention	51.6	(10.8)	50.6	(10.6)	.689	0.09	[-3.76, 5.67]
Recognition Dis.	53.0	(5.1)	50.9	(9.5)	.217	0.28	[-1.27, 5.45]

Note. HVLT = Hopkins Verbal Learning Test; Recognition Dis. = Recognition Discriminability; *d* = Cohen's d. Natural Condition = standard HVLT-R auditory administration. Crossed Conditions = simulated age-related hearing loss audio (normal hearing group); volume-boosted audio (hearing loss group). Visual Condition = visual presentation of HVLT-R words.

Table 6. *Descriptive Statistics and Group Comparisons of Other Neuropsychological Test Performance for HL (n = 41) and NH (n = 41) Groups.*[1]

	HL		NH				
Variable	*M*	*SD*	*M*	*SD*	*p*	*d*	*95% CI of the difference*
Digit Span Total	25.8	(5.0)	24.9	(5.5)	.470	0.17	[-1.48, 3.17]
eCorsi							
Forward Span	4.9	(1.5)	5.3	(0.9)	.161	0.32	[-0.96, 0.16]
Backward Span	4.0	(1.6)	4.1	(1.2)	.683	0.07	[-0.76, 0.50]
Symbol Search	24.1	(6.2)	26.8	(7.5)	.081	0.39	[-5.71, 0.34]
Coding	53.5	(15.7)	57.4	(15.3)	.261	0.25	[-10.70, 2.94]
Trails A	37.2	(12.8)	34.1	(9.5)	.213	0.28	[-1.83, 8.08]
Trails B	103.3	(60.8)	100.3	(38.7)	.796	0.06	[-19.49, 25.34]
JOLO	23.9	(5.0)	22.0	(6.1)	.128	0.34	[-0.56, 4.36]
BVMT							
Total Recall	18.6	(6.3)	20.0	(7.8)	.370	0.20	[-4.54, 1.71]
Delayed Recall	8.0	(2.4)	8.2	(3.0)	.690	0.07	[-1.46, 0.97]
Retention (%)	95.1	(15.4)	96.4	(15.7)	.708	0.08	[-8.13, 5.54]
Recognition Dis.	5.6	(1.0)	5.4	(1.1)	.363[a]	0.19	

Note. JOLO = Judgment of Line Orientation; BVMT = Brief Visual Memory Test; Recognition Dis. = Recognition Discriminability; *d* = Cohen's d; a = Mann-Whitney test used.

1. Sample size for the *t* tests range from 78 (eCorsi) to 82 due to missing data.

Table 7a. *HVLT-R Verbal Memory Correlations with Neuropsychological Variables: Hearing Loss Group (n = 41).*

Variable	HVLT Natural				HVLT Visual			
	Total Recall	Delayed Recall	Retention	Recognition Dis.	Total Recall	Delayed Recall	Retention	Recognition Dis.
Digit Span Total	.22	.19	.10	.15	.30*	.26	.02	-.09
eCorsi Forward Span	.20	.16	.10	.05	.10	.31*	.27*	-.05
eCorsi Backward Span	.12	-.02	-.23	.25	.08	.10	.20	.09
Symbol Search	.13	.27*	.35*	-.09	.51**	.53**	.38**	.13
Coding	-.01	.17	.37**	-.23	.45**	.53**	.22	.38**
Trails A	.01	-.09	-.11	.02	-.31*	-.36*	-.10	-.12
Trails B	-.15	-.10	-.12	.23	-.42**	-.27*	-.06	-.16
JOLO	.05	.02	.08	-.02	-.04	.05	.10	-.11
BVMT Total Recall	.10	.20	.22	.08	.34**	.35*	.23	.28*
BVMT Delayed Recall	-.10	-.03	.03	-.05	.17	.25	.19	.23
BVMT Retention	-.02	-.06	-.07	-.04	-.08	.13	.28*	-.04
BVMT Recognition Dis.^{a}	-.09	-.06	-.12	-.21	.27*	.33*	.17	.24
Age	-.20	-.18	-.09	-.03	.02	-.17	-.24	-.26
Education	.17	.31*	.35*	.19	.44**	.39**	.03	.10
Estimated IQ	.20	.27*	.29*	.21	.48**	.48**	.29*	.19

Note. HVLT = Hopkins Verbal Learning Test; Recognition Dis. = Recognition Discriminability; JOLO = Judgment of Line Orientation; BVMT = Brief Visual Memory Test; a = Spearman correlations were used for BVMT Recognition Dis.

$^{*}p < .05$, $^{**}p < .01$.

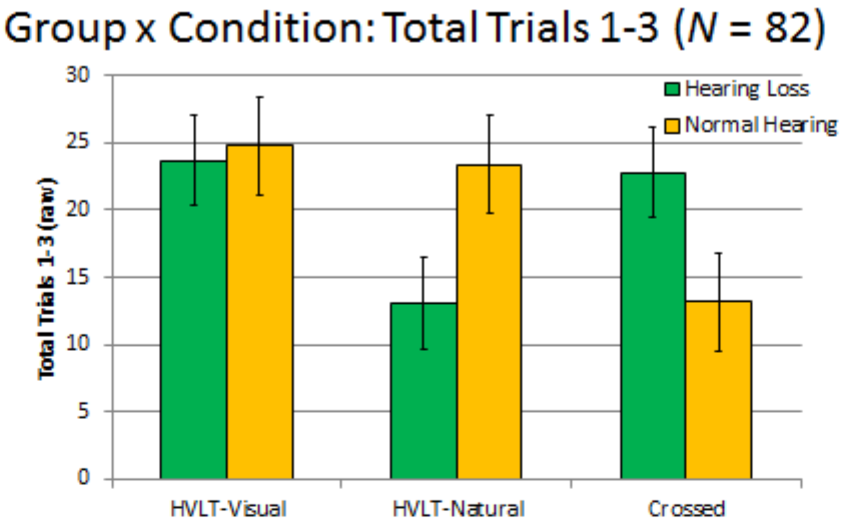
Table 7b. *HVLT-R Verbal Memory Correlations with Neuropsychological Variables: Normal Hearing Group (n = 41).*

	HVLT Natural				HVLT Visual			
Variable	Total Recall	Delayed Recall	Retention	Recog. Discrim.	Total Recall	Delayed Recall	Retention	Recog. Discrim.
Digit Span Total	.51**	.46**	.41**	.36*	.57**	.63**	.47**	.38**
eCorsi Forward Span	.30*	.21	.14	.21	.33*	.47**	.42**	.46**
eCorsi Backward Span	.20	-.01	-.04	.08	.06	.18	.15	-.18
Symbol Search	.36*	.17	.13	.19	.36*	.39**	.12	.22
Coding	.43**	.34*	.30*	.25	.46**	.52**	.34*	.31*
Trails A	-.30*	-.26*	-.19	-.16	-.37**	-.41**	-.13	-.21
Trails B	-.24	-.14	-.05	-.13	-.39**	-.34*	-.09	-.28*
JOLO	.25	.17	.09	.16	.34*	.28*	.05	.14
BVMT Total Recall	.56**	.45**	.37**	.44**	.59**	.68**	.45**	.37**
BVMT Delayed Recall	.58**	.42**	.33*	.48**	.56**	.64**	.46**	.31*
BVMT Retention	.14	.09	.09	.21	.03	.13	.24	-.17
BVMT Recognition Dis.^{a}	.56**	.45**	.38**	.48**	.51**	.50**	.22	.30*
Age	-.08	-.06	-.05	.03	.03	-.12	-.22	.10
Education	.35*	.16	.12	.35*	.34*	.30*	.16	.16
Estimated IQ (TOPF)	.28*	.07	.03	.28*	.40**	.35*	.16	.21

Note. HVLT = Hopkins Verbal Learning Test; Recognition Dis. = Recognition Discriminability; JOLO = Judgment of Line Orientation; BVMT = Brief Visual Memory Test; a = Spearman correlations were used for BVMT Recognition Dis.
$^{*}p < .05$, $^{**}p < .01$

APPENDIX B

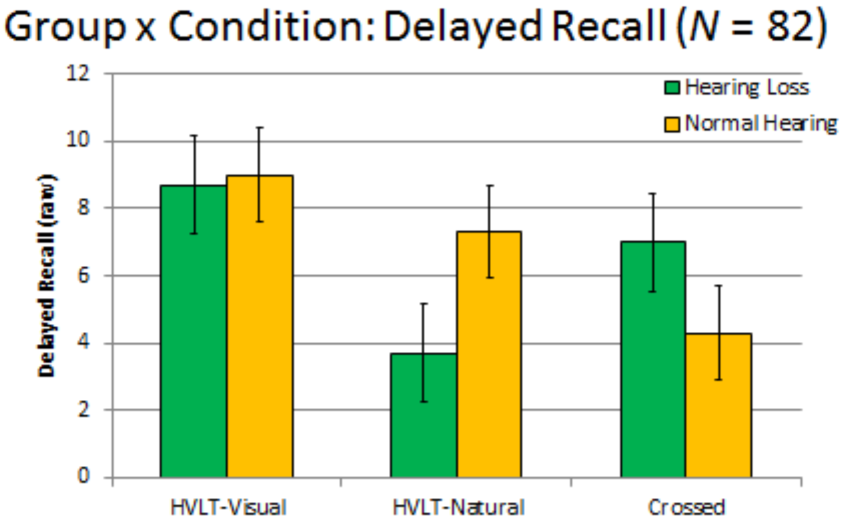
Figure 3. *Group by Condition Interaction for HVLT-R Total Recall.*



Group x condition interaction, *F*(2, 79) = 83.25, *p* < .001, η_p^2 = .68

Effect size HVLT Natural, Cohen's d = 1.4
Effect size HVLT Crossed (HL > NH), Cohen's d = 1.5
Effect size HVLT Visual, Cohen's d = 0.2

Figure 4. *Group by Condition Interaction for HVLT-R Delayed Recall.*



Group x condition interaction, *F*(2, 79) = 27.56, *p* < .001, η_p^2 = .41

Effect size HVLT Natural, Cohen's d = 1.0
Effect size HVLT Crossed (HL > NH), Cohen's d = 0.8
Effect size HVLT Visual, Cohen's d = 0.1

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ABSTRACT

HEARING LOSS AND VERBAL MEMORY ASSESSMENT IN OLDER ADULTS

by

CHRISTINA G. WONG

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Advisor: Dr. Lisa J. Rapport

Major: Psychology (Clinical)

Degree: Doctor of Philosophy

Prior research has found that adults with hearing loss perform worse on cognitive testing than adults without hearing loss, and some studies have suggested that hearing loss is associated with dementia. Heavy emphasis on tests involving auditory stimuli for memory assessment may result in overdiagnosis of cognitive impairment in individuals with hearing loss. The present study compared visual and auditory versions of a verbal memory test among older adults with and without hearing loss.

Forty-one adults with moderate-to-severe, sensorineural hearing loss (HL) and 41 age-matched adults with normal hearing (NH) participated. Age ranged from 55 – 80 years. They completed a neuropsychological battery that included auditory and visual versions of the Hopkins Verbal Learning Testing-Revised (HVLT-R). The auditory conditions included a Natural Auditory condition for which stimuli was presented at a normal speaking volume and a Crossed Auditory condition for which individuals with hearing loss completed the test with amplified volume and individuals with normal hearing completed the test under a hearing loss simulation.

Mixed-model ANOVA indicated significant group (HL vs. NH) by condition (Visual vs.

Natural Auditory vs. Crossed Auditory HVLT-R) interactions with large effect sizes. Post hoc contrasts showed that the HL group performed significantly worse than the NH group on the Natural Auditory version. The opposite pattern was found for the Crossed Auditory condition: The NH group performed significantly worse than the HL group. The groups were equivalent on the Visual condition and showed small effect sizes. Auditory and visual versions were highly correlated for the NH group but not for the HL group. Groups did not significantly differ on other neuropsychological tests and showed small effect sizes. Moreover, for the HL group, the visual version of the verbal memory test was strongly correlated with other neuropsychological tests whereas the standard auditory version was not.

Cognitively intact older adults with hearing loss appeared impaired on an auditory-verbal word list memory test under typical administration conditions. Visual assessment of verbal memory shows evidence of superior validity and is a viable alternative method to assess memory function especially in older populations.

AUTOBIOGRAPHICAL STATEMENT

CHRISTINA G. WONG

Education and Training

August 2016 (Expected)	Doctor of Philosophy in Psychology Wayne State University, Detroit, Michigan Major: Clinical Psychology, Minor: Neuropsychology
July 2016-Present	Internship in Clinical Psychology (APA accredited) VA San Diego Healthcare System/UC San Diego San Diego, CA
December 2013	Master of Arts in Psychology Wayne State University, Detroit, Michigan Major: Clinical Psychology, Minor: Neuropsychology
May 2009	Bachelor of Arts, *with honors distinction* University of Connecticut, Storrs, Connecticut Major: Psychology, Minor: Neuroscience

Research Experience

2014 – present	*Graduate Research Assistant, Doctoral Trainee* Lisa J. Rapport, Ph.D. Department of Psychology, Wayne State University
2013 – 2014	*Widowhood Research Assistant* Joseph Fitzgerald, Ph.D. Department of Psychology, Wayne State University
2012	*Educational Intervention Research Assistant* Cheryl Somers, Ph.D. College of Education, Wayne State University
2011 – 2013	*Graduate Research Assistant* Lisa J. Rapport, Ph.D. Department of Psychology, Wayne State University
2009 – 2011	*Neuropsychiatry Research Assistant* Michael Stevens, Ph.D. & Michal Assaf, M.D. Olin Neuropsychiatry Research Center, Hartford Hospital
2008 – 2009	*Infant Motor Development Research Assistant* Anjana Bhat, P.T., Ph.D. Physical Therapy Department, University of Connecticut
2007 – 2009	*Autism Research Assistant* Deborah Fein., Ph.D. Department of Psychology, University of Connecticut