INVESTIGATING THE ROLE OF AUDITORY PROCESSING ABILITIES IN HEARING AID OUTCOMES AMONG OLDER ADULTS

by

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As members of the Dissertation Committee, we certify that we have read the dissertation prepared by: *Alyssa Jordan Davidson*, titled: *Investigating the Role of Auditory Processing Abilities in Hearing Aid Outcomes Among Older Adults.*

and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

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the completion of this project would likely still be a ways away. Mark encouraged me when I needed it and guided me out of writer's block more times than I can count. As one could imagine, achieving a PhD is not one that comes easily. There were many occasions where I felt like I would never reach this point, like I wasn't smart enough or driven enough to complete my project, like I just needed to curl up in a ball and call it quits. Luckily, Mark was there to hold my hand and reassure me that he believed in me and I should continue to believe in myself because I deserve to be here. I guess husbands can be right sometimes! Thank you, Mark, I love you and cannot wait to embark on our next journey together in my post-doctoral position at Northwestern University.

Dedication

To Mark Allen Davidson, my husband and best friend.

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Abstract

Background: Hearing aid outcomes are highly variable and important to improve. The overall objective of this dissertation is to determine how auditory processing assessments of temporal, spatial, and binaural processing are related to hearing aid outcomes in older adults. The long-term goal is to establish the evidence base supporting auditory processing evaluation as an expanded part of rehabilitative management to help target appropriate treatment and counsel on realistic expectations with recommendations not solely based on audibility alone. **Methods:** In this dissertation, three studies were undertaken. First, a systematic review, then clinical research in a patient population, finally a more detailed evaluation and comparison of speech-in-noise testing. In the first study, a systematic review was conducted to answer the question: "*How do auditory processing abilities affect hearing aid satisfaction among adults?"* Then in the second study, 78 older adults were recruited to take part in multiple evaluations of their auditory processing abilities and their non-auditory self-reports. Multiple linear regression was used to determine the strength of the relation between the different factors and hearing aid outcomes. In the third study, speech-in-noise results from the QuickSIN, Listening in Spatialized Noise Sentence Test (LISN-S), and a spatial release from masking task using the Coordinate Response Measure (CRM) materials, were evaluated and compared in 61 older adults from the second study. For this study, Pearson's correlations, multiple linear regressions, and point-biserial correlations were used to evaluate and compare the three speech in noise tests. **Results:** In study one, seven studies met the inclusion criteria for the systematic review. Of these studies, the Dichotic Digits Test, the Synthetic Sentence Identification Test, and the Performance-Perceptual Test were the only tests of auditory

processing ability that were significant contributors to hearing aid satisfaction. Although these studies were not rated highly for study quality, they do suggest the potential for associations between auditory processing abilities and hearing aid satisfaction. In study two, temporal processing as measured by the Gaps-in-Noise, spatial processing as measured by the LISN-S, and self-efficacy as measured by the Measure of Audiologic Rehabilitation Self-Efficacy for Hearing Aids (MARS-HA), were all statistically significant predictors of hearing aid satisfaction. However, contradictory to prior studies in the literature, binaural processing on the Dichotic Digits Test was not a significant predictor. For hearing aid benefit, only the MARS-HA and self-report of disability as measured by the Speech, Spatial, and Qualities of Hearing (SSQ) questionnaire were statistically significant predictors. In study three, Pearson’s Correlations showed that only the LISN-S and QuickSIN and the LISN-S and CRM were significantly correlated to one another. The SSQ score was not correlated with performance on any of the speech-in-noise tests. Finally, no correlations could be determined between subjective or objective testing and group aural rehabilitation attendance or assistive listening device use.

Conclusions and Future Directions: While hearing aid intervention does not change the individual’s underlying processing abilities, understanding the extent of residual disability illuminates avenues for targeted rehabilitation beyond a hearing aid. The current data imply a need for a prospective clinical trial of hearing aid intervention including multiple auditory processing abilities and other non-auditory factors. Targeted auditory training or other novel rehabilitative approaches for hearing loss management could also be pursued as a result of this research.

Chapter One: Introduction

Hearing loss in both ears affects an estimated 38 million people in the U.S. (Goman & Lin, 2016), yet fewer than 25% of adults with mild hearing loss or greater report using hearing aids (Chien & Lin, 2012; Hartley et al., 2010; Lee et al., 1991; Nieman, Marrone, Szanton, Thorpe, & Lin, 2016; Popelka et al., 1998). Statistics showing less than a quarter of people using these medically necessary devices suggest that despite the advances in hearing aid technology, measures for evaluating and treating hearing loss may not fully identify the underlying auditory challenges facing patients. Baylor et al. (2011) and Fried-Oken et al. (2012) concluded that as a result of acquired communication disorders, including hearing loss, poor social interactions, activity limitations, participation restrictions, and mental health related problems may increase. One way to manage the negative consequences of hearing loss is with hearing aids. Although, the perceptual outcomes from hearing aids play a key role in the effectiveness of this management option.

In the current hearing aid literature, researchers have investigated such outcomes of satisfaction and benefit, and although they may seem interchangeable at times, these outcomes assess separate domains of hearing aid success. Hearing aid benefit is a measure comparing the user's change in performance (on self-report) from an unaided to aided condition (Vestergaard-Knudsen et al., 2010). Satisfaction is distinguished from benefit as it is an emotional response to an experience or service (Oliver, 1997; Tse, 1988). In regard to hearing aids, research suggests that satisfaction and hearing aid use are positively related but benefit and use are not (Cox & Alexander, 1999; Kochkin, 2005). Comparing benefit and satisfaction, studies have found the outcomes are weakly related to one another (Souza et al., 2000; Vestergaard-Knudsen et al., 2010; Wong et al., 2003). Across studies, these findings suggest that these outcome domains should be evaluated independently.

One way to think of satisfaction versus benefit is in a practical sense. For example:

"*Wow! Your speech understanding improved by 20% with the hearing aids!*"

-Audiologist.

"*Okay…but I am still not satisfied and take them out whenever I am in a noisy place*."

-Patient.

This type of exchange occurs far too often in practice where an audiologist may measure objective benefit from a hearing aid, but the patient reports the opposite perception. Although objective measures of benefit are important to determine the functionality of the hearing aid itself, self-report is necessary to the audiologist and the patient because it reflects the patient's actual experience of using the device in the real world. In the example described here, the patient had improved benefit but poor satisfaction, but the opposite could also occur. Conversely, both benefit and satisfaction could be reported as improved or both could be reported as poor.

Problem to be Addressed

Unexplained Variability in Hearing Aid Satisfaction and Benefit among Older Adults

One of the main known reasons for poor hearing aid outcomes is trouble understanding speech in the presence of background noise (Kozlowski et al., 2017; McCormack & Fortnum, 2013; Popelka et al., 1998). When hearing aids are used in noise, reports of satisfaction and benefit decrease (Bentler, 2005; Wong et al., 2009), in some cases, dropping as low as 29% of users reporting any amount of satisfaction (Kochkin, 2002). When users are dissatisfied with their devices, consequences may include discontinued hearing aid use and poor quality of life (Kitterick & Ferguson, 2018).

Clinical expectations are based, in part, on the person's needs and their potential improvement relative to a given management plan (hearing aids). The American Academy of Audiology Guidelines for Audiologic Management (AAA, 2006) highlights the importance of identifying auditory needs to better address an individual's hearing and communication concerns. The current problem is that these individual needs are only roughly captured by an audiogram, only giving a window on hearing loss severity. In an effort to explain why so many people who need hearing aids do not seek help or discontinue their hearing aid use, outcomes have been evaluated using both behavioral and electrophysiological means across multiple domains. The focus of these studies will be on behavioral means.

Auditory Processing Abilities

A recent study by Lopez-Poveda et al. (2017) aimed to determine why there is great variability in hearing aid benefit (aided objective performance) and if predicting this outcome was possible. In their model, they included standard audiometric measures, temporal processing abilities (as measured by frequency modulation detection), hearing aid settings, aided audibility, and self-perceived abilities. Using multiple linear regression, Lopez-Poveda et al. found that variables "indicative of temporal processing" were correlated to aided speech perception in noise and perceived aided improvement was correlated to hearing aid satisfaction (p. 5). In order to advance this important research finding into a clinical application, a direct clinical assessment measure is needed to connect temporal processing with satisfaction. A challenge with these findings, as raised by the authors, is that objective benefit does not always correlate with self-reported perceptions of satisfaction and benefit. A model to determine if auditory processing abilities (and non-auditory factors) are related to self-reported outcomes is still needed to fill the gap in the literature.

Gatehouse (1994) suggested that evaluating the auditory system beyond hearing sensitivity, such as with temporal processing, may provide insight into successful amplification. An electrophysiological study showed that older adults with mild-to-moderate hearing loss had increased latency and decreased amplitudes on cortical auditory evoked potentials, suggesting more time needed (temporal processing) to activate cortical areas and process what is being heard when listening to sound (Campbell & Sharma, 2013).

When listening to speech, we utilize temporal and spatial processing of the acoustic input. For example, for temporal processing in quiet, we segment speech sounds based on the gaps of silence between syllables and words. However, when we listen to speech-in-noise, the noise interferes with the desired speech signal by filling in silent gaps between syllables and words, decreasing clarity. When temporal processing is poor, understanding speech-in-noise is more challenging and therefore, could contribute to hearing aid outcomes. With excellent temporal processing, the desired signal is understood clearly rather than being muffled by the noise (Souza et al., 2015).

Binaural interference can also contribute to unsuccessful binaural hearing aid use (Carter et al., 2001; Cox et al., 2011; Jerger & Silverman, 2018). For binaural processing, when we listen with two ears, or use two hearing aids, integration of input is required between ears. Dichotic listening has a tremendous amount of literature over the past 60 years and is interpreted as a direct indicator of how the higher auditory system is working (Kimura, 1967; Hugdahl & Westerhausen, 2016). A study analysed binaural processing abilities in 19 participants with symmetrical pure-tone sensitivities using the Dichotic Digits Test (DDT) among others (Leigh-Paffenroth et al., 2011). The DDT was presented using free recall, targeted recall, and targeted ear. Leigh-Paffenroth and colleagues found that 10 of the 19 participants had reduced binaural processing that could not be explained by the amount of hearing loss. This suggests that there is variability among auditory processing abilities of those with hearing loss.

Further, Carter et al. (2001) evaluated hearing aid benefit in both monaural and binaural hearing aid users. Results from this study found that when binaural processing was poor, users preferred and acquired more benefit from only one hearing aid, despite symmetrical hearing loss. These findings suggest that auditory processing abilities differ among those with hearing loss and may be helpful in determining why some hearing aid users are satisfied and receive benefit with their devices though others with similar audiograms struggle.

The results from the current literature suggest that although auditory processing capacity decreases with hearing loss, the decrease is not consistent among all individuals. These findings also suggest that auditory processing abilities differ among those with hearing loss and may be helpful in determining why some hearing aid users are satisfied with their devices and receive benefit when others with similar peripheral hearing losses do not.

Summary of the Research Gap to be Addressed

In summary, hearing aid outcomes are variable but important to improve. The rationale for the present dissertation studies is that temporal, spatial, and binaural processing have been identified as important contributors to the main complaints of patients: difficulty hearing and communicating in noise (Aarabi et al., 2016; Helfer & Vargo, 2009; Musiek et al., 2005; Neher et al., 2008). Early research into the auditory processing abilities of adult hearing aid users showed a significant positive association with hearing aid satisfaction in background noise, $r(56) = 0.48$ (Givens et al., 1998). There has been limited subsequent clinical research in this area to confirm or expand upon this promising finding. The wide variation in hearing aid satisfaction outcomes makes it challenging for clinicians to predict who will be satisfied with their devices (Bertoli et al., 2009; Cox et al., 2007; Hougaard & Ruf, 2011; Lopez-Poveda et al., 2017; Williger & Lang, 2015).

The results from the current literature suggest that although auditory processing capacity decreases with hearing loss and age, the decrease is not consistent among all individuals (Gallun et al., 2013; Souza, 2016; Vermeire et al., 2016). It cannot be assumed that audibility is reflective of an individual’s auditory processing ability, as suggested by the variation in test results among adults with hearing loss (John et al., 2012).

The overall objective of this dissertation is to determine how auditory processing assessments of temporal processing, spatial processing, and binaural processing are related to hearing aid outcomes in older adults. The long-term goal is to establish the evidence base supporting auditory processing evaluation as an expanded part of rehabilitative management to help target appropriate treatment and counsel on realistic expectations, with recommendations not solely based on audibility alone. The translation of existing measures from research to practice would contribute to better support of the patient's rehabilitation plan and early intervention if they are experiencing difficulty.

Auditory abilities of temporal, spatial, and binaural processing are the primary focus for these studies because literature suggests that they play an important role in an individual's ability to understand speech-in-noise (Bamiou et al., 2006; Givens et al., 1998; Musiek et al., 2005; Neher et al., 2008; Pienkowski, 2017; Snell, 1997). Further, it has been speculated in the literature that aging may influence underlying differences in auditory processing capacities of middle-aged and elder listeners (Murphy et al., 2018) and older adults with sensorineural hearing loss who use hearing aid users (Pichora-Fuller & Singh, 2006). Temporal and spatial processing are impacted by aging and hearing loss (Gallun et al., 2013; Souza, 2016; Vermeire et al., 2016). It is well known that as we age, auditory-related processing declines (Atcherson et al., 2015; Humes et al., 2012; Murphy et al., 2018; Snell & Frisina, 2000). John et al. (2012) found the greatest amount of variability in temporal processing thresholds among older adults with hearing loss as compared to older adults with essentially normal hearing. Across studies, these findings suggested that assessment of temporal processing could have clinical utility with enough variance in performance to discern individual differences in hearing aid outcomes.

Reader's Orientation to Dissertation Structure

In this dissertation, three studies were undertaken. First, a systematic review was conducted to evaluate the literature on auditory processing abilities and hearing and satisfaction. Second, a patient population was recruited and included for clinical research on these topics. Third, clinical methods were explored in more details regarding speech-in-noise testing. Older adults with hearing loss were recruited to complete questionnaires and participate in a variety of audiologic tasks. Each participant's hearing aids were also evaluated to determine current settings. The tests administered focused on aspects of behavioral auditory abilities. Results were interpreted using multiple linear regression analyses, Pearson's correlations, and point-biserial correlations. In the following dissertation chapters, each paper will be addressed in turn, followed by a chapter on overall conclusions and future directions across all studies.

Chapter Two: Can Auditory Processing Abilities Predict Hearing Aid Satisfaction? A Systematic Review[1]

Introduction

The purpose of this systematic review is to evaluate the existing literature on the connection between auditory processing abilities and hearing aid satisfaction among adults. Hearing aids are the main form of management for the nearly 36 million adults with mild to moderate bilateral hearing loss in the United States (Goman & Lin, 2016). However, only about 15% of the people who could receive benefit from hearing aids use them consistently (Chien & Lin, 2012). Hearing aid non-use and dissatisfaction poses problems because poorly managed hearing loss can increase the risk of social isolation, depression, and negatively affect overall quality of life (Kitterick & Ferguson, 2018).

Among the impacts of sensorineural hearing loss are changes in auditory processing abilities. For the purpose of this study, auditory processing includes suprathreshold auditory abilities related to understanding speech in complex listening environments which go beyond detecting for the presence of a sound. Complex listening environments can include, but are not limited to, multi-talker masking and dichotic presentations. Based on a scoping review, these abilities are thought to affect hearing aid satisfaction because the primary reason for dissatisfaction in adult hearing aid users is poor understanding of speech-in-noise (Gygi & Ann Hall, 2016).

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[1] Submitted: Everett, A., Marrone, N., Wong, B., & Musiek, F. (*in review*). Can auditory processing abilities predict hearing aid satisfaction in adults with hearing loss? A systematic review. *Ear and Hearing*. Oral Podium Presentation at the International Hearing Loss Conference, Niagara-on-the-Lake, Ontario, Candada (May, 2019). Presented for poster presentation at the International Hearing Loss Conference, Niagara-on-the-Lake (May, 2019), and the American Auditory Society's 46th Annual Scientific & Technology Conference, Scottsdale, AZ (February, 2019).

In the literature, hearing aid satisfaction has been linked to many different auditory, non-auditory, and hearing aid fitting experience factors. Hearing aid satisfaction is important to consider as an outcome because the amount of self-reported satisfaction is related to the average daily use for hearing aids (Bisgaard & Ruf, 2017). Hearing aid satisfaction is an outcome that is widely variable and not easily explained, despite historical trends towards improvement in satisfaction with advances in hearing aid technology. A review by Vestergaard-Knudsen et al. (2010) found a number of factors that may contribute to hearing aid satisfaction. Self-efficacy and personality consistently related to satisfaction across studies, while other factors had mixed or non-significant relationships.

The impact of degree of hearing loss on hearing aid satisfaction is a factor that has been previously studied with mixed findings. Degree of hearing loss is an important auditory factor to consider because it forms part of the basis for how hearing aids are fit to meet prescriptive targets. Vestergaard-Knudsen et al. (2010) reviewed 7 separate studies that discussed both degree of hearing loss and hearing aid satisfaction, of which only 3 studies reported positive correlations between the 2 variables. However, the correlations found did not explain significant amounts of variance in hearing aid satisfaction. The overall conclusion drawn from this review was that severity of hearing loss was not a clinically significant contributor to hearing aid satisfaction. Worsening hearing loss is a measure of change in hearing sensitivity. However, worsening hearing loss is also associated with declines in suprathreshold auditory perception, including intensity discrimination, temporal resolution, temporal integration, localization for narrowband stimuli, and speech intelligibility (Moore, 1996). These changes are not only perceptual consequences of hearing loss but are also auditory processing abilities that underlie speech perception in noise.

Current literature suggests that auditory processing abilities contribute to speech-in-noise understanding, making tests of auditory processing ability potentially important to consider in hearing aid prefitting evaluations (Ricketts, Bentler, & Mueller, 2019). Humes and Humes (2004) concluded that evaluating aspects of auditory processing may play an important role in the hearing aid success among older adults with hearing loss. In fact, clinical guidelines from the American Academy of Audiology state that counseling should include a discussion on “problems associated with understanding speech-in-noise,” (Valente et al., 2006) although there was not consensus based on the literature for a clinical protocol to assess these problems. Since the publication of this guideline, research has advanced in this area with development and identification of clinically ready measures of auditory processing for incorporation into practice. These measures have primarily been used to assess auditory function in individuals with stroke (Jafari et al., 2016) and other neurological etiologies (Musiek & Pinheiro, 1987). The rationale for the present systematic review is to determine if there is evidence that auditory processing abilities contribute to hearing aid satisfaction.

Assessment of an individual’s auditory processing abilities may help to explain the variability in hearing aid satisfaction. When auditory processing is evaluated, it can be categorized broadly into areas such as binaural processing, spatial processing, temporal processing, and speech understanding in noise. However, the specific underlying ability that is actually being assessed differs depending on the test selection. In one example, Leigh-Paffenroth, Roup, and Noe (2011) evaluated binaural processing using two tests:

The Dichotic Digits Test (DDT) and the Masking Level Difference (MLD). The DDT is a test of binaural integration (Musiek 1983), whereas the MLD is a test of binaural release from masking (Quaranta, Cassano, & Cervellera 1978). In addition to integration and release from masking, binaural processing can also include binaural separation (Schow, Seikel, Chermak, et al. 2000). Another example is that of temporal processing. Temporal processing can be divided into 4 subcategories: ordering or sequencing (pattern), resolution or discrimination, integration or summation, and forward/backward masking (Shinn 2003). Further, speech-in-noise abilities can be measured using different types of maskers varying in similarity to the target and spatial location, such as collocated masking noise or spatially separated masking noise. With these differences in the characteristics of the auditory stimuli, the level of difficulty differs across tests.

One challenge faced by many researchers and clinicians is that tests of auditory processing abilities have been normed on individuals with normal hearing sensitivity and not those with hearing loss. In fact, many tests of auditory processing cannot be done for those with more severe hearing losses. In some cases, as a result of the output limits of audiometers for administering supra-threshold tests and in other cases, because there is an interaction between test performance and sensation level. However, testing auditory processing abilities in those with mild to moderate hearing loss has also had limited adoption. This limited adoption may stem from the fact that when the auditory periphery is damaged, the central auditory system will also show dysfunction. Therefore, it is difficult to separate whether someone does poorly on an assessment due to the peripheral hearing loss itself or a more complex etiology in the central pathway. It is agreed upon in the literature that a person’s auditory processing ability is negatively affected by hearing loss

(Miltenberger, Dawson, & Raica 1978; Vermeire, Knoop, Boel, et al. 2016). As a result, implementation of tests of auditory processing abilities becomes challenging in a population with hearing loss due to the unclear interpretations.

Further complicating the interpretation is that the effects of peripheral hearing loss on auditory processing abilities differ depending on the individual. In a study by Neijenhuis, Tschur, and Snik (2004), auditory processing abilities were evaluated among individuals with symmetric hearing losses. Results showed more variability across participants with hearing loss compared with the control group with normal hearing on several auditory processing tests: frequency pattern, duration pattern, filtered speech, and binaural fusion. Another study analysed binaural processing abilities in 19 participants with symmetrical pure-tone sensitivities using the DDT and the MLD (Leigh-Paffenroth, Roup, & Noe 2011). Leigh-Paffenroth and colleagues found that 10 of the 19 participants had reduced binaural processing abilities which could not be predicted by their degree of hearing loss. This suggests that individuals with hearing loss show variability in their auditory processing abilities. Köbler, Lindblad, Olofsson, et al. (2010) evaluated 11 successful and 11 unsuccessful hearing aid users with similar sensorineural hearing losses. They concluded that auditory processing abilities for speech-in-noise, binaural integration, and self-reported spatial abilities were variable across individuals and that these variabilities contributed to successful or unsuccessful hearing aid use.

In summary, despite decades of research on the effects of hearing loss on auditory perception (Moore 1996; Buss, Hall III, Grose, et al. 1998; Tremblay, Piskosz, & Souza 2003; Plack, Barker, & Prendergast 2014), questions remain on how to predict hearing aid satisfaction. The aim of this study is to systematically evaluate the literature to examine (1) whether auditory processing abilities in adults can predict hearing aid satisfaction and (2) whether some clinically available tests predict poorer satisfaction outcomes better than others. The literature review presented here provides the first systematic review to answer the question: "*How do auditory processing abilities affect hearing aid satisfaction among adults?*"

Materials and Methods

This systematic review was planned and performed following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher, Liberati, Tetzlaff, et al. 2009). A 27-item checklist that PRISMA outlines was followed to produce a robust systematic review protocol. The 4 phases of the data collection process for a systematic review following PRISMA guidelines are: 1) identification, 2) screening, 3) eligibility, and 4) inclusion.

Phase 1: Identification.

The following bibliographic databases were searched: PubMed (1946-present), EMBASE (1947-present), CINAHL (1981-present), PyschINFO (1880's-present), SCOPUS (2004-present), and Web of Science (1898-present). Search terms were initially compiled by experts in the field of Speech, Language, and Hearing Sciences, controlled terms (e.g., MeSH, EMtree, and CINAHL Headings), and key words developed with guidance from a research librarian at the University of Arizona. Search terms for "hearing impairment" or "hearing aid" were combined with search terms expressing "auditory processing" and "hearing aid satisfaction." An example of the PubMed search strategy with search terms used can be found in Appendix 1. The search was completed between

February 22, 2018 and March 15, 2018 and no time restriction was used while searching the databases.

Phase 2: Screening

Two independent authors (AE, BW) screened the titles and abstracts for relevance. In cases of discrepancies, a discussion occurred between the 2 authors to try to resolve the disagreement. A third author (NM) was consulted as needed for final consensus on eligibility if a decision could not be made through discussion. In addition to database searches, a manual search of bibliographies from books, chapters, and articles were also reviewed for inclusion. Additionally, the reference lists of all the included studies were reviewed for the screening process.

Phase 3: Eligibility

The following were required for study inclusion: 1) participants were adults at least 18 years or older with hearing loss who use air-conduction hearing aids (studies that looked at implantable devices were excluded); 2) hearing aid satisfaction was measured using any form of self-reported evaluation, including formal and informal questionnaires (measures of hearing aid benefit, use, or other hearing aid outcomes were not considered for this review); and 3) behavioral measures of auditory processing abilities were assessed. Studies of electrophysiologic measures-only were excluded because there is not a conclusive relationship between prefitting evoked potentials and hearing aid outcomes (Tremblay, Billings, Friesen, et al. 2006; Billings, Tremblay, Souza, et al. 2007; Jenstad, Marynewich, & Stapells 2012; Marynewich, Jenstad, & Stapells 2012). Experimental studies published in peer-reviewed journals in English-only were included. Systematic reviews, non-peer reviewed sources, case reports, discussion papers, or presentations were excluded.

Phase 4: Data Collection From Included Studies

Data extraction from the included studies involved recording the following: study characteristics (author, title, journal, year), number of participants, age of participants, hearing loss degree and type, duration of current hearing aid use, type, and fitting style (unilateral vs bilateral), auditory processing test used and the result, hearing aid satisfaction measure used and the result, variance explained, and relevant statistics. In phase 4, for all studies included for data extraction, analysis, and synthesis, measures were categorized according to the auditory processing ability being tested. Results were evaluated based on the hypothesis that better/worse auditory processing abilities are associated with better/worse hearing aid satisfaction. If the study results supported this hypothesis, it fell into the category of “positive” (+) and if the results did not support the hypothesis, then it fell into the category of “negative” (-). If results did not show a significant association between an auditory processing ability and hearing aid satisfaction, it was categorized as “null” (denoted in Table 1 as “~”).

Study quality was evaluated to aid with the synthesis of information collected. Quality was determined using ASHA’s Level of Evidence (LOE) system for appraising the quality of the study (Mullen 2007). The LOE system includes an appraisal of 8 quality indicators: 1) study design, 2) assessor blinding procedures, 3) sampling procedures, 4) subject comparison, 5) validity and reliability of outcomes, 6) reporting of significance, 7) reporting precision, and 8) intention to treat. The eighth indicator, intention to treat, is for clinical trials only and was not included in the quality ratings. For all included studies, a yes or no is determined for each of the remaining 7 indicators. For the purpose of this study the following items were considered a ‘yes’ for each indicator: controlled trials and cohort studies, assessors were blinded, random sampling was used, subjects were comparable on hearing loss and age, the hearing aid satisfaction measure was valid and reliable, the *p* value was reported, and the effect size was reported. The total number of 'yes' results were counted and reported out of 7. A score of 0-1 was classified as weak, 2-4 was classified as moderate, and 5-7 was classified as strong (de Wit, Visser-Bochane, Steenberge, et al. 2016). The determined score was considered a measure of the internal validity of each study. Independently, 2 authors (AE, BW) reviewed the quality ratings for each included study and compared findings. A discussion was had if discrepancies arose between ratings and a third reviewer (NM) was consulted if an agreement between raters could not be reached.

Results

Selection and Characteristics of Included Studies

Figure 2.1 illustrates the flow of information through the systematic review, showing the process of identification, screening, eligibility, and final inclusion following PRISMA guidelines. A total of 3,864 records were identified through database searching and a manual search of additional bibliographies added 17 records. After 923 duplicates were removed, 2,941 titles and abstracts were screened for possible relevance. Subsequently, 312 full texts were assessed of the remaining records. During the full-text review, a strict inclusion/exclusion criterion was applied, and 305 articles were excluded because they did not meet the age requirements (n = 4), include an auditory processing measure (n = 81), include a hearing aid satisfaction measure (n = 176), meet the study type criteria (n = 43), and report in English (n = 1). After these assessments, 7 records met the full criteria to include for this review. All study designs except for systematic reviews, case reports, discussion papers, and presentations were included. A cross-sectional study was the most common design, applying to all but one study which used a cohort design (Thorup, Santurette, Jorgensen, et al. 2016).

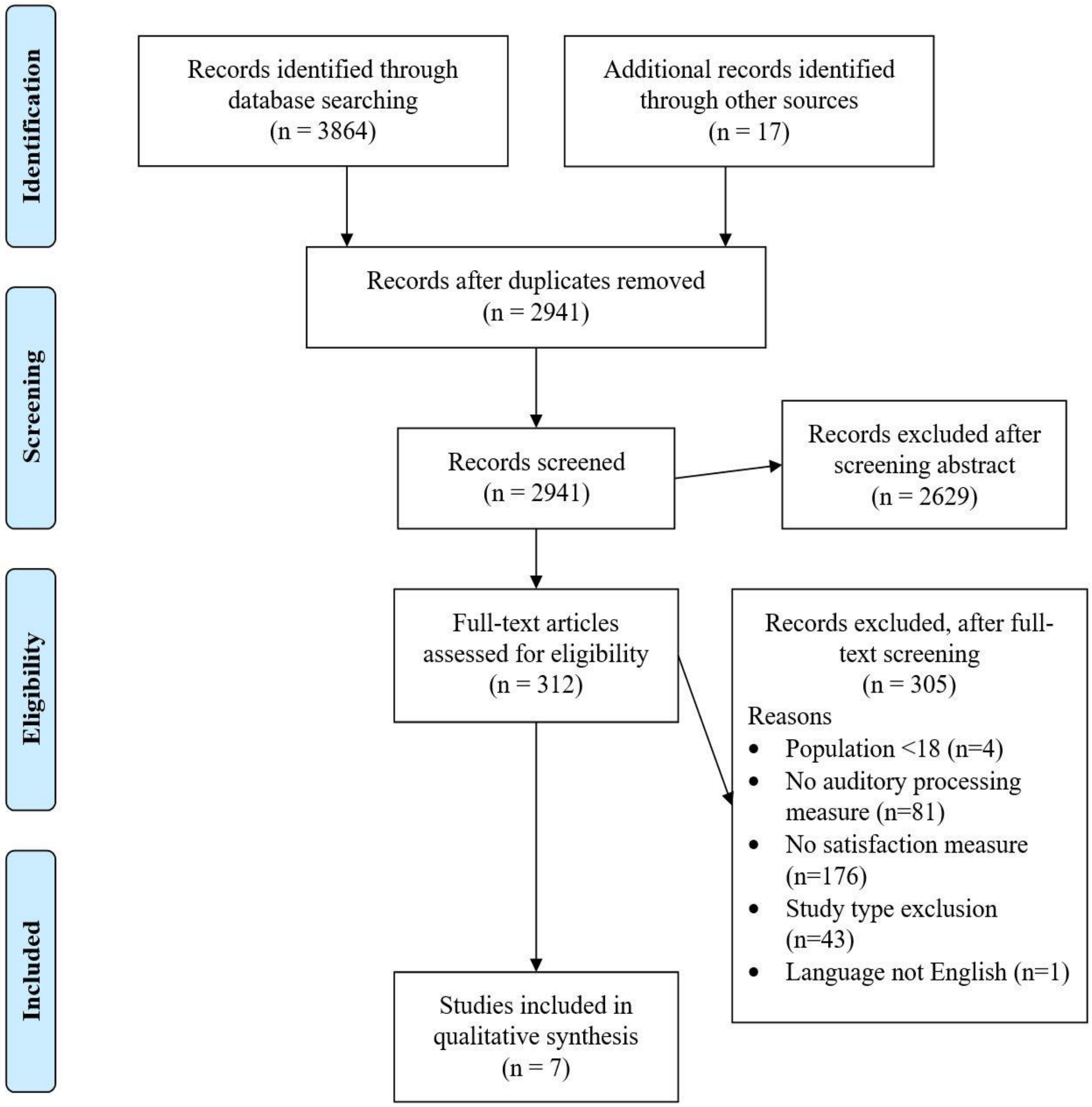

Figure 2.1. *Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines flow diagram.*

The flow diagram depicts the method for inclusion of studies in the systematic review.

In all 7 studies, adults with hearing loss were included; one study also included individuals with near-normal hearing (Thorup et al. 2016). The total number of people with hearing loss included across the 7 studies was 447, with an age range of 20 to 91 years. Hearing aids for these participants varied across manufacturer, fitting (unilateral/bilateral), and hearing aid style. Additionally, there was wide variation in the amounts of hearing aid experience and use. Participants' hearing losses ranged from mild to severe degrees with varying configurations. Two studies did not include participants' hearing loss status, only describing the hearing in terms of group mean pure tone averages (Hayes, Jerger, Taff, et al. 1983) and group mean thresholds at each frequency (Grunditz & Magnussion 2013). Of the remaining 5 articles, bilateral, symmetric sensorineural losses were reported.

The intervention evaluated in this systematic review was hearing aids and the patient-reported outcome of device satisfaction. Five of the 7 studies used standardized, validated satisfaction questionnaires: the satisfaction questions from the Glasgow Hearing Aid Benefit Profile (GHABP; Ahlstrom, Horwitz, & Dubno 2009), the Satisfaction with Amplification in Daily Life (SADL; Saunders & Forsline 2006; Ahlstrom et al.), the satisfaction questions from the Profile of Hearing Aid Performance (PHAP; Givens, Arnold, & Hume 1998), and the satisfaction questions from the International Outcome Inventory-Hearing Aids (IOI-HA; Grunditz & Magnusson 2013; Thorup et al. 2016). The remaining 2 studies used a study-specific, scaled 1-item question on overall satisfaction. Specifically, Bentler, Niebuhr, Getta, et al. (1993) used a 6-point scaled question and Hayes, Jerger, Taff, et al. (1983) used a 4-point scaled question.

The auditory processing assessments used were different across studies with two exceptions. Two studies evaluated auditory processing abilities using the Hearing in Noise

Test (HINT; Ahlstrom et al. 2009; Thorup et al. 2016) and 2 studies used the Synthetic Sentence Identification test (SSI; Hayes et al. 1983; Givens et al. 1998). The remaining articles evaluated auditory processing abilities using different tests: The Nonsense Syllable Test (NST) and the Speech Perception in Noise test (SPIN; Bentler, Niebuhr, Getta, et al. 1993), the DDT and Duration Pattern Test (DPT; Givens et al.), the Phonetically Balanced words + ICRA noise (PB+ICRA noise; Grunditz & Magnusson 2013), and the Performance Perceptual Test (PPT; Saunders & Forsline 2006).

Results on Clinically Available Assessments of Auditory Processing

We evaluated the findings on whether clinically available assessments of auditory processing abilities would predict hearing aid satisfaction by grouping the 7 studies according to their corresponding processing ability assessed: binaural integration, binaural separation, speech perception in noise (with collocated or spatially separated maskers), and temporal processing (ordering/sequencing). Table 2.1 summarizes the study characteristics and results for each reviewed study on the effect of auditory processing abilities on hearing aid satisfaction. The results of this review are next further described within these categories.

Table 2.1.
Summary of Study Characteristics and Findings

	Population			Outcomes	Intervention	Correlations	
Study	N	Age	Hearing Loss	Auditory Processing Ability (Test)	Hearing Aid Satisfaction Measure	Outcomes (hypothesis support)	Variance Explained/ Strength
Ahlstrom et al. 2009	21	69-83 years (M=75)	Bilateral symmetric mild to severe sensori-neural	Collocated Speech-in-Noise (HINT)	GHABP, and SADL	No significant correlations for collocated or spatially separated noise. (~)	--
Bentler et al. 1993	65	21-84 years (M=64)	Mild to moderate	Collocated Speech-in-Noise (NST, SPIN)	Overall Satisfaction on a 6-point question	No significant correlations to hearing aid satisfaction. (~)	Less than 8%
Givens et al. 1998	58	65-91 years	Bilateral symmetric mild to moderately severe sensori-neural	Temporal Processing (DPT), Binaural Integration (DDT), Binaural Separation (SSI)	PHAP	Significant correlations on the DDT. (+) No significant correlation on DPT. (~) Significant correlations on the SSI. (+)	<u>DDT:</u> 6.27-23% (r = -0.26-0.48) <u>SSI:</u> 7.8-25% (r = -0.28--0.5)
Grunditz & Magnusson 2013	102	24-91 years (M=72)	Not specified	Collocated Speech-in-Noise (S-PB+noise)	IOI-HA	No significant correlations at +6 dB SNR. (~)	--
Hayes et al. 1983	78	20+ years	Not specified	Spatially separated Speech-in-Noise (SSI)	Satisfaction question on a 4-point scale	Significant correlations on SSI. (+) 30% better SSI scores for users who were satisfied.	<u>SSI:</u> $p < 0.001$
Saunders & Forsline 2006	94	47-86 years (M=69)	Symmetric mild to moderately severe sensori-neural	Spatially Separated Maskers (PPT)	SADL	No significant correlations to the perceptual SRTN. (~) Significant correlations between	<u>PPT:</u> 4.4-16.5% (r = 0.2-0.41)

						performance SRTN and satisfaction. (+)	
Thorup et al. 2016	29	52-80 years (M=68)	Bilateral symmetric mild to moderate sensori-neural	Collocated Speech-in-Noise (D-HINT)	D-IOI-HA	No significant correlation. (~)	--

Abbreviations/Acronyms: DDT: Dichotic Digits Test; D-HINT: Danish Hearing-in-Noise Test; D-IOI-HA: Danish International Inventory for Hearing Aids; DPT: Duration Pattern Test; GHABP: Glasgow Hearing Aid Benefit Profile; HINT: Hearing-in-Noise-Test; IOI-HA: The International Outcome Inventory for Hearing Aids; NST: Nonsense Syllable Test; PHAP: Profile of Hearing Aid Performance; PPT: Performance-Perceptual Test; SADL: Satisfaction with Amplification in Daily Life Questionnaire; SC: Service Cost; S-PB+noise: Swedish Phonetically Balanced words in multi-talker noise; SPIN: Speech-in-Noise Test; SRTN: Speech Reception Threshold in Noise; SSI: Synthetic Sentence Identification Test

Collocated Speech-in-Noise Abilities and Hearing Aid Satisfaction.

Four articles assessed auditory processing abilities using clinically available collocated speech-in-noise tests: HINT, NST, SPIN, and the PB+ICRA noise (Bentler et al. 1993; Ahlstrom et al. 2009; Grunditz & Magnusson 2013; Thorup et al. 2016). There were 217 participants included across all 4 articles. Ahlstrom et al. (2009) assessed the correlation between self-reported hearing aid outcomes (satisfaction and benefit) and speech-in-noise in adults 69-83 years (M = 75.3 years). Here, speech understanding in noise was evaluated using the HINT with collocated speech babble. Hearing aid satisfaction was evaluated used the SADL questionnaire and the GHABP. Results of correlation analyses between self-report and collocated testing did not reach statistical significance.

Bentler et al. evaluated auditory processing using various speech perception tests including the NST and the SPIN, both of which can be used clinically. Participants' ages ranged from 21-84 years with a mean of 63.8 years. The NST uses cafeteria noise and the SPIN uses 12-talker speech babble. Satisfaction was assessed using a 6-item rating for the question, "*How would you rate your satisfaction with your new hearing aid?"*. No significant correlations between hearing aid satisfaction and any outcome measure in noise for the NST or SPIN were determined; the authors reported less than 8% of hearing aid satisfaction variance explained by any of the speech perception tests.

Grunditz and Magnusson (2013) examined the use of a speech-in-noise test to predict hearing aid outcomes in adults aged 24-91 years (M = 72 years). The test list was comprised of Phonetically Balanced, Swedish words mixed with a multi-talker babble at +6 dB Signal-to-Noise Ratio (SNR). The noise was unintelligible but had a speech-like spectrum. The speech-in-noise test included 50-words and was implemented into a hearing aid fitting appointment. Hearing aid satisfaction was measured using the IOI-HA. No significant correlations were determined for the speech-in-noise test in what was deemed a “moderately difficult listening condition” and satisfaction ratings on the IOI-HA.

More recently, Thorup et al. evaluated hearing aid satisfaction and auditory processing abilities by incorporating a Danish version of the HINT for the auditory processing measure and the IOI-HA for the hearing aid satisfaction measure. Participants had an age range of 52-80 years with a mean of 68 years. No significant correlation was determined between hearing aid satisfaction and the Danish version of the HINT.

Overall, these 4 articles demonstrated no significant correlations between the speech-in-noise measures of auditory processing abilities used in their studies and hearing aid satisfaction. All studies used collocated speech-in-noise, but the type of noise and presentation style (fixed or adaptive) differed for each measure.

Temporal Ordering/Sequencing Abilities and Hearing Aid Satisfaction.

The 1998 study by Givens et al. aimed to determine the relation between auditory processing skills and hearing aid satisfaction (n = 58 participants, 65-91 years). One test the authors used was the DPT, a test of temporal ordering/sequencing (pattern) processing. Satisfaction with hearing aids was determined using the PHAP. Results showed no significant correlations to the DPT.

Binaural Integration Abilities and Hearing Aid Satisfaction.

Givens et al. also evaluated the relationship between binaural integration and hearing aid satisfaction. Here, the authors used the DDT to determine binaural integration abilities. Significant correlations were determined for the DDT (r = -0.26-0.48 depending on the subscale of the PHAP, all $p < 0.05$) in that the poorer the participant's binaural integration ability was, as measured by the DDT, the poorer they reported their hearing aid satisfaction.

Binaural Separation Abilities and Hearing Aid Satisfaction.

Two studies, including 136 participants in total, evaluated binaural separation abilities using the SSI (Hayes et al. 1983; Givens et al. 1998). The SSI uses competing intelligible speech as the masking noise. Givens et al. determined a significant positive correlation between binaural separation abilities and hearing aid satisfaction using the SSI (r = -0.28−-0.5 depending on the subscale of the PHAP, all $p < 0.05$). For those with poorer scores on the binaural separation task, poorer satisfaction ratings were reported. Overall, the authors concluded that auditory processing measures, such as the SSI, could prove useful in a hearing aid prefitting evaluation test battery and may assist with providing realistic expectations of satisfaction to patients. Hayes et al. included the SSI for evaluation using multiple SNR conditions (+20 dB, +10 dB, 0 dB, -10 dB, and -20 dB) in adults 20+ years. Hearing aid satisfaction was evaluated with a 4-point, single item question. When the SSI was presented at -10 dB SNR, performance was significantly better (30%) for those who reported higher levels of satisfaction ($p < 0.001$). At 0 dB SNR, performance was 17% better, which did not reach statistical significance. All other SNR performances were less than 5% better.

Speech Perception in Noise With Spatially Separated Maskers and Hearing Aid Satisfaction.

The 2006 study by Saunders and Forsline utilized clinical tests to compare auditory processing abilities and hearing aid satisfaction (n = 94 participants, 47-86 years, M = 69.1 years). The clinical test utilized here was the PPT. The PPT utilized an adaptive HINT protocol with the speech presented at 0 degrees and noise from ± 90 degrees or ± 270 degrees. Scoring the PPT utilizes a performance score for speech reception threshold in noise (SRTN) where the participant correctly identifies 50% of the sentences in noise and a perceptual SRTN where the participant reports on their ability to understand the speech through the noise. Hearing aid satisfaction was evaluated using the SADL. The authors concluded a positive association between the scores on the SADL and PPT performance SRTN (r = 0.2-0.41 depending on the subscale of the SADL, all $p < 0.05$). These results indicate that those who reported lower satisfaction required a more favorable SNR as compared with those who reported average and high ratings of satisfaction. However, no significant correlations could be determined for the perceptual SRTN and hearing aid satisfaction.

Age and Audibility Influence

Of the 7 studies meeting the inclusion criteria, 4 reported on the correlations between participant age, hearing sensitivity and hearing aid satisfaction (Hayes et al. 1983; Bentler et al.1993; Saunders & Forsline 2006; Thorup et al. 2016). Evaluations of age effects did not show a significant correlation to hearing aid satisfaction (Hayes et al.; Bentler et al.; Saunders & Forsline 2006). Additionally, no significant correlations between degree or configuration of hearing loss and hearing aid satisfaction could be determined (Hayes et al.; Bentler et al.; Saunders & Forsline 2006; Thorup et al.).

Methodological Quality of Studies

The total quality score, assessed using the LOE system, showed that each study had moderate internal validity (2-4 points out of a possible 7). Table 2.2 shows the quality assessment profile for the included studies. Blinding and random sampling was not used in any of the 7 studies. The subjects' minimum age was comparable (50+ years) in 3/7 studies (Givens et al. 1998; Ahlstrom et al. 2009; Thorup et al. 2016), while the age range was much wider (20+ years) in the other studies. The hearing aid satisfaction measure was validated in 5 studies (Givens et al.; Saunders & Forsline 2006; Ahlstrom et al.; Grunditz & Magnusson 2013; Thorup et al.) but not in 2 others (Hayes et al. 1983; Bentler et al. 1993). All but one study reported the *p* value of the findings (Ahlstrom et al.) and 4 studies reported the precision in terms of effect size (Hayes et al.; Bentler et al.; Saunders & Forsline 2006; Thorup et al.).

Table 2.2.
Quality Assessment Profile for Included Studies

Study	Study Design	Blinding	Sampling	Subjects	Outcome	Significance	Precision	Total
Ahlstrom et al. 2009	Cross-sectional study (No)	No	No	**Yes**	**Yes**	No	No	2/7
Bentler et al. 1993	Cross-sectional study (No)	No	No	No	No	**Yes**	**Yes**	2/7
Thorup et al. 2016	Cohort Study (No)	No	No	**Yes**	**Yes**	**Yes**	**Yes**	4/7
Grunditz & Magnusson 2013	Cross-sectional study (No)	No	No	No	**Yes**	**Yes**	No	2/7
Givens et al. 1998	Cross-sectional study (No)	No	No	**Yes**	**Yes**	**Yes**	No	2/7
Saunders & Forsline 2006	Cross-sectional study (No)	No	No	No	**Yes**	**Yes**	**Yes**	3/7
Hayes et al. 1983	Cross-sectional study (No)	No	No	No	No	**Yes**	**Yes**	2/7

Discussion

This systematic review evaluated the question, "*How do auditory processing abilities affect hearing aid satisfaction among adults?*". The results from this review show a need for well-designed studies assessing the predictive value of auditory processing abilities on hearing aid satisfaction, with attention to the specific ability assessed. Of the 7 studies, 3 demonstrated significant findings for binaural integration, binaural separation, and speech perception in noise with spatially separated maskers as contributors to hearing aid satisfaction, while assessments of speech perception in noise with collocated maskers and temporal processing ordering/sequencing were not significantly related to satisfaction. Despite the extensive literature search across multiple databases, only 7 articles met the inclusion criteria and 5 of these were published 10 to 36 years ago. None of the available studies utilized hearing aid technology that is still commercially available, revealing the need for replication of the included studies with current hearing aid technology. All studies had a moderate methodological quality rating.

There are many ways to evaluate the "success" of using hearing aids, but satisfaction is one of the most common due to its importance as a patient-centered outcome. Another common way to evaluate success is with hearing aid benefit. The difference between satisfaction and benefit is that benefit evaluates the change in performance from the unaided to aided condition (either by performance or self-report) whereas satisfaction is the user's perceptual experience post-fitting obtained only through self-report (Tse & Wilton 1988; Oliver 1997). Although some studies may combine satisfaction and benefit as overlapping outcomes, "benefaction" (Humes 2006), Vestergaard-Knudsen et al. (2010) found that different factors influence self-reported benefit and satisfaction outcomes. For example, personality traits were determined to influence hearing aid satisfaction but did not influence hearing aid benefit (Vestergaard-Knudsen, Öberg, Nielsen, et al. 2010). Furthermore, in other studies, satisfaction and benefit were weakly correlated with one another (Souza, Yueh, Sarubbi, et al. 2000; Wong, Hickson, & McPherson 2004) and for these reasons were considered as independent outcomes. In the current review, satisfaction was chosen because it is often positively correlated with hearing aid use (Cox & Alexander 1999; Kochkin 2000) whereas benefit does not show this strong relationship (Hickson, Meyer, Lovelock, et al. 2014). Finally, a main reason for dissatisfaction is poor understanding speech-in-noise (Gygi & Ann Hall 2016), whereas the primary reasons for poor benefit with hearing aids typically involve the hearing aid feature characteristics (Hornsby & Ricketts 2007).

This review revealed that significant correlations have been reported in the literature between hearing aid satisfaction and tests of binaural integration, binaural separation, and speech perception in noise with spatially separated maskers. Specifically, the tests evaluating these abilities were the Dichotic Digits Test (Givens et al. 1998), the Synthetic Sentence Identification Test (Hayes et al. 1983; Givens et al.), and the performance section on the Performance-Perceptual Test (Saunders & Forsline 2006). Studies that measured temporal processing ordering/sequencing and speech perception using collocated maskers did not demonstrate significant correlations to hearing aid satisfaction (Bentler et al. 1993; Ahlstrom et al. 2009; Grunditz & Magnusson 2013; Thorup et al. 2016). In the next sections we address aim 1, whether there is evidence that auditory processing abilities in adults can predict hearing aid satisfaction. We discuss the auditory processing abilities evaluated within the reviewed studies and why they do, or do not, correlate to hearing aid satisfaction.

Tests Significantly Related to Hearing Aid Satisfaction

Binaural Integration.

Binaural integration abilities provide insight into how well the auditory system is processing and combining auditory information from both aided ears. The DDT assesses binaural integration by instructing the listener to process auditory information from both ears at the same time and report anything that is heard from either ear, also known as "free recall" (e.g., Kimura 1967; Hugdahl & Westerhausen 2016). On this test, interpretations are based upon comparisons between the right and left ear test scores, with the possibility of observing a slight right ear advantage regardless of hearing loss (Musiek 1999). When performance of one ear is much worse than the other, such as when a strong, non-symmetrical ear advantage is observed, binaural interference is suggested (Köbler, Lindblad, Olofsson, et al. 2010).

Multiple researchers have proposed that pre-fitting evaluation of binaural interference would inform unilateral or bilateral hearing aid selection or could explain poor outcomes of bilateral fittings (Carter, Noe, & Wilson 2001; Walden & Walden 2005; Köbler et al. 2010; Cox, Schwartz, Noe, et al. 2011; Mussoi & Bentler 2017). A study by Carter et al. evaluated unilateral versus bilateral hearing aid preference in individuals with different binaural integration abilities, as measured by the DDT. Carter and colleagues determined that those with dichotic listening deficits (binaural interference) benefited more from a unilateral fitting compared to a bilateral one. Walden and Walden showed comparable results to Carter et al. These researchers found that some individuals with symmetrical hearing loss may benefit more from a unilateral fitting in noisy listening situations compared to a bilateral fitting when binaural interference was present on the DDT. Similarly, Cox, Schwartz, Noe, et al. (2011) also reported variability in binaural integration abilities on the DDT in the free recall condition. Participants who preferred one hearing aid had a larger right ear advantage on average and when the DDT right ear advantage score was combined with additional measures, preference for two hearing aids was predicted with 66% accuracy. It could be argued that the patient's preference is analogous to satisfaction, as those who are dissatisfied with a binaural fitting would prefer to wear one.

Binaural Separation.

Binaural separation combined with binaural integration can be considered the binaural interaction abilities of an individual. The SSI is a monaural, low-redundancy speech-in-noise test that evaluates binaural separation and auditory closure (i.e., the ability to make auditory discriminations despite missing or degraded portions of the target signal). Participants are instructed to correctly identify target sentences from a closed set of ten randomized synthetic sentences in the presence of an informational masker, defined here as competing intelligible speech (Jerger & Jerger 1974). In the reviewed studies by Hayes et al. (1983) and Givens, Arnold, and Hume (1998), the SSI involved actively attending to the target while simultaneously suppressing the distractor, akin to a dichotic task with "directed ear" instructions.

There are differences between the SSI and other tests of speech-in-noise perception reviewed here that may be important when considering the relationship of binaural separation to hearing aid satisfaction. Firstly, tests of low redundancy speech help to isolate binaural interaction from reliance on linguistic cues. By making sentences semantically meaningless yet retaining temporal features and syntax of the English language, participants are less able to guess or use context to improve their score. Secondly, unlike many other speech-in-noise tests utilizing open-set and verbal responses, in the SSI, test stimuli are drawn from a closed set and participants respond in a non-linguistic format (e.g., button pressing or pointing). These testing procedures reduce the confounding variables of memory and language that could otherwise potentially influence results. In terms of hearing aid satisfaction, isolating binaural separation from other factors may be a better representation of an individual's auditory-perceptual experience. Separating who or what we want to hear from background noise is a part of daily communication and common in real-world listening environments (Woods, Merks, Zhang, et al. 2010).

Speech Perception in Noise With Spatially Separated Maskers.

In Saunders and Forsline (2006), the PPT assessed speech perception in noise abilities with spatially separated maskers. Individuals who are able to utilize binaural cues with spatially separated speech and noise have shown improved speech understanding compared to collocated listening (Kidd, Mason, Brughera, et al. 2005; Pienkowski 2017). If an individual has poor spatially separated speech perception in noise abilities, their ability to rely on spatial cues diminishes along with their speech understanding, which could contribute to their dissatisfaction with hearing aids. Although this measure was adapted from the HINT [which did not correlate to hearing aid satisfaction (Ahlstrom et al. 2009; Thorup et al. 2016)] an alternate explanation for this correlation could be the variability in spatial processing abilities. In fact, Helfer and Freyman (2008) and Gallun, Diedesch, Kamel, et al. (2013) suggested that spatial processing abilities decrease with increasing age and hearing loss, though with differing rates of decline. This individual variation could contribute to the differences in correlation results across studies.

Tests Not Significantly Related to Hearing Aid Satisfaction

Speech Perception in Noise With Collocated Maskers.

Collocated presentations of speech-in-noise may not represent realistic listening environments. In a study of hearing aid users, Woods, Merks, Zhang, et al. (2010) collected recordings of sound sources and signal levels in participant's daily lives. They determined that hearing aid users are in situations where signal and noise sources are spatially separated, and the environment involves multiple sound sources. Further, a recent article by Wu, Stangl, Chipara, et al. (2018) characterized real-world listening environments for older adults with mild to moderate hearing loss into subcategories, two of which were talker location and noise location. These researchers found that the most common noisy environment experienced by their sample involved diffuse noise with the talker location from the front. A collocated speech-in-noise task would not fully encompass the challenges individuals face with their hearing aids in these types of real-world noisy situations. Thus, a collocated speech-in-noise task could be too far removed from the types of situations that form the basis of hearing aid users' judgments about hearing aid satisfaction in noisy environments. This, in theory, could help explain why a task with spatially separated maskers correlated with hearing aid satisfaction whereas tasks with collocated maskers did not.

Temporal Ordering/Sequencing.

The DPT was used to measure temporal processing and was not correlated to hearing aid satisfaction (Givens et al. 1998). Specifically, three blocks of noise are presented binaurally with breaks in between. The participant is asked whether the noises were of short or long duration and to respond in the correct order (Musiek, Baran, & Pinheiro 1990). The underlying construct being assessed here is the ordering/sequencing subcategory of temporal processing. Both the DPT and DDT require interhemispheric transfer of information. However, evaluating ordering/sequencing abilities does not provide information on laterality or ear effects (Musiek 1994), unlike tests of binaural interaction. Perhaps these ear differences could be one of the main contributors to hearing aid satisfaction rather than the interhemispheric transfer.

As discussed previously, there are 4 main categories of temporal processing: ordering or sequencing (pattern), resolution or discrimination, integration or summation, and forward/backward masking. It is possible that although the ordering and sequencing dimension of temporal processing did not significantly relate to hearing aid satisfaction, another dimension may be more predictive. For example, temporal resolution has been shown to be significantly related to speech perception in noise abilities (Feng, Yin, Kiefte, et al. 2010). That is, when temporal resolution abilities diminish, speech perception abilities in noise also decrease, which ultimately may affect hearing aid satisfaction in noise.

Clinically Available Assessments of Auditory Processing

Unfortunately, we are unable to address aim 2 from this review, whether some clinically available tests predict satisfaction outcomes better than others. While the assessments used across studies to evaluate auditory processing abilities were all readily available for clinical use, their clinical efficiency was not assessed. Although Bentler et al. (1993) and Givens et al. (1998) included more than one test of auditory processing abilities in their design, the analyses were done independently. This type of methodology limits the findings of which predictor is better because it does not take into account the other possible predictors that could be explaining some of the variance. A comprehensive prospective study with up-to-date hearing technology is needed that includes multiple auditory processing abilities in one model to determine the relationship to hearing aid satisfaction. Some researchers have concluded that an auditory processing test battery may have the most clinical utility in predicting hearing aid satisfaction (Hayes et al. 1983; Givens et al.), while others suggested that a clinical protocol should prioritize certain measures (Cox et al. 2011, Mussoi & Bentler 2017).

Limitations of the Review

The purpose of this systematic review was to determine whether auditory processing abilities influence hearing aid satisfaction, which is only one aspect of the patient's hearing aid experience. A comprehensive systematic review of additional hearing aid outcomes such as benefit and use are also warranted. These additional reviews would help to understand a patient's self-reported and functional benefit and their relation to auditory processing abilities.

Conclusions to be drawn from this review are also constrained by the availability of information about the study populations. Participant demographics were not consistently reported across studies, particularly for characterizing hearing status. In most cases, hearing loss was described in broad terms (e.g., bilateral symmetric sensorineural hearing loss) and without audiometric details. Further, the hearing aids and amplification characteristics were not described extensively, restricting comparisons by devices or features in explaining hearing aid satisfaction. Information regarding unilateral vs bilateral fittings, time after hearing aid fitting, and previous experience with hearing aids were also not well reported across studies. This lack of reported data limits the analyses and generalizability of findings.

Conclusions and Future Directions

Testing for auditory processing abilities pre-fitting would allow for a more comprehensive evaluation of an individual's functional abilities in complex listening environments as compared to threshold testing alone. The aim of this systematic review was to determine if there is evidence that auditory processing abilities contribute to hearing aid satisfaction. The results from this review suggest that binaural integration, binaural separation, and speech perception in noise with spatially separated maskers contribute to hearing aid satisfaction. Age and degree of hearing loss did not conclusively predict hearing aid satisfaction; all of the included articles that evaluated degree of hearing loss found no significant correlations to hearing aid satisfaction. While it is reasonable to conclude that certain auditory processing abilities contribute to hearing aid satisfaction to some extent and may benefit the hearing aid evaluation appointment, updates on this topic, including replication and prospective studies, are needed.

Chapter Three: Investigating the Role of Auditory Processing Abilities in Hearing Aid Outcomes Among Older Adults

Introduction

There is a growing body of literature that recognizes that sensory loss, and its resulting communication disorders, can impact an individual's psychosocial functions, feelings of well-being, communication, social interaction, and overall quality of life (Heine & Browning, 2002; Hickson & Scarinci, 2007; Mick et al., 2014). To mediate these negative mental health implications, hearing aids are a viable management option. To determine if a hearing aid is helping the individual, subjective measures are typically conducted at subsequent hearing aid appointments.

Subjective measures, or self-report, are commonly used to estimate benefit and changes in perceived performance of hearing aids (Anderson et al., 2018; Cox & Alexander, 1992; Gatehouse, 2001). It is also common for an audiologist to see patients with the same hearing loss and similar hearing aid settings (in terms of their advanced features) who self-report a wide range of benefit and satisfaction from their devices. This is a problem because when users are more satisfied, they report more hearing aid use (Vestergaard-Knudsen et al., 2010). However, to this day, patient-reported outcomes remain highly variable and difficult to predict based on current audiological evaluations (Bertoli et al., 2009; Cox et al., 2007; Lopez-Poveda, et al., 2017). When individuals are not satisfied with their devices and stop using them, they fall back into the category of untreated hearing loss. What is not known are the reasons behind this variability of outcomes. There is a need to determine how to predict patient-reported hearing aid outcomes in a comprehensive way so that the number of adults who use hearing aids to treat their hearing loss increase (Healthy People, 2020).

A literature review by Vestergaard-Knudsen et al. (2010) concluded that self-reported hearing aid satisfaction is necessary for continued hearing aid use and further research is needed to better understand the underlying factors related to satisfaction. Extensive research into hearing aid satisfaction has addressed possible contributing factors. Predisposing characteristics of the individual were hypothesized to play a role, including attitude towards hearing aids and hearing loss (Wilson & Stephens, 2003), expectations (Cox & Alexander, 2000; Gatehouse 1994) and personality (Cox et al., 2007; Gatehouse, 1994). Other factors explored have related to resources that may influence a person's health behavior, including self-efficacy (Ferguson et al., 2016; Smith & West, 2006) and the individual's perceived need for intervention such as self-report of disability (Helvik et al., 2008; Hosford-Dunn, 2001; Mulrow et al., 1992; Takahashi et al., 2007; Uriarte et al., 2005). Additionally, research has addressed the influence of the hearing health care system, including the role of the hearing aid professional (Uriarte et al., 2005), counseling (Eriksson, 1990; Kemker, 2004; Norman et al., 1995), time after hearing aid fitting (Munro & Lutman, 2004), and personal practices such as lifetime hearing aid usage (Hosford-Dunn, 2001; Uriarte et al., 2005).

There has been a considerable amount of research on the perceptual consequences of hearing loss (Buss et al., 1998; Moore, 1996; Plack et al., 2014; Tremblay et al., 2003), yet, there is limited clinical translation on how these outcomes may impact hearing aid outcomes. The premise of this study was that understanding speech in the presence of background noise depends upon multiple auditory processing mechanisms, yet these are not being measured clinically for the purpose of hearing aid fittings (Aarabi et al., 2016;

Lagacé et al., 2008). Further, a recent systematic review found that there is a lack of research on aural rehabilitation interventions to improve hearing aid use (Barker et al., 2014; *Cochrane*). In order to develop treatments to improve outcomes, we need to better assess individual abilities, which will be measured here with multiple aspects of auditory processing. Auditory processing can be simply thought of as the capability of an individual to process and understand complex sound signals, such as speech (Diges et al., 2017; Flanagan et al., 2018; Musiek, Shinn, Chermak, & Bamiou, 2017).

Far fewer studies have considered auditory objective need factors, including hearing sensitivity (Hosford-Dunn, 2001) and binaural processing (Carter et al., 2001; Givens et al., 1998). The literature to date on auditory factors contributing to hearing aid outcomes have shown mixed findings; while some studies have shown no correlation, other studies have found some degree of correlation. Non-auditory measures of self-efficacy, personality, self-reported hearing problem, hearing aid professional, lifetime hearing aid use, and binaural processing are factors that predict higher satisfaction more consistently. In fact, personality and self-efficacy have both shown to reliably explain significant amounts of variance in hearing aid satisfaction: 25-30.4% for personality (Cox et al., 2007; Gatehouse, 1994) and 43% for self-efficacy (Ferguson et al., 2016). Subsequently, Hickson et al. (2014) reviewed factors associated with hearing aid success, as defined by moderate benefit, and found perceived hearing disability and self-efficacy were significant contributors to self-reported benefit.

Theoretical Framework

The literature review by Vestergaard-Knudsen et al. (2010) found that 31 different factors have been investigated as potential contributors to hearing aid satisfaction with mixed results. Most of these factors have been studied in isolation, lacking a unifying theory to guide research on hearing aid services and outcomes. In other health disciplines, the Andersen Behavioral Model of Health Services Use (1995) has been adapted to explain a variety of health behaviors and outcomes that are influenced by multi-faceted variables (Babitsch et al., 2012). Figures 3.1 and 3.2 illustrate adaptations of Andersen's model as the theoretical framework chosen for this study. Specifically, Figure 3.1 depicts the logic model for hearing aid satisfaction and Figure 3.2 illustrates the logic model for hearing aid benefit. The authors posit that multiple factors influence consumer outcomes. For this study, objective measures of need were evaluated using temporal, spatial, and binaural processing and audibility [Speech Intelligibility Index (SII)] to determine how they are related to hearing aid outcomes. Although extensive research has been carried out on factors that may be related to hearing aid outcomes, no single study exists before this which combines these factors together.

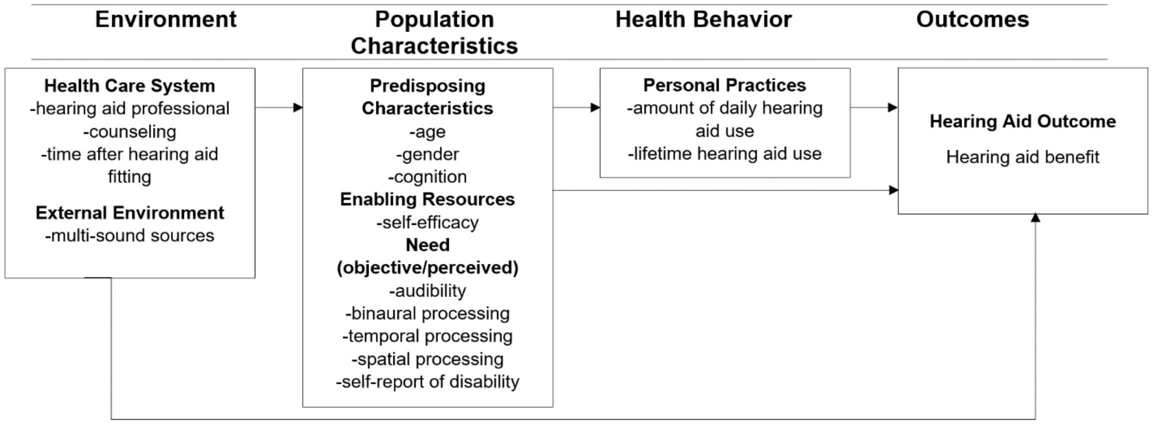

Figure 3.1. *Andersen Behavioral Model of Health Services Use (1995) framework for hearing aid satisfaction.*

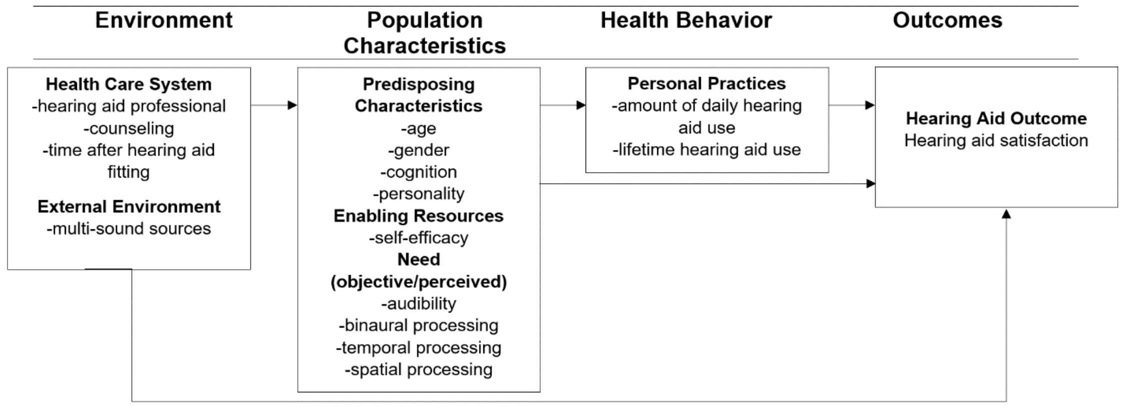

Figure 3.2. *Andersen Behavioral Model of Health Services Use (1995) framework for hearing aid benefit.*

Here, a systematic approach was used to determine the extent to which auditory and non-auditory factors are related to hearing aid outcomes among older adults. While hearing aid intervention does not change the individual's underlying processing abilities, understanding the extent of the residual disability will illuminate avenues for targeted rehabilitation beyond a hearing aid. Having knowledge about a person's auditory processing abilities may provide insight into additional management approaches such as implementing assistive technology, aural rehabilitation, and patient education. The findings from this study will provide a positive impact on patient-centered care by further explaining the functional deficits of hearing loss.

Specific Aims

1) Determine how auditory processing abilities (temporal, spatial, and binaural processing) and non-auditory factors (personality and self-efficacy) are related to hearing aid satisfaction among older adults with bilateral hearing aid experience.
2) Determine how auditory processing abilities (temporal, spatial, and binaural processing) and non-auditory factors (self-report of hearing disability and self-efficacy) are related to hearing aid benefit.

Hypotheses

1) Controlling for aided audibility and use, temporal, spatial, and binaural processing abilities will independently relate to hearing aid satisfaction. (Aim 1)
2) Controlling for aided audibility and use, auditory processing abilities, personality and self-efficacy will independently relate to hearing aid satisfaction. (Aim 1)

3) Having accounted for aided audibility and use, temporal, spatial, and binaural processing abilities will independently relate to self-reported hearing aid benefit. (Aim 2)

4) Having accounted for aided audibility and use, auditory processing abilities, self-report of disability and self-efficacy will each independently relate to hearing aid benefit. (Aim 2)

These hypotheses have been formulated on the basis of prior research that differences in hearing aid outcomes across individuals may be due to underlying differences in their auditory processing abilities (Lopez-Poveda et al., 2017; Pichora-Fuller & Singh, 2006). Additionally, literature has shown a large amount of hearing aid outcome variance explained by temporal processing (Gatehouse, 1994), spatial processing (Saunders & Forsline, 2006), binaural processing (Givens et al., 1998), personality (Cox et al., 2007; Gatehouse, 1994), self-efficacy (Ferguson et al., 2016; Hickson et al., 2014), and self-report of disability (Hickson et al., 2014). Auditory processing occurs with all forms of auditory input, including speech, background noise, and alert signals, yet clinical evaluations of sensorineural hearing loss for the purpose of recommending amplification and other forms of aural rehabilitation do not routinely utilize measures of auditory processing to predict patient-reported outcomes.

For this study, the focus is on the contribution of temporal, spatial, and binaural processing to hearing aid satisfaction and benefit, while assessing or addressing other non-auditory aspects of hearing aid outcomes. Understanding these aspects of an individual's auditory processing may provide insight into the variability of hearing aid outcomes. A major contribution of this work is to obtain one of the most comprehensive assessments to date of auditory and non-auditory factors contributing to outcomes in a cohort of experienced hearing aid users. The goal of this study was to pinpoint the contributions of auditory processing abilities and other personal characteristics of the individual on hearing aid outcomes. The motivation to study this issue among older adults stems from the well-known age-related declines in auditory processing (Atcherson et al., 2015; Humes et al., 2012; Murphy et al., 2018; Snell & Frisina, 2000). Auditory processing assessments measure more aspects of the hearing experience outside of standard audiometric testing (Musiek et al., 2017). The perceptual consequences of sensorineural hearing loss on auditory processing, and their association with hearing aid outcomes are addressed using the approach described here.

Methods

This study took place over one session that lasted up to three hours (Table 3.1). Procedures were administered in one of two ways: 1) in a double-walled sound-treated booth with stimulus presentation under insert earphones using a PC-based audiometer (Otometrics Astera) that was calibrated according to the American National Standards Institute (ANSI S3.6-2004), or 2) in a quiet room under Sennheiser HD 280 Pro Headphones connected to a Phonak USB self-calibrating sound card that was then plugged into the headphone jack of a Dell Inspiron laptop. Daily listening checks were conducted to ensure consistency and integrity of the data. Informed consent and private health information forms were discussed in an oral and written format and signed prior to any testing. Next, a cognitive screening measure was used to determine eligibility. Then, self-assessment questionnaires and auditory assessments were performed for data collection. Finally, the participant’s own hearing aids and aided audibility were evaluated. This study was approved by the University of Arizona’s Institutional Review Board prior to any human recruitment or data collection.

Table 3.1. *Summary of testing protocol across sessions.*

Construct	Assessment Tool	Testing Time
Self-Report Forms and Assessments	Consent/PHI Listener Questionnaire Measure of Audiologic Rehabilitation Self-Efficacy for Hearing Aids (MARS-HA) Speech, Spatial, and Hearing Qualities (SSQ) Questionnaire Neo-Five-Factor-Inventory-3 (Neo-FFI-3)	~30 minutes
Patient-Reported Outcome Measures	Satisfaction with Amplification in Daily Life (SADL) The Client Oriented Scale of Improvement (COSI)	~10 minutes
Cognitive Screening	Montreal Cognitive Assessment (MoCA)	~10 minutes
Clinical Auditory Assessments	Pure-tone audiometry (air and bone conduction) Word recognition in quiet	~20 minutes
Temporal Processing	Gaps-in-Noise (GIN) unaided with earphones (2 lists for each ear)	~35 minutes
Spatial Processing	Listening in Spatialized Noise Sentence Test (LISN-S)	~15 minutes
Binaural Processing	Dichotic Digits	~10 minutes
Hearing Aid Evaluation	Real-ear Measures Data-logging Feature set-up documentations	~10 minutes

Participants

Adults (n = 78) were recruited for this study. The inclusion and exclusion criteria are provided in Table 3.2. Exclusionary criteria did not include sex, race, or ethnicity. The University of Arizona is located in Pima County, Arizona and the demographic of the participants were expected to approximate the U.S. Census data for this area (U.S. Census, 2010). The following participant demographics were anticipated: 51.8% White alone, not Hispanic or Latino; 37.3% Hispanic or Latino; 4% Black or African American; 4% American Indian and Alaska Native; 3% Asian; 2.9% two or more races; 0.2% Native Hawaiian and other Pacific Islander. As this census information is not specific to those with hearing loss or age, there was some deviation in the study sample.

Table 3.2. *Inclusion and exclusion criteria.*

Inclusion	Exclusion
60 years of age or older	Under 60 years of age
Current, bilateral hearing aid use for at least 1 year	Non-hearing aid user or recently fit user
Symmetrical, mild-to-moderate sensorineural hearing loss based on 3 frequency PTA (1.0, 2.0, and 4.0 kHz) bilaterally	Does not meet audiologic criteria or has a conductive hearing loss component (>10 dB between air- and bone-conduction thresholds)
Proficiency in written and spoken English	Fails a cognitive screening (MoCA) with a score of 25 or below

Recruitment and Retention.

Participants were recruited through the University of Arizona Adult Hearing Clinic. This clinic currently serves over 2,400 patients with hearing loss. Potential participants provided consent to be recruited for future research studies as part of the registration process to be seen at the clinic. This information gets stored in the clinical databases: Lytec and TIMS. To obtain information and access the clinical databases for research purposes, The HIPAA Privacy Officer for The University of Arizona Speech, Language, and Hearing Sciences Department, Janet Hawley, provided approval. After data collection was complete, a list of names, dates the chart was accessed, and the nature of information collected were reported to Janet.

Using the clinical databases, a list of bilateral hearing aid users who were fit at least 1-year prior and were over the age of 60 years was developed. From here, the audiogram module on Noah 4 was accessed to determine if the patient fit the audiologic criteria. This process of acquiring patient lists was repeated until the desired n was reached. Recruitment criteria for participation did not include sex or gender. The proportion of male to female participants is not expected to impact the findings of this research due to a literature review concluded that gender is not a factor in hearing aid outcomes (Vestergaard-Knudsen, 2010).

Retention and attrition was not a major concern for this study because each participant only needed to attend one experimental session. Compensation of $10/hour was also provided to the participants to encourage remaining for the entire length of the one session.

Elements Addressed for Experimental Control

To address the influence of health care system factors within Andersen's Model, participants were recruited from the same hearing clinic to minimize contributions of the quality of counseling and the hearing aid professional. All audiologists of the University of Arizona Hearing Clinic follow evidence-based standards of care and verification. To address other factors in Andersen's Model, recruitment was limited to patients who have similar hearing losses (mild-to-moderate, bilateral, sensorineural loss) with at least 1-year of hearing aid experience.

Cognitive Screening

The Montreal Cognitive Assessment (MoCA) is a validated cognitive screening measure that was used to exclude individuals who present with a possible mild cognitive impairment. This 30-point, one-page assessment evaluates short-term memory, visuospatial abilities, executive functioning, attention and working memory, language fluency, and orientation. This screening has a sensitivity of 90% and specificity of 87% in detecting mild cognitive impairment (Nasreddine et al., 2005). Scoring of the MoCA ranges between 0 and 30 with a score of 26 or more points considered to be in the normal range.

Audiometric Testing

All audiometric testing took place in SLHS 109 in a sound-treated double-walled booth with single-use E-A-RLink 3A or 3B insert earphones. Otoscopy was conducted to determine the outer ear health of each participant including cerumen build-up inspection. Participants then completed a comprehensive audiologic evaluation beginning with air-and bone-conduction pure-tone threshold assessment (250-8000 Hz) for each ear. Thresholds were measured using a diagnostic PC-based audiometer (Otometrics Astera). Methods for word recognition testing in quiet followed the procedures established by Guthrie and Mackersie (2009): using the NU-6, 50-word list presented at a sensation level (SL) relative to the participant's 2 kHz threshold: <50 dB HL, 25 dB SL; 50-55 dB HL, 20 dB SL; 60-65 dB HL, 15 dB SL; 70-75 dB HL, 10 dB SL.

Outcome Measures

All outcome measures were collected interview-style. The researcher asked each question to the participant who provided an appropriate response. The response was then recorded by the researcher on REDCap, an online data management system.

The Satisfaction with Amplification in Daily Life (SADL) questionnaire (Cox & Alexander, 1999) was administered as the main outcome measure for hearing aid satisfaction. Review of the literature showed that this was a commonly referenced questionnaire to evaluate an individual's hearing aid satisfaction that has been validated and shown to have good test-retest reliability (Vestergaard-Knudsen, 2010). This 15-item questionnaire was also chosen because it considers four aspects of hearing aid satisfaction. These aspects can be evaluated separately and with a cumulative Global Score (Cox & Alexander, 1999). These four aspects take into consideration Positive Effect, how well do the hearing aids help with understanding familiar conversation, the naturalness of sound, and reducing the need for repetition; Service and Cost from the hearing professional; Negative Features, how do the hearing aids handle extraneous sounds, feedback, and telephone calls; and Personal Image, do the hearing aids make you feel less capable or give you a negative stigma.

The Client Oriented Scale of Improvement (COSI) questionnaire (Dillon et al., 1997) was administered as the main outcome measure for hearing aid benefit. The COSI has shown to be a valid and replicable measure for estimating patient-reported hearing aid benefit (Dillon et al., 1997; Lopez-Poveda et al., 2017). This clinical tool provides documentation of individual goals and needs prior to being fit with a hearing aid and then allows for self-reported measurements of hearing aid benefit at the time of this study. This measure has a great advantage over objective need because it shifts the focus to individualized rehabilitation plans rather than laboratory improvement.

Self-Report Assessments

All self-report assessments were conducted and recorded in the same manner as the outcome measures, using interviewing and REDCap.

The Listener questionnaire is a form developed in Dr. Marrone's Aural Rehabilitation Laboratory that allows the researcher to obtain a detailed hearing case history from the participant. Relevant to this study, data from the following questions was collected for analysis of perceived need, health care system, and personal practices: "*Do you have a known hearing loss?*"; "*How long have your worn your current hearing aids?*"; "*When did you first start wearing a hearing aid?*"; and "*How long did you notice a hearing problem before obtaining hearing aids?*";

Additional questionnaires were administered to assess factors that may influence hearing aid outcomes based on the Andersen Behavioral Model of Health Services Use such as predisposing characteristics, enabling resources, and perceived need. Predisposing characteristics were assessed through the Neo-Five-Factor-Inventory-3 (Neo-FFI-3; Costa et al., 1989), a personality measure. The NEO-FFI-3 assesses multiple personality domains including Neuroticism, Extraversion, Openness, Agreeableness, and Conscientiousness on a 60-item questionnaire. The Neo-FFI-3 was normed on 1000 men and women aged 21 to 96 years old and has demonstrated stability among different age groups and genders (Costa, Herbst, McCrae, & Siegler, 2000). This finding suggests that the Neo-FFI-3 can be administered to any aged adult with any gender without resulting in significant differences. The scores for this questionnaire range from 0 to 48 for each domain and a standardized score can be calculated from here:

10[(raw score – mean score)/standard deviation] + 50.

The Neo-FFI-3 has been incorporated into the hearing research literature to evaluate its correlations with hearing loss and hearing aid satisfaction. Cox, Alexander, and Gray (2005) assessed 230 hearing aid users aged 41-87 years on the correlation between participant's personality and hearing loss. There were no significant correlations determined for any personality domain and severity of hearing loss. Cox et al., (2007) went on to further these initial findings to determine the correlations between personality and hearing aid satisfaction using the Neo-FFI-3. These researchers found that the Satisfaction with Amplification in Daily Life (SADL) questionnaire, specifically the Personal Image aspect, was significantly related to 4 of the 5 domains of personality (all except Openness). An additional study reported on the percent of variance explained due to personality using the Neo-FFI-3 (Cox, Alexander, & Xu, 2014). This study showed that about 15% of the variance in the SADL-PI aspect is due to personality. The other aspects of the SADL accounted for less than 6%. Participants were asked to state the extent to which they agree or disagree with a statement on a five-point scale from "strongly agree" through "strongly disagree."

Enabling Resources were evaluated with a self-efficacy measure, the Measure of Audiologic Rehabilitation Self-Efficacy for Hearing Aids (MARS-HA; West & Smith, 2007). The MARS-HA is a 24-item questionnaire that evaluates self-efficacy beliefs on basic hearing aid handling, advanced handling and knowledge, adjustment to the sound of hearing aids, and aided listening skills. The participant is asked questions about their ability to do certain activities with hearing aids and asked to respond how certain they are that they can do that task from 0-100%.

Perceived need was addressed by administering the Speech, Spatial, and Hearing Qualities (SSQ; Gatehouse & Noble, 2004) questionnaire. For the SSQ, there are three sections divided into speech, spatial, and hearing quality questions. The speech section addresses questions related to understanding speech when different distractors are present or when in different environments. The spatial section contains questions pertaining to the participant's localization abilities. The third section, hearing quality, asks questions about the participant's perceived sound segregation abilities. All sections are ranked on a scale from 0-10, 10 indicating that the participant believes they would "be perfectly able to do or experience what is described in the question," and 0 meaning the opposite. For example, one question asks, "*You are in a group of about five people in a busy restaurant. You CANNOT see everyone else in the group. Can you follow the conversation?*" The participant rates their own ability to answer this question from 0 (*Not at all*) to 10 (*Perfectly*). Part 1: Speech hearing, incorporates 14 questions (for a total of 140 possible points), Part 2: Spatial hearing, includes 17 questions, and Part 3: Qualities of hearing, asks 18 questions. Each section is scored individually of one another. A higher percentage on each section infers that the participant has less challenges with the different aspects of their hearing.

Hearing Aid Characteristics/Verification

The electroacoustic characteristics of the participants' hearing aids were collected using the Aurical FreeFit system. Data was also recorded from each hearing aid in terms of its manufacturer, model, program features, and data logging related to hearing aid use (hours per day in each device) as this is the most accurate way to determine duration of use (Perez & Edmonds, 2012; Taubman et al., 1999). This data was acquired by connecting each hearing aid to its respective hearing aid software through Noah.

Aided audibility was measured using the Speech Intelligibility Index score featured in the Aurical system based on real ear measures of moderate level speech relative to NAL-NL2 targets (Keidser et al., 2012). Daily calibration in addition to OpenREM calibration when necessary (for open fit style devices) was performed prior to each participant. Adequacy of fit was also measured using Real Ear verification measures by comparing the difference between the measured levels 250-4000 Hz and the target levels. A difference score of 10 dB or less at each frequency was considered to be meeting targets (Aazh, Moore, & Prasher, 2012). Note that the hearing aids were not adjusted from user settings and were only evaluated in program one or their most used program. Hearing aid setup information was also collected for analysis of program features. For example, directionality, noise reduction, and experience level were all recorded for potential future analyses and predictors of hearing aid outcomes. No significant problems were noted from any of the 78 bilateral hearing aids (156 devices total).

Auditory Processing Measures

Three aspects of auditory processing were evaluated as potential predictors of hearing aid outcomes: temporal, spatial, and binaural processing.

Temporal Processing: Gaps-in-Noise.

Temporal processing was evaluated for each ear individually under ER 3A or 3B Insert Earphones in the same sound booth as the audiometric testing. The Gaps-in-Noise (GIN; Musiek et al., 2005) test is a clinical assessment of temporal resolution that has been shown to achieve thresholds comparable to psychophysical gap-detection thresholds and adequately represent an individual's functional ability (Hoover et al., 2015). A recent meta-analysis showed the consistent diagnostic power of the GIN in individuals with central auditory disorders across various labs and clinics (Filippini, Wong, Schochat, & Musiek, 2020).

The Gaps-in-Noise procedure was administered with at 35 dB SL above the participant's pure-tone average (1.0, 2.0, and 4.0 kHz) for each ear, to determine their threshold level for detecting gaps in noise. Performance at this sensation level has not yielded significantly different results compared to the typical 50 dB SL presentation in individuals with normal hearing (Weihing et al., 2007). Participants were administered a practice list prior to scored testing. The GIN evaluates how well an individual can detect breaks of silence in continuous, uniform white noise (the intensity level of the noise was unchanging) in each ear. The durations of the gaps in the noise range from 2 to 20 milliseconds.

Procedures and scoring.

The uniform white noise is presented for 6 seconds and can include 0 to 3 gaps per track. A detection threshold is determined by the level (in milliseconds, 2-20) where the individual is able to correctly identify the correct number of gaps in 4 out of the 6 tracks with that duration. This threshold level score is recorded for analysis and considered to be each individual's temporal processing ability. The higher the threshold, the poorer the temporal processing abilities. Two lists were presented to each ear in a randomly generated order.

Instructions to participant.

You will be hearing short bursts of noise. Listen carefully and press the button every time and as soon as you hear a gap or brief period of silence. The gap may sound like an interruption or slight change in the noise rather than a clear gap of silence. Each test will have a beep followed by the noise. The first few items will be for practice. (An example was provided "beep shhhhhh____shhhhhhh. Here you would press the button when you did not hear the noise".)

Spatial Processing: Listening in Spatialized Noise Sentence Test.

Spatial processing was evaluated bilaterally under Sennheiser HD 280 Pro Headphones using the Listening in Spatialized Noise-Sentence test (LISN-S; Cameron & Dillon, 2007) on a laptop. The LISN-S evaluates the influence different noise source locations can have on speech understanding using a three-dimensional auditory environment simulated under headphones. This test is appropriate to use and interpret for those 14 years of age and older and incorporates four conditions (Cameron & Dillon, 2008). The LISN-S consists of 120 target speech sentences recorded by an American speaker and competing speech is presented by two clearly audible, American speakers. In the typical LISN-S presentation for all four conditions, the competing speech is presented at 55 dB SPL and the target speech at 62 dB SPL. The signal to noise ratio (SNR) is adjusted automatically in each condition by 2 dB depending on if the listener achieves or does not achieve 50% of the words correct. For example, if the listener correctly repeats 50% or more of the words in a given sentence, the SNR decreases by 2 dB (gets more challenging). Conditions differ from one another in terms of the perception of noise location (0 degrees or +/- 90 degrees) and talker voice. Here, the modified version of the LISN-S software was used to account for the effect of hearing loss (Glyde et al., 2013). The software incorporates a prescribed gain amplifier that allows the speech stimuli of both the target and maskers to be amplified and shaped for each participant based on their inputted hearing loss and NAL-RP prescription. Besser et al. (2015) and Glyde et al. (2013) found that hearing loss did negatively impact the normative scores on the LISN-S and showed considerable variability.

Procedures and scoring.

Thirty short sentences (about five words per sentence) were presented bilaterally for each of the four conditions and the individual was asked to repeat as many words as possible. The target sentence is designed for a 4-year old's understandability and are presented at the perception of 0° azimuth. Two competing maskers take the form of repeatedly read children's stories recorded from both male and female talkers. Before each sentence begins, a 1000 Hz tone is played to signal the start of the presentation. For each condition, the talker maskers are either the same or different voice, and the talker masker location is perceived at either at 0° azimuth or +/- 90 degrees. Refer to Table 3.3 for an outline of each condition.

Table 3.3. *Conditions for the Listening in Spatialized Noise-Sentence Test.*

	Condition 1	Condition 2	Condition 3	Condition 4
Evaluated Measure	Low Cue SRT	Talker Advantage	Spatial Advantage	Total Advantage/High Cue SRT
Masker Talkers	Same	Different	Same	Different
Masker Location	0°	0°	+/- 90°	+/- 90°.

Testing for each condition ended once the participant completed all 30 sentences or after a calculated standard error of less than 1 dB was achieved after a minimum of 17 sentences. Scoring is completed by calculating talker advantage (condition 1 – condition 2), spatial advantage (condition 1 – condition 3), total advantage (condition 1 – condition 4) (Cameron & Dillon, 2007). Further, a low cue SRT (condition 1) and a high cue SRT (condition 4) are also reported. Scoring was done automatically through the LISN-S software.

For the purpose of this study, the spatial advantage score was used for analysis to evaluate the individual's spatial release from masking and considered their spatial processing ability. This paradigm of noise source and spatial release from masking has been utilized for individuals with hearing loss in Marrone et al. (2008). Figure 3.3 illustrates the perceptual spatial positions used in the study. For the spatially separated condition 3, the target speech was presented at a perceived 0° azimuth with two independent maskers perceived to be spatially separated at -90° and +90°, following the procedures utilized in Marrone et al. (2008).

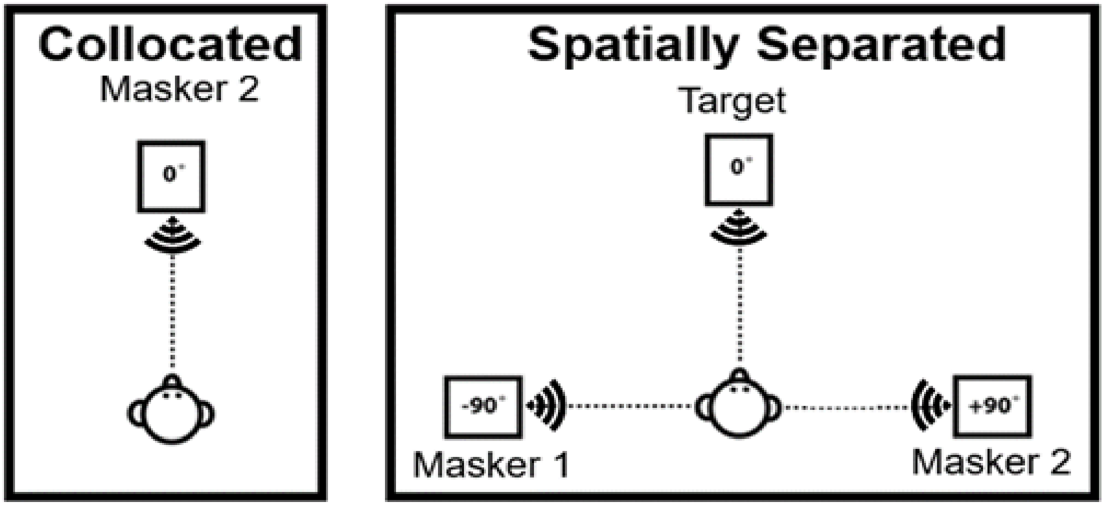

Figure 3.3. *Schematic of the Listening in Spatialized Noise Sentence Test.*

This schematic is for the listening perception of the Listening in Spatialized Noise-Sentence Test task under headphones. Target signal is presented in front of the listener and maskers are presented either at 0 degrees azimuth or 90 degrees azimuth.

Instructions to participant.

You are going to hear some sentences over these headphones. The sentences are said by a lady called "Miss Smith." Miss Smith will sound as if she is standing just in front of you. There will be a "beep" before each sentence, so you will know when it is about to start. Your job is to repeat back the sentence that Miss Smith says. I'll pretend to be Miss Smith, and I want you to repeat the sentence you hear. "Beep." "The dog had a bone." And you repeat back the sentence I said. Good, that's easy, isn't it? But there's a trick. At the same time that Miss Smith is telling you the sentence there are some very tricky people talking at the same time. Sometimes the tricky people sound like they are standing right next to Miss Smith, sometimes they will sound like they are standing next to you. No matter where the tricky people are, I don't want you to listen to them. Just listen for the "beep" and the sentence to repeat.

Binaural Processing: Dichotic Digits Test.

Poor binaural processing can contribute to unsuccessful binaural hearing aid use (Carter et al., 2001; Cox et al., 2011; Jerger & Silverman, 2018). Some individuals perceive speech better when listening from one ear rather than two, regardless of having symmetrical hearing thresholds. In fact, the difference in perception between ears can be so significant that it causes an interference to occur when listening. Here, the Dichotic Digits free recall task (Musiek, 1983) measured binaural processing and was presented under insert earphones at 20-50 dB SL, depending on comfort level (Weihing et al., 2007).

Procedures and scoring.

Following three practice trials, participants repeated all digits from both ears from a list of 20 trials with two numbers presented to each ear simultaneously for a total of 40 numbers per ear, this is known as “free recall”. The list included single-syllable numbers from one to ten (all except seven). The correct amount of numbers were recorded out of 40 for each ear to determine the ear-specific percent correct. The Dichotic Difference Score (DDS) was calculated by subtracting the percent correct between ears. The DDS has been suggested to be a more auditorily-driven score rather than having input from supra-modal factors such as memory, attention, and cognition (Cameron et al., 2016; Musiek et al., 2005).

Instructions to participant.

You will be hearing two numbers in each of your ears. Listen carefully in both ears and repeat all the numbers you hear. The order doesn’t matter. If you are unsure of the numbers, please guess. The first few items will be for practice. [Oral examples of the numbers were provided (i.e., in the right ear you may hear 2, 7, and in the left ear 5, 3)].

Outcome Measures Summary

For a summary of the factors that may influence hearing aid outcomes and how this study addressed for or assessed them, refer to Table 3.4.

Table 3.4. *Factors that may influence hearing aid outcomes (satisfaction and benefit).*

Behavioral Model of Health Services Use	Possible factors associated with hearing aid outcomes	Literature source	How study will address or assess
Need (objective/perceived)	Temporal Processing	*Research Gap*	Gaps-in-Noise
	Spatial Processing	*Research Gap*	LISN-S
	Hearing Sensitivity	Hosford-Dunn, 2001	Mild-to-moderate sensorineural loss (addressed)
	Aided Audibility	Hickson et al., 1999; Jerram & Purdy, 2001	Real Ear Measures (SII)
	Binaural Processing	Carter et al., 2001; Givens et al., 1998 *Research Gap*	Dichotic Digits Test "free recall"
	Self-Reported of Disability (Benefit)	Gatehouse & Noble, 2004; Helvik et al., 2008; Hosford-Dunn, 2001; Takahashi et al., 2007	Speech, Spatial, and Hearing Qualities questionnaire (49-items)
Predisposing Characteristics	Personality (Satisfaction)	Gatehouse, 1994; Wilson & Stephens, 2003	Neo-FFI-3 (60-itmes)
Enabling Resources	Self-Efficacy (Satisfaction & Benefit)	Ferguson et al., 2016; Smith & West, 2006	MARS-HA questionnaire (24-items)
Health Care System	Counseling	Eriksson, 1990; Kemker, 2004; Norman et al., 1995	Participants from consistent hearing clinic (addressed)
	Hearing Aid Professional	Uriarte et al., 2005	Participants from consistent hearing clinic (addressed)
	Time After Fitting	Munro & Lutman, 2004	> 1yr experience with hearing aids (addressed)
Personal Practices	Lifetime Hearing Aid Usage	Hosford-Dunn, 2001; Uriarte et al., 2005	1-item on Listener questionnaire
	Amount of Daily Hearing Aid Use	Perez & Edmonds, 2012	Data logging and self-report
Hearing Aid Outcomes	Hearing Aid Satisfaction	Cox & Alexander, 1999; Vestergaard-Knudsen et al., 2010	SADL (15-items)
	Hearing Aid Benefit	Dillon et al., 1997	COSI

Data Analyses

To address Hypothesis 1 (that temporal, spatial, and binaural processing are significantly related to hearing aid satisfaction), a linear regression model was fit to the hearing aid satisfaction data. The model included predictors for temporal (Gaps-in-Noise threshold), spatial (spatial advantage score from the Listening in Spatialized Noise Sentence Test), and binaural processing (difference score on Dichotic Digits) after controlling for aided audibility and use. Prior to fitting the model, correlations of all pairs of auditory processing variables were explored in order to ensure that the three variables can be used in the same model. It was anticipated that these measures would be uncorrelated since they correspond to different auditory processing abilities.

To test whether non-auditory processing abilities explained any of the variance in hearing aid satisfaction (Hypothesis 2), the hearing aid satisfaction data was fit to a more comprehensive linear regression model. Specifically, seven total factors were included in the models: the personality domain neuroticism score, the self-efficacy score, the temporal, spatial, and binaural processing variables previously discussed, hearing aid use, and the aided audibility variable (also previously discussed).

Hypothesis 3 addressed hearing aid benefit. As it is possible that auditory processing abilities explain hearing aid benefit rather than hearing aid satisfaction, the same linear regression analysis carried out for hypothesis 1 was repeated using self-reported hearing aid benefit as the outcome measure. Hypothesis 4 mimicked hypothesis 2, except self-report of disability using the SSQ cumulative score replaced the personality domain score.

Sample Size and Power.

Prior to data collection, a power analysis was conducted in RStudio for Hypotheses 1 and 3. The power to detect an effect of at least one of the three auditory processing variables resulted in 78 participants with an alpha of 0.05, power of 0.80, and a medium effect size (f2 = 0.15). An analogous power analysis for Hypotheses 2 and 4 indicated that with 78 participants, an alpha of 0.05, and power of 0.80, would be able to detect an even smaller effect size (f2 = 0.135).

Results

Participants

Of the 78 participants, 58% were male and 42% were female, the majority of participants were in the 65-59 and 75-79 age groups, and 90% reported their ethnicity as non-Hispanic. Refer to Table 3.5 for the full demographic profile of the study participants. In the United States adult population of those 60 years and older, the gender distribution between males and females is 45% and 55%. Similar to the current study's sample, in the US, the majority of the older population fall into the 65-74-year age group. In terms of ethnicity, the population in the US report 82% non-Hispanic. (US Census 2018).

Table 3.5. *Demographics of study participants.*

Characteristic	Cohort (*n*=78)
Gender, *n*	
Men	45 (58%)
Women	33 (42%)
Age Groups, *n*	
60-64 years	12 (15%)
65-69	16 (20%)
70-74	12 (15%)
75-79	20 (26%)
80-84	9 (12%)
85-89	9 (12%)
Ethnicity, *n*	
Hispanic	7 (9%)
Non-Hispanic	70 (90%)
Other	1 (1%)

Additional participant data were collected to evaluate the characteristics of participant's hearing loss management (Table 3.6). Hearing aids were mostly acquired through out of pocket expenses. Most of the hearing aid manufacturers that the participants were using were Starkey, Oticon, and Phonak. Time before hearing aid adoption was calculated based on when they reported they first noticed a hearing problem and when they acquired their first hearing aid. Years since first hearing aid use is reported from the question, "*When did you first start wearing a hearing aid?"* The range for first time use was 1-32 years ago (M = 6.31, SD = 5.23). Current hearing aid use is duration of time for when they first acquired their current hearing aids. Participants have been using their current hearing aids between one and 11 years (M = 3.7, SD = 2.5).

Table 3.6. *Characteristics of hearing loss management.*

Characteristic	Cohort (*n*=78)
How Aid was Acquired, *n*	
Out of Pocket Expenses	36 (46.1%)
Out of Pocket + Medicare Part B	12 (15.4%)
EPIC Paid Full Amount	27 (34.6%)
Vocational Rehabilitation	2 (2.6%)
Rehabilitative Services	1 (1.3%)
Hearing Aid Manufacturer, *n*	
GN Resound	4 (5%)
Oticon	19 (24%)
Phonak	18 (23%)
Signia/Siemens	3 (4%)
Starkey	23 (30%)
Unitron	5 (6.5%)
Widex	5 (6.5%)
Bernafon	1 (1%)
Time Before Hearing Aid Adoption, *n*	
0-5 years	42 (54%)
6-10	13 (17%)
11-20	11 (14%)
21+	12 (15%)
Years Since First Aid Use, *n*	
1-5	45 (58%)
6-10	22 (28%)
11-15	6 (8%)
16-20	4 (5%)
20+	1 (1%)
Current Hearing Aid Use, *n*	
1-3	45 (58%)
4-6	24 (31%)
7-9	5 (6%)
10+	4 (5%)

Audiometric Testing

The average audiogram for left (X) and right (O) ears for all participants is shown in Figure 3.4**.** The results indicate, on average, the participants had a mild (25 dB) gently sloping to severe (65 dB) sensorineural hearing loss from 250-8000 Hz for each ear. For the purpose of this study, a pure-tone average at 1.0, 2.0, and 4.0 kHz of no more than 55 dB HL was required for each ear. Participants left PTA's ranged from 13-55 dB HL (M = 42.87, SD = 9.21) and right PTA's ranged from 15-55 dB HL (M = 42.38, SD = 3.85). An independent-samples two-tailed *t* test was conducted to compare the left and right PTAs. There was not a significant difference in the thresholds t (77) = 1.04, *p* = 0.30. Word recognition scores for the left ear ranged from 44 to 100% and 25 to 100% for the right ear. There was not a significant difference for left ear (M = 83.08%, SD = 16.11%) and right ear (M = 81.19%, SD = 17.57%) scores; t (77) = 1.56, *p* = 0.12.

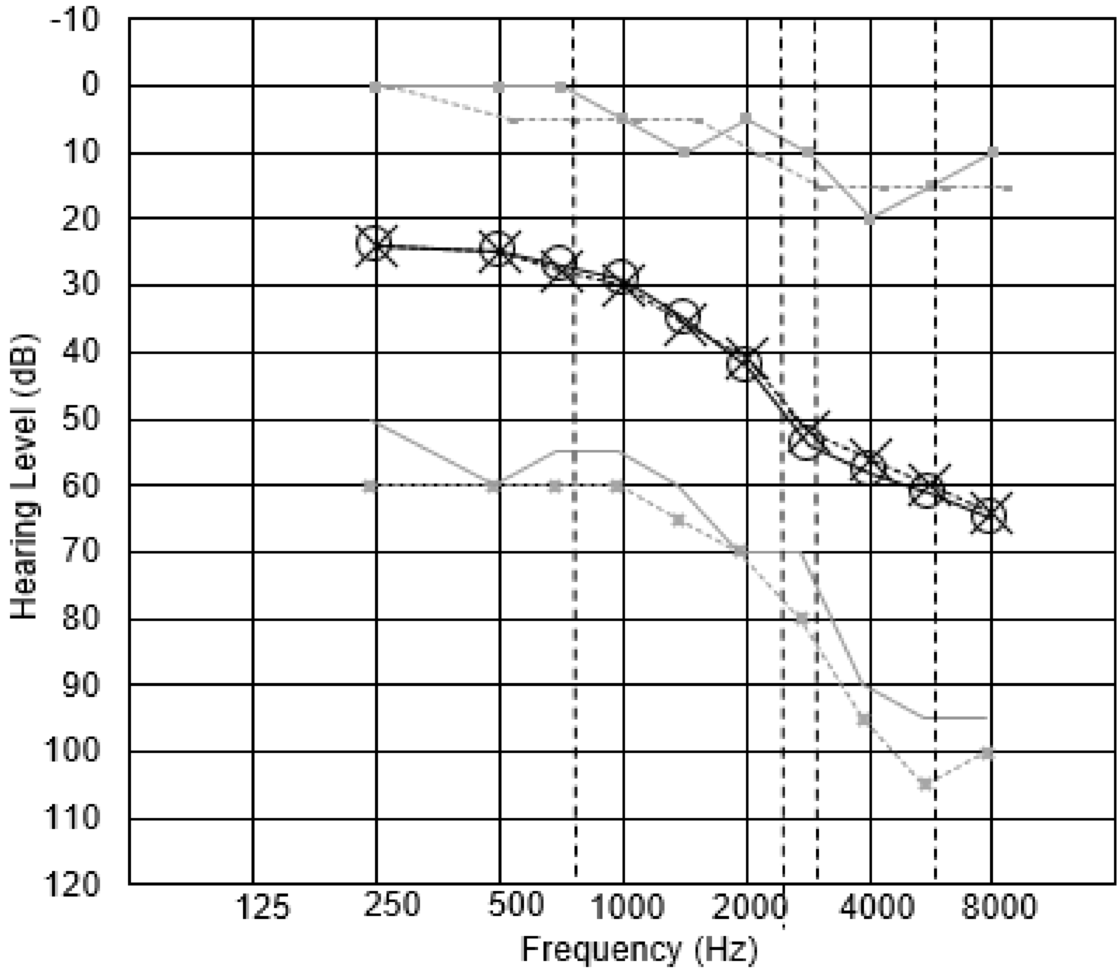

Figure 3.4. *Average pure-tone thresholds across all participants*

Right ear is represented by solid lines and an O, while the left ear is represented by dashed lines and an X. Lighter grey lines depict the minimum and maximum thresholds for each frequency across participants. Right and left ear thresholds were not statistically different from one another.

Outcome Measures

Satisfaction with Amplification in Daily Life.

The SADL questionnaire has subscales and a global score. For data analysis purposes, the Global Score (0 to 7) was reported. Global Score results ranged from 2.8 to 6.9 (M = 5.38, SD = 0.82). See Figure 3.5 for a visual representation of the data. The average score fell within the range of normative data from previous literature measuring performance on the SADL (Cox & Alexander, 1999).

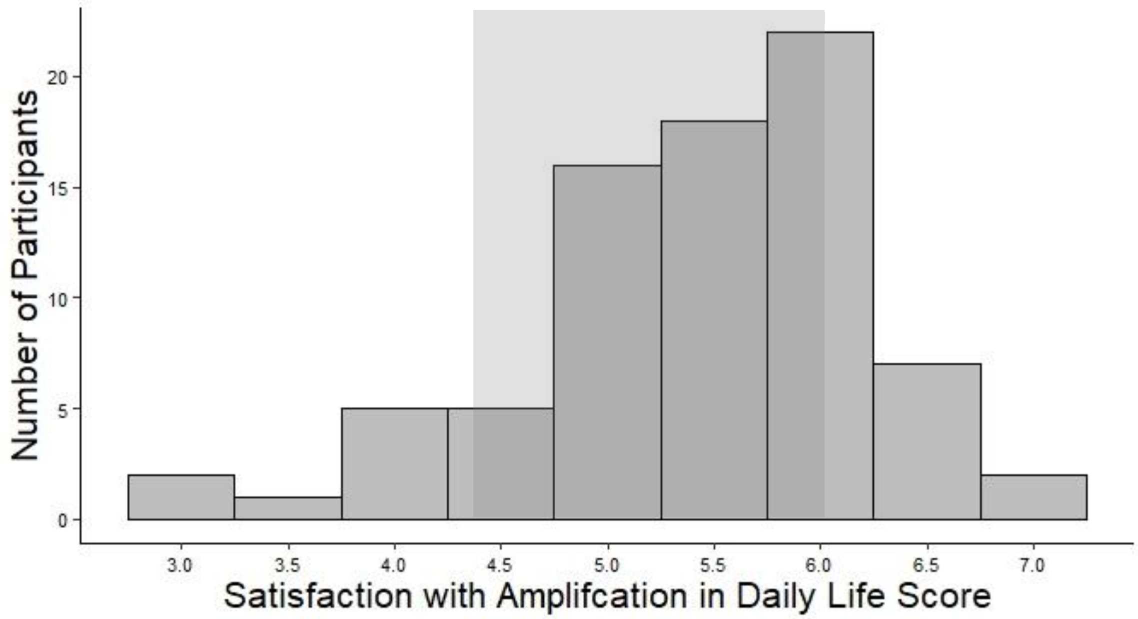

Figure 3.5. *Individual spread of Satisfaction with Amplification in Daily Life scores.*

Data represents the distribution of scores on the satisfaction questionnaire. Boundaries of the shaded box region represents the normative data from Cox and Alexander (1999).

Client Oriented Scale of Improvement.

The COSI questionnaire allowed participants to report up to five of their most important listening situations and a score from 1 to 5 was determined. Not all participants reported all five situations, as a result, a different number of data points per participant were recorded. To account for both this variation and the potential correlation among data from the same participant, a random intercept was fit in the model per participant. This helped to account for correlations in the data from the same participant. COSI scores ranged across the scale from 1 to 5 (M = 3.66, SD = 1.18) (see Figure 3.6). The mean score for the COSI was below the normative average performance reported by Dillon et al. (1999).

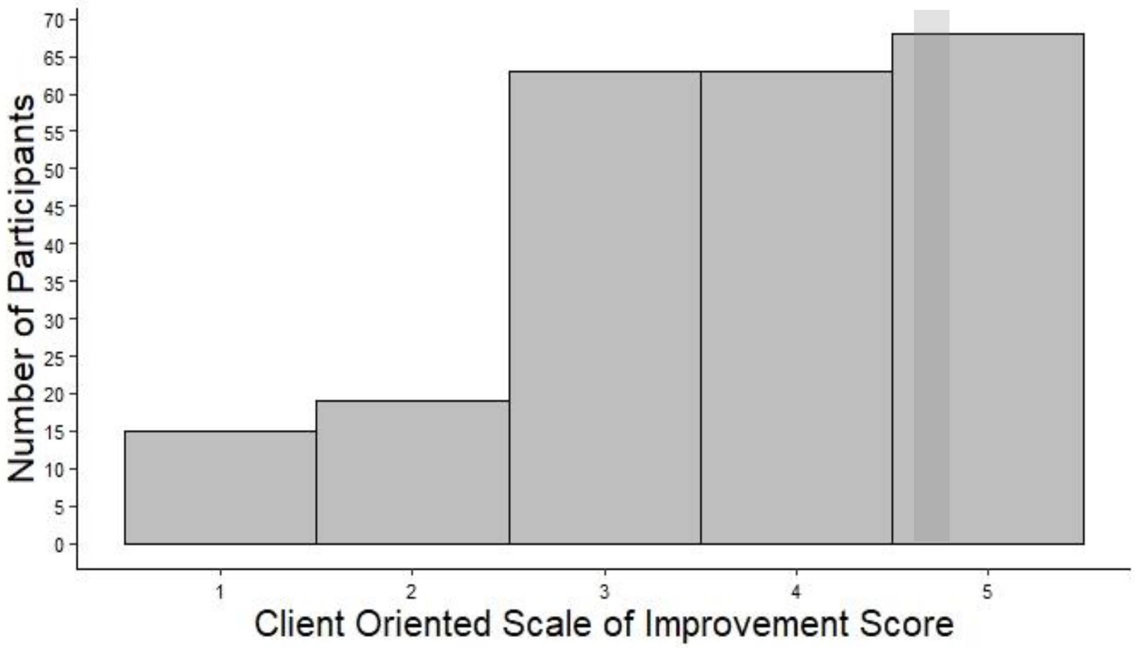

Figure 3.6. *Spread of individual Client Oriented Scale of Improvement scores.*

The number of participants reporting degree of change for each listening situation. Participants can report between 1 and 5 listening situations and rate each one in terms of the degree of improvement. The shaded region represents the boundaries of normative data from Dillon et al. (1999).

Self-Report Assessments

Listener Questionnaire.

Multiple questions were administered on the Listener Questionnaire including, "*How long have your worn your current hearing aids?*"; and "*When did you first start wearing a hearing aid?*". Participants reported that they have worn their current hearing aids between 1 and 11 years (M = 3.74, SD = 2.47) and they first started wearing hearing aids between 1 and 32 years ago (M = 6.31, SD = 5.23).

Neo Five-Factor Inventory.

The NEO-FFI assess five personality domains that can each be scored from 0 to 48, but only the Neuroticism domain is reported here for data analysis purposes. This domain ranged from 1 to 42 (M = 17.04, SD = 7.65), practically representing the entire spread of possible outcomes (see Figure 3.7). The mean from the current study was just below the normative range of scores for this domain (18-20; Manga et al., 2004)

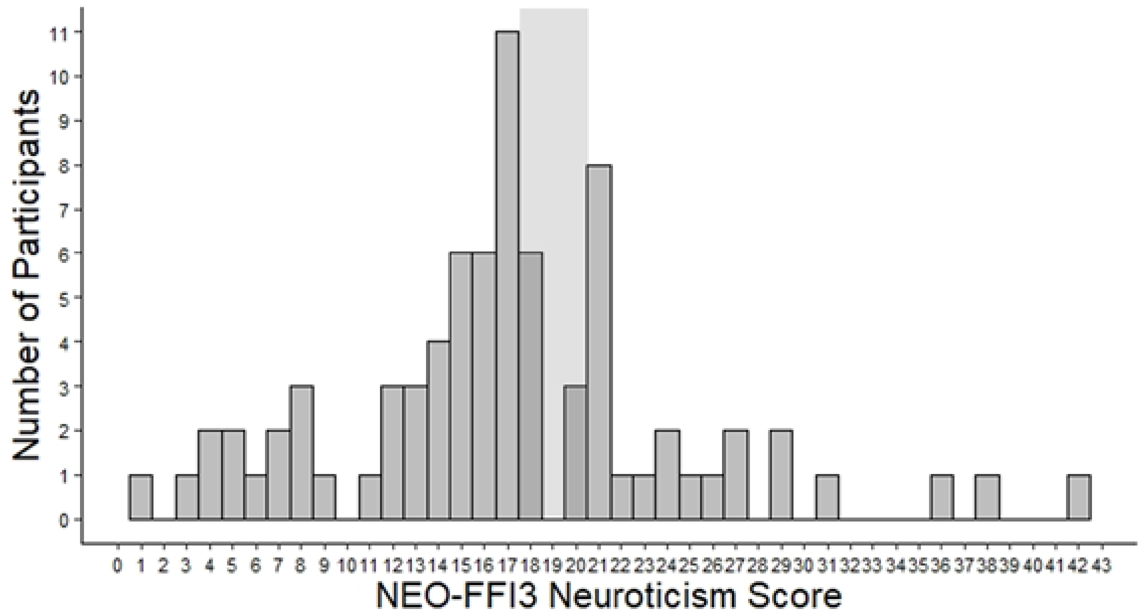

Figure 3.7. *Range of NEO-FFI3 neuroticism scores across all participants.*

Data shows the distribution of scores on the personality questionnaire. The shaded region represents the boundaries for normative data for this subscale based on Eagan et al. (2000) and Mango et al. (2004).

Measure of Audiologic Rehabilitation Self-Efficacy for Hearing Aids.

The MARS-HA had four sub-categories of hearing aid self-efficacy. Here, all four categories were averaged together to form one cumulative score from 0 to 100%. The range of scores was from 34-98% (M = 81.80%, SD = 10.21%) and can be seen in Figure 3.8. The mean for this measure fell within the range of normative data from previous literature (Johnson et al., 2018).

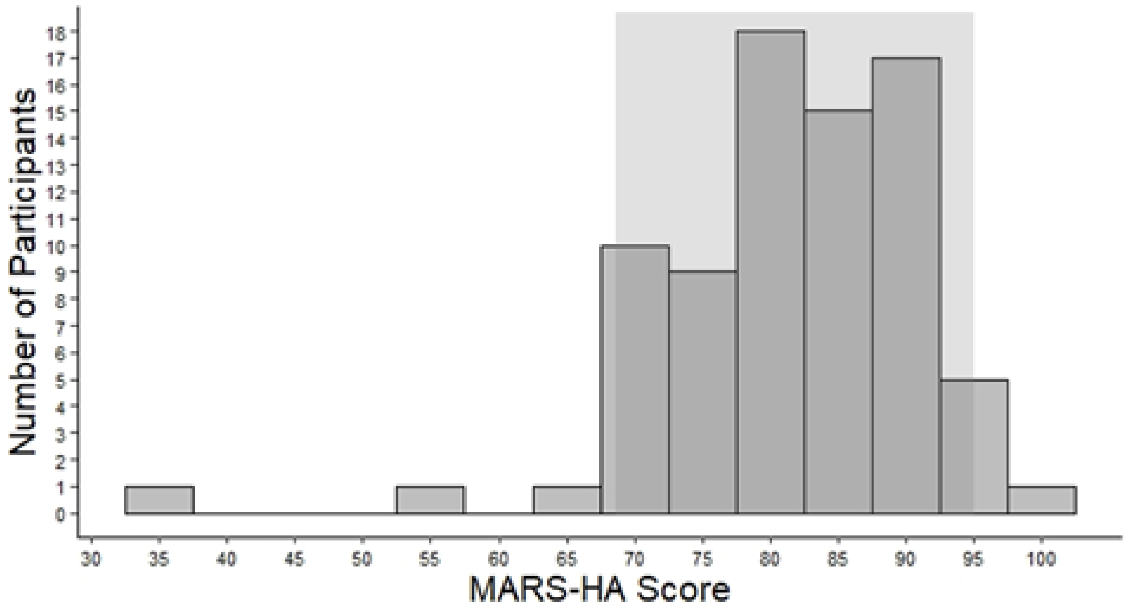

Figure 3.8. *The range of the number of participants' scores on the Measure of Audiologic Rehabilitation Self-Efficacy for Hearing Aids.*

Histogram shows the distribution of scores for the self-efficacy questionnaire. The shaded box region represents the boundaries for normative data (Johnson et al., 2018).

Speech, Spatial, and Hearing Qualities.

The SSQ can be scored separately on the Speech, Spatial, or Hearing Qualities subscales, but here the three scores are averaged together to one total composite score from 0-10. Participant's composite scores ranged from 3.4 to 8.9 (M = 6.71, SD = 1.10), which falls within the range for normative performance (Demeester et al., 2012) and can be seen in Figure 3.9.

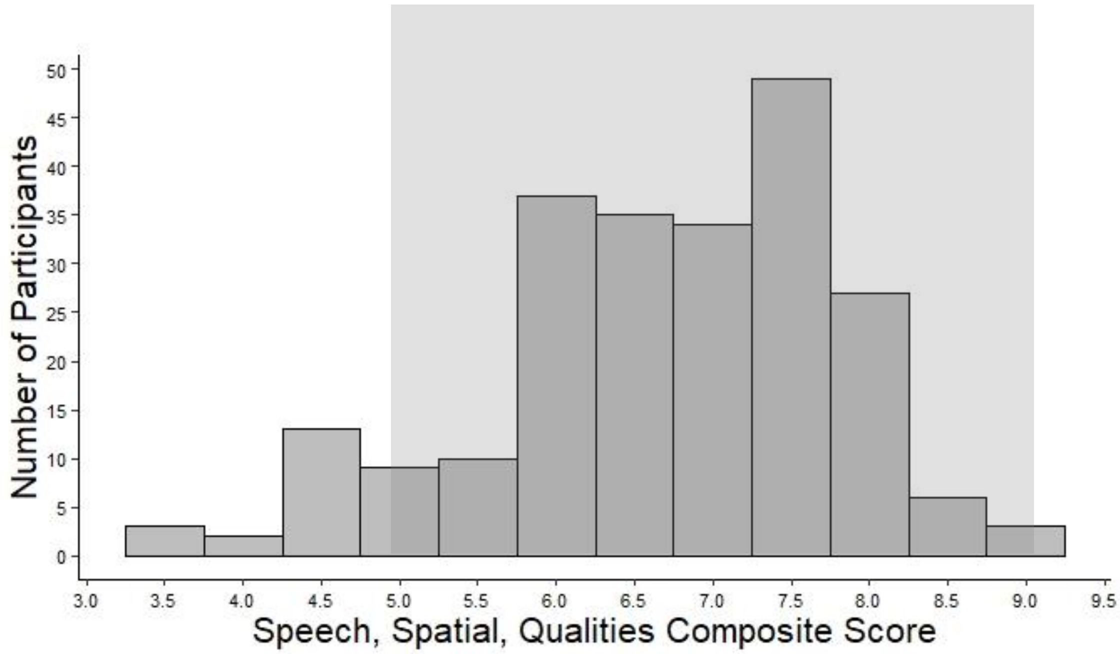

Figure 3.9. *The range of the number of participants' scores on the Speech, Spatial, and Qualities of Hearing Composite score.*

The histogram shows the distribution of scores on the self-report of disability questionnaire. The shaded box region represents the boundaries for normative data for the total of the three subscales for older adults with hearing loss (Demeester et al., 2012).

Hearing Aid Characteristics/Verification

Hearing Aid Use.

Hearing aid use was evaluated with self-report and through data logging. Self-report of hearing aid use ranged from 0 to 16 hours per day (M = 7.74, SD = 5.4), data logging for the left ear ranged from 0 to 16.8 hours per day (M = 6.37, SD = 4.7), and data logging for the right ear ranged from 0 to 14.93 hours per day (M = 6.30, SD = 4.66). There was not a statistically significant difference between the left and right ear data logging hours per day, $t(77) = 0.44$, $p = 0.66$. To compare self-reported hearing aid use to data logging, a two-tailed *t* test was performed between the two variables. Instead of averaging the left and right ear data logging hours together, the greater of the two was used for comparison purposes as this may most closely reflect a self-reported amount. A significant difference was determined for self-report compared to data logging, $t(77) = 3.06$, $p = 0.003$. This suggests that participants, on average, reported 1.21 more hours of use compared to what was recorded in their most used device.

Refer to Table 3.7 for a summary of results from the outcome measures and self-report measures used in the hypothesis models.

Table 3.7. *Summary of descriptive statistics for outcome measures and self-report assessments.*

	Question(naire)	Question(naire) Scale	Data Range	Mean	Standard Deviation	Previous Literature
Outcome Measures	SADL	1-7	2.8-6.9	5.38	0.82	4.4-6.0 (Cox & Alexander, 1999)
	COSI	1-5	1-5	3.66	1.18	4.47 (Dillon et al., 1999)
Self-Report Assessments	NEO-FFI	0-48	1-42	17.04	7.65	18-20 (Manga et al., 2004)
	MARS-HA	0-100%	34-98%	81.80%	10.21%	68.9-94.5% (Johnson et al., 2018)
	SSQ	0-10	3.4-8.9	6.71	1.10	5.6-9.8 (Demeester et al., 2012)

Audibility using the Speech Intelligibility Index.

Speech Intelligibility Index scores were determined for the left and right ear. A two-tailed paired *t* test for the left (M = 36.18, SD = 15.5) and right (M = 40.41, SD = 13.58) SII scores were significant different from one another $t(77) = -5.27$, $p<0.001$. For the purpose of data analysis, the higher (better) SII score was used.

Audibility using Real Ear Measures.

Another way to determine audibility is by subtracting the test REM score from the target REM score for each frequency. This difference score indicates how far off target the hearing aids are set by frequency. The range of difference scores by frequency can be seen in Figure 3.10**.** Here, a negative number represents the tested scores being above the target resulting in “over-target”, whereas an “under-target” score is represented by a positive number. Recall, a range of +/- 10 dB SPL from target is considered meeting targets (Aazh, Moore, & Prasher, 2012; Oticon Ltd., 2010). On average, 24% (1.3-62.8%) of participants were under-target, .2% (0-1.3%) were over-target, and 75.8% were meeting targets across all frequencies for the left ear. For the right ear on average, 16% (0-46.2%) of participants were under-target, 1% (0-2.6%) were over-target, and 83% were meeting targets across all frequencies.

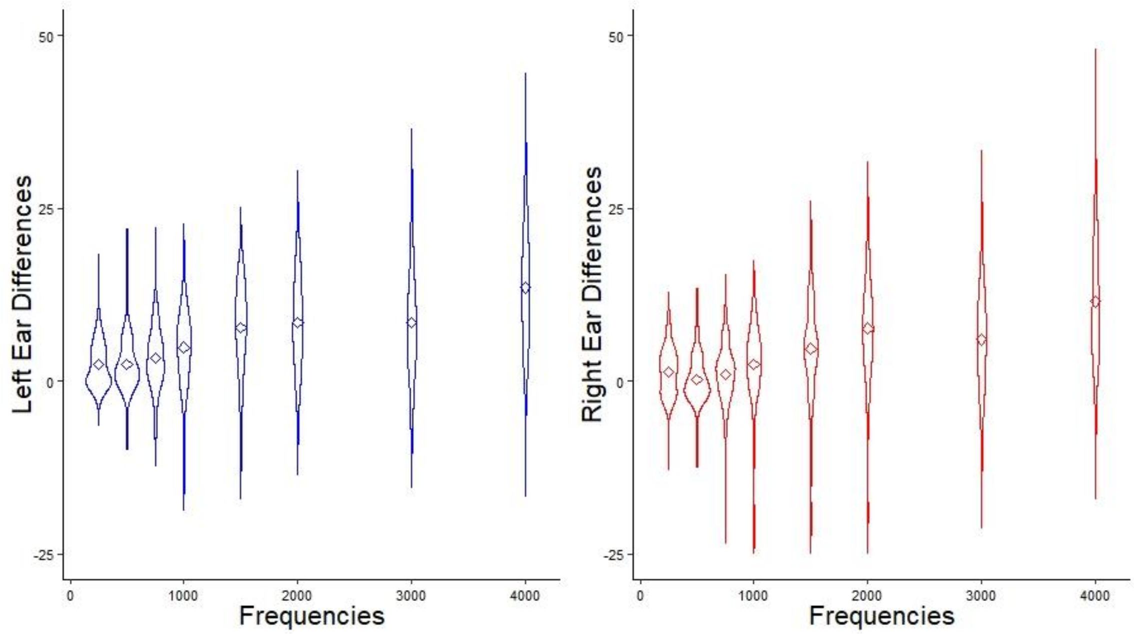

Figure 3.10. *Real Ear Measures: Range of left and right ear differences from Target to Test scores across frequencies.*

The figure shows the distribution of right and left ear differences. Over-target is represented by negative numbers and under-target is represented by positive numbers. Normal difference from target is +/- 10 dB SPL.

The absolute difference score was calculated for mean comparisons between ears. Participant's real ear measures were conducted at preferred user settings. That is, the participant was asked to set their hearing aid in the program or volume level that they would typically adjust to when they first put the hearing aids on for the day. There was a small, but statistically significant difference between left (M = 7.10, SD = 6.26) and right (M = 6.04, SD = 5.72) absolute difference scores between real ear targets and aided response, $t(623) = -6.07$, $p<0.001$. Refer to Table 3.8 for the paired *t* tests completed to compare the means of the absolute differences for each frequency. The left hearing aid was more under-target than the right hearing aid at 750, 1000, 1500, 3000, and 4000 Hz.

Although the absolute difference for left and right ears were statistically significantly different from one another at an individual level, these were not clinically significant differences (~1 dB SPL). Evaluating all absolute left and right differences at every frequency across all participants (78 left/right ear difference scores x 8 frequencies = 624 data points total), only nine participants exceeded a 10 dB SPL difference between ears. Further, a comparison was made between absolute left and right ears in terms of classifying the amount of deviation from target (≤ 10: within normal deviation; > 10: outside normal deviation). The comparison showed that 82 of 624 data points (13%) resulted in a difference of classification in the amount of deviation from target from left to right ear. That is, for these individuals, one ear was within the +/- 10 dB SPL acceptable deviation from target (Aazh, Moore, & Prasher, 2012) while the other ear was outside of this normal deviation. The 82 data points represent that of 45 (58%) of the 78 participants.

Table 3.8. *Paired t test comparison of absolute differences between left and right ear Real Ear Aided Response for medium level sounds (target-test) across frequencies.*

Frequency	*t*(df)	*p* value	Mean of Differences
250 Hz	0.28(77)	0.78	0.08 dB
500 Hz	-1.56(77)	0.12	-0.47 dB
750 Hz	-2.31(77)	**0.02***	-0.90 dB
1000 Hz	-2.69(77)	**0.009***	-1.24 dB
1500 Hz	-4.43(77)	**$3.05e^{-05}$****	-2.13 dB
2000 Hz	-0.41(77)	0.68	-0.23 dB
3000 Hz	-2.96(77)	**0.004***	-1.79 dB
4000 Hz	-2.62(77)	**0.01***	-1.74 dB

*Statistical Significance p<0.05
** Statistical Significance p<0.001
A negative mean of differences indicates a lower right mean difference

Real Ear Measures and Duration of Hearing Aid Use.

Real ear measures are typically evaluated following individual adjustment of initial fitting or at follow-up appointments. When a patient is fit with a hearing aid for the first time, the target levels may appear too loud for the individual and would likely be adjusted to an under-target recording. If the patient did not return for any additional follow-up appointments, under real ear targets would be their result. However, at follow-up appointments, the individual may want increased amplification because they allowed their auditory system the chance to adjust to the sound and thus be closer to target levels. On the other hand, if a patient was fit to target for real ear measurements but their hearing loss changed and the patient did not come back to get their hearing aids adjusted, they again would be under-target based on their new hearing loss. It can be argued from either side that the difference from target is affected by how long the individual has been wearing their hearing aid. From one perspective, they may be further off from target in the beginning because they are not accustomed to the sound. From the other perspective, they may be further off target because their hearing loss has changed from when they were originally fit, and their hearing aids have not been adjusted.

To examine this, separate Pearson Correlations were computed to assess the relationship between duration of current hearing aid use and absolute difference from target, for each frequency. Note that all participants had at least one year of current hearing aid experience and real ear was conducted as user settings. The relationship could go in one of two directions. The first is a positive relationship that as the duration of hearing aid use increases, the difference from target also increases. The second is the opposite, a negative relationship, as the duration of hearing aid use increases, the difference from target decreases. It is also possible that a relationship does not exist, which would suggest there is no pattern to real ear differences and hearing aid use duration. See Figure 3.11 and 3.12 for visual scatterplot representations of all the comparisons for the right (3.11) and left (3.12) ears. Despite the different perspectives, time after fitting only showed a small negative correlation to difference in target at 1500 Hz in the right ear and 1000-1500 Hz in the left ear. Overall, the time after fitting is not a good indicator of how far off target the individual is for most frequencies or ear.

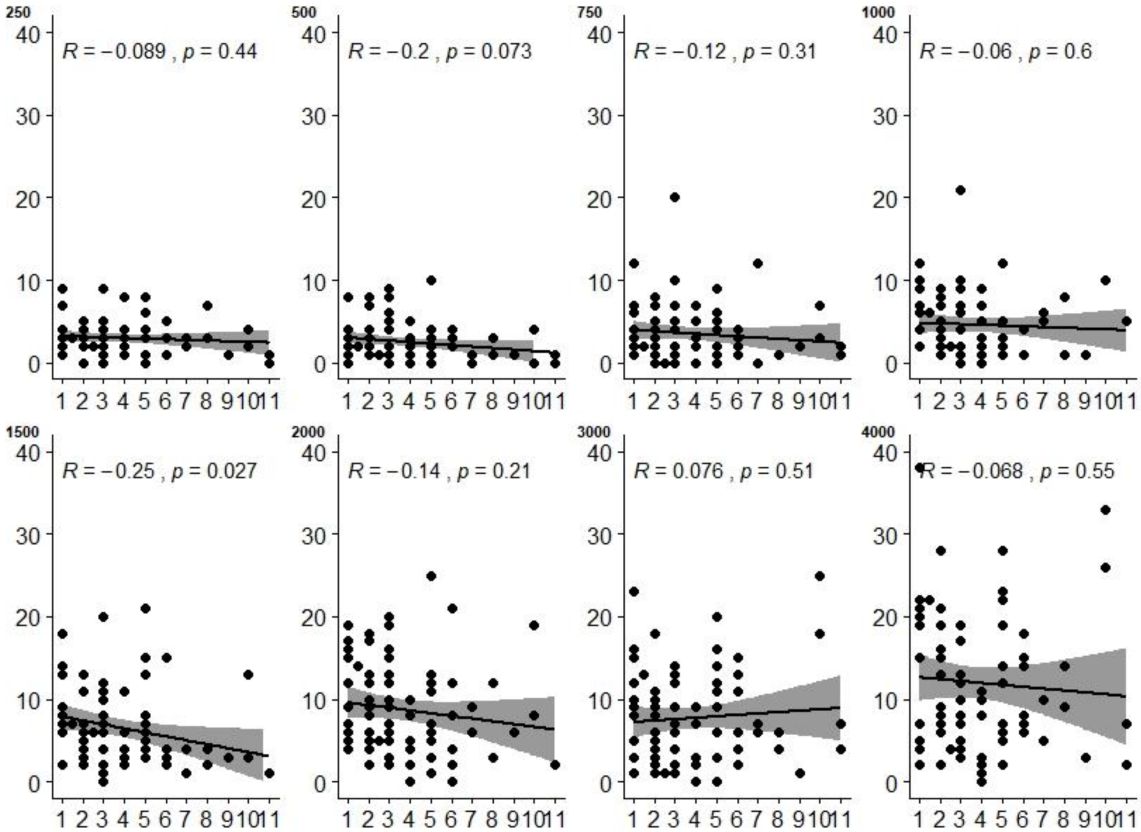

Figure 3.11. *Correlations between duration of current hearing aid use and difference from Real Ear Measured targets for the right ear.*

The scatterplots display the correlations between years of current hearing aid use (x axis) and the absolute difference from real ear measure targets in the right ear (y axis) at each frequency. A small significant negative correlation can be seen at 1500 Hz only.

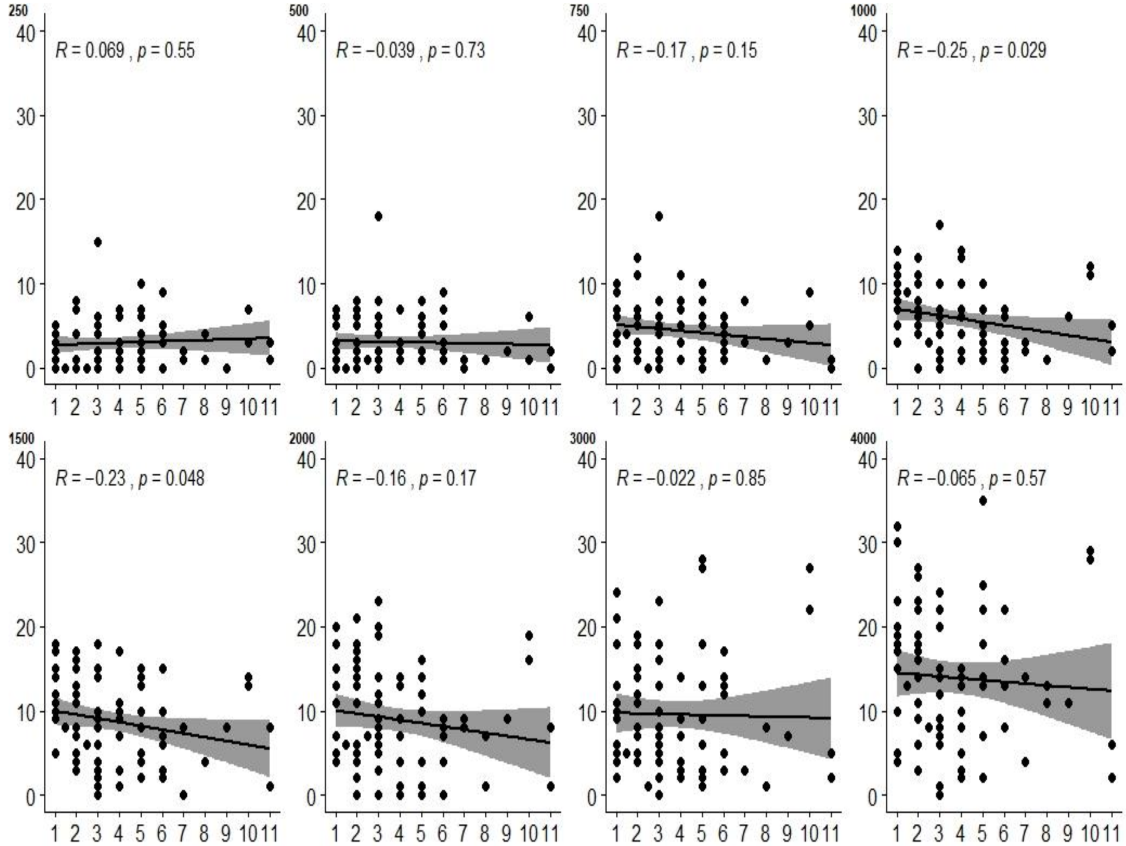

Figure 3.12. *Correlations between duration of current hearing aid use and difference from Real Ear Measured targets for the left ear.*

The scatterplots display the correlations between years of current hearing aid use (x axis) and the absolute difference from real ear measure targets in the left ear (y axis) at each frequency. A small significant negative correlation can be seen at 1000 and 1500 Hz only.

Auditory Processing Measures

Gaps-in-Noise.

The GIN score was determined for both the left and right ears. There was not a significant difference between ears, t(77) = -0.92, $p = 0.84$, so the scores were averaged together into one threshold value. Averaged GIN thresholds ranged from 4.75 to 14.8 ms (M = 8.46, SD = 2.33). The spread of this data can be seen in Figure 3.13.

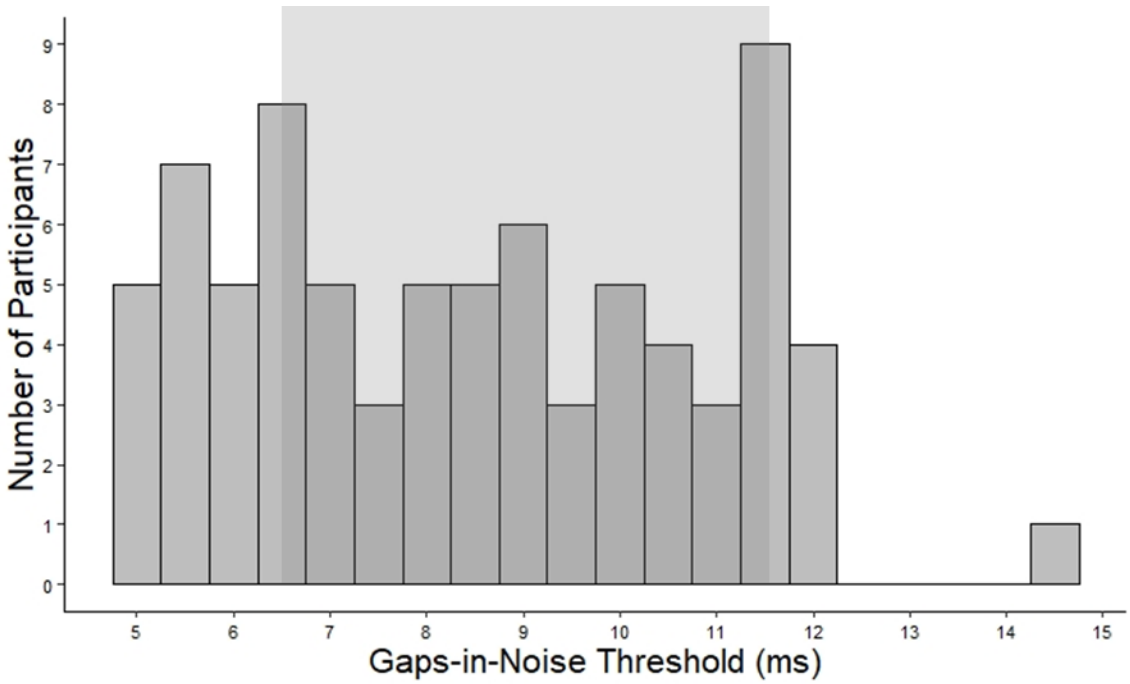

Figure 3.13. *Histogram of Gaps-in-Noise Thresholds.*

The shaded box region represents the boundaries for normative data of older adults with hearing loss (M = 8.82, SD = 2.54) (John et al., 2012).

Listening in Spatialized Noise Sentence Test.

The LISN-S results for the Spatial Advantage were evaluated for data analysis purposes. Spatial Advantage scores ranged from 0.6 to 9.6 (M = 5.51, SD = 2.09), with large numbers indicating more spatial release from masking (better spatial processing). The distribution of LISN-S scores can be seen in Figure 3.14.

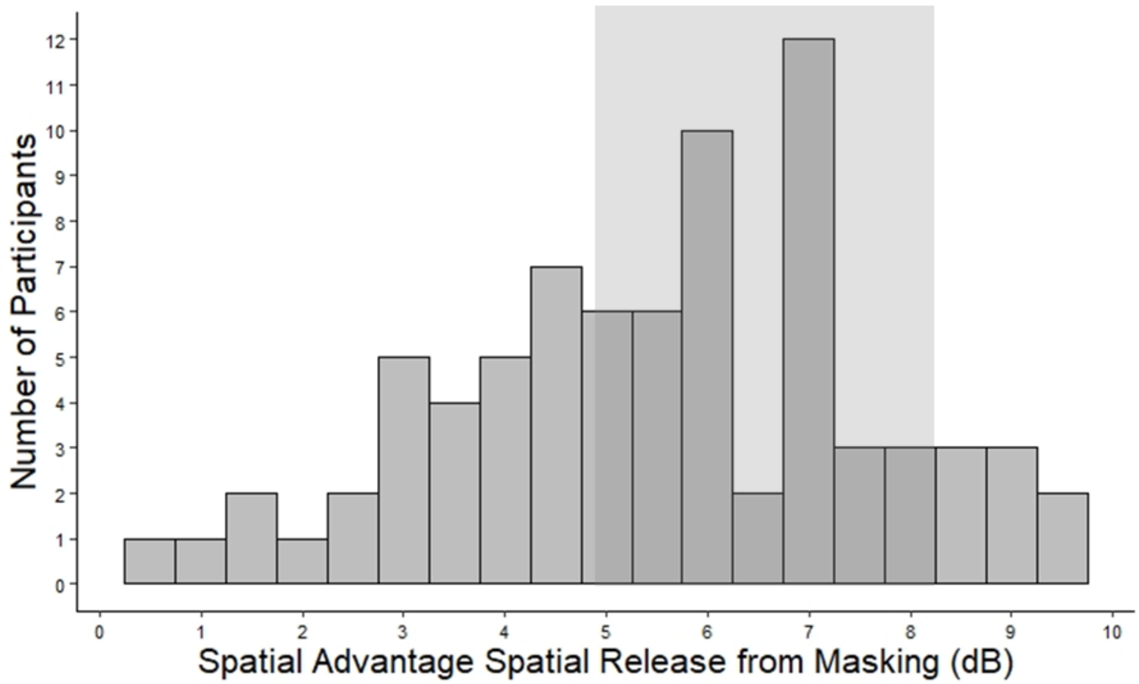

Figure 3.14 *Number of participants' receiving a given spatial advantage score on the Listening in Spatialized Noise Test.*

The shaded box region represents the boundaries for normative data for older adults with hearing loss, four frequency average 500, 1000, 2000, and 4000 Hz = 40-55 dB HL in the worse ear (range = 5-8.4 dB) (Glyde et al., 2013).

Dichotic Digits Test.

The DDT was scored for percent correct for each ear. A paired t test comparison of means showed that the percent correct for the right ear (M = 90%, SD = 12%) was significantly different that the percent correct for the left ear (M = 81%, SD = 17%), t(80) = -5, $p<0.001$. Although statistically different, a mean of 80% is still within normal limits for those with hearing impairment (Ricketts, Bentler, & Mueller, 2019). To assess binaural processing, an absolute difference score was calculated between ears. The difference score ranged from 0 to 48% between ears (M = 12.3%, SD = 12.4%). The difference scores can be seen in Figure 3.15. These results indicate that the majority of participants had a difference score between 0 and 25% (one SD from the mean = 68% of the data).

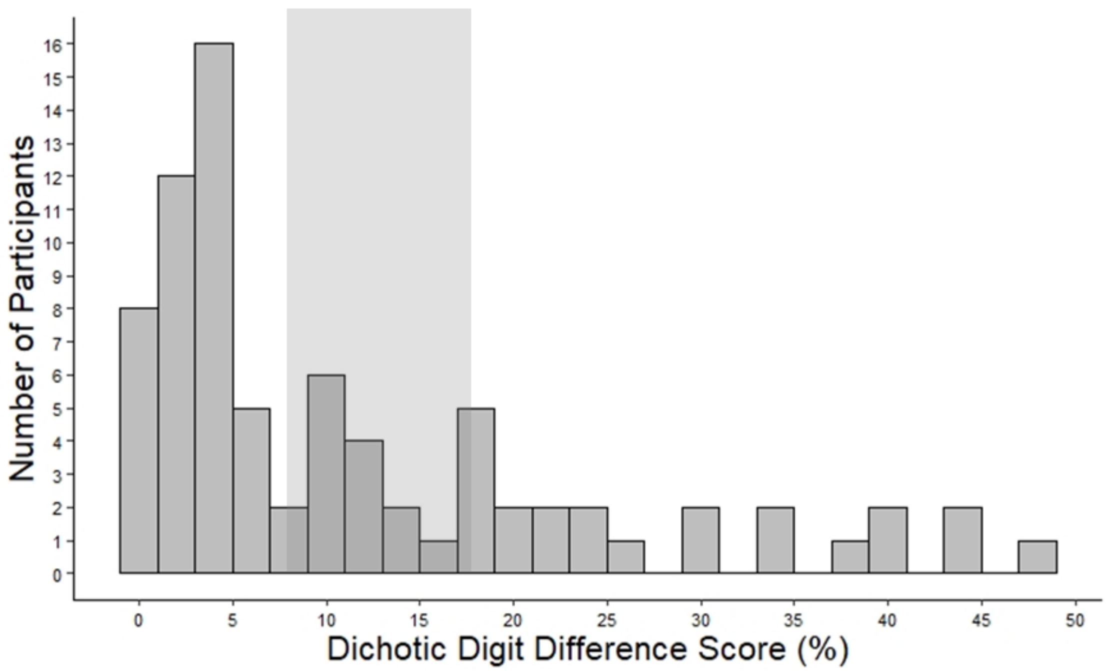

Figure 3.15. *Number of participants' that received a given Dichotic Digit Difference score.*

The shaded box region represents the boundaries for normative data for older adults (60+ years) with hearing loss (average range = 8.1-16.3) (Strouse & Wilson, 1999).

Hypothesis Testing.

Model/hypothesis 1.

Controlling for aided audibility and use, temporal, spatial, and binaural processing abilities will independently relate to hearing aid satisfaction. (Aim 1)

A multiple linear regression was calculated to predict hearing aid satisfaction based on temporal, spatial, and binaural processing abilities, controlling for aided audibility and use. A significant regression equation was found [$F(5, 72) = 5.44$, $p<0.001$)], with an R^2 of 0.27. The individual predictors were examined further and indicated that hearing aid usage (t =2.31, p = 0.02) and the GIN thresholds (t = -3.33, p = 0.001) were significant predictors in the model (Table 3.9).

Effect sizes for each predictor were determined using Cohen's f^2 (Cohen, 1988). Cohen's' f^2 is recommended for evaluating effect sizes in regression models and is determined with the following equation (Selya, Rose, Dierker, Hedeker, & Mermelstein, 2012):

$$f^2 = \frac{R^2}{1 - R^2}$$

Cohen's f^2 is typically interpreted as small, medium and large effect sizes: ≥ 0.02; ≥ 0.15; and ≥ 0.25 respectively (Cohen, 1988). The effect size for hearing aid use to predict hearing aid satisfaction was found to be small ($f^2 = 0.07$), whereas a medium effect size was determined for the Gaps-in-Noise test evaluating temporal processing ($f^2 = 0.15$).

Table 3.9. *Model 1: Predicting satisfaction with auditory processing abilities alone.*

	Estimate	Confidence Intervals (95%)	Standard Error	t Value	*p* value	R^2	Cohen's f^2	Effect Size
Intercept	5.83	4.66, 7.00	0.59	9.94	3.86×10^{-15}***	.274	.38	Large
SII	-0.0008	-0.01, 0.01	0.006	-0.13	0.90	.000	0	Small
Use	0.041	0.006, 0.08	0.02	2.31	0.02*	.069	.07	Small
GIN	-0.13	-0.21, -0.05	0.04	-3.33	0.001**	.133	.15	Medium
DDT	0.007	-0.006, 0.02	0.007	1.07	0.29	.016	.02	Small
LISN-S	0.06	-0.03, 0.14	0.04	1.38	0.17	.026	.03	Small

Significance codes: ****p*<0.001; ***p*<0.01; **p*<0.05

Cohen's f^2 is typically interpreted as small, medium and large effect sizes: ≥ 0.02; ≥ 0.15; and ≥ 0.25 respectively (Cohen, 1988)

A second model was fit to determine the effect and variance explained by the GIN threshold. This was accomplished by removing the GIN threshold from the first model and comparing the R^2 values of the models with and without the GIN threshold. With the GIN threshold removed, the R^2 value of the model is 0.16 as compared the model with the GIN threshold ($R^2 = 0.27$). Thus, the GIN threshold explains 11% of the variance in hearing aid satisfaction with a medium effect size. An analysis of variance of the model terms revealed the models with and without the GIN threshold were significantly different ($p = 0.001$). This suggests that the GIN threshold is a significant predictor in explaining hearing aid satisfaction.

Model/hypothesis 2.

Controlling for aided audibility and use, auditory processing abilities, personality and self-efficacy will independently relate to hearing aid satisfaction. (Aim 1)

A multiple linear regression was calculated to predict hearing aid satisfaction based on temporal, spatial, and binaural processing abilities, personality, and self-efficacy, controlling for aided audibility and use. A significant regression equation was found [$F(7, 70) = 6.73$, $p<0.001$)], with an R^2 of 0.40. The individual predictors were examined further and indicated that the GIN thresholds ($t = -3.18$, $p = 0.002$), the LISN scores ($t = 2.23$, $p = 0.03$), and the MARS-HA scores ($t = 3.74$, $p = 0.0004$) were significant predictors in the model (Table 3.10). The GIN, the LISN, and the MARS-HA had a small to medium ($f^2 = 0.14$), small ($f^2 = 0.07$), and medium ($f^2 = 0.20$) effect sizes respectively.

Table 3.10. *Model 2: Predicting satisfaction with auditory processing abilities and non-auditory factors.*

	Estimate	Confidence Intervals (95%)	Standard Error	t Value	*p* value	R^2	Cohen's f^2	Effect Size
Intercept	3.25	1.10, 5.40	1.08	3.01	0.004**	.402	.67	Large
SII	0.005	-0.007, 0.02	0.006	0.80	0.43	.009	.009	Small
Use	0.02	-0.02, 0.05	0.02	1.01	0.31	.014	.01	Small
GIN	-0.12	-0.19, -0.04	0.04	-3.18	0.002**	.126	.14	Small/Medium
DDT	0.01	-0.003, 0.02	0.006	1.56	0.12	.034	.04	Small
LISN-S	0.09	0.01, 0.17	0.04	2.23	0.03*	.066	.07	Small
NEO	-0.01	-0.04, 0.01	0.01	-0.90	0.37	.011	.01	Small
MARS-HA	0.03	0.02, 0.05	0.009	3.74	0.0004***	.167	.20	Medium

Significance codes: ***p<0.001; **p<0.01; *p<0.05

Cohen's f^2 is typically interpreted as small, medium and large effect sizes: ≥ 0.02; ≥ 0.15; and ≥ 0.25 respectively (Cohen, 1988)

A second model was fit to determine the effect and variance explained of the GIN threshold, LISN-S score, and self-efficacy score (MARS-HA). This was accomplished by removing the GIN threshold from the first model and comparing the R^2 values of the models with and without the GIN threshold. This method was repeated for the LISN-S and MARS-HA scores. With the GIN threshold removed, the R^2 value of the model is 0.32 as compared to 0.40. This suggests that the GIN threshold explained 0.40-0.32 = 0.08 or 8% of the variance of hearing aid satisfaction. Comparing the fits of these regression models shows a significant difference, $p = 0.002$, suggesting that the GIN threshold is a significant predictor of hearing aid satisfaction with a small to medium effect size. When the LISN-S score is removed from the original model, the R^2 value becomes 0.36, suggesting 4% of the variance explained with a small effect size. There is a significant difference between these models as well, $p = 0.03$. Finally, with the MARS-HA score removed, the R^2 value of the new model is 0.28, suggesting that MARS-HA explains 12% of the variance, which is a significant amount, $p = 0.0004$ with a medium effect size. The GIN threshold, LISN score, and MARS-HA score were all significant predictors of hearing aid satisfaction with significant amounts of variance explained.

Model/hypothesis 3.

Having accounted for aided audibility and use, temporal, spatial, and binaural processing abilities will independently relate to self-reported hearing aid benefit. (Aim 2)

The repeated measures were handled by including a random intercept per participant. Adding a random intercept to the model is necessary because in administering the COSI, individual participants may not have the same number of data points to average when calculating the total score for benefit (due to variation in the number of prioritized listening situations). The approach allows each participant to have different numbers of data points and statistically accounts for the possible correlation among data from the same participant.[2]

A conditional R^2 value of 0.37 and a marginal R^2 value of 0.12 was determined for this random intercept model. Conditional R^2 is the variance explained by the fixed effects and the random effects (Nakagawa & Schielzeth, 2013). Here the random effects is the individual variation in the number of COSI responses provided. The marginal R^2 is the portion of the model that is explained by just the fixed effects (Nakagawa & Schielzeth, 2013). The marginal R^2 was chosen for evaluation over conditional because the random effects of number of COSI responses is not the primary interest. Within this model, hearing aid use ($F = 12.22$, $p = 0.002$) and the GIN thresholds ($F = 5.03$, $p = 0.02$) were significant predictors of hearing aid benefit (Table 3.11). Both of these significant predictors had a small effect size ($f^2 = 0.06$ and 0.04).

[2] An alternative option for analyzing the COSI would have been to average the COSI scores per participant. However, because participants had different numbers of scores (e.g., up to 5 listening situations), these averages would have differed in their variability and this in turn would have needed to be accounted for in the model. Thus, the first approach was chosen as a simpler option.

Table 3.11. *Model 3: Predicting benefit with auditory processing abilities alone.*

	F value	Confidence Intervals (95%)	*p* value	R^2	Cohen's f^2	Effect Size
SII	0.28	-0.02, 0.006	0.31	.007	.007	Small
Use	12.22	0.03, 0.10	0.002**	.064	.06	Small
GIN	5.03	-0.19, -0.02	0.02*	.038	.04	Small
DDT	3.11	-0.001, 0.03	0.08	.022	.02	Small
LISN-S	0.06	-0.11, 0.08	0.81	.000	0	Small

Significance codes: ***p<0.001; **p<0.01; *p<0.05

Cohen's f^2 is typically interpreted as small, medium and large effect sizes: ≥ 0.02; ≥ 0.15; and ≥ 0.25 respectively (Cohen, 1988)

A second model was run to determine the effect and variance explained of the GIN threshold. This was accomplished by evaluating the partial R^2 values of the significant fixed variables when all other covariant were accounted for. The partial R^2 value of hearing aid use was 0.064 or 6.4%, and for the Gaps-in-Noise test, the value was 0.038 or 3.8% of the variance explained in hearing aid benefit.

Model/hypothesis 4.

Having accounted for aided audibility and use, auditory processing abilities, self-report of disability and self-efficacy will each independently relate to hearing aid benefit. (Aim 2)

A random effects predictor was again used to account for the variation in COSI responses. A conditional R^2 value of 0.37 and a marginal R^2 value of 0.26 was determined for this random intercept model. Again, the marginal R^2 was chosen for evaluation over conditional because the random effects of number of COSI responses is not the primary interest. Within this model, hearing aid use ($F = 12.84$, $p = 0.0006$), the MARS-HA ($F = 30.98$, $p < 0.0001$), and the SSQ ($F = 5.00$, $p = 0.03$) were significant predictors of hearing aid benefit (Table 3.12). All significant predictors had a small effect size, except for the MARS-HA which had a medium effect ($f^2 = 0.18$).

Table 3.12. *Model 4: Predicting benefit with auditory processing abilities and non-auditory factors.*

	F value	Confidence Intervals (95%)	*p* value	R^2	Cohen's f^2	Effect Size
SII	1.02	-0.02, 0.006	0.32	.006	.006	Small
Use	12.84	0.03, 0.10	0.0006***	.069	.07	Small
GIN	3.25	-0.14, 0.03	0.08	.018	.02	Small
DDT	3.73	-0.00003, 0.03	0.06	.022	.022	Small
LISN-S	0.002	-0.08, 0.08	0.97	.000	0	Small
MARS-HA	30.94	0.02, 0.05	5.18×10^{-07}***	.152	.18	Medium
SSQ	5.00	-0.37, -0.03	0.03*	.028	.03	Small

Significance codes: ***p<0.001; **p<0.01; *p<0.05
Cohen's f^2 is typically interpreted as small, medium and large effect sizes: ≥ 0.02; ≥ 0.15; and ≥ 0.25 respectively (Cohen, 1988)

A second model was run to determine the effect and variance explained of the self-efficacy score (MARS-HA) and the self-report of disability score (SSQ). This was accomplished by evaluating the partial R^2 values for each fixed effect. The partial R^2 value of hearing aid use was 0.069 or 6.9%, for the MARS-HA, the value was 0.152 or 15.2%, and for the SSQ, the value was -0.028 or 2.8% of the variance explained in hearing aid benefit.

Discussion

The current study involves testing individual's abilities in a naturalistic way. Participant's own hearing aids were evaluated at user settings, speech material used for testing was intelligible and un-altered, and all tests used are clinically available. The results presented may be helpful in determining a clinical protocol for determining hearing aid outcomes. Although the results represent one university clinic, they are meaningful at a broader level. Twenty-two percent of the population is made up of those 60 years of age and older, making it a significant impact to study individuals within this age group. The study sample has a similar gender and ethnicity distribution to the overall US population and though there are many factors that contribute to a demographic representation, the similarities between the current sample and the population help to generalize the results further than one university.

Previous literature suggests that patient-reported hearing aid outcomes are highly variable (Ferguson et al., 2016; Saunders et al., 2016), which is in agreement with the current study's results. Results showed high variability in auditory processing outcomes regardless of degree of hearing loss. Literature reviews by Vestergaard-Knudsen et al. (2010) and Hickson et al. (2014) reported on multiple factors that may help to explain the variability in hearing aid satisfaction and benefit, the most significant of which were addressed or assessed here.

Self-reported outcomes for this study included the Satisfaction with Amplification in Daily Life questionnaire, the Client Oriented Scale of Improvement, the Neo-Five-Factor-Inventory, the Measure of Audiologic Rehabilitation Self-Efficacy for Hearing Aids questionnaire, and the Speech, Spatial, and Qualities of Hearing questionnaire. Overall, the average scores suggest that satisfaction, self-efficacy, and self-report of disability were all within the normal range when compared to previous literature. Hearing aid benefit and personality, however, were outside the average range of normative data. This comprehensive look at self-reported outcomes raises the question of why satisfaction might be reported within normal limits when benefit is not. It is possible that the answer lies in one of the main differences between satisfaction and benefit: benefit measures the change from an unaided to aided condition. As noted previously, on average, 16% of real ear measures for the right ear and 24% for the left ear were under-target across all frequencies. This reduced audibility may diminish the unaided to aided benefit and become apparent in the poor COSI reports when compared to normative data.

Determining ways to predict hearing aid outcomes has been a goal of research scientists for decades. This prospective study moves the research another step forward by combining auditory and non-auditory factors into a comprehensive model for predicting outcomes of hearing aid satisfaction and benefit. Although hearing aid satisfaction and benefit both encompass an individual’s hearing aid experience, they represent different domains. To address aim one, auditory processing tests of temporal, spatial, and binaural processing abilities and non-auditory assessments of personality and self-efficacy are combined to predict hearing aid satisfaction. For aim two, the same auditory processing abilities are combined with non-auditory assessments of self-report of disability and self-efficacy to predict hearing aid benefit.

For both aims addressed in this study, hearing aid use and aided audibility were factors that were accounted for in the prediction models. Hearing aid use can be patient-reported, but here, data logging was used. Hearing aid use was a significant predictor of hearing aid satisfaction and benefit when auditory processing abilities were evaluated without non-auditory factors, although the effect sizes were small. Additionally, hearing aid use was a significant predictor of hearing aid benefit when auditory processing abilities were combined with non-auditory factors but again, the effect size was small. Aided audibility can also be evaluated in multiple ways, but here it refers to the largest (best) SII score. Aided audibility varied across individuals but was not a significant predictor of hearing aid satisfaction or benefit in any of the linear regression models.

Hearing Aid Satisfaction Predictors

Temporal Processing.

Hearing loss has been found to negatively affect the Gaps-in-noise threshold assessment (John et al., 2012). Further, John et al. (2012) found the greatest amount of variance in the GIN is among older adults with hearing loss when compared to older and younger adults without hearing loss. The results of the current study are in agreement with the current literature that Gaps-in-Noise thresholds were variable among the older adult participants with mild to moderate hearing loss.

Temporal resolution or acuity is the underlying construct that the Gaps-in-Noise test measures. Gap detection is a behavioral assessment that assess temporal acuity in the auditory system. Within the auditory system, temporal acuity can refer to segmenting both phonetic information (speech sounds) and suprasegmental information (tone of voice, intonation) (Musiek & Chermak, 2013). As a result, abilities of segmentation differ across individuals (person to person) and within one's own brain (phonetic vs suprasegmental abilities). This process of temporal resolution allows speech sounds to be segmented and processed for intelligibility to a listener.

When temporal resolution is impaired for any reason such as with hearing loss, aging, or other dysfunction, the brevity of a speech sound may not be resolved for comprehensibility. The transition between sounds and words in conversation happens quickly and requires good temporal processing abilities. In the current study, the GIN threshold was able to significantly predict 8-11% of the variance in hearing aid satisfaction with a medium effect size, depending on if non-auditory factors were included or not. This is not surprising given that the auditory system is such an elegant timekeeper.

As discussed previously, one of the main reasons for dissatisfaction in hearing aids is poor speech in noise understanding. The results of the study indicated that as the GIN threshold increases (poorer performance), hearing aid satisfaction decreases. This is likely the result of the positive relationship between temporal resolution and speech understanding in noise.

Temporal resolution abilities may play a significant role in an individual's speech understanding in noise abilities (Feng et al., 2010; Kumar et al., 2012), especially in the elderly (Nair & Basheer, 2017). Feng et al. (2010) evaluated temporal resolution abilities using gap detection thresholds and speech perception in noise abilities using the Hearing in Noise Test in individuals with normal hearing and high frequency, symmetrical, sensorineural hearing loss. Overall, gap detection and speech perception in noise performance was significantly poorer for those with hearing loss compared to those with normal hearing. The authors concluded that these differences are a result in deficits in the central auditory system, although cochlear lesion implication could not be counted out. Although, the degree of cochlear lesion implications remain unclear. Using multiple linear regression, temporal resolution was determined to be significantly related to speech-in-noise performance, $p<0.05$ (Feng et al., 2010). An interesting finding was that those who experienced hearing loss earlier in life had poorer temporal resolution abilities compared to those who acquired hearing loss later in life.

A study by Kumar et al. (2012) evaluated the relationship between temporal processing, evaluated with a gap detection task, and speech perception in noise abilities, measured using multi-talker babble at -5 dB SNR in 118 participants. In agreement with Feng et al. (2010), temporal processing was significantly related to speech recognition in noise scores. In fact, temporal processing skills, on a temporal resolution measure, were able to explain 26% of the variability in speech recognition in noise abilities. A more recent study by Nair and Basheer (2017) evaluated temporal resolution and speech discrimination abilities in 30 elderly participants (55-75 years). Their findings are consistent with Feng et al. and Kumar et al. which showed that the GIN was significantly inversely related to speech discrimination. It is encouraging that Nair and Basheer suggested that patients should be evaluated for the temporal resolution abilities during an auditory evaluation regardless of hearing loss status.

Spatial Processing.

Understanding speech in a spatially separated environment is an ability that is utilized in every day listening situations. Specifically, individuals regularly rely on spatial processing abilities to locate where a sound source is coming from. Orienting to a sound with hearing aids provides benefit to the hearing aid user (Ricketts, 2005). Surprisingly, the LISN-S spatial advantage score was found to explain only 4% of the variance in hearing aid satisfaction. Although this was a significant finding, 4% may not be a clinically applicable amount to justify implementation into a clinical protocol given that only a small effect size was determined. These significant results therefore need to be interpreted with caution.

Self-Efficacy.

Self-efficacy, as measured by the MARS-HA, provided the largest amount of significant variance explained in hearing aid satisfaction. These results reflect those of Ferguson et al. (2016) who also found a significant relationship between scores on the MARS-HA questionnaire and scores on the SADL questionnaire in 30 first-time hearing aid users. The level of variance explained differs from the present study, in that Ferguson et al. determined 43% where the current study explained 12% with a medium effect size. A possible explanation for the difference might be the predictors included in the hearing aid satisfaction model. These authors performed a linear regression that included self-efficacy, expectations, and hearing aid readiness, while the current study included aided audibility, hearing aid use, and three auditory factors.

Factors Not Predictive of Hearing Aid Satisfaction

Personality.

Personality was measured using the Neuroticism subscale of the NEO-FFI-3 questionnaire and no significant findings were found to hearing aid satisfaction. Subsequent linear regressions were conducted for each of the NEO-FFI-3 subscales (Extraversion, Openness, Agreeableness, and Conscientiousness) and no significant correlations were determined between any of the personality subscales and hearing aid satisfaction when combined with auditory and non-auditory factors (Model 2). These findings are contrary to previous findings (Gatehouse, 1994; Cox et al., 2007). Gatehouse measured the significant effect in 309 first-time hearing aid users. Not only did these researchers have a larger subject pool, but they also used a different personality measure, the Crown-Crisp Experiential Index. Cox et al. evaluated personality in 205 patients on the Neo-FFI, similar to the current study. One major difference between the current methods and the Cox et al. study was how participants were recruited. In the current study, all participants were recruited from the same clinic, while participants in the Cox study were recruited across 11 different clinics. It is also possible that the increased sample size in both the Gatehouse and Cox studies, is needed to obtain a large enough power to see a significant relationship between hearing aid satisfaction and personality.

Hearing Aid Benefit Predictors

The GIN was a significant predictor of hearing aid benefit, explaining 3.8% of the variance when only auditory predictors were considered in the model. However, when non-auditory factors were included for a comprehensive view on hearing aid benefit, only the MARS-HA and the SSQ scores were significant predictors. The MARS-HA significantly predicted 15.2% of the variance in hearing aid benefit, while the SSQ significantly predicted 2.8%. These results corroborate the findings of a previous retrospective study which evaluated 160 participants on the MARS-HA the Hearing Handicap Questionnaire (HHQ), and the International Outcome Inventory for Hearing Aids (IOI-HA; Hickson et al., 2014). These authors found significant contributions between the MARS-HA, HHQ, and the IOI-HA, a hearing aid benefit self-reported measure.

Factors not Predictive of Hearing Aid Satisfaction or Benefit

Binaural Processing.

Binaural processing was measured here using the Dichotic Digits Test and was not determined to be a significant predictor of hearing aid satisfaction or benefit. This finding is contrary to previous studies which have suggested that there is in fact a relationship between binaural processing and hearing aid outcomes (Carter et al., 2001; Givens et al., 1998). As discussed previously, Carter et al. measured a positive relationship between poorer performance on the DDT and decreased success with two hearing aids. Although, this study only evaluated performance on four participants, while the current study evaluated 78 participants. Additionally, other possible predictors were not considered in the analysis.

Givens et al. (1998) evaluated 58 older participants on their dichotic digits scores and hearing aid satisfaction. These researchers found that higher reported satisfaction positively correlated with between dichotic digits scores. The difference between these positive findings and the lack of significant results found in the current study may be a result of the measures used. Givens et al. used the Profile of Hearing Aid Performance (PHAP), while the current study used the SADL. Although the subscales of both measures have similar aspects, such as ease of communication and aversiveness of sounds, the PHAP may be more comprehensive with its 66-question administration. The SADL also evaluates the service and cost factors of hearing aid satisfaction, whereas the PHAP does not. The inconsistency in the findings by Givens et al. and the current study may stem from the Dichotic Digits test itself. The current study incorporated the dichotic digits difference score (difference between the left and right ear scores), while Givens et al. use the raw dichotic digits scores without subtracting. These aspects of study design, measures used, and data analyses chosen may help to explain the differences found in significance between binaural processing and hearing aid satisfaction.

Conclusions and Future Directions

This study is the first comprehensive investigation of auditory processing abilities, audibility, use, and non-auditory factors. The goal of this study was to determine the contributions of auditory processing abilities and other non-auditory factors on hearing aid outcomes. One of the more significant findings to emerge from this study is that the Gaps-in-Noise test, measuring temporal resolution abilities, was a significant predictor of hearing aid satisfaction with and without non-auditory factors. Before this study, evidence of the role of auditory processing abilities in hearing aid outcomes was purely anecdotal.

The research has also shown that self-efficacy was able to explain the greatest amount of hearing aid satisfaction. Taken together, these findings suggest that there is a role for auditory processing abilities in the hearing aid evaluation appointment in determining hearing aid satisfaction. In order to do so, a longitudinal prospective study to evaluate hearing aid satisfaction in new users may be the next step in determining the clinical utility of temporal processing.

This study has found that auditory processing abilities were unable to predict hearing aid benefit when both auditory and non-auditory factors were considered together. These findings contribute in several ways to our understanding that hearing aid satisfaction and benefit are indeed separate entities for evaluation. Interpretations of the results are limited because hearing aid benefit was measured only using self-report and not with any objective measure.

One unanticipated finding was that the left and right ear aided audibility scores were determined to be significantly different from one another. This finding is surprising given that the subject population had symmetrical hearing losses and the same hearing aid in each ear. It is possible that the hearing aids themselves were not functioning symmetrically, especially given that the age of the current devices ranged from 1 to 11 years. It is also possible that these differences are explained by individual variance in user setting preference not extensively evaluated here.

The findings of this study have a number of important implications for future practice. Although this study was conducted in older adults, separate age-specific studies in children and young adults are also warranted and preferable but for this study, the hypotheses pertained only to the adult population and differences in aging. Temporal processing abilities have been shown to be significantly different below 40 years of age compared to those 50 years of age and older (Kumar et al., 2012), so the results determined here are not thought to generalize to the younger populations. It would also be of interest to clinicians to see how the results would differ in individuals with non-symmetric hearing losses. Future studies may want to consider the possible interaction between spectral and temporal resolution because spectral resolution was not evaluated here. Further, determining that an individual has poor auditory processing abilities may provide a rationale for auditory training. Auditory training has been shown to improve auditory processing abilities in animals (Green et al., 2017) and older adults (Anderson & Jenkins, 2015). A natural progression of this work is to analyse the impacts of auditory training on those with poor auditory processing abilities and determine if improved abilities also improve hearing aid satisfaction.

Chapter Four: Is There Clinical Rationale for Assessment of Speech Perception in Spatially Separated Noise?

Introduction

Speech perception in noise abilities are a typical outcome measured for individuals with hearing loss. Although, this is very broad terminology which could encompass several different meanings. Speech perception in noise tests differ on the noise type used, spatial orientation(s) of the noise, and the presentation method. This paper will discuss these different test types, how they are being used clinically, and evaluate data from older adults with mild to moderate sensorineural hearing loss to measure spatial processing abilities. These are important to consider when choosing which speech perception test or tests to administer in a clinical setting.

One factor to consider in speech perception in noise tests is which type of noise is the test using. The noise type in a speech perception test is typically energetic masking or informational masking (Kidd, Mason, Richards, Gallun, & Durlach, 2007). These terms have historically been challenging to define without overlap (Durlach, 2006). However, for the purpose of this paper, a distinction must be made between the two. Brungart (2001) suggested that energetic masking involves the energy produced by the masker interfering with the target signal at the same time and frequencies through the entire presentation. In this sense, the target stimuli would not activate any auditory nerve neurons that were not already elicited by the energetic masker. Conversely, informational masking can be thought of as a masker or maskers that contribute to the confusability of which stimuli to listen for and identify as the target (Freyman, Balakrishnan, & Helfer, 2004). For the purpose of this study, confusability stems from the intelligibility of the maskers presented simultaneously to the target stimuli. Multiple studies have shown that talker gender in relation to the target, rate of speech, number of competing talkers, and accents can contribute even further to the confusability of the informational masker (Freyman, Balakrishnan, & Helfer, 2001; Brungart & Simpson, 2002; Best, Marrone, Mason, & Kidd, 2012).

Another factor to take into consideration when choosing or interpreting a speech perception in noise test is the spatial orientation(s) of the noise. Some test materials utilize a collocated orientation, meaning the target and masker stimuli are coming from or perceived to come from the same location, typically 0 degrees azimuth. The Quick Speech-in-Noise Test (QuickSIN; Killion et al., 2004) is one example of a collocated speech perception in noise task.

The QuickSIN is a clinically used test to measure speech intelligibility in noise and inform patient counseling. Specifically, the QuickSIN evaluates individual performance in comparison to a normative sample of the signal-to-noise ratio (SNR) needed for 50% correct performance and measured in dB SNR loss. A comparative study between the Bamford-Kowal-Bench Speech in Noise (BKB-SIN), Hearing in Noise Test (HINT), QuickSIN, and Words-in-Noise (WIN) was conducted to determine which of these clinically available speech perception in noise test was most sensitive to speech recognition performance in background noise among individuals with hearing loss (Wilson et al., 2007). The authors concluded that the QuickSIN elicited the greatest individual variation in recognition scores which is more beneficial for determining its interpretation and utility. Although the QuickSIN is typically administered with collocated speech-in-noise (Mueller et al., 2013), collocated speech in noise tests may not represent the real-world listening environment because of its single-source location for the target and masker.

Speech perception in noise tests can also be administered with the target and masker stimuli spatially separated from one another. The ability to understand speech from multiple sound sources is diminished by sensorineural hearing loss and may better represent real-world listening (Best et al., 2016; Dai et al., 2018; Marrone et al., 2008). In fact, older adults experience multi-source listening situations in everyday life (Wu et al., 2018) and spatial listening tasks mimic these environments.

When the spatially separated and collocated scores are compared and the difference in performance is evaluated, insight into a person's spatial processing abilities can be determined through a spatial release from masking (SRM) score. Such tests include the Coordinate Response Measure (CRM; Bolia et al., 2000) corpus and the Listening in Spatialized Noise Sentence Test (LISN-S; Cameron & Dillon, 2007). Both of these tests evaluate speech perception abilities in collocated and spatially separated informational masking conditions and determine a difference SRM score which can be interpreted as their spatial processing abilities.

Spatial processing involves knowing where to listen and orient yourself in the presence of background noise. Research shows that when a listener can focus their attention to a particular sound source over the noise, speech understanding improves (Kidd et al., 2005; Kitterick et al., 2010; Marrone et al., 2008). However, when spatial processing ability is poor, the listener cannot rely on spatial cues to segregate sources, which could contribute to poor hearing aid outcomes because most hearing aid microphones are designed to work optimally when the individual faces the intended sound source. Excellent spatial processing occurs when the listener is able to utilize their spatial cues and identify the sound source, regardless of location.

A third aspect of speech perception in noise to consider is how to administer the test and what equipment is needed. For the QuickSIN, a free module can be added on to the NOAH software which audiologists use to evaluate hearing. Administering this test in conjunction with the NOAH software, as an audiologist typically would, requires a sound booth and headphones (supra-aural or inserts). Conversely, the LISN-S does not require a sound booth. Instead, the LISN-S software and hardware is purchased from the hearing aid manufacturer and can be installed on a laptop. The CRM was created to be used with multiple speakers in a sound booth to simulate stimuli coming from different locations (Bolia et al., 2000). This sound booth plus speaker set-up has been used across a number of labs for evaluating speech perception abilities in different spatial orientations (Marrone et al., 2008; Best, et al., 2012; Humes, Kidd, & Fogerty, 2017).

Another way to evaluate speech perception abilities using the CRM does not involve the need for a sound booth or multiple speakers. In 2018, Frederick Gallun and his team created a Portable Automated Rapid Testing (PART) application to be used on an iPad (Gallun et al., 2018). With a valid calibration and Sennheiser HD 280 Pro Headphones, the acoustical outputs of this application have all been well within the range of stimulus presentations from psychophysical laboratories worldwide (Gallun et al., 2018; Jakien & Gallun, 2018). Not only does the portability of an iPad eliminate the need for various equipment, the application itself increases the utility for a clinical setting by reducing the testing time considerably.

Evaluating speech perception in noise is important for determining objective outcomes but subjective self-report questionnaires are needed to view the individual's abilities and challenges holistically. One way to evaluate speech perception abilities, including spatial listening abilities, subjectively is using the Speech, Spatial, and Qualities of Hearing (SSQ; Gatehouse & Noble, 2004) questionnaire. The SSQ has been used to help explain whether a hearing aid user is considered successful or not with their devices. Köbler et al. (2010) evaluated 11 successful and 11 unsuccessful hearing aid users on their speech-in-noise and spatial listening abilities. Successful hearing aid use was determined through responses on self-report questionnaires. These researchers found significant differences among these two groups with similar sensorineural hearing losses for speech-in-noise and the ‘spatial’ abilities section only on the SSQ questionnaire. Conclusions suggested that the effect of their speech perception abilities contributed to their successfulness with hearing aids.

In recent literature, the SSQ and speech perception tests have been studied and significant correlations were found between them (Heo, Lee, & Lee, 2013; Saunders, Frederick, Silverman, Arnold, & Myers, 2014). Heo et al. determined significant correlations ($r = 0.57$) between the SSQ and a localization speech perception test involving 1-2 talkers and an 8-speaker array for individuals with unilateral cochlear implants. Specifically, the poorer the SSQ score, the poorer the objective scores were on the speech perception test. A case study by Saunders, Frederick, Chisolm, Silverman, Arnold, and Myers (2014) evaluated the HINT, LISN-S and the SSQ in blast-exposed Veterans experiencing auditory difficulties. Saunders et al. found that the speech subscale section on the SSQ was significantly correlated to the HINT ($p < 0.005$) and to the LISN-S spatial advantage score ($p < 0.05$). As performance on the HINT and LISN-S decreased, SSQ scores also decreased, suggesting poorer reports.

When a clinician evaluates a patient holistically, compiling both objective and subjective results, a personalized management plan is able to be made. In terms of auditory dysfunction, the management plan may include hearing aids, assistive listening devices (ALD), group aural rehabilitation/counseling, or a combination of these options. An assistive listening device is used to improve the signal to noise ratio between a listener and the intended speaker in an attempt to improve speech understanding. In a study by Jerger, Chmiel, Florin, Pirozzolo, and Wilson (1996), 180 older participants (60-96 years) with mild to severe hearing loss [using a Pure Tone Average (PTA_2) of 1000, 2000, and 4000 Hz] were tested for aided speech understanding using the Speech Perception in Noise (SPIN) test in three conditions: hearing aid alone, ALD alone, and hearing aid plus ALD. Jerger et al. concluded that the ALD alone and ALD + hearing aid conditions had significantly higher scores on the SPIN compared to the hearing aid alone condition, suggesting a noteworthy impact on the individual's listening experience when this management strategy was implemented. Additional studies have shown that users also self-report significant benefits from their assisted listening devices (Holmes, Kaplan, & Saxon, 2000; Harkins & Tucker, 2007).

Another form of management that can be utilized for hearing loss is group aural rehabilitation (AR). A systematic review by Hawkins (2005) evaluated 12 studies on the effectiveness of group AR on the self-report of disability and communication strategies from participants. The review found that group AR was able to provide a decrease in self-perceived hearing handicap and an increase in communication strategies, at least in the short-term. Preminger (2003) went on to conclude that group AR can help with communication between the individual with hearing loss and communication partner. The benefits of ALDs and group AR in addition to hearing aids are important to consider when determining a personalized hearing loss management plan (ASHA, n.d.).

The current study will evaluate the speech perception in noise abilities, the self-report of hearing abilities, and hearing loss management strategies in older adults with hearing loss. Although this is not an experimental manipulation of management strategies, a naturalistic experiment such as this is more closely related to a clinical protocol. For example, participant's own hearing aid real ear measurements will be evaluated at user settings rather than being fit with study test aids; unaided testing will be conducted at approximate PB Max levels to determine optimal speech perception in noise abilities; and self-report will be based on current hearing loss management rather than them giving feedback about a demo device.

Although speech perception abilities have been researched in previous literature, a comparison of objective and subjective measures that assess these abilities with different speaker orientations in one study has yet to be reported on. If the link between listening abilities and self-report of abilities could be established, then this information could provide the clinical rationale to develop a clinical protocol. The participants will all be from one University clinic but the results can still be generalized further than this setting. At this clinic, the assumption of best clinical practice is followed with individual management, opportunities for group aural rehabilitation, assistive listening devices, and personalized counseling.

Aims

1. Compare clinically available collocated and spatially separated speech perception in noise tasks.

2. Determine if there is a clinical rationale for a subjective self-report of disability measure to predict functional abilities on speech perception in noise tasks.
3. Determine if self-reported spatial listening abilities (assessed here by the Speech, Spatial, and Qualities of Hearing questionnaire) and speech perception in noise tests with varying speaker orientations (assessed in this study be the Spatial Release from Masking task, the Listening in Spatialized Noise-Sentence Test Spatial Advantage score, and the QuickSIN) are related to attendance in a group aural rehabilitation class or assistive listening device use among people who use bilateral hearing aids.

Methods

Participants

Adult hearing aid users were recruited for participation from the University of Arizona's Adult Hearing Aid Clinic which serves more than 2,400 patients. The results presented here are a subset of the full data collection. The University of Arizona's Institutional Review Board evaluated and approved this study prior to any human data collection. The following inclusion criteria had to be met for initial recruitment:

1) 60 years or older
2) Current bilateral hearing aids for at least one year
3) Bilateral, symmetrical sensorineural hearing loss from 250-8000 Hz
4) No more than 55 dB HL high-frequency pure-tone average (1000, 2000, and 4000 Hz)

Participants were excluded if they did not meet the audiologic criteria, such as having a conductive component present or a high-frequency pure-tone average that exceeded 55 dB HL. Additionally, participants were excluded if they did not pass a cognitive screening. The cognitive screening implemented was the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005).

Self-Report Assessments

Two main self-report assessments were evaluated for the subset of this study: The Listener questionnaire and the SSQ questionnaire. Both assessments were administered interview-style where the researcher read the question aloud to the participant and recorded their response. The Listener questionnaire was developed in the Audiologic Rehabilitation Laboratory (PI: Nicole Marrone, PhD) to address hearing health history and current hearing loss management strategies. Although part of a longer questionnaire, two questions were evaluated from the Listener questionnaire for the current study: 1) "*Have you ever used an assistive device?"* and *2)* "*Have you ever attended the Living Well with Hearing Loss Aural Rehabilitation Class?".*

The SSQ was used to evaluate self-report of disability on three subscales. The speech section of the SSQ consists of 14 questions, the spatial section 17 questions, and the hearing qualities section has 18 questions, for a total of 49 questions. Each section has its own scoring from 0 – 10, averaging the responses from each set of questions. There is also a composite score which averages together the scores from all three sections. On this scale, 10 represents that the participant believes they are "perfectly able to do or experience what is described in the questions" and 0 would indicate that the participant feels they are completely unable to do the what the question asks.

Hearing Aid Verification

The participant's own hearing aids were evaluated to collect aided audibility information. The Aurical System was used to measure real ear measurements of moderate level speech relative to NAL-NL2 targets (Keidser et al., 2012) from 250-6000 Hz. Daily calibration was incorporated along with OpenREM calibration for open fit hearing aids prior to data collection.

Audiometric Testing

Audiometric testing was conducted using E-A-Rlink 3A or 3B insert earphones in a sound-treated double-walled booth. Otoscopy was completed first to evaluate the status of the outer ear and determine if cerumen removal was necessary. Air- and bone- pure-tone audiometry was performed in both ears between 250 and 8000 Hz. Then, word recognition was evaluated using the NU-6 50-word list presented at a sensation level (SL) relative their 2000 Hz threshold in each ear, following procedures from Guthrie and Mackersie (2009).

Speech Perception in Noise with Collocated Maskers

Quick Speech-in-Noise Test (QuickSIN).

The QuickSIN (Killion et al., 2004) was administered bilaterally to determine each participant's signal-to-noise ratio (SNR) loss under E-A-RLink 3A or 3B insert earphones in the sound booth. Two QuickSIN lists of six sentences with five key words each were presented in multi-talker babble under earphones (Etymotic Research, 2001). Note that lists 4, 5, 13, and 16 were not used due to lack of homogeneity to the other lists (McArdle & Wilson, 2006).

Initially, the noise is 15 dB softer than the sentences but increases by 5 dB after each sentence, getting progressively more challenging. Participants are asked to repeat any of the sentence that they can understand for an overall score. Scores are calculated based on how many of the five key words they correctly repeat across all six sentences. SNR Loss is determined for each list with the following equation: 25.5 – total number correctly repeated key words across all six sentences. Then, dB SNR loss scores from each list were averaged together.

Although this measure can be administered using both collocated and spatially separated presentations, for the purpose of this study, only a collocated presentation was used under headphones. The six target sentences for each list in addition to the multi-talker babble were presented to be perceptually coming from the front (0 degrees azimuth).

Speech Perception in Noise with Spatially Separated Maskers

Listening in Spatialized Noise-Sentence Test.

The Listening in Spatialized Noise Sentence Test is a clinically available test that is administered bilaterally using Sennheiser HD 280 Pro Headphones. The headphones are connected to a Phonak USB calibrated soundcard which is inserted into a laptop. Here, a Dell Inspiron laptop was used. The LISN-S evaluates individual performance compared to a normative sample based on their speech perception abilities in four conditions: two with collocated speech and noise and two with spatially separated speech in noise at +/- 90 degrees. The target sentence was always presented at 0 degrees azimuth. See Figure 4.2 for a schematic of the listening perception for collocated and spatially separated conditions.

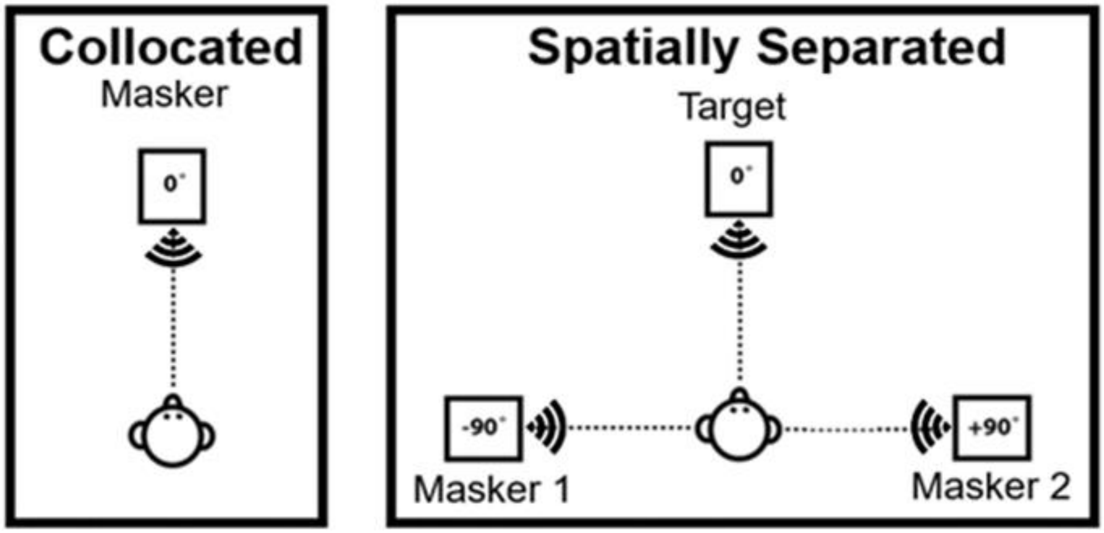

Figure 4.2. *Schematic of the listening perception for the Listening in Spatialized Noise Sentence Test.*

The talker and the masker are both perceived to come from the front in the collocated condition. In the spatially separated condition, the target sentence is perceived to come from the front while the maskers are perceived to come from the sides at 90 degrees azimuth.

For each speaker condition, there are two talker conditions, one with the same talkers for both target and maskers, and the second with different talkers for the target and maskers. Specifically, the four conditions are: 1) same talker and maskers with collocated noise; 2) different talker and maskers with collocated noise; 3) same talker and maskers with spatially separated noise; and 4) different talker and maskers with spatially separated noise. The talker for this test is recorded by an American speaker while the maskers are two audible American speakers. Note that although the conditions have different "speaker" configurations, the background noise is only perceived to be changing spatial orientation using the three-dimensional auditory environment simulated under headphones.

Due to the population being tested, the modified version of the LISN-S was used to account for the variation in hearing loss by incorporating a prescribed gain amplifier (Glyde et al., 2013). The test itself consists of 120 short sentences, divided between the four speaker/talker conditions. For each sentence, the participant was asked to repeat back any of the words they heard in the sentence. If the participant correctly identified 50% of the words correctly, the signal to noise ratio got poorer by 2 dB for the next sentence, making it more challenging. Conversely, if they did not achieve 50% correct, the signal to noise ratio improved by 2 dB for the upcoming sentence, making it easier. Scores were automatically calculated after the participant completed 30 sentences for each condition or if they achieved a score with a calculated standard error of 1 dB or less (after a minimum of 17 sentences).

Scoring for the LISN-S can be calculated for the talker advantage, spatial advantage, and total advantage but only the spatial advantage (condition 3-condition 1) is reported here due to the interest in comparing spatially separated speech perception in noise tasks.

Coordinate Response Measure.

The Coordinate Response Measure was evaluated for spatial processing by determining a spatial release from masking score under Sennheiser HD 280 Pro Headphones. This measure was conducted using a laboratory-grade psychoacoustic modified application on an iPad, P.A.R.T, rather than the traditional sound field presentation (Gallun et al., 2018). The iPad was calibrated using a Larson Davis 824 sound level meter prior to the start of testing.

This measure evaluates an individual's ability to utilize spatial cues in spatially separated speech-in-noise mixtures by comparing collocated and spatially separated speech and noise scores. The Coordinate Response Measure corpus has good test-retest reliability (Semeraro et al., 2017) and the difference between the collocated and spatially separated scores indicates the benefit of spatial cues the participant can utilize when in an environment with multiple sound source locations.

Procedures and scoring.

Using this application recently developed by Gallun's team, participants were evaluated on their speech recognition scores when listening to sentences in collocated and spatially separated noise conditions. A spatial release from masking threshold was determined by obtaining the difference between the two conditions' scores. This procedure is automated, self-paced, and was presented bilaterally at a sensation level of 30 dB above each participant's poorest pure-tone average (1.0, 2.0, 4.0 kHz). The target speech was presented at 0° azimuth with the perception of two independent maskers perceived to be spatially separated at -45° and +45°. See Figure 4.3 for a schematic of how the listener perceived the stimuli.

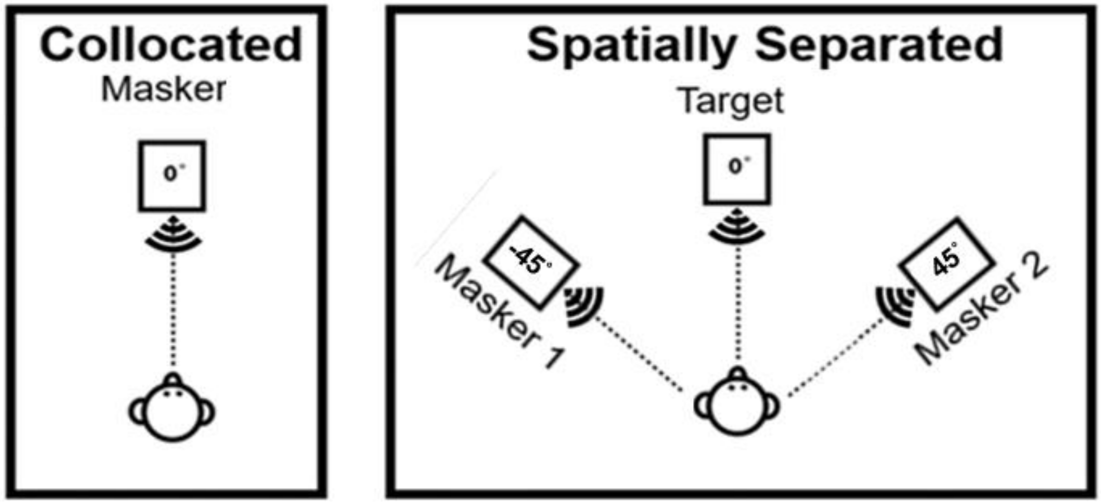

Figure 4.3. *Schematic of the listening perception of the Coordinate Response Measure test materials as presented under headphones.*

The talker and the masker are both perceived to come from the front in the collocated condition. In the spatially separated condition, the target sentence is perceived to come from the front while the maskers are perceived to come from the sides at 45 degrees azimuth.

Instructions to participant.

Practice instructions: You will be listening for the phrase "Ready Charlie go to [color] [number] now." The color and number said by the speaker will change after each trial. Your job is to press the number of the corresponding color that you heard on the iPad. At first, you will only hear the phrases for "Ready Charlie."

Collocated instructions: For this next part, you will still be listening for the phrase, "Ready Charlie go to [color] [number] now." The color and number said by the speaker will change after each trial. Your job is to press the number of the corresponding color that you heard on the iPad. Now, you will hear other speakers saying sentences at the same time as the "Ready Charlie" sentences. These speakers will say different names such as "Ringo" or "Hopper" instead of "Charlie" with different color/number combinations. All speakers may seem like they are coming from the same location. Try to ignore these other speakers as they will get louder and only listen for "Ready Charlie." Press the number corresponding to the color you think you hear and guess as needed.

Separated instructions: For this next part, you will still be listening for the phrase, "Ready Charlie go to [color] [number] now." The color and number said by the speaker will change after each trial. Your job is to press the number of the corresponding color that you heard on the iPad. Now, you will hear other speakers saying sentences at the same time as the "Ready Charlie" sentences. These speakers will say different names such as "Ringo" or "Hopper" instead of "Charlie" with different color/number combinations. Speakers may seem like they are coming from different locations this time. Try to ignore these other speakers as they will get louder and only listen for "Ready Charlie." Press the number corresponding to the color you think you hear and guess as needed.

Data Analyses

To address aim 1, to compare the speech perception tests, the linear relationships were determined using Pearson's correlation measures. For aim 2, determining if there is a clinical rationale for subjective self-report of disability assessments to predict functional ability on any of the speech perception tests, multiple linear regression models were run. To address aim 3, to determine if attendance in a group aural rehabilitation class or assistive listening device use is related to scores on subjective or objective abilities, point-biserial correlations were run. Point-biserial correlations are used when one variable is continuous (scores on the subjective and objective tests) and the other is binary (Yes/No responses on aural rehabilitation class attendance and assistive listening device use).

Results

Participants

Seventy-eight adults were recruited for the study. The following were reasons for removal from the analyses: seven did not complete the CRM, four were tested at the incorrect presentation type on the CRM (fixed instead of adaptive), and data from six participants could not be included because of the output limitation of the CRM procedure. That is, these six participants' spatial release from masking score could not be obtained in an adaptive way due to the pre-set maximum output (97 dB), underestimating their abilities. This resulted in 61 participants with full data sets for analysis.

In this cohort, 33 (54%) were men and 28 (46%) were female, the majority of participants were 75 years of age and older, and 92% reported their ethnicity as non-Hispanic. See Table 4.1 for a further breakdown of the study participant demographics.

Table 4.1. *Demographics of study participants.*

Characteristic	Cohort (*n*=61)
Gender, *n*	
Men	33 (54%)
Women	28 (46%)
Age Groups, *n*	
60-64 years	7 (12%)
65-69	13 (21%)
70-74	10 (16%)
75-79	17 (28%)
80-84	8 (13%)
85-89	6 (10%)
Ethnicity, *n*	
Hispanic	5 (8%)
Non-Hispanic	56 (92%)

Self-Report Assessments

The Listener questionnaire was implemented to evaluate self-reported hearing aid use, duration of current hearing aid use, assistive listening device use, and attendance in the Living Well with Hearing Loss class at the University of Arizona. Participants reported between 0 and 16 hours of hearing aid use per day (M = 7.4 hours, SD = 5.6) and current hearing aid use between 1 and 11 years (this information was also confirmed with patient records). The ten-year difference in current hearing aid use suggests a wide variation in hearing aid condition and technology across participants.

In this participant cohort, 12 (20%) have used an assistive device, and 18 (30%) have attended the Living Well with Hearing Loss Aural Rehabilitation Class at the University of Arizona. Assistive listening devices included TV streamers for hearing aid compatibility (n = 6), Bluetooth headsets for the TV separate from using a hearing aid (n = 2), Loop system for TV (n = 2), Remote Mic (n = 2), and ComPilot (n = 2), note that two participants used two assistive devices. Table 4.2 provides an overview of hearing loss management from the self-reported Listener questionnaire responses.

Table 4.2. *Characteristics of hearing loss management.*

Characteristic	Cohort (*n*=61)
Hearing Aid Manufacturer, *n*	
GN Resound	2 (3%)
Oticon	16 (26%)
Phonak	15 (25%)
Signia/Siemens	3 (5%)
Starkey	16 (26%)
Unitron	5 (8%)
Widex	3 (5%)
Bernafon	1 (2%)
Current Hearing Aid Use, *n*	
1-3 years	32 (52%)
4-6	20 (33%)
7-9	5 (8%)
10+	4 (7%)
Aural Rehabilitation Participation, *n*	
Yes	18 (30%)
No	43 (70%)
Assistive Device Use, *n*	
Yes	12 (20%)
No	49 (80%)

Self-reported disability was evaluated using the Speech, Spatial, and Qualities of Hearing questionnaire. The following averages were determined on each subscale of the SSQ: Speech (M = 6.4, SD = 1.7); Spatial (M = 6.5, SD = 1.6); Quality (M = 7.2, SD = 0.7); and Global (M = 7.0, SD = 2.6). None of the subscales were significantly different from one another.

Pearson's correlations analyses were run to determine if significant correlations existed between any of the SSQ subscales and the duration of current hearing aid use. No significant correlations were found between SSQ-speech (r = -0.06), SSQ-spatial (r = 0.03), SSQ-qualities (r = -0.18), or SSQ-global (r = -0.06) and the duration of use.

Hearing Aid Use and Verification

Participant's own hearing aids were connected to their corresponding software to determine hearing aid use in each device. Left data logging (M = 6.3 hours per day, SD = 4.9) and right data logging (M = 6.2 hours per day, SD = 4.8) were recorded for the participant's primarily used program. Self-reported hearing aid use and data logging in each ear were compared using a two-tailed *t* test. There was a significant difference between the left ear data logging and self-reported hearing aid use ($p < 0.01$) and right ear data logging and self-reported hearing aid use ($p < 0.05$). Because self-reported hearing aid use could represent the maximum use in one device, the maximum data logging score was determined for each participant and compared to self-reported data logging. A significant difference between subjective and objective hearing aid use per day was again determined ($p < 0.05$).

Real ear measures were evaluated because the functionality of the hearing aids themselves could impact a patient's self-perceived hearing abilities. For example, if the hearing aids are under-target, the patient may not be able to utilize their actual functional abilities due to the improper amount of amplification.

Real ear measurements were recorded at user settings for frequencies 250 to 6000 Hz. Tested levels were compared to target NAL-NL2 levels to determine how closely the devices were fit to target. Tables 4.3-4.5 illustrate the breakdown of the cumulative percentage of those who were under-target, over-target, and meeting targets. Under-target and over-target were determined by a difference between tested and target levels >10. Closer inspection of the Table 4.4 shows no more than 3.3% of individuals were over-target across all frequencies. The majority of individuals were under-target in frequencies 1500 – 6000 Hz. Participants met targets from 250-750 Hz, 95 -100% of the time. On average, the left ear was more under-target than the right ear, the right ear was over-target more than the left ear, and the right ear met targets more than the left ear.

Table 4.3. *Percentage of Real Ear Measures under-target at each frequency.*

	250	500	750	1000	1500	2000	3000	4000	6000	Avg
Left	1.6%	1.6%	4.9%	11.5%	36.1%	39.3%	36.1%	62.3%	70.5%	29.3%
Right	0%	0%	1.6%	3.3%	21.3%	34.4%	23.0%	44.3%	65.6%	21.5%

Table 4.4. *Percentage of Real Ear Measures over-target at each frequency.*

	250	500	750	1000	1500	2000	3000	4000	6000	Avg
Left	0%	0%	0%	1.6%	0%	0%	0%	0%	0%	0.18%
Right	0%	0%	3.3%	1.6%	3.3%	1.6%	1.6%	0%	1.6%	1.4%

Table 4.5. *Percentage of Real Ear Measures meeting targets at each frequency.*

	250	500	750	1000	1500	2000	3000	4000	6000	Avg
Left	98.4%	98.4%	95.1%	88.5%	63.9%	60.7%	63.4%	37.7%	29.5%	70.6%
Right	100%	100%	96.7%	96.7%	78.7%	65.6%	77.0%	55.7%	34.4%	78.3%

Hearing Aid Directionality Settings

Directionality settings in participant's hearing aids were recorded for their primarily used program. Right and left ear hearing aid directionality settings were identical for the primary program. Settings were categorized into: Fixed, Omnidirectional, Adaptive, Automatic, or Other. Fixed indicated that the hearing aid's microphones were forward-facing at all times unless manually changed into another program or setting. The omnidirectional setting suggested that the hearing aid microphones detected sounds from all around without automatically adjusting with different signal-to-noise ratios (SNRs). The adaptive directionality setting suggested that the hearing aid microphones did automatically adjust to different cardioid patterns based on the SNR in a given environment. Automatic differed from adaptive in that it only changed from fixed to omnidirectional settings based on the SNR. Finally, 'Other' was denoted for specific-manufacturer terminology that did not fit into the previous categories: "Dynamic", "Binaural Directionality with Spatial Sense", "Real Ear Sound", "HD Locator", or "HD Locator with Digital Pinna". See Table 4.6 for the distribution of directionality settings.

Table 4.6. *Hearing aid directionality settings.*

Directional Category, *n*	Cohort (*n*=61)
Fixed	7 (12%)
Omnidirectional	6 (10%)
Adaptive	22 (36%)
Automatic	16 (26%)
Other	10 (16%)
Other, *n*	
Dynamic	6 (60%)
Binaural Directionality with Spatial Sense	1 (10%)
Real Ear Sound	1(10%)
HD Locator	1(10%)
HD Locator with Digital Pinna	1(10%)

Audiometric Testing

Air- and bone- conduction pure-tone audiometry was conducted for all participants. The average pure-tone thresholds revealed a symmetrical mild sloping to moderately-severe sensorineural hearing loss bilaterally from 250-8000 Hz. See Figure 4.4 for a depiction of these values and the minimum and maximum at each frequency.

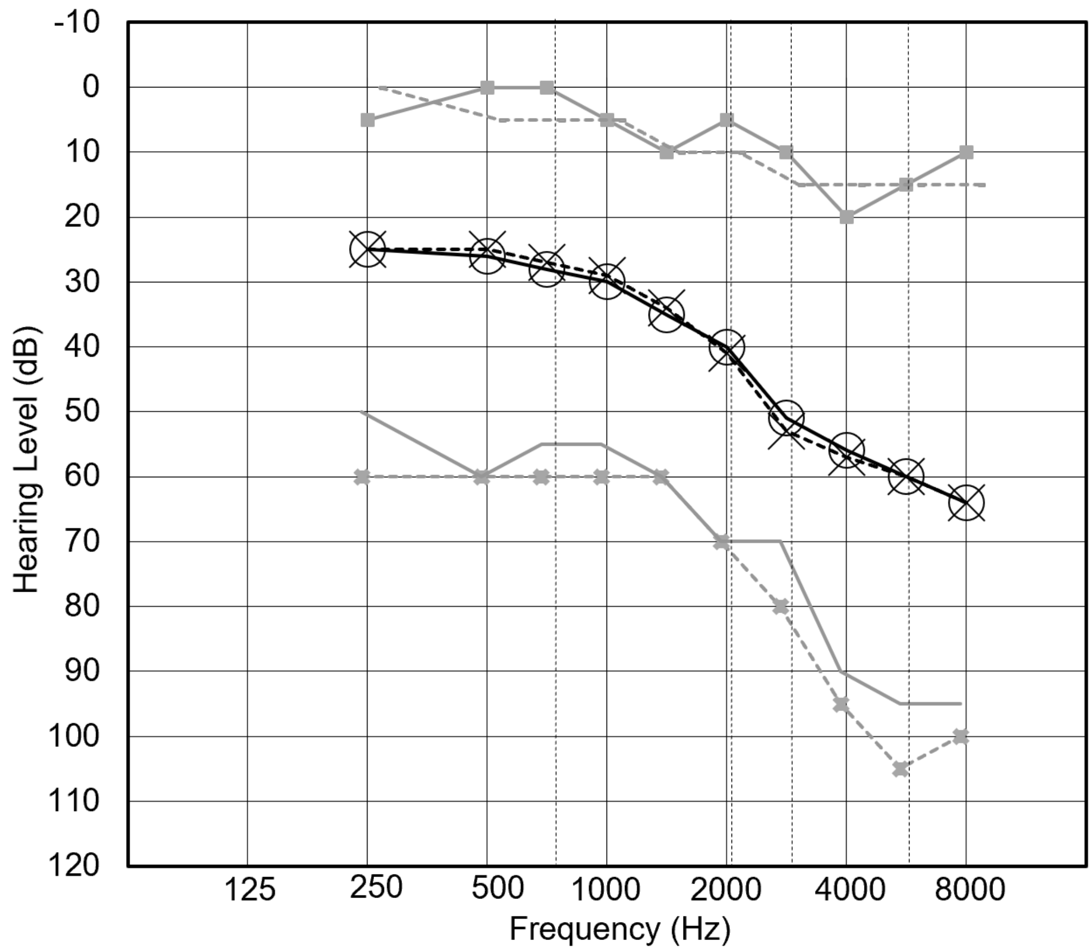

Figure 4.4. *Average audiogram across 61 participants.*

Right ear is represented by solid lines and an O, while the left ear is represented by dashed lines and an X. Light grey dashed and solid lines represent the minimum and maximum thresholds across participants.

Average word recognition in quiet for the right ear (M = 80.8%, SD = 20.3) and left ear (M = 83.9%, SD = 16.4) was computed. There was not a significant difference between ears $t(60) = 2.0$, $p = 0.06$.

Speech Perception in Noise

Speech perception was evaluated using three different tests, the QuickSIN, the LISN-S SA, and the CRM. Characteristics of all three tests were compared in Table 4.7. The main clinical difference between the tests is the spatial location of masker: 0 degrees for the QuickSIN, +/- 90 degrees for the LISN-S, and +/- 45 degrees for the LISN-S. In the next sections, the three tests will be further discussed.

Table 4.7. *Characteristics of test materials.*

Test Name	QuickSIN	LISN-S SA	CRM
Test Reference	Killion et al., 2004	Cameron & Dillon, 2007	Bolia et al., 2000
Test Administration	Binaural insert earphones in sound booth via audiometer	Sennheiser 280 headphones in a quiet room	Sennheiser 280 headphones in a quiet room
Talker Location	0 degrees	0 degrees	0 degrees
Spatial Location of Masker	0 degrees (collocated)[3]	0 degrees (collocated) and +/- 90 degrees (spatially separated)	0 degrees (collocated) and +/- 45 degrees (spatially separated)
Masker Type	Four talker multi-talker babble	Speech-spectrum-shaped intelligible competing talkers	Speech-spectrum-shaped intelligible competing talkers
Scoring Range	-4.5 – 25.5 dB SNR Loss	0 – 20 dB Spatial Release from Masking Score	-5-12 dB Spatial Release from Masking Score
Clinical Availability	Free add-on module in audiometer	Software and hardware for purchase from hearing aid manufacturer	Free iPad application download (P.A.R.T.)

[3] Note: The QuickSIN can also be administered in the soundfield using separately recorded tracks to present the target speech and maskers from spatially separated locations.

Speech Perception in Noise with Collocated Maskers.

The QuickSIN score represents an average of two lists. Based on the user manual guidelines, a score of 0-2 dB SNR loss is considered normal, 2-7 dB SNR loss is suggestive of a mild SNR loss, 7-15 dB SNR loss is considered a moderate SNR loss, and greater than 15 is associated with a severe SNR loss (Etymotic Research, 2001). Based on these categories, Etymotic Research suggests that a score of 7 or greater would warrant directional microphones and/or additional assistive devices.

Based on previous normative data, the QuickSIN scores for older adults with hearing loss typically range between 2.6 and 10 dB SNR loss, with an average of 6.3 dB SNR loss (Walden & Walden, 2004). See Figure 4.5 for a distribution of the QuickSIN scores in the current study (M = 4.67, SD = 3.21).

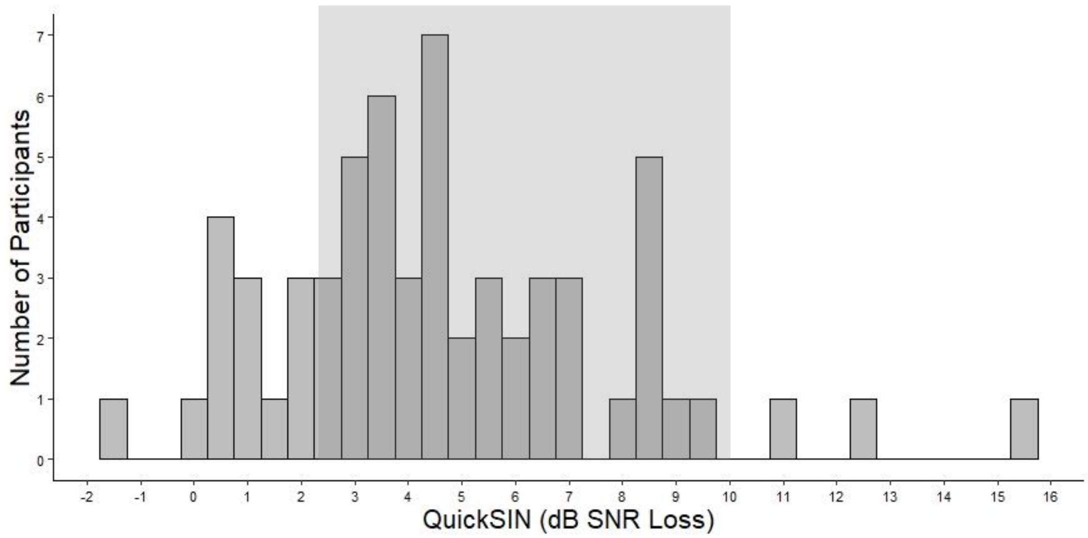

Figure 4.5. *Distribution of QuickSIN scores.*

Boundaries of the shaded box region represents the data from participants with bilateral, symmetrical, sensorineural hearing loss in Walden and Walden (2004).

Speech Perception in Noise with Spatially Separated Maskers.

The Listening in Spatialized Noise Sentence Test has three main scores: Total Advantage, Talker Advantage, and Spatial Advantage. Here, the Spatial Advantage score, measured in dB, takes the speech perception threshold in the spatially separated condition and subtracts it from the speech perception threshold in the collocated condition. The resulting spatial advantage score was measured in all participants (M= 5.5, SD = 2.1). Refer to Figure 4.6 for a representation of the distribution of scores in comparison to normative values for individuals with hearing loss.

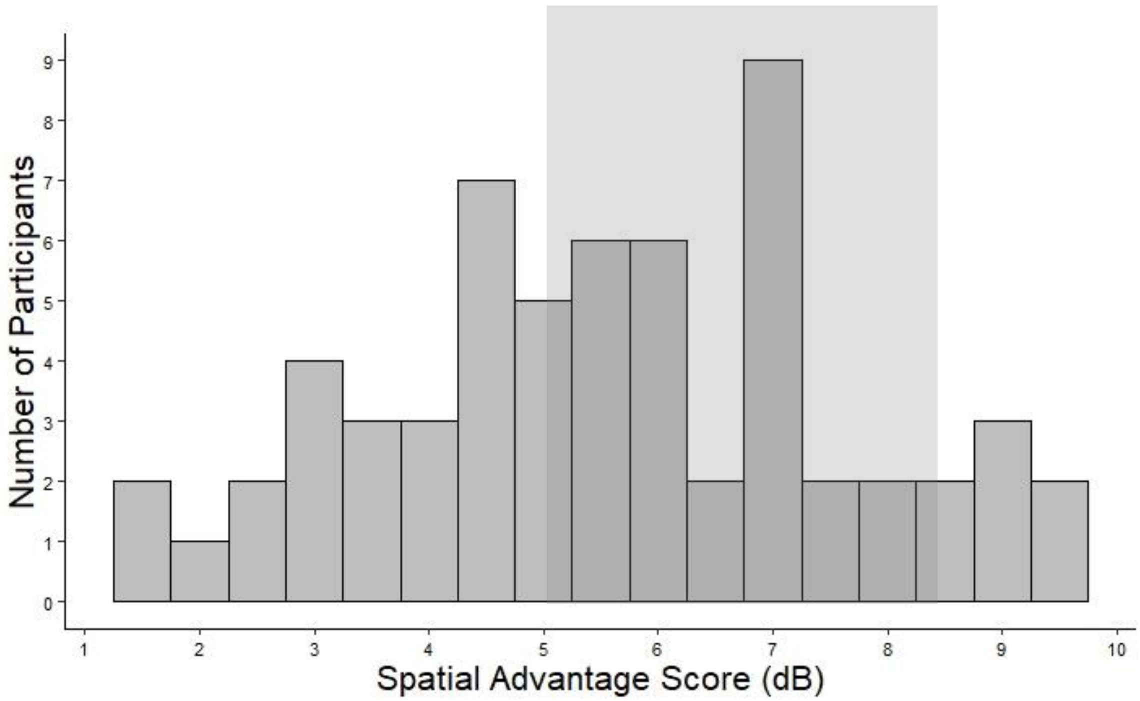

Figure 4.6. *Number of participants' receiving a given spatial advantage score on the Listening in Spatialized Noise Sentence Test.*

The shaded box region represents the boundaries for normative data for older adults with hearing loss (range = 5-8.4 dB) (Glyde et al., 2013).

The Coordinate Response Measure apparatus was used as an iPad application under headphones. This test allows for determination of a spatially separated speech reception threshold as well as a collocated threshold. To obtain the spatial release from masking score (SRM), the two thresholds were subtracted from one another. Here, the SRM score resulted in a mean of 2.5 dB with a standard deviation of 3.9 dB. Figure 4.7 shows the distribution of SRM scores for the current study. A lower SRM score suggests poorer use of spatial cues compared to a higher SRM score which suggests a better use of spatial cues.

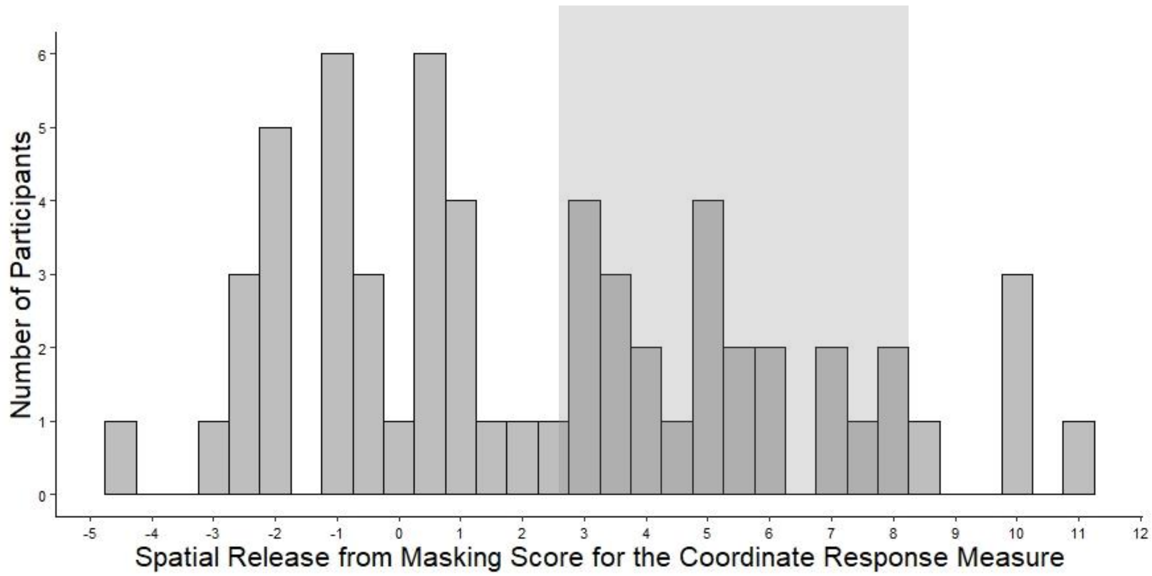

Figure 4.7. *Distribution of spatial release from masking scores (dB) on the iPad coordinate response measure task.*

The shaded box region represents the boundaries for a range of scores from two sites for adults 18-85 with normal to moderate hearing loss (range = 2.92-8.48 dB) (Gallun et al., 2018; Jakien & Gallun, 2018). However, normative data for this iPad measure are still in development for different age groups and hearing sensitivities.

Relationship Between Self-Report and Functional Auditory Abilities

To address aim 1 and compare the linear relationships between multiple speech perception measures, Pearson's correlations were run (Table 4.8). Significant correlations were determined between pure-tone average (500, 1000, and 2000 Hz) in the better ear and the CRM as well as the LISN-S spatial advantage score and between the QuickSIN and LISN-S. All SSQ subscales were correlated with one another. However, no significant correlations were determined between the SSQ on any subscale and any of the speech perception tasks.

Table 4.8. *Pearson's correlation coefficients (r).*

	PTA Better Ear	QuickSIN	SSQ Speech	SSQ Spatial	SSQ Quality	SSQ Total	CRM	LISN-S
PTA Better Ear	1	0.187	-0.159	-0.189	-0.132	-0.201	-0.341**	-0.466**
QuickSIN	0.187	1	-0.159	0.041	-0.017	-0.065	-0.212	-0.419**
SSQ Speech	-0.159	-0.159	1	0.512**	-0.417**	0.848**	0.086	0.12
SSQ Spatial	-0.189	0.041	0.512**	1	0.537**	0.862**	0.128	0.002
SSQ Quality	-0.132	-0.017	-0.417**	0.537**	1	0.691**	0.095	-0.114
SSQ Total	-0.201	-0.065	0.848**	0.862**	0.691**	1	0.126	0.037
CRM	-0.341**	-0.212	0.086	0.128	0.095	0.126	1	0.384**
LISN-S	-0.466**	-0.419**	0.12	0.002	-0.114	0.037	0.384**	1

To further investigate if self-report of disability, as measured by the SSQ, can be used to predict functional abilities on the QuickSIN, LISN-S, or CRM, multiple linear regressions were run (aim 2).

First, a multiple linear regression was calculated to predict the QuickSIN score based on the SSQ subscales. A non-significant regression equation was determined, ($F(4, 56) = 0.67$, $p = 0.62$), with an R^2 of -0.02. A second multiple linear regression was calculated to predict the LISN-S spatial advantage score based on the SSQ subscales. A non-significant regression equation was determined, ($F(4, 56) = 0.71$, $p = 0.59$), with an R^2 of -0.02. Finally, a third multiple linear regression was calculated to predict the CRM score based on the SSQ subscales. A non-significant regression equation resulted ($F(4, 56) = 0.32$, $p = 0.86$), with an R^2 of -0.05.

Aural Rehabilitation Attendance and Assistive Listening Device Use

To address aim 3, to determine if the SSQ, the QuickSIN, the LISN-S, or the CRM are related to group aural rehabilitation attendance or assistive listening device use, point-biserial correlation calculations were run (Table 4.9). The table shows that there are no significant correlations between group aural rehabilitation attendance or assistive listening device use and functional speech perception in noise scores. Additionally, no significant relationships were determined between any of the SSQ subscales and group aural rehabilitation attendance or assistive listening device use.

Table 4.9. *Point-biserial correlation coefficients.*

	QuickSIN	LISN-S	CRM	SSQ-Speech	SSQ-Spatial	SSQ-Quality	SSQ-Global
Group Aural Rehabilitation	-0.009	0.20	-0.10	0.08	-0.20	-0.03	0.20
Assistive Listening Device	0.20	0.01	-0.10	-0.02	0.10	-0.02	0.04

Discussion

Based on the findings from this laboratory study, there is clinical rationale for the assessment of speech perception in spatially separated noise tests. An important aspect of deciding which test to administer is the difficulty of the test. If the test is too easy, the majority of patients will perform at ceiling and interpretation will be challenging. Similarly, if the test is too challenging, score performance could hover near the floor. Here, a wide range of scores was found for each speech perception in noise test allowing for data to be grouped into different skill levels. In this paper, three speech perception tests were compared. Results from this study showed that the scores on the LISN-S were significantly correlated to scores on the QuickSIN and scores on the CRM. This suggests that the LISN-S is assessing similar constructs to that of the QuickSIN and the CRM.

As mentioned in the literature review, there are many ways to evaluate speech perception abilities with no consensus on which measure to use in a clinical setting. Research has shown that spatial processing abilities, as measured by speech perception tests, may be important when listening with and fitting hearing aids (Ricketts, 2005). In fact, Best et al. (2017) have shown that setting optimal configurations of hybrid beamformer hearing aid microphones would depend on the listener and their individual abilities. However, in order to make suggestions for a personalized management plan, objective testing and subjective testing is advised to evaluate the extent of each patient's needs. Data from holistic testing may inform the need for a management plan that involves more than just hearing aids, such as group aural rehabilitation and/or assistive listening devices.

All speech perception measures used in this study are clinically available and contribute to understanding an individual's abilities. The CRM, however, may be difficult to interpret at this time. Normative data for this iPad measure are currently in progress for different age groups with varying hearing sensitivities (Gallun et al., 2018). The use of this iPad measure provides a clinical test of spatial processing without the need for a speaker array in a sound booth or anechoic chamber, which many clinics may not have. There are many benefits to this type of testing, as free-field testing can be limited by head movement, replication of listener placement, and reverberation effects (Koehnke & Besing, 1997; Wilber, 2002).

This study set out with three aims: 1) compare clinically available and spatially separated speech perception in noise tasks, 2) determine if there is a clinical rationale for a subjective self-report of disability measure to predict functional abilities on speech perception in noise tasks, and 3) determine if self-reported spatial listening abilities and speech perception in noise tests with varying speaker orientations are related to attendance in a group AR class or ALD use. The results of this study indicate that abilities on the CRM and LISN-S tasks were significantly related to better-ear pure tone average. Additionally, abilities on the QuickSIN and LISN-S were also significantly correlated to one another. Surprisingly, no correlations were found between any SSQ subscale and the speech perception tasks. This outcome is contrary to that of previous literature which did find significant correlations between the SSQ and speech perception in noise tests (Heo et al., 2013; Saunders et al., 2014). Specifically, both Heo et al. and Saunders et al. found that the poorer the score on the SSQ, the poorer performance on the objective test. This discrepancy could be attributed to the population differences among the studies. For example, Heo et al. evaluated those with cochlear implants rather than hearing aids, and Saunders et al. investigated outcomes among non-hearing aid users. The most important clinically relevant finding was that speech and spatial listening abilities on the SSQ were not able to predict abilities on any of the objective speech perception tests.

The results of this study did not detect an association between subjective or objective speech perception abilities and attendance in a group AR class or the use of ALDs. The lack of associations between these measures may be partly explained by the low uptake of ALD and low attendance in group AR among this cohort. In this study, only 20% used an ALD and 30% attended the group AR class offered through the University of Arizona Adult Hearing Clinic. It is important to note that no other group AR attendance outside of the University was part of the inquiry. Comparable to the current findings, Souza, Hoover, Blackburn, and Gallun (2018) found that 25% of their participants used an ALD. These results also reflect those of Hartley, Rochtchina, Newall, Golding, and Mitchell (2010) who found that older individuals reported a low usage of ALD.

A secondary objective to this study was to determine how well the hearing aids were fit to NAL-NL2 targets. One unanticipated finding was that 21-29% of participants were under-target, primary at frequencies 1500-6000 Hz. In fact, up to 62.2% of participants were under-target at 4000 Hz. This was surprising given that all participants were fit at the same clinic presumably following the same verification protocols. Although it is important to note that these users are under-target based on their current level of hearing, it is unknown from this data set if their hearing aid was updated based on their most recent hearing test or not. Comparable to the under-target percentages found here, Aazh and Moore (2007) showed up to 40% of their participants were under-target in the high frequencies.

When a hearing aid user is under-target, they would not have access to the sounds in order to utilize their localization cues. This may be a possible explanation as to why the unaided objective abilities did not correlate to the aided subjective abilities. That is, they may possess more spatial processing abilities than they are self-reporting; however, since they are not receiving the appropriate amount of amplification, they are unable to use these abilities in their day-to-day listening experiences. Henson and Beck (2010) suggested that there was an 18% increase in self-reported satisfaction when real ear measures were utilized and targets were met appropriately. It is possible that with more appropriate amplification, the relationship between objective and subjective performance could become more apparent. One issue that remains unknown from the current dataset is the duration of time these individuals have been under-target and how that affects their hearing aid outcomes.

There are still many unanswered questions regarding which speech perception measure(s) to incorporate into the clinical setting and how to use these assessments in the development of the hearing loss management plan. It is important for audiologists to consider the purpose of conducting each test and how the results can be used in identifying an individual's needs. The underlying goal of aim 3 was to determine if objective or subjective measures could inform who may benefit from ALD use or a group AR class; however, due to the low uptake of these management strategies, these conclusions could not be drawn. Future studies on the current topic are therefore recommended.

Chapter Five: Conclusions and Future Directions

Overall Objective

The objective of this dissertation was to investigate the clinical utility of evaluating auditory processing abilities for the purpose of informing hearing loss management plans. Chapter Two highlights the need for this area of research through a systematic review. Chapter Three tests the hypotheses that auditory processing abilities are related to hearing aid outcomes. Finally, in Chapter Four, a more in-depth look at different clinical tests to evaluate auditory processing abilities are compared. Together, these three manuscripts will bring to light that evaluating auditory processing abilities may play a significant role in managing hearing loss. This chapter will provide overall conclusions to each chapter's findings and recommendations for future directions.

Chapter Two: Systematic Review

When deciding on a topic to research, a literature review is crucial in knowing the available literature and which gaps need to be filled. A systematic review differs from a literature review by systematically searching multiple databases rather than just one or two. Research suggests that each search engine database for looking up articles are significantly different from one another in terms of the preciseness and importance to the inquired topic (Samadzadeh, Rigi, & Ganjali, 2013). In the current systematic review, *Can Auditory Processing Abilities Predict Hearing Aid Satisfaction in Adults with Hearing Loss? A Systematic Review,* six electronic databases were searched for inclusion on this topic. Another way a systematic review is preferred to a literature review is by evaluating the quality. The methodological quality of each study included in the systematic review is rated and those ratings are then compared against another reviewer for agreement. For this systematic review, the American Speech-Language-Hearing Association's Level of Evidence ratings were used by two independent reviewers.

As discussed in Chapter Two, the systematic review showed that the relationship between auditory processing abilities and hearing aid satisfaction is not a saturated topic in the literature and needs more attention. In fact, out of 3,864 articles evaluated, only seven met the criteria to be included in the systematic review. Although the included studies were sparse, abilities on three auditory processing tests were significantly related to hearing aid satisfaction. The overall conclusions of this review were that auditory processing abilities *may* play a role in hearing aid satisfaction and provided a rationalee for Chapter Three's hypotheses.

Chapter Three: Hearing Aid Outcomes

The goal of this chapter was to investigate if auditory processing abilities were related to hearing aid outcomes (satisfaction and benefit). The population included 78 older adults, 60 years or older, who purchased two hearing aids from the University of Arizona Adult Hearing Clinic. All participants had no more than a 55 dB HL pure-tone average at frequencies 1000, 2000, and 4000 Hz. Auditory processing abilities were measured using the Dichotic Digits Free Recall test (DDT), the Gaps-in-Noise test (GIN), and the Listening in Spatialized Noise Sentence Test (LISN-S). Hearing aid outcomes were evaluated through self-report. Satisfaction with Amplification in Daily Life (SADL) was used to measure hearing aid satisfaction and the Client Oriented Scale of Improvement (COSI) was used to measure hearing aid benefit. The SADL was intended to determine the individual's current satisfaction with their hearing aids while the COSI determined the participant's current benefit to listening situations they reported as important before they acquired the hearing aids. This is a limitation to using the COSI because the participant's important listening situations may change once they start wearing the devices in everyday life.

Discussed thoroughly in Chapter Three, many factors play a role in a user's hearing aid outcomes. As a result, non-auditory subjective measures were also included for evaluation. Specifically, self-efficacy was measured using the Measure of Audiologic Rehabilitation Self-Efficacy for Hearing Aids (MARS-HA), self-report of benefit was measured with the Speech, Spatial, and Hearing Qualities (SSQ) Questionnaire and personality was evaluated using the Neo-Five-Factor-Inventory-3 (Neo-FFI-3). Together with the auditory processing abilities, multiple linear regression models were created and run. When auditory processing measures were the only variables included in the model, the GIN was able to predict 11% of the variance in hearing aid satisfaction and 3.8% of the variance in hearing aid benefit. No other predictor was significant for these models. Then, non-auditory factors were considered in the models of satisfaction and benefit. With all factors included in the models, the GIN, the LISN-S, and the MARS-HA significantly predicted 8, 4, and 12% of the variance in hearing aid satisfaction, respectively, while the MARS-HA and SSQ were able to predict 15.2 and 2.8% of the variance in hearing aid benefit, respectively.

This was the first study to evaluate auditory processing abilities in addition to non-auditory abilities comprehensively in one study with the purpose of predicting hearing aid outcomes. The results suggest that auditory processing abilities of temporal processing (as measured by the GIN) and spatial processing (as measured by the LISN-S) are associated with hearing aid satisfaction but the causation between these factors still remain unclear.

Chapter Four: Comparison of Tests

Chapter Four was designed to compare speech perception in noise abilities among three clinically available tests with different speaker orientation of the competing maskers: QuickSIN, LISN-S, and the Coordinate Response Measure (CRM) using the iPad. A self-report of disability measure, with a focus on self-perceived spatial abilities (SSQ) was also implemented into this study design in addition to questions regarding group aural rehabilitation and assistive listening device use.

Pearson's Correlations were used to compare the three speech perception tests in addition to the SSQ and the participant's better ear pure-tone average. Results showed that only the QuickSIN and LISN-S were significantly correlated to one another. Additionally, the SSQ was unable to significantly predict any of the objective abilities when multiple-linear regression was run. Finally, no relationship could be determined between any of the measures described and group AR attendance or use of ALDs. Low uptake of group AR was reported. However, it is a limitation of this study that why uptake was low was not inquired upon through follow-up. Further, low ALD use was also not used as a line for follow-up questioning but it can be assumed that cost played a role since the majority of participants were self-pay.

This is one of the first studies using the iPad application, PART, to evaluate abilities using the CRM. This iPad measure may help with clinical evaluation in the future because of this no cost application, low cost equipment compared to a full sound booth, and its faster testing time compared to psychoacoustic testing procedures.

Future Directions

Clinically, challenges in early identification of those who may struggle with hearing aids present a barrier for audiologists in designing a rehabilitation plan that will support the patient's needs. Improved hearing aid outcomes may ultimately expand the number of adults who use hearing aids to treat their hearing loss. New horizons of auditory research may be opened for exploration to select the most appropriate treatment for adults with sensorineural hearing loss. The results shown here may benefit people with hearing loss through a better understanding of the unique variations in temporal, spatial, and binaural processing among hearing aid users.

It is necessary to determine measures that predict hearing aid satisfaction because of the importance this outcome plays in the successful use of hearing aids (Cox and Alexander, 1999; Vestergaard Knudsen et al., 2010; Wong et al., 2003). Additionally, Perez, McCormack, and Edmonds (2014) found a connection between reported hearing aid benefit improvements and better temporal fine structure sensitivities. Temporal processing is traditionally evaluated with a psychophysical gap-detection measure and has been used to document differences in aided temporal processing abilities with different hearing aid algorithms (Brennan et al., 2013). However, traditional psychophysical gap-detection measures may require additional equipment and testing time not found in the typical audiology clinic (Hoover et al., 2015). Therefore, an alternative approach is to use a clinically available test of temporal processing (Gaps-in-Noise). Hoover et al. (2015) found comparable results with the Gaps-in-Noise test and psychophysical gap-detection in older adults with mild-to-moderate sensorineural hearing loss.

As noted by Lopez-Poveda et al. (2017), although their temporal processing measure predicted a significant amount of variance in objective benefit, this would not be useful for clinical audiences because the psychoacoustic measure is not clinically available. Across studies, these findings suggest that assessment of temporal processing could have clinical utility and provide enough variance in performance to discern individual differences in hearing aid satisfaction. Chapter Three goes beyond the current findings in the literature because results can be readily translated to clinical research. In fact, results from this research may lead to the development of a more ecologically valid approach than traditional audiometric assessment.

Targeted auditory training or other novel rehabilitative approaches could be pursued as a result of this research. Although auditory training has been shown to improve auditory processing abilities in laboratory settings, there has been limited clinical translation (Anderson et al., 2015; Green et al., 2017). A future research topic could be investigating the role of auditory training into the current management of these participants. For example, if auditory training improves temporal or spatial processing abilities in these participants, will this in-turn improve their hearing aid outcomes? This will be an important question to answer in the future for making patient-centred hearing loss management decisions.

As discussed in Chapter Four and highlighted in the previous section, group aural rehabilitation and assistive listening device use was low among the participants. This finding, in agreement with other studies, opens the door to other future topics for research. Barriers to taking these classes and using these assistive devices should be further explored in order to answer the question, who will receive the most benefit from and should be recommended to try these management strategies?

An association between auditory processing abilities and hearing aid outcomes was determined; however, the causation was not. In order to determine a possible causation, a prospective study should be conducted. This study should focus on evaluating the temporal processing and spatial processing abilities of new hearing aid users prior to the hearing aid fitting. Long-term outcomes should then be recorded in terms of satisfaction and benefit. From this information, a more reliable conclusion could be drawn if these measures play an important role in predicting who will receive the most benefit and be the most satisfied with their hearing aids. After reviewing all information from the three manuscripts, this prospective study should also include intervention arms with and without group AR and possibly another with assistive listening device use.

Hearing loss management is a necessary part of an audiologist’s responsibilities. Providing the clinician with evidence-based research to help inform patient centred clinical decisions is still very much needed. The conclusions drawn from this dissertation provide the rationale needed to continue research into how auditory processing abilities may play a role in managing hearing loss.

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