Improving hearing aid outcomes in background noise: An investigation of outcome measures and patient factors

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Abstract

Background noise is reported to be one of the most difficult listening environments by hearing aid users. Digital noise reduction and directional microphones have been added to hearing aids and remote microphones and frequency modulation systems as accessories to help augment speech understanding in background noise for hearing aid users. Despite having this technology, patients still have concerns in background noise. This indicates that there is still a need for evidence-based tools for assessing patient speech understanding needs as well as quantifying amplification benefits in noise to help improve these situations. This dissertation seeks to investigate the advantages and disadvantages of current evidence-based practices tools available for improving speech understanding in noise for individuals with hearing loss.

Three main research findings are reported in this dissertation. The first study examined the viability of using functional near infrared spectroscopy (fNIRS), a tool that can be used to measure the hemodynamic response to neural activity in the brain. This study sought to examine if fNIRS is a viable clinical tool for assessing the impact of different listening conditions, speech materials, and hearing aid settings on listening effort. Behavioral data supported the impact of signal degradation on intelligibility and that syntactically complex speech results in greater difficulty parsing content. fNIRS data supported that this difficulty in parsing content could be considered listening effort due to contrasts in hemodynamic responses in the lateral inferior frontal gyrus between

grammatically simple and complex constructions. Future work should consider evaluating fNIRS in an older hearing loss group with contrasting degrees of hearing loss and speech complexity.

The second study examined the viability of using spectral-ripple modulation detection thresholds (SMD), a tool that could help assess a person's broadband spectral processing abilities as an alternative for a person's speech understanding in noisy environments. In this study, SMD thresholds were examined in a group with normal hearing and a group with hearing loss to determine the impact of bandwidth and intensity on SMD thresholds. Results revealed a significant difference in bandwidth and level within the hearing loss and normal hearing groups, but not across groups. Future work should examine this effect using audibility-controlled conditions across the listener groups, such as simulating a hearing aid in these situations to determine the impact of amplification on SMD thresholds.

The final study examined various listener factors that could influence a person's noise tolerance. The acceptable noise level test was used as a metric for noise tolerance. The listener factors that were examined included personality traits, digits in noise ability, and working memory along with hearing aid factors to determine if they can predict a person’s acceptable noise level. Results revealed that the Device Oriented Subjective Outcome subscale of listening effort and the digits in noise task were able to predict the acceptable noise level of a hearing

aid user. Future work should look at other patient factors to predict noise tolerance.

These three research studies aimed to determine what tests can provide a better assessment of listening needs in noise for persons with hearing loss. The second goal was to determine if individual factors were able to predict a person’s ability to tolerate background noise. The end goal of these studies is to use this information along with future research to determine which individuals would benefit from specific hearing aid settings and/or auditory training based on outcome measures and individual factors.

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Chapter 1: Introduction

Overview

An environment with background noise can be one of the most difficult listening environments for hearing aids users (Picou, 2020). Improving speech understanding in background noise is a complicated issue that the hearing healthcare profession has been attempting to solve for decades. Several features such as digital noise reduction and directional microphones have been added to augment speech listening in noise for hearing aids. Furthermore, additional hearing aid accessories, such as remote microphones, have been developed to improve upon speech listening in noise, specifically the signal-to-noise ratio, for hearing aids users. Listening in noise, however, remains a concern for hearing aid users with limited effective solutions or options. Presently, when a person with hearing loss visits an audiology clinic with noise-related listening concerns, the evidence-based tools available to personalize hearing aid settings for such a person's noise-related listening needs are limited.

This dissertation seeks to investigate the advantages and disadvantages of current evidence-based tools for improving speech understanding in noise for individuals with hearing loss. The goal is to investigate which tools and individual factors might best predict a hearing aid user's ability to understand speech in background noise, as well as which factors contribute to the hearing aid user's ability to tolerate background noise. The ultimate goal is to determine which tools are most effective at assessing a hearing aid user’s real-world experience and which individual factors can be changed to improve a hearing aid user's tolerance and listening experience in background noise.

Current Understanding of Background Noise and Hearing Aids

Most of the current knowledge about fitting hearing aids is based on evidence-based best practice guidelines. There are two guidelines available that discuss fitting hearing aids for adults, one from the American Academy of Audiology (AAA; Valente et al., 2006) and one from the American Speech Language Hearing Association (ASHA; Valente et al., 1998). These evidence-based practice guidelines describe hearing aid verification using electroacoustic and real-ear measures, aided measures such as speech recognition tests (unaided and aided in quiet and noise), and validation using subjective measures such as questionnaires.

The AAA (Valente et al., 2006) and ASHA (Valente et al., 1998) guidelines recommend methods for evaluating advanced hearing aid features such as noise reduction and directional microphones. The only document that briefly mentions verification of these advanced features is the AAA guideline (Valente et al., 2006). The AAA guideline (Valente et al., 2006) recommends electroacoustic measures or a listening check to verify advanced features such as directional microphones and noise reduction. Modern hearing aid analyzers include testing protocols that are specific to that analyzer and will check to see if these two features are functioning properly. These tests determine whether noise reduction and directional microphones are working properly and effective in reducing noise.

Additional guidance is provided for directional microphones by recommending that audiologists use real-ear measurements to verify the front-to-back ratio of the directional microphone (Valente et al., 2006). While these measures are important for quality control and troubleshooting whether the device is functioning properly, there are no standards for how much gain reduction is acceptable to provide optimal performance with the hearing aids. Additionally, current noise reduction and directional microphone testing protocols cannot predict how well these features will improve speech understanding in noise for hearing aid users.

The guidelines also recommend unaided and aided speech recognition testing, but AAA (Valente et al., 2006) warns about the limitations of in-clinic measures due to limited speech and noise stimuli, and that using a single loudspeaker is not the most accurate method for estimating real-world benefits (Valente et al., 1998, 2006). The estimate from this type of single loudspeaker measurement would not accurately represent a real-world environment such as a restaurant because in a typical listening situation, speech and noise rarely come from only one direction and only the same direction.

According to (Valente et al., 2000), a directional microphone in a two loudspeaker set-up (speech 0°/noise 180°) outperformed an omnidirectional microphone using Hearing in Noise Test (Nilsson et al., 1994; HINT) sentences by 3.2 to 3.7 dB. A 2.7-3.5 dB benefit for the directional microphone was reported when used in a diffuse environment (from 45°, 135°, 225°, and 315°). This suggests that a diffuse environment decreases the effectiveness of a directional microphone compared to the two loudspeaker condition, and the differences between environments were statistically significant ($p < 0.02$). Using HINT sentences, Compton-Conley et al. (2004) investigated which loudspeaker array best approximated a real-world environment in the lab in a group of participants with normal hearing. The researchers evaluated live restaurant noise and compared the results to a diffuse loudspeaker array (noise from eight surrounding loudspeakers) and two different two loudspeaker arrays (speech at 0° and noise at either 90° or 180°). The results showed that the diffuse array approximated the live restaurant recording better than the two loudspeaker arrays. The diffuse condition performed within 0.5 dB of the live restaurant condition. Participants performed about 1.1 to 2.4 dB better with two loudspeakers for a supercardioid directional microphone than in the live condition. Participants also performed 2 to 9.1 dB better than the live condition with the hypercardioid directional microphone. As a result, aided measures using one or two loudspeaker arrays should be interpreted with caution, as the benefit is likely overstated compared to how the patient performs in real world listening environments.

Taylor (2003) discusses clinical speech in noise tests that could be used in routine patient care. The benefits of speech in noise testing, according to Taylor (2003) include guidance in choosing a hearing aid, determining potential benefit from hearing aids, and patient counseling. Taylor (2003) offers some advice on how to use common speech in noise tests in the clinic. For example, fixed signal-to-noise ratio (SNR) tests are one type of speech in noise test that can be used to assess speech understanding in noise. The results of these tests are expressed as a percent correct score at a fixed SNR. This test has the advantage of being simple to interpret. However, there are some drawbacks, such as ceiling and floor effects and limited applicability because only one environment is studied. Taylor (2003) suggests some SNR levels based on commonly encountered background noise levels (55 dB SPL noise; speech at 61 dB SPL (+6 dB SNR); 65 dB SPL noise; speech at 68 dB SPL (+3 dB SNR); 75 dB SPL noise; speech at 74 dB SPL (-1 dB SNR)). It is recommended that unaided and aided conditions with a single loudspeaker be compared, but this contradicts AAA guidelines (Valente et al., 2006) due to poor correlation with real-world performance. The Connected Speech Test (Cox et al., 1987) and the Speech Perception in Noise (Bilger et al., 1984) test are two examples of fixed SNR tests that can be used clinically.

Adaptive SNR tests are another type of speech in noise test. These tests determine the SNR for a given correct percent score, such as the SNR at which 50% of sentences can be correctly repeated. This test is simple to administer and avoids ceiling effects, but it is more difficult to interpret because SNRs can vary greatly between patients. This test, on the other hand, avoids floor and ceiling effects. The HINT and the Quick Speech in Noise (Killion et al., 2004; QuickSIN) test are two examples of these adaptive SNR tests.

Taylor (2003) suggests testing at a lower intensity to demonstrate the benefit of aided and unaided microphones, as well as using more than one loudspeaker to demonstrate the advantage of directional microphones. However, one issue with these measures is that they frequently do not correlate with real-world performance. Surr et al. (2002) attempted to correlate microphone performance and preference using different signal-to-noise ratios. The findings revealed no correlation and found that a laboratory setting frequently overestimated how well a person thought they were performing. While these measures are used to determine benefit, there is less research on whether these measures are sensitive enough to determine whether adjustments improve performance and perceived benefit.

While there is limited literature on how to fine-tune noise reduction and directional microphones and assess the success of this fine-tuning in the clinic, measures used in research studies can be examined. Speech in noise tests are some of the most important measures of noise reduction and directional microphones. As previously stated, a single microphone source may not be the most accurate representation of real-world experience. Diffuse noise is a better way to approximate real-world performance (noise surrounding the listener). This may not be clinically feasible, but clinicians should keep in mind that results obtained with one or two loudspeakers are likely overestimated when compared to the real-world. Another important point to consider is that, while speech in noise testing can be effective for demonstrating improvements for directional microphones over omnidirectional microphones, it may not be sensitive to subtle differences within directional microphones. In addition, noise reduction has not been shown to improve speech recognition in noisy environments (Magnusson et al., 2013; Valente et al., 2000), but it has been shown to improve comfort in noisy environments. Due to these results, improvements in subjective measures of comfort and sound quality may be a more appropriate approach to consider.

The Acceptable Noise Level (ANL) test (Nabelek et al., 1991) is another suggested research methodology beyond speech recognition in noise tests to measure noise reduction and microphone modes. This test can be used to determine a person’s ability to tolerate noise. Recker et al. (2019) investigated whether the ANL test could be used to determine patient preferences for four noise reduction levels (off, 6, 10, and 20 dB), three microphone modes, (omnidirectional, high frequency directional, and broadband directional), and four combinations of noise reduction and microphone modes (6/high frequency, 10/broadband, 20/high frequency, and 20/broadband). The results showed that preferences for individual advanced feature settings could not be predicted using ANL. Regardless of ANL score, the majority of participants preferred the most aggressive noise reduction setting of 20 dB. Although the results of this study match those of Ricketts & Hornsby (2005), they suggest that the ANL may not be as sensitive to hearing aid changes. More research should be done to examine if the ANL is sensitive to different levels of noise reduction and directional microphones.

There are no specific subjective measures mentioned in the hearing aid fitting guidelines for evaluating advanced hearing aid features such as noise reduction and directional microphones (Valente et al., 1998, 2006). The following questionnaires are recommended for hearing aid validation by the guidelines: Abbreviated Profile of Hearing Aid Benefit (Cox & Alexander, 1995; APHAB), Client Oriented Scale of Improvement (Dillon et al., 1997; COSI), the Hearing Handicap Inventory for the Elderly (Ventry & Weinstein, 1982), and the Expected Consequences of Hearing Aid Ownership (Cox & Alexander, 2000; ECHO) questionnaire. While these questionnaires are used to help determine decreased handicap and benefit from hearing aids, they are not used to determine if a fine-tuning adjustment resolved the patient’s concern. More research is needed to determine how these questionnaires, in addition to self-report, could be used to evaluate a successful hearing aid adjustment. Because some questionnaires, such as the APHAB, are designed for specific situations, a more open questionnaire, such as the COSI, may be better suited to meet the specific listening situations of each hearing aid user.

Bentler (2005) conducted a systematic review of current knowledge on directional microphone preferences and noise reduction. Based on the findings of the systematic review, questionnaires such as the Profile of Hearing Aid Benefit (Cox et al., 1991) and the APHAB have been used to assess omnidirectional and directional settings. Bentler (2005) noted that some studies found that directional versus omnidirectional subjective benefits were superior, while others found that they were equivalent. The Satisfaction with Amplification in Daily Life inventory (Cox & Alexander, 1999) was also examined, and participants reported equal benefit for the omnidirectional and directional microphones, though some reported using directional microphones less frequently. This demonstrates that the questionnaires may not be sensitive enough to detect subtle differences in microphone settings or that hearing aid users do not notice the benefits of directional microphones in real world environments. The same was true for noise reduction, with Bentler (2005) finding that some studies reported a benefit with noise reduction and other subjective measures indicating an equal benefit with and without noise reduction.

Ricketts & Hornsby (2005) investigated whether patients with hearing loss preferred the sound quality of the Connected Speech Test passages with and without noise reduction. Paired ratings were obtained in conditions with noise reduction turned on or off, with a directional or omnidirectional microphone, and in low noise, favorable SNR (6 dB SNR) or high noise, poor SNR conditions (1 dB SNR). In all conditions, there was a significant preference for noise reduction on versus off. This suggests that, while noise reduction may not improve speech recognition in noise, it may improve comfort and sound quality, and paired comparisons may be a useful tool when fine-tuning noise reduction to determine whether or not outcomes have improved.

There is also little guidance on how to fit and adjust advanced features like noise reduction and directional microphones, which are especially important for speech in noise programs. This is a significant gap in evidence-based practice since this is a major concern for patients. As previously stated, while some guidance is provided on verifying whether advanced features in hearing aids are functioning properly, there is no guidance in these evidence-based guidelines on how to fit and adjust these features, and there is limited information on how to verify improved speech recognition in noise after adjustments are made. Anderson et al. (2018) developed a survey to assess how audiologists are currently making clinical decisions about selecting and fitting these features based on the limited information that is available.

The survey (Anderson et al., 2018) was completed by 248 audiologists and was divided into four sections: demographics, hearing aid and feature selection, how decisions are made to fit these features, and how decisions are made to fine-tune these features. When asked what factors audiologists considered during a hearing aid evaluation, the top factors, in order, are a patient's listening environments, specific signal processing features of the device, degree of hearing loss, and audiologist experience with the manufacturer. When asked what tools audiologists use to fit hearing aids, they said, in order of importance, that the audiologic evaluation, real-ear measures, questionnaires, loudness measures, and other aided and unaided speech testing are the most common. Audiologists were asked about various hearing aid features and how they fit advanced features. For noise reduction, 58% use manufacturer first fit, 38% use their own expertise, 3% use another approach, and 2% turn off noise reduction. For directional microphones, 67% use manufacturer first fit, 30% use their own expertise, and 3% use a different method. This suggests that most audiologists use the default setting and do not adjust these two advanced features individually.

When fine-tuning a device, most audiologists reported often using, in order of importance, self-report (98%), real-ear measures (50%), questionnaires (27%), speech in noise testing (25%), speech in quiet testing (24%), and functional gain (24%) to help them decide when fine-tuning is warranted. When making noise reduction adjustments, the following tools were used to determine how to make adjustments: 96% use the patient’s report of concerns, 91% use their own expertise, 55% use manufacturer software recommendations, 42% use information from articles, conferences, and colleagues, and 36% use manufacturer information. The following tools are used to aid in the adjustment of directional microphones: 87% use own expertise; 86% use patient’s report of concerns; 50% manufacturer's software recommendation; 40% information from articles, conferences, and colleagues; and 35% manufacturer information. According to the findings of the Anderson et al. (2018) study, when evidence-based guidelines are unavailable, audiologists rely on manufacturer default settings and their own expertise to fit and fine-tune hearing aids. This, once again, aids in determining the sources being used, but no research has been conducted to determine how effective this evidence is in determining outcomes.

Jenstad et al. (2000) evaluated common patient concerns and asked audiologists how they would handle them. While the audiologists were in agreement, the adjustments were limited to gain, maximum power output, or compression features rather than advanced hearing aid features. There is also no data to show whether these changes solve the hearing aid user's problem. Future research should assess how effectively each of these tools resolves speech recognition in noise complaints, as well as whether these tools are sufficient in improving patient satisfaction with hearing aids in background noise (or as best as it can be with limitations of the hearing loss).

Other Potential Advanced Feature Measures

Datalogging is a tool that could be used to classify the environments in which hearing aid users spend most of their time. This could be especially useful for troubleshooting and fine-tuning because if the patient has only one hearing aid on or has the hearing aids in the wrong program, counseling rather than fine-tuning may be necessary. Banerjee (2011), for example, studied datalogging in a group of participants with hearing loss and discovered that directional microphones were active less than 50% of the time. This suggests that participants may be in quiet environments the majority of the time and may need these features only in limited situations. This could be useful data to obtain from datalogging because if the situation does not activate the directional microphone, a special speech in noise program that is manually accessed may be required.

Another tool that shows clinical promise involves measuring the hemodynamic response to neural activity in the brain via functional near infrared spectroscopy (fNIRS). Listening effort is one area of interest. Some preliminary studies on listening effort with fNIRS (Lawrence et al., 2018; Rowland et al., 2018; Wijayasiri et al., 2017) have reported that this tool is capable of showing activation in the area of the lateral inferior frontal gyrus especially when comparing difficult versus easy listening conditions. This technology is still in the process of being developed, and its potential benefits could become clearer as the technology advances and more is learned about it. This is also not a tool that can be used in clinical settings, but it could be used in research to decipher what adjustments enhance speech understanding in noise performance.

Spectral-ripple modulation detection thresholds (SMD) is another tool that can be used to assess a person's speech understanding in noisy environments. This test can measure the spectral processing of the cochlea’s auditory filters. SMD thresholds have been linked to speech recognition abilities in some studies (Anderson et al., 2012; Davies-Venn et al., 2015). Using this test, one could determine who, based on their SMD thresholds, might benefit from receiving additional assistance with their hearing loss, such as assistive technology.

Another potential tool is ecological momentary assessment (EMA). Due to concerns about remembering what a patient experienced during a two-week acclimatization period and questionnaire limitations in certain situations, a tool such as ecological momentary assessment could be used to alleviate these issues. EMA polls patients throughout the day to see how they are doing at various points in time, which helps reduce errors caused by memory. Initial research (Jenstad et al., 2019; Timmer et al., 2018; Wu et al., 2015) indicates that this can be a useful and valid tool for determining hearing aid benefit. This tool could help with recreating the environment in the clinic for fine-tuning the hearing aids by more accurately capturing the environments in which the hearing aid user is having difficulty. This is a viable tool because many patients will have smartphones to which they can download an app. One disadvantage could be that patients do not respond to surveys as they appear on their phone.

Finally, in addition to all these assessments, it would be useful to know if individual factors such as personality and cognitive factors such as working memory can influence a person's tolerance to noise. Some preliminary research suggests that personality traits like conscientiousness, openness, and negative reactivity (Franklin et al., 2013; Huber & Johnson, 2021) and cognitive factors like working memory (Brännström et al., 2012) may influence a person's ability to tolerate noise. If these individual factors can be identified, they may be modifiable to improve noise tolerance.

Research Questions

The following studies evaluated various tools and individual factors that could be used to examine hearing aid outcomes or factors that could influence noise tolerance. In study 1, fNIRS is investigated to determine if it is a viable tool for assessing the impact of different listening conditions, speech materials, and hearing aid settings on listening effort. The goal is to determine if these different settings can be measured with fNIRS and, if so, if fNIRS can be used to determine the benefit of different hearing aid features.

SMD thresholds are examined in study 2 in a group with normal hearing and a group with hearing loss to determine the effect of bandwidth and intensity on SMD thresholds. This data could be used to determine what influences broader auditory filters and what types of technology could help those with poorer SMD thresholds.

Finally, in study 3, individual factors that may influence noise tolerance are assessed, such as personality, device performance, speech understanding in noise abilities, and working memory. The purpose of this study was to determine if any of these factors have an effect on a person's ability to tolerate noise. The ultimate goal of this study is to determine if those factors can be changed to improve a person's ability to tolerate noise or to determine which groups of people would benefit from specific hearing aid settings and technology.

Overall, these studies together seek to find meaningful outcome measures that can be used to predict and evaluate hearing aid outcomes in background noise. The goal is to find outcome measures that more accurately reflect a patient’s real-world experience with hearing aids and individual patient factors that can be potentially modified to improve hearing aid outcomes. In addition, this information can be used to lay the groundwork for improved fine-tuning adjustments based on individual patient traits.

Chapter 2: Exploring functional near-infrared spectroscopy as a hearing aid outcome measure

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Introduction

Outcome measures are critical in identifying and quantifying the benefit received from hearing aids. Traditional hearing aid outcome measures include behavioral measures of word or sentence recognition in quiet and/or noise and a subjective questionnaire about performance. Hearing aid outcomes for speech in noise, however, often present a disconnect between the hearing aid user's perceived performance compared to behavioral outcomes. Studies often report benefit with different hearing aid features for objective speech in noise tests, but this benefit is often not found on subjective measures or vice versa (Walden et al., 2000; Wu et al., 2019). Laboratory measures are not always representative of a hearing aid user's real-world experience (Walden et al., 2000; Wu et al., 2019). Also, these different outcome measures may be examining different aspects of hearing and may not be comparable (Lawrence et al., 2018; Walden et al., 2000; Wu et al., 2019).

One aspect of a listener's experience that can impact their benefit with a hearing aid is listening effort. Listening effort involves higher cognitive processes and tests such as sentence recognition and subjective preferences may not be sensitive to listening effort differences (Ohlenforst et al., 2017; Rovetti et al., 2019). Often difficult to define and measure, listening effort is a critical dimension of the hearing experience. Listening effort is defined as “the mental exertion required to attend to, and understand, an auditory message” (McGarrigle et al., 2014). It is impacted by talker factors (i.e., accented speech [Van Engen & Peelle, 2014]), environmental factors (i.e., noise [Picou et al., 2013]), and receiver factors (i.e., hearing loss [Krueger et al., 2017] and cognitive load [Peelle, 2018]). This complex web of factors contributes to the challenge of isolating and effectively measuring listening effort (Alhanbali et al., 2019; McGarrigle et al., 2014; Pichora-Fuller et al., 2016).

The relationship between listening effort and increased listening difficulty is also not linear. Fatigue and motivation are intrinsically related per the FUEL model of listening effort (Pichora-Fuller et al., 2016). As listening difficulty increases, listening effort decreases due to fatigue and motivation (Lawrence et al., 2018; Winn et al., 2018; Wu et al., 2016). This is especially true if there is no reward to motivate a listener to overcome the fatigue, such as listening to an important person in their life versus a stranger with no connection to them. One important factor in listening effort is hearing loss. Loss of audibility and natural cues can cause stress, fatigue, and a decreased ability to multi-task (Hornsby, 2013; Kramer et al., 2006; Nachtegaal et al., 2009; Sarampalis et al., 2009).

Identification of hearing aid programs that reduce listening effort would have important implications for hearing aid users.

Ohlenforst et al. (2017) conducted a systematic review examining the impact of hearing loss and hearing aid use on listening effort for subjective, behavioral, and physiological measures. Subjective measures included questionnaires and self-report measures, behavioral measures included response time and dual task paradigms, and physiological measures included functional magnetic resonance imaging (fMRI), electroencephalography (EEG), and pupillometry. Results revealed adults with hearing loss expend more effort than adults with normal hearing when evaluated using physiological outcome measures, specifically EEG. Results on subjective and behavioral measures, as well as pupillometry, revealed no significant differences or not enough/weak data to answer this question. Results examining hearing aids and listening effort revealed no significant differences between aided and unaided listening for subjective and behavioral measures. Only one physiological study indicated decreased listening effort when using hearing aids. Results are inconclusive about reduction of listening effort for aided versus unaided due to lack of research and high variation in methodology. Overall, Ohlenforst et al. (2017) noted a lack of standardization across studies and that more research with similar methodology and clarification of what listening effort mechanisms are being studied is needed.

Physiological measures may be more sensitive than behavioral measures for quantifying listening effort (Ohlenforst et al., 2017) and could be essential in evaluating if hearing aids reduce listening effort. One promising physiological measure is functional near-infrared spectroscopy (fNIRS). fNIRS is relatively new in auditory research and uses infrared light to measure the hemodynamic response of cortical regions of interest (ROI; Zhang & Ihlefeld, 2019). As a cap-based optical technique, fNIRS has many advantages over other physiological measures. These advantages include similar or slightly finer temporal resolution than fMRI (Pinti et al., 2020; Rovetti et al., 2019; Scarapicchia et al., 2017), improved movement resistance over EEG, quieter operation and lower equipment cost than magnetoencephalography or fMRI, and elimination of electromagnetic interference with hearing aids and cochlear implants unlike other electromagnetic techniques (Ohlenforst et al., 2017; Pinti et al., 2020; Rovetti et al., 2019; Rowland et al., 2018; Zhang et al., 2018). There are, however, some disadvantages to fNIRS, including poor spatial resolution relative to fMRI (better than EEG), poor coupling of the optodes to the scalp for thick hair, poor penetration of the infrared light for dark colored hair (Khan et al., 2012), and discomfort of the optodes, which limits testing duration.

A few studies evaluated listening effort with fNIRS. Wijayasiri et al. (2017) focused on the left inferior frontal gyrus (LIFG), an area thought to differentiate levels of listening effort by responding significantly more for degraded, but intelligible speech compared to clear speech. Studies examining listening effort as well as syntactic complexity have noted that the LIFG plays a role in both of these processes, in addition to the bilateral superior temporal gyrus and middle temporal gyrus (Lee et al., 2016; Rovetti et al., 2019; White & Langdon, 2021). In adults with self-reported normal hearing, results demonstrated activation of the LIFG for degraded speech, but not for clear speech. Lawrence et al. (2018) examined fNIRS on normal hearing adults to determine which areas of the brain are important for speech intelligibility. The hemodynamic responses of the superior temporal cortex, inferior frontal cortex, and inferior parietal cortex were recorded. Results demonstrated increased activation of the LIFG as sentence intelligibility decreased, except for the 0% intelligibility condition. Lawrence et al. (2018) note this decrease may be due to participants giving up due to task difficulty. Activation was also noted in the right and left auditory cortex. The left auditory cortex did not have increased activation on correct trials, leading Lawrence et al. (2018) to hypothesize that the left auditory cortex may be more sensitive to acoustic changes rather than intelligibility of the signal. Similar results were reported by Lee et al. (2016) in adults with normal hearing with fMRI data. Intelligible speech shows greater activation in the bilateral temporal cortex and LIFG than unintelligible speech. When evaluating syntactically complex (object- versus subject-relative center embedded clauses) sentences, results revealed involvement of the LIFG.

Studying the brain's response to hearing aid processing can be seen as an extension of studying the brain's response to degraded speech. Hearing loss and subsequent amplification alters several dimensions of acoustic signals. A goal of hearing aid fittings is to individualize and balance the benefits and drawbacks of various programs. fNIRS could be used to determine which settings are most beneficial for certain hearing and individual profiles (Rovetti et al., 2019; Wijayasiri et al., 2017). Rovetti et al. (2019) studied unaided versus aided listening to determine if fNIRS can measure listening effort. Adult hearing aid users completed a n-back task unaided and aided. There was a significant main effect of n-back on overall prefrontal cortex oxygenation, with oxygenation increasing as n-back condition increased up to two n-back. There were no significant hemodynamic contrasts between unaided and aided listening. The largest effect size was noted in the LIFG. The LIFG also had a significant correlation with hearing aid benefit and age and pure-tone average. As age increased and pure-tone average increased, more benefit was noted on the task for the aided condition.

Rovetti et al. (2019) noted that aided hearing may improve audibility and listening effort, however, the signal processing may add distortion which negates any benefit. A study limitation may have been the n-back task, which differs from real-world auditory comprehension. It is important to note that aided benefit may not have been as prominent due to testing in quiet. There are still unanswered questions, therefore, about whether different hearing aid signal processing schemes would impact listening effort.

This study sought to extend on Wijayasiri et al. (2017) and Rovetti et al. (2019) by investigating hearing aid processing as a source and mitigator of speech degradation. There is little physiological evidence examining whether listening effort is reduced with different hearing aid features. Comparisons were designed to probe two hearing aid microphone patterns (omnidirectional and directional), two levels of syntactic complexity (subject- versus object-embedded clauses), and two levels of vocoding (24-channel versus 12-channel). We anticipated replication of the vocoding results reported by Wijayasiri et al. (2017) and Lee et al. (2016), as well as outcomes showing that more difficult listening conditions (challenging syntactic structure and/or less advantageous microphone pattern) would trigger markers of listening effort in the LIFG (Lee et al., 2016). We also anticipated that benefit (decreased listening effort) would be noted for the directional microphone, even with normal hearing, based on previous research studies that noted benefit with a directional microphone for those with normal hearing (Hawkins & Yacullo, 1984; Mirkovic et al., 2019).

The purpose of this study was to determine:

1) Is there a significant difference in the hemodynamic response between two microphone patterns for degraded speech recognition in noise?
2) Is there a significant difference in the hemodynamic response between two levels of syntactic complexity for degraded speech recognition in noise?

3) Is there a significant difference in the hemodynamic response between two levels of noise vocoding resolution for degraded speech recognition in noise?

Methods

Participants

Twenty-five adults (16 female and 9 male) with a mean age of 28.0 years (SD = 9.5 years) were recruited using methods approved by the University of Minnesota’s Institutional Review Board. Inclusion criteria included normal hearing (<20 dB HL 250 – 8000 Hz) and being a native English speaker (verified via questionnaire). One participant did not qualify due to hearing loss. Three participants were excluded due to poor calibration of the optodes. Poor calibration was caused by either having dark colored hair, which absorbs the infrared light, and/or thick hair, which reduces contact of the optodes with the scalp (Khan et al., 2012). Three additional participants’ data were removed due to equipment malfunction. This left 18 participants with fNIRS data.

Hearing Aids

Bilateral receiver-in-the-canal hearing aids were pre-programmed with two standard programs. In both programs, a flat gain of 8 dB was set for inputs of 50 and 80 dB SPL (only two input levels available in the research software). Digital feedback suppression, noise reduction, and the volume control were disabled. Program 1 contained an omnidirectional microphone configuration. Program 2 contained a static bilateral directional microphone configuration. The hearing aids were fit using an appropriately sized closed double dome. A closed dome was used to allow for participant judgements to be based mainly on amplified versus residual sound.

fNIRS Equipment

A NIRx Scout fNIRS system (NIRx Medical Technologies, LLC, USA) was used with 15 sources and 16 detectors (total of 46 measurement channels; see Figure 2.1). The fNIRS sampling rate was 4.16 Hz with wavelengths at 760 nm (for deoxygenated) and 850 nm (for oxygenated). The equipment was calibrated prior to testing using the NIRStar (NIRx Medical Technologies) automatic calibration procedure. If any optodes were not within the acceptable range, the contact between optode and scalp was re-evaluated and manipulated until at minimum an acceptable quality rating was achieved. The NIRStar software was also used to collect the fNIRS data.

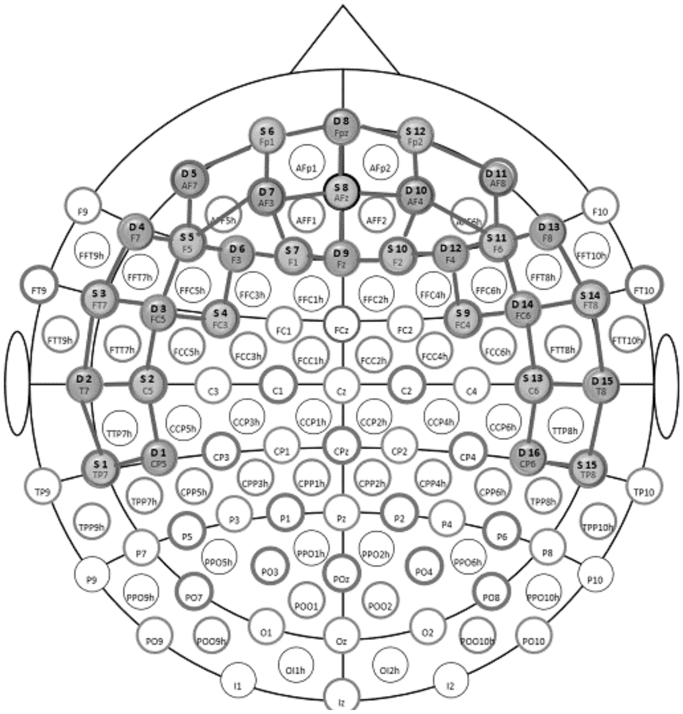


Figure 2.1. Configuration of the sources and detectors (gray circles). Note: S = source and D = detector.

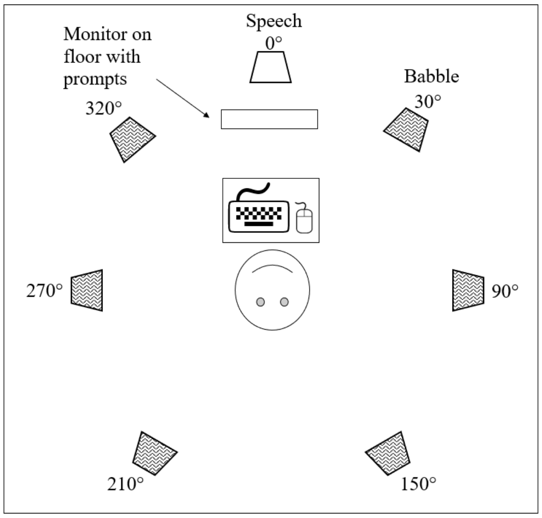
Speech Recognition Task

The speech recognition task used adapted sentence materials from Dr. Jonathan Peelle (2016; Open Science Framework: https://osf.io/szt2g/). The sentences consist of six words and are either object- or subject-relative center embedded clauses spoken by a female talker. The sentence materials consisted of 284 sentences, with 142 sentences being object-relative and 142 being subject-relative embedded clauses. The action in the sentences was performed half of the time by a male subject and half of the time by a female subject. An example of an object-relative center embedded clause is: Kings that queens praise are nice. An example of a subject-relative center embedded clause is: Kings that praise queens are nice. The sentences were noise-vocoded using Praat (Boersma & Weenink, 2021) to create two different frequency resolutions: a 24-channel and 12-channel condition. The purpose of two frequency resolutions was to create a more intelligible condition (24-channel) versus a reduced intelligibility condition (12-channel) to increase listening effort. The speech recognition task was a sequential dual-task paradigm where participants first identified the gender of the subject performing the action in the sentence and then typed the sentence they heard.

Participants were seated in the center of a sound-treated booth (see Figure 2.2A). Participants were instructed, “You will be listening to sentences in background noise. Pay close attention to the sentence and try to remember it. Each sentence will have a male and a female person and you must decide if the male or female was performing the action in the sentence. For example, in, “Princes that princesses hug are gentle”, the princesses are hugging the princes, so the female is performing the action and you would click the female button. For, “Princes that hug princesses are gentle”, the princes are hugging the princesses, so the male is performing the action and you would click the male button. After determining who performed the action you will type the sentence you heard.” Instructions were provided in written form to reference later.

Participants completed a practice session without hearing aids using a half list (10 sentences) of the 24-channel vocoded sentences. Sentences were presented via a loudspeaker at 0° and 6-talker babble was presented at a +5 dB signal-to-noise ratio (speech at 65 dBA) via loudspeakers at 30°, 90°, 150°, 210°, 270°, and 320°. After listening to the sentence (about two seconds long) the participant chose the gender of the subject performing the action in the sentence (response about five seconds). Next, the participant typed the sentence they heard (response about 9 seconds). In total, each trial lasted about 17 seconds. A jittered delay was imposed between responses and the end of each trial and initiation of the next sentence, ensuring a minimum of 16 seconds between sentence onsets (see Figure 2.2B). A randomized 2x2x2 block design was used with two levels of vocoding resolution (24-channel and 12-channel), two microphone settings (omnidirectional and directional), and two types of syntactic complexity (object- versus subject-relative sentences). This block design used

A.



B.

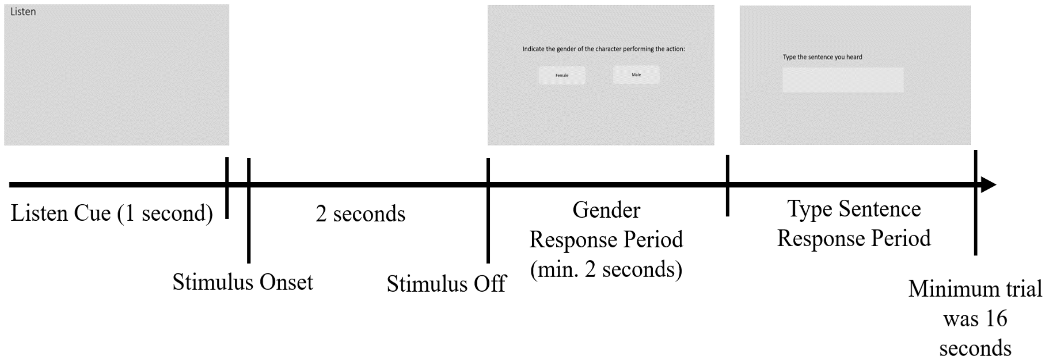


Figure 2.2. Room configuration (A) and time course (B) for the speech recognition task.

analysis modeled after each condition. Twenty sentences were presented per condition, half subject-relative and half object-relative. The first block of 24-channel and 12-channel sentences was randomized to be either omnidirectional or directional and the program was switched for the second half of testing. Testing lasted about one hour and participants were provided with breaks in between each session, if needed.

Data Analysis Tools

Data processing and data analysis (Abdelnour et al., 2009, 2010; Abdelnour & Huppert, 2011) were carried out in MATLAB using NIRS Toolbox (Santosa et al., 2018; https://github.com/huppertt/nirs-toolbox). ROIs were determined using AtlasViewer (Aasted et al., 2015) and consultation with NIRx. Fiducial markers were used to anchor the cap to 10-20 positions. These methods resulted in the LIFG being represented by channels 7, 9, 11, and 12 and the left auditory cortex with channels 1, 2, and 3 (see Table 2.1 for optode and channel coordinates). There was an inter-optode distance of 30-40 mm. ROIs were selected a-priori. Then the raw data were converted to optical density (nirs.modules.OpticalDensity) and hemoglobin concentration was determined using the modified Beer-Lambert law (nirs.modules.BeerLambertLaw). Next, first-level general linear modeling was completed using nirs.modules.AR_IRLS. Then group level analysis was completed using a general linear mixed effects model (nirs.modules.MixedEffects; j = nirs.modules.MixedEffects(); j.formula = 'beta ~ -1 + cond + (1|subject)').

Contrast statistics were used to determine differences between conditions in the ROIs using the tapered contrast vector method (see Zhai et al., 2020). T-tests were analyzed for significance and multiple comparisons were controlled for in NIRS Toolbox using the Benjamini-Hochberg procedure (q value) by adjusting the false discovery rate.

Table 2.1. Source, detector, and channel brain MNI coordinates.

	MNI Coordinates		
	X	**Y**	**Z**
Source (S)			
1	-84.057	-46.448	-12.942
2	-84.098	-13.846	24.756
3	-79.225	13.769	-18.190
4	-63.100	23.879	52.682
5	-64.987	49.590	10.244
Detector (D)			
1	-82.542	-47.309	27.800
2	-84.830	-16.239	-16.314
3	-77.435	19.001	18.879
4	-70.550	42.879	-19.263
Channel			
1 (S1; D1)	-83.896	-46.505	6.45
2 (S1; D2)	-87.447	-30.648	-14.486
3 (S2; D1)	-85.028	-29.926	25.727
7 (S3; D3)	-78.803	16.889	0.924
9 (S4; D3)	-71.835	22.115	37.64
11 (S5; D3)	-72.412	34.597	14.859
12 (S5; D4)	-68.363	46.595	-4.375

Results

Behavioral

Percentage of correct keywords by main effect is reported in Figure 2.3 and percentage of correctly identified subject gender is reported in Figure 2.4. Results indicate wide variation in speech recognition scores across participants. A repeated measures analysis of variance (ANOVA) on keyword recognition was

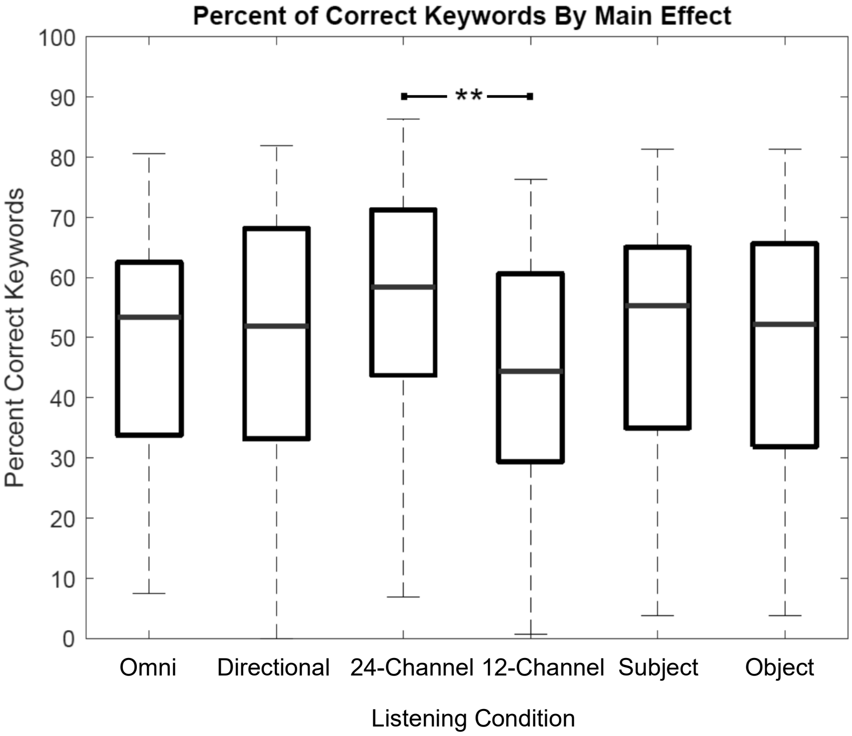


Figure 2.3. Box plots of percentage of keywords correct for the speech recognition task. Note: the bar is the median, the box is the 25th and 75th percentiles, and the whiskers show the range of data points that are not considered outliers; ** = $p < 0.01$

performed using the Statistical Package for Social Sciences (SPSS) program, version 26.0 (SPSS Inc., Chicago Illinois, USA) to examine main effects and interactions of microphone directionality, noise-vocoding, and syntactic complexity. Results indicate a significant main effect of noise-vocoding (F(1,17)=15.124; p=0.001) with 24-channels resulting in a 10.2% improvement in speech recognition compared to the 12-channel condition. Neither microphone

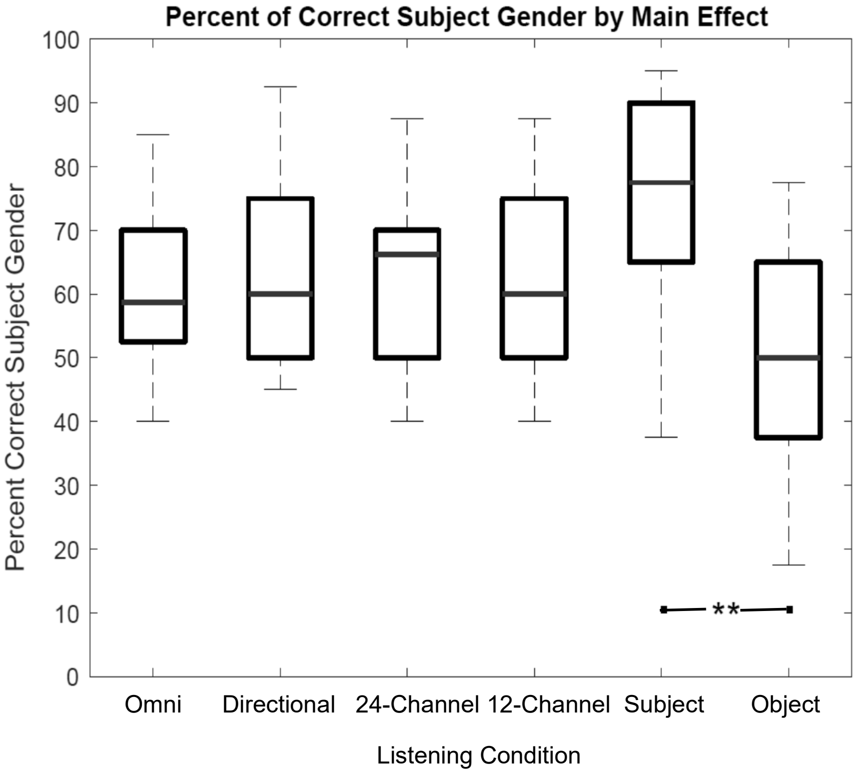


Figure 2.4. Box plots of percentage of correct subject gender identification for the main effects. Note: the bar is the median, the box is the 25th and 75th percentiles, and the whiskers show the range of data points that are not considered outliers; ** = $p < 0.01$

pattern (F(1,17)=0.030; p=0.865), syntactic complexity (F(1,17)=1.744; p=0.204), nor any interactions were significant.

A repeated measures ANOVA was performed on subject gender identification to examine main effects and interactions of microphone directionality, noise-vocoding, and syntactic complexity. Results indicate a significant main effect of syntactic complexity (F(1,17)=26.334; p<0.001) and a significant interaction between noise-vocoding and syntactic complexity (F(1,17)=7.635; p=0.013). A Bonferroni pairwise comparison revealed that object-relative center embedded clauses had poorer subject gender identification for 24-channel (p<0.001) and 12-channel (p=0.001) sentences compared to subject-relative center embedded clauses.

fNIRS

General linear mixed effects across the contrasts for ROIs are reported in Tables 2.2 (LIFG) and 2.3 (left auditory cortex). Note that for easier wording, the different conditions have been provided with the following labels in the text and tables: Condition A = 24-Channel; Condition B = 12-Channel; Condition C = Omnidirectional; Condition D = Directional; Condition E = subject-relative; Condition F = object-relative. Results for LIFG revealed a significant hemodynamic response for syntactic complexity for hbo (q=0.04). No other main effects were significant. This result aligns with Lee et al. (2016) and Wijayasiri et al. (2017) who noted activation contrasts in the LIFG when speech is degraded and grammar is complex. Significant activation was reported between microphone pattern and syntactic complexity in the LIFG. A significant activation was found between Condition CBE – DBF (hbo q=0.03) and Condition CBF – Condition DBF (hbo q=0.01), within Condition C (Condition CBE - Condition CBF; hbo: q=0.05; hbr: q=0.04), and within Condition D (Condition DBE – Condition DBF; hbo: q=0.02). These data suggest as acoustic and syntactic challenge increase, hemodynamic changes in the LIFG follow a pattern consistent with increased listening effort.

No main effects contrasts were found in fNIRS data for the left auditory cortex ROI (Table 2.3). A significant activation was found for Condition CA – Condition CB (hbr q=0.0074). Previous reports (i.e., Lawrence et al., 2018) note that activation in the auditory cortex may reflect intelligibility and acoustics rather than listening effort. This conclusion is weakened as the main effect of noise-vocoding was not significant. The task may have been too difficult to illustrate intelligibility contrasts because behavioral performance was close to chance, despite significant differences between 24-channels and 12-channels.

Table 2.2. General linear mixed effects model for LIFG.

Contrast	**Hemoglobin**	**Beta**	**SE**	**df**	**t**	**p**	**q**	**Power**
Condition A-B	hbo	-5.29	20.37	136	-0.26	0.80	0.90	0.86
	hbr	-5.13	8.92	136	-0.58	0.57	0.84	0.77
Condition C-D	hbo	10.25	20.38	136	0.50	0.62	0.84	0.79
	hbr	1.66	8.90	136	0.19	0.85	0.90	0.89
Condition E-F	**hbo**	**57.30**	**20.07**	**136**	**2.86**	**0.00**	**0.04***	**0.88**
	hbr	4.17	8.55	136	0.49	0.63	0.84	0.79
Condition CBF-DBF	**hbo**	**36.04**	**10.15**	**136**	**3.55**	**0.00**	**0.01***	**0.97**
	hbr	1.25	4.40	136	0.28	0.78	0.95	0.85
Condition CBE-CBF	**hbo**	**-27.84**	**10.31**	**136**	**-2.70**	**0.01**	**0.05***	**0.85**
	hbr	**-13.17**	**4.53**	**136**	**-2.90**	**0.00**	**0.04***	**0.89**
Condition DBE-DBF	**hbo**	**34.96**	**10.01**	**136**	**3.49**	**0.00**	**0.02***	**0.97**
	hbr	4.71	4.29	136	1.10	0.27	0.51	0.69

	hbo	**29.47**	**10.15**	**136**	**2.90**	**0.00**	**0.03***	**0.89**
Condition CBE–DBF	hbr	4.25	4.43	136	0.96	0.34	0.95	0.71

Note: Condition A = 24-Channel; Condition B = 12-Channel; Condition C = Omnidirectional; Condition D = Directional; Condition E = subject-relative; Condition F = object-relative; * = statistical significance

Table 2.3 General linear mixed effects model for left auditory cortex.

Contrast	**Hemoglobin**	**Beta**	**SE**	**df**	**t**	**p**	**q**	**Power**
Condition A-B	hbo	-31.34	31.56	136	-0.99	0.32	0.48	0.38
	hbr	20.84	10.64	136	1.96	0.052	0.28	0.30
Condition C-D	hbo	36.21	31.55	136	1.15	0.25	0.47	0.36
	hbr	-5.88	10.64	136	-0.55	0.58	0.75	0.47
Condition E-F	hbo	35.28	31.11	136	1.13	0.26	0.47	0.36
	hbr	-0.10	10.23	136	-0.01	0.99	0.99	0.94
Condition CA-CB	hbo	-32.46	22.38	136	-1.45	0.15	0.34	0.33
	hbr	**27.29**	**7.53**	**136**	**3.62**	**0.0004**	**0.0074***	**0.87**

Note: Condition A = 24-Channel; Condition B = 12-Channel; Condition C = Omnidirectional; Condition D = Directional; Condition E = subject-relative; Condition F = object-relative; * = statistical significance

Discussion

Behavioral results revealed noise-vocoding degrades keyword recognition and syntactic complexity worsens gender identification. Blood oxygenation in the LIFG was primarily impacted by syntactic complexity, although interactions with microphone pattern and noise-vocoding were present. fNIRS results are similar to previous studies (Lawrence et al., 2018; Lee et al., 2016; Rovetti et al., 2019; Wijayasiri et al., 2017) that reported increased activation in the LIFG for degraded speech and grammatical complexity compared to clear speech and syntactically simple grammar. Similar results were reported for physiological measures, such as pupillometry. Ayasse and Wingfield (2018) examined listening effort with pupillometry for syntactically complex sentences. Results support that more effort was required for older adults, with and without hearing loss, compared to younger adults for syntactically complex sentences. This suggests that many factors influence listening effort.

While behavioral and fNIRS data suggest effects of listening effort, they were not fully aligned. Behavioral results for keyword recognition indicated a significant main effect of noise-vocoding, but microphone pattern and syntactic complexity were not significant. Behavioral results for subject gender identification indicated a significant main effect of syntactic complexity and a significant interaction between noise-vocoding and syntactic complexity. Similar to gender identification behavioral results, fNIRS data supported a significant effect of syntactic complexity. Similar to keyword recognition, fNIRS data supported that 12-channel noise-vocoding was necessary to see significant interactions between microphone patterns and syntactic complexity. Factors of acoustic degradation and syntactic complexity impact listening effort and microphone pattern may impact that effort, but the picture remains complex. Similarities and divergences between behavioral and fNIRS results support combining these data modalities. A limitation of our behavioral data is that we do not have data on self-reported listening effort. The addition of this information would provide the participant’s impressions of how they performed during each task.

A limitation is that our participants were young with normal hearing and may not have benefited from a directional microphone. Listening effort has mainly been examined in a few studies (Picou et al., 2017; Winneke et al., 2020) using different microphone patterns in participants with hearing loss. Results from these studies noted benefit with a directional microphone on behavioral (Picou et al., 2017; Winneke et al., 2020) and subjective and physiological measures (Winneke et al., 2020). While some studies have reported benefit with directional microphones in normal hearing participants (Hawkins & Yacullo, 1984; Mirkovic et al., 2019), this study did not. It is possible the task was too difficult for participants and due to low reward, motivation was low as evidenced by the behavioral data with no significant differences between the omnidirectional and directional settings. Also, not having time to acclimatize to the sound of amplification may have caused equal listening effort. In addition, years of education were not collected. It is possible that having a higher educational level could make it easier for someone to decipher the syntactically complex sentences versus someone with a different background. Anecdotally, all participants noted that the task was difficult.

Lawrence et al. (2018) note that noise-vocoding manipulation may not assess listening effort as much as intelligibility and acoustics. This distinction is informed by the comparative activation of the auditory cortex (Lawrence et al., 2018). While contrasts between 24-channel and 12-channel noise-vocoding resolution for the omnidirectional microphone were found in the auditory cortex, there was no significant main effect for noise-vocoding. These findings in LIFG are primarily reflective of listening effort, but additional study of these two regions and the distinctions they can support between audibility and effort is warranted.

Neither the behavioral nor the hemodynamic data support listening effort benefit of microphone patterns, although fNIRS data demonstrated an interaction of microphone pattern with other factors. This result is similar to Rovetti et al. (2019) where there was no significant main effects or interactions in listening effort for aided versus unaided listening for behavioral and fNIRS measures. fNIRS may be able to detect hearing device program effects in the LIFG, but these effects may interact heavily with other factors, including study design. For example, it is critical that the optode design is created using tools to determine ROIs and piloted to ensure that these areas are being measured. It is also critical to ensure there is enough time within and between trials to measure the hemodynamic response and allow it to return to baseline. This has implications for future research as the fNIRS time scale poses challenges to designing combined behavioral-physiological auditory tasks. Rovetti et al. (2019) used an n-back task and participants with hearing loss, while this study used a sequential dual-task paradigm and participants without hearing loss. Several factors of study design and subject cohort remain to be studied before strong conclusions can be made about the benefit of hearing device programs or the ability of fNIRS to detect that benefit.

Efficacy of fNIRS in auditory research depends on considerations specific to the tool. Optode coupling in dark and/or thick hair poses a unique challenge. Three participants were excluded because of poor optode/scalp coupling. fNIRS protocols must be designed with a short duration (no longer than one hour due to comfort) and ensure that the outcome measures being used measure the desired physiological response. Piloting is critical to creating sound protocols with fNIRS. Another consideration is fNIRS' inability to penetrate beyond superficial brain structures. Rowland et al. (2018) noted that structures possibly involved in listening effort such as the cingulo-opercular system are not accessible with fNIRS. A final consideration is the limited extent of fNIRS studies using similar methodologies and populations. With time, a larger body of literature will identify the proper questions and approaches for fNIRS, establishing an appropriate scientific niche for the tool.

An advantage of fNIRS is its resistance to movement artifact and portability, creating potential use in evaluating listening effort with amplification in real-world contexts. This approach would enable study of realistic multi-modal sensory load and conversational complexity, allowing researchers to understand how environment, speech materials, and amplification interact. Rowland et al. (2018) note there is likely a larger brain network being used versus a single region in more complex environments. Rowland et al. (2018) also note that different environmental and talker factors may change the neural pattern used to decode the situation. More research is needed to characterize how the brain responds to complex interactions of various factors in natural listening environments versus ideal laboratory conditions

Conclusions and Future Directions

fNIRS and behavioral methods resulted in a complex picture of listening effort when attending to speech in background noise. Behavioral data support the impact of signal degradation on intelligibility and that grammatically complex speech results in greater difficulty parsing content. fNIRS data support that this difficulty in parsing content could be considered listening effort due to contrasts in hemodynamic responses in the LIFG between grammatically simple and complex constructions. These data replicate previous work and support that behavioral and fNIRS techniques should be used together. While these results build on the previous literature, more research is needed to validate the use of fNIRS in auditory research to see what it’s capable of evaluating and what its limitations are. If fNIRS is valid in a lab setting, it could be used in the future to probe listening effort with hearing devices, especially in environments where speech and context are more realistic and complex. Future work should consider evaluating fNIRS in an older hearing loss group with contrasting degrees of hearing loss and speech complexity. Also, fNIRS holds promise for providing measures in realistic settings that can be compared to laboratory measures. Finally, as Ohlenforst et al. (2017) concluded, standardization of methods and increased reliance on physiological measures is needed in listening effort research.

Chapter 3: Effects of carrier bandwidth and intensity on spectral ripple perception in listeners with and without hearing loss

Introduction

Spectral Processing

Spectral processing is critical in audition. It takes a complex signal, such as speech, determines the individual frequency components of the signal, and integrates this information into an auditory percept. Auditory filters are naturally sharpened for better frequency resolution by the outer hair cells. Research has provided us with some basic knowledge on spectral processing. Green & Mason (1985) reported that the auditory system is most sensitive to frequencies within the 500-2000 Hz range. Spectral processing is better with two ears than with one in noting changes to spectral stimuli (Green & Kidd, 1983). When the outer hair cells become damaged, the auditory filters become broader, adding distortion to the incoming signal and decreasing spectral resolution of the signal (Liberman & Dodds, 1984). In addition, Wier et al. (1977) reported spectral processing is most sensitive at low versus high frequencies and intensity or sensation level impacts lower frequencies more than higher frequencies.

When examining speech recognition in noise, studies (Dorman et al., 1998; Dorman & Loizou, 1998; Friesen et al., 2001; Fu & Shannon, 1998) have reported that more channels or bands are needed for a cochlear implant user in order to achieve performance similar to someone with normal hearing. Since the auditory filters broaden, having broader tuning could impact speech recognition.

The following review will discuss what is known about the relationship between spectral processing and bandwidth and intensity in adults with normal hearing and hearing loss and what knowledge is still needed.

Spectral Processing and Bandwidth: Auditory Filter Bandwidths and SMD Thresholds

Spectral-ripple modulation detection (SMD) using spectral-rippled noise is a method that can be used to measure spectral processing of these auditory filters. SMD results are closely linked to factors such as the spectral bandwidth and test signal intensity. Houtgast (1977) determined that SMD thresholds estimated the bandwidth or sharpness of auditory filters. Summers & Leek (1994) evaluated SMD thresholds in listeners with normal hearing and hearing loss to determine differences in spectral resolution. SMD thresholds were examined using a bandwidth of 1000 and 4000 Hz and auditory filters were examined at 1000 and 3000 Hz. Ripple noise cycles per octave (cpo) were evaluated from 1 to 9 cpo. A three-alternative forced choice paradigm was used with two stimuli having a flat spectrum and one rippled. Participants indicated which stimulus was different and the notched-noise method was used to determine auditory filters at 1000 and 3000 Hz. Results revealed wider auditory filter bandwidths for the hearing loss group than the normal hearing group. In addition, for most hearing loss participants, there was a larger asymmetry in filter bandwidth than normal hearing, with a tendency to have shallower low-frequency skirts. Results for SMD thresholds revealed that the normal hearing group had thresholds about 4 dB lower (better) than the hearing loss group across all cpos. As cpo increased, SMD thresholds also increased for both groups. A trend was noted that if a listener had broader auditory filters, their SMD thresholds were higher (poorer), but if a listener with hearing loss had near normal auditory filters, their SMD thresholds were lower.

Bandwidth Effects on SMD Thresholds

Having a wider bandwidth could potentially improve SMD thresholds as listeners are provided with a larger window with which to detect the ripples. A few studies have examined if there is a relationship between spectral processing and bandwidth. The impact of bandwidth on SMD was examined by Eddins & Bero (2007) on young normal hearing listeners. Bandwidths of 1, 2, 3, and 6 octaves were examined along with ripple densities from 0.25 to 10.0 cpo. They reported that spectral modulation transfer functions were significantly different across bandwidth for the 1 octave condition. Eddins & Bero (2007) reported a small, but similar effect of bandwidth, especially when the octaves were centered on low frequencies. The results suggest a minimal impact of bandwidth on SMD. Saoji & Eddins (2007) examined unmasked SMD thresholds across 0.25 to 14 cpo and a masked modulation frequency at 1, 3, or 5 cpo in persons with normal hearing. Bandwidths of 1 and 6 octaves (one low and one high frequency octave bandwidth) were examined. Results revealed no significant differences in SMD thresholds for the 1 and 6 octave bandwidth conditions. These results seem to suggest that bandwidth has minimal effects on SMD thresholds when testing at a fixed signal intensity level and in listeners with normal hearing.

Supin et al. (1998) also explored the relationship between ripple-density and bandwidth in four adults with normal hearing. A three-interval two-alternative force-choice procedure was used with either the first and third stimulus having a phase reversal or just the second stimulus. The participant had to report if the first and third were different than the second stimulus or if the second stimulus was different than the first and third stimulus. Different filters and bandwidths were examined. SMD thresholds with the stimulus centered on 1000, 2000, and 4000 Hz were examined with a bandwidth of 0.5, 1, 2, and 4 octaves. Results revealed relatively little change in thresholds, although a trend was noted that as bandwidth increased, SMD thresholds decreased. SMD thresholds were higher at higher frequencies for 0.5 octave bandwidth and SMD thresholds became similar as bandwidth increased.

Spectral Processing and High Intensity

Several studies have reported that the tuning of auditory filters becomes broader as intensity increases (Møller, 1983). In addition, persons with hearing loss, due to the loss of outer hair cells, will have more broadly tuned auditory filters (Oxenham & Bacon, 2003). These previous findings suggest that narrowband and broadband frequency selectivity will be poorer as the intensity of the stimulus increases. Dreisbach et al. (2005) examined five intensities from 30 to 70-80 dB SPL in 10 dB SPL increments in persons with normal hearing and hearing loss (depending on thresholds). Results revealed improved (lower) spectral contrast thresholds as intensity increased for 2000 Hz for persons with hearing loss. This pattern was not noticed at 3000 and 4000 Hz and Dreisbach et al. (2005) speculate that this is due to poor audibility for the spectral-ripple noise in these higher frequencies. However, when audibility deficits are adequately controlled, individuals with hearing loss also require greater ripple density to discriminate between spectral ripples with close peak frequencies. Thus, suggesting that at high intensities, individuals with hearing loss may be more susceptible to the degrading effects of high-level signals on their spectral processing abilities. Thus, even though normal hearing listeners show a decrease in spectral processing at high intensities due to a more passively controlled cochlear amplifier they preserve their spectral processing abilities better than those with sensorineural hearing loss.

Spectral Processing and Speech Recognition

A few studies have also examined the relationship between spectral processing and speech perception in individuals with normal hearing and hearing loss. Davies-Venn et al. (2015) examined the relationship between SMD thresholds and speech recognition scores in persons with normal hearing and hearing loss. Unaided Northwestern University Test Number 6 (Tillman & Carhart, 1966; NU-6) words in quiet, amplified vowel-consonant-vowel (VCV) nonsense syllables in quiet, and the Quick Speech in Noise (QuickSIN) test were completed. SMD thresholds were completed using four ripple densities of 0.25, 0.5, 1.0, and 2.0 cpo. The presentation threshold for the spectral-ripple noise was 10 dB SL relative to the pure-tone average (PTA) for persons with hearing loss and 55 dB SPL for persons with normal hearing. Results revealed that the interaction between SMD and listener group was significant. It was reported that persons with normal hearing had lower SMD thresholds at 1.0 and 2.0 cpo compared to persons with hearing loss. SMD at 1.0 and 2.0 cpo were also significantly correlated with PTA. When a regression model was performed, results revealed that SMD explained 23% of the variance for unaided NU-6 words in quiet, 63% of the variance for amplified VCV in quiet, and 27% of the variance for the QuickSIN for 2.0 cpo. Their findings suggested that SMD was a good predictor of speech recognition in quiet, especially for individuals with hearing loss.

Henry et al. (2005) examined spectral resolution and speech recognition in quiet across persons with normal hearing, hearing loss, and persons who used cochlear implants. Speech recognition was assessed using VCV and spectral resolution using a SMD test. Persons with normal hearing had the best SMD thresholds followed by persons with hearing loss and lastly persons using cochlear implants. Optimal vowel recognition was reported for SMD with 4 cpo and 4.5 cpo for consonant recognition across the three groups. A weak linear correlation was reported for vowel and consonant recognition for persons with hearing loss and a moderate correlation for vowel and consonant recognition for persons with cochlear implants. A correlation was noted between PTA and speech recognition for the hearing loss group, but no correlation was noted between PTA and SMD.

Anderson et al. (2012) examined the relationship between SMD and speech perception in cochlear implant users. SMD thresholds for 0.25, 0.5, 2, and 3 cpo were examined. IEEE sentences (Rothauser, 1969) were examined for speech perception in quiet and in noise. A strong correlation was reported between 0.25 and 0.5 cpo and speech perception for sentences and vowel recognition in quiet. Borderline significance was achieved for vowel recognition in noise, but not for quiet for 0.25 and 0.5 cpo. A weak, but significant correlation was noted for sentence and vowel recognition in quiet for 2.0 and 3.0 cpo. Warren et al. (2013) also completed a study examining the impact of broadband speech and high intensities on speech intelligibility. Results from their study revealed that when white noise flanked the speech band signal, intelligibility did not decrease as drastically, particularly for moderate intensity signals.

It would be expected that as intensity increases, SMD thresholds would be poorer for persons with normal hearing and hearing loss due to broader auditory filters from high intensity, but in particular for persons with hearing loss due to already broader auditory filters from hearing loss. Hearing devices in addition increase the auditory input, causing the auditory filters to be broader as well. There is little research examining the relationship between SMD thresholds and intensity. Bandwidth may also be important in spectral resolution as having a wider bandwidth should allow more opportunities to detect the spectrally modulated signal. The primary purpose of this research study, therefore, was to determine:

1) the effect of input level across four bandwidths (1, 2, 3, and 4 octaves) on SMD thresholds;
2) the effect of input level across four intensity levels (60, 70, 80, and 90 dB SPL) on SMD thresholds;
3) and the differences in SMD thresholds between persons with hearing loss compared to persons with normal hearing.

Method

Participants

This study included 21 adult listeners with normal hearing (mean age 25.0 years; SD 10.8 years) and 10 adult listeners with mild to moderate hearing loss (mean age 70.1 years; SD 8.3 years). Pure-tone air (250-8000 Hz) and bone conduction thresholds (250-4000 Hz) were measured using a Madsen Astera audiometer (Natus, Schaumburg, IL) and circumaural headphones. Word recognition scores were also evaluated using word lists from the Northwestern University Test Number 6 (Tillman & Carhart, 1966; NU-6). All speech stimuli were presented at the participant's most comfortable listening level. Age differences were statistically significant in both groups ($t(29) = 11.6$, $p < 0.001$), but not in SMD thresholds for signal intensity ($F(1.9, 48.7) = 0.9$, $p = 0.9$) or bandwidth ($F(1.8, 45.7) = 0.2$, $p = 0.78$). All participants were compensated for their time on an hourly basis. The local institutional review board (IRB) approved the procedure, and participants signed informed consent forms prior to participating in this study.

Stimuli

The stimuli used in this experiment were similar to those used in Davies-Venn et al. (2015) and Litvak et al.'s (2007) SMD task. MATLAB software was used to generate all stimuli (The Mathworks, Natick, MA). The standard signal was Gaussian noise with a spectral contrast of 0 dB (peak-to-trough). The test signal was spectrally modulated broadband Gaussian noise with sinusoidal level variations (dB) on a log-frequency axis at a sampling rate of 48 kHz and a ripple density of 2.0 cpo. The AFC package was used to present the test stimuli to the participants (Ewert, 2013). The SMD threshold, defined as the peak-to-peak modulation depth, was determined by adaptively varying the rippled noise's spectral modulation depth. The total stimulus duration was 400 msec, which included raised-cosine onset and offset ramps of 20 msec. The rippled signal was presented at four different intensities (60, 70, 80, and 90 dB SPL) and four different octave wide steps spanning 350 - 5600 Hz. To discourage the use of local intensity cues, the stimuli were roved in intensity between intervals over a range of 2.5 dB (Green et al., 1987). To reduce potential spectral pitch cues, the starting phase of the modulation was randomized across presentations.

Procedures

Participants were tested using ER-3A insert earphones in a sound-isolating booth. They were instructed that they would hear three consecutive sounds, one of which would be different. The participant had to identify the interval that sounded different using a two-up, one-down tracking procedure, in a 3-alternative forced-choice task. The spectral modulation depth (dB) of the test signal was varied adaptively using a two-up, one-down tracking procedure. With this tracking procedure, the modulation depth of the test signal decreased after two consecutive correct responses and increased after an incorrect response.

The first three reversals were performed with a 2 dB step size, and the remaining trials were performed with a 0.5 dB step size. The smallest modulation depth at which each listener could detect the presence of a spectral modulated signal was noted as their SMD detection threshold. Thresholds were determined using the average of the last even number of reversals (excluding the first three reversals). The average thresholds were calculated using three runs for each of sixteen (four bandwidths x four intensities) test conditions. The order of bandwidth was randomized, as was intensity. The SMD thresholds were determined in two sessions, each lasting approximately two hours.

Results

A mixed-model repeated measures ANOVA was used to evaluate 1) the effect of high intensities on SMD thresholds; 2) the effect of carrier bandwidth on SMD thresholds; and 3) the effect of hearing loss on SMD threshold susceptibility. The Statistical Package for Social Sciences (SPSS) program, version 26.0 (SPSS Inc., Chicago Illinois, USA) was used for analysis. Hearing loss was the between-subject variable (normal versus hearing loss). The intensity

(60, 70, 80, and 90 dB SPL) and carrier bandwidth (1, 2, 3 or 4 octaves) were the within subject variables. Where appropriate, a Greenhouse-Geisser correction for lack of sphericity was applied, and the degrees of freedom were adjusted accordingly.

What Effect *Does High Intensity* Have on *SMD Thresholds?*

Figure 3.1 shows the mean scores and ±1 standard error for intensity across all bandwidths for the hearing loss (A) and normal hearing (B) groups. For the listeners with hearing loss, the main effect of intensity was significant [F (3, 21) = 8.46, $p < 0.001$, $\eta_p^2 = 0.55$]. After Bonferroni adjustments for multiple comparisons, post-hoc Bonferroni-adjusted pairwise comparisons revealed that SMD thresholds degraded systematically with increasing intensity and were statistically different between 70 dB SPL and 90 dB SPL ($p < 0.05$).

For the listeners with normal hearing, the intensity main effect was significant [F (3, 60) = 8.29, $p < 0.001$, $\eta_p^2 = 0.293$]. After Bonferroni adjustments for multiple comparisons, post-hoc Bonferroni-adjusted pairwise comparisons revealed that SMD thresholds degraded systematically with increasing intensity and were statistically different between 60 and 80 dB SPL ($p < 0.05$) and 60 and 90 dB SPL ($p < 0.01$).

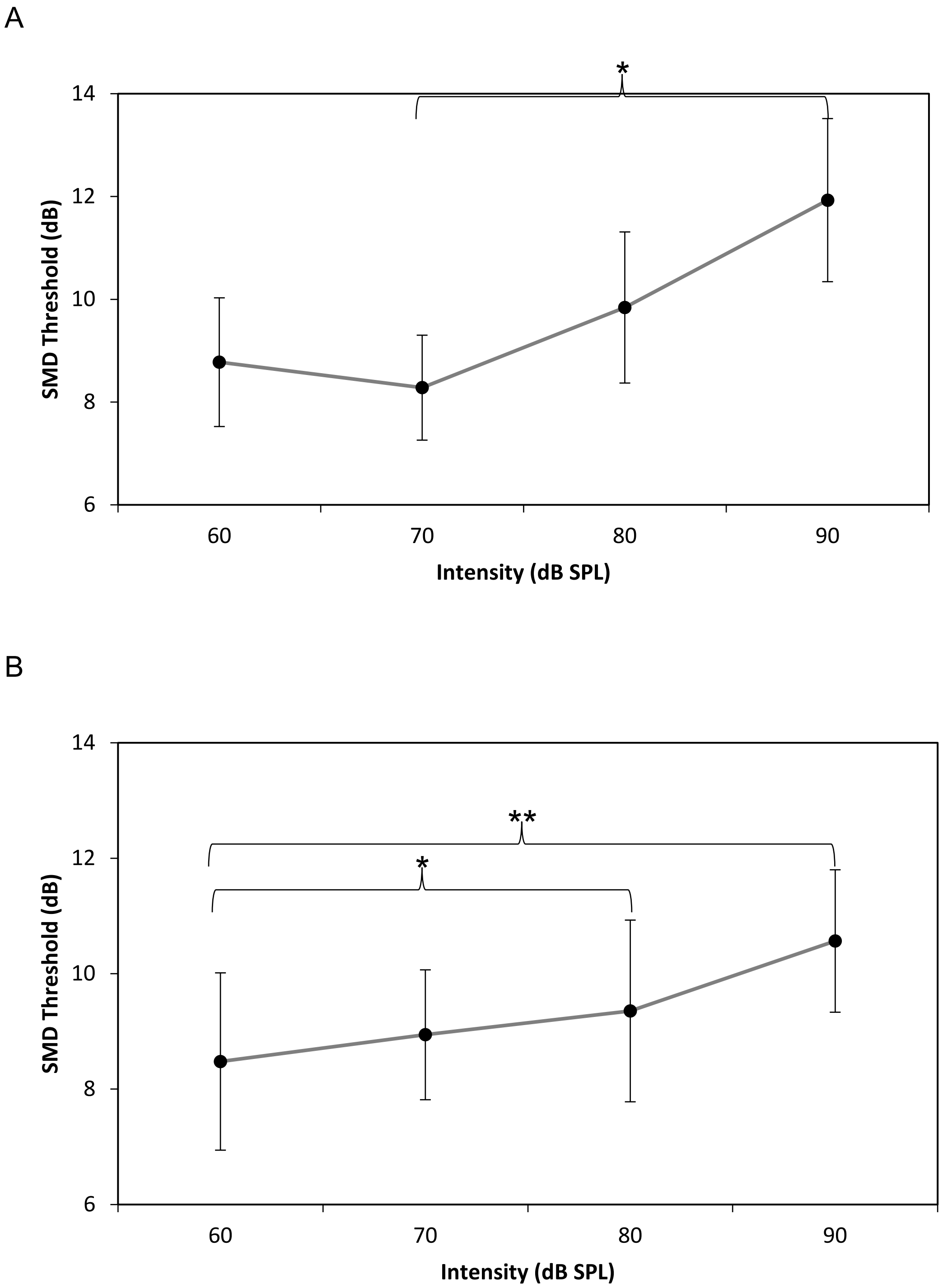

A
*
14
12
10
8
6
SMD Threshold (dB)
60
70
80
90
Intensity (dB SPL)
B
**
*
14
12
10
8
6
SMD Threshold (dB)
60
70
80
90
Intensity (dB SPL)

Figure 3.1. Mean and ±1 standard error of the mean for the four intensity levels averaged across bandwidth (1, 2, 3, and 4 octaves) for the hearing loss (A) and normal hearing (B) groups. Note: * = $p < 0.05$; ** = $p < 0.01$

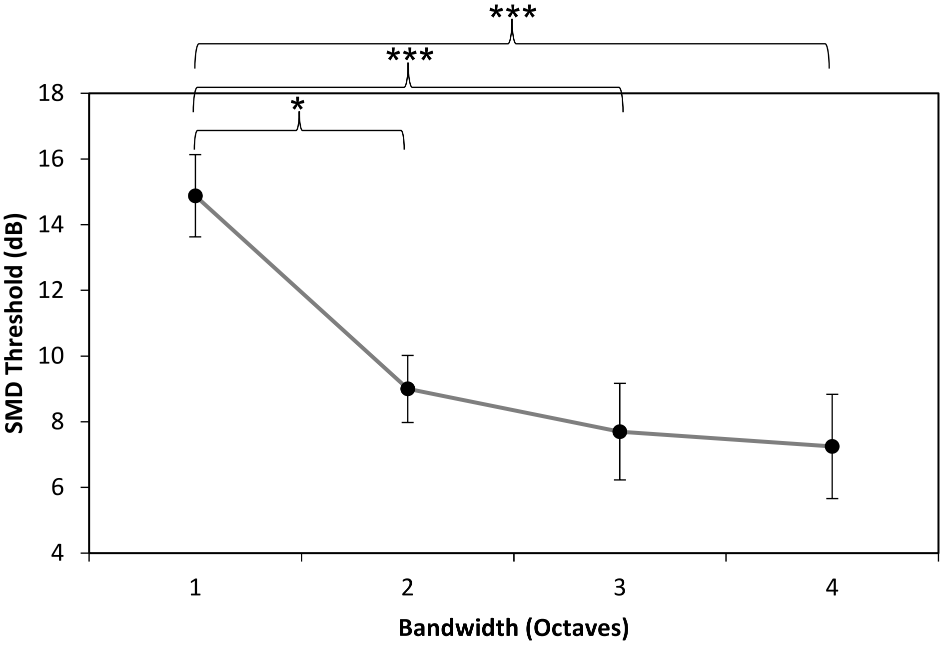
What Effect Does Carrier Bandwidth Have on SMD Thresholds?

Figure 3.2 shows the mean scores and ±1 standard error for the four different carrier bandwidths averaged across all intensities for the hearing loss (A) and normal hearing (B) groups.

For the listeners with hearing loss, the main effect of carrier bandwidth was significant. [F (3, 21) = 29.59, $p < 0.001$, $\eta_p^2 = 0.81$]. Post hoc Bonferroni-adjusted pairwise comparisons revealed that SMD thresholds with a 1 octave carrier bandwidth were significantly higher (i.e., worse) than thresholds with a 2 octave ($p < 0.05$), 3 octave ($p < 0.001$), and 4 octave ($p < 0.001$) carrier bandwidth. The interaction between carrier bandwidth and intensity was not significant [F (9, 63) = 0.77, $p = 0.52$, $\eta_p^2 = 0.1$].

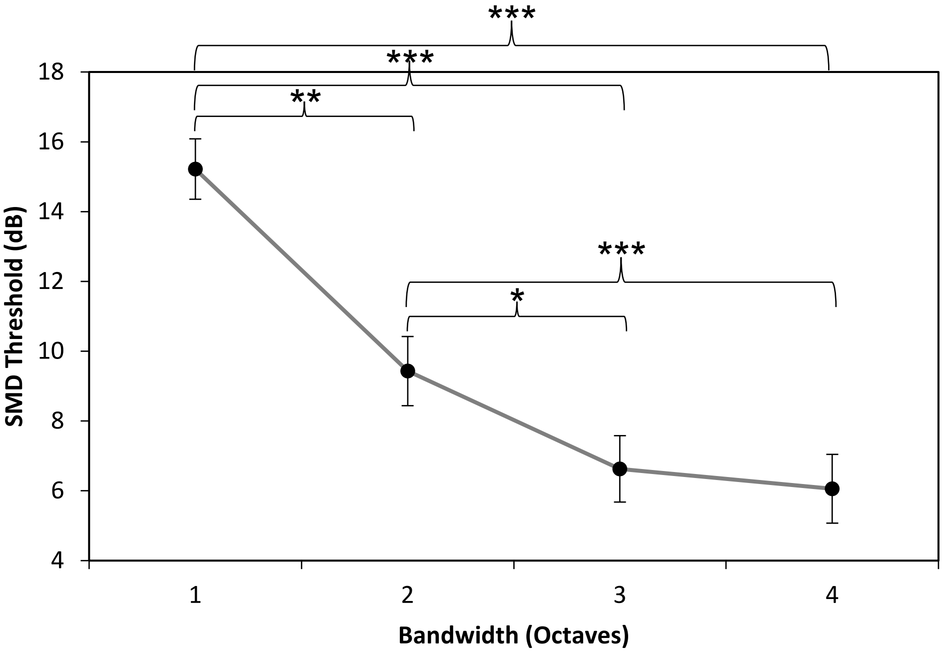
For the listeners with normal hearing, the main effect of carrier bandwidth was also statistically significant [F (3, 60) = 37.79, $p < 0.001$, $\eta_p^2 = 0.65$]. Post hoc Bonferroni-adjusted pairwise comparisons revealed that SMD thresholds with a 1 octave carrier bandwidth were significantly higher (i.e., worse) than thresholds with a 2 octave ($p < 0.01$), 3 octave ($p < 0.001$) and 4 octave ($p < 0.001$) carrier bandwidth. SMD thresholds for 2 octave bandwidths were also significantly higher than thresholds for 3 octaves ($p < 0.05$) and 4 octaves (p

A



***
***
*
18
16
14
12
10
8
6
4
SMD Threshold (dB)
1
2
3
4
Bandwidth (Octaves)

B



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*
18
16
14
12
10
8
6
4
SMD Threshold (dB)
1
2
3
4
Bandwidth (Octaves)

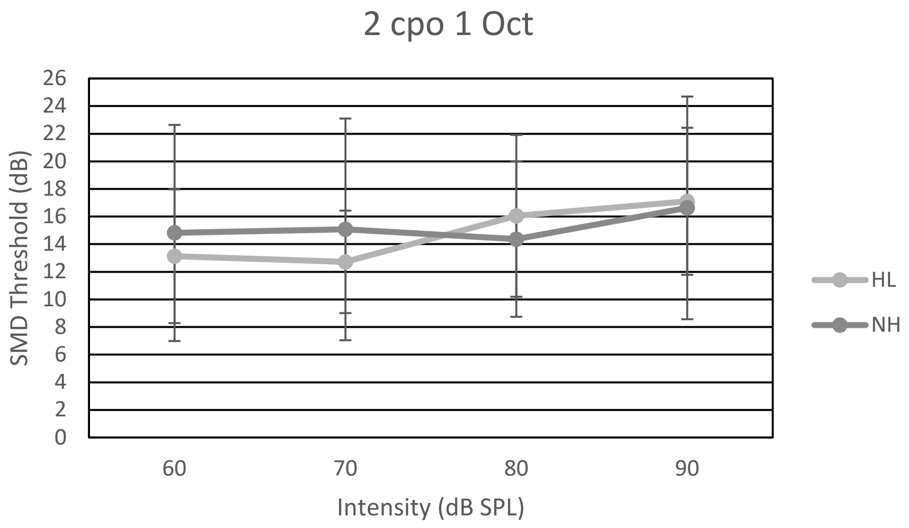
Figure 3.2. Mean and ±1 standard error of the mean for the four different carrier bandwidths. SMD thresholds for each carrier bandwidth were averaged across four intensity levels (50, 60, 70, 80 dB SPL) for the hearing loss (A) and normal hearing (B) groups. Note: * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$

< 0.001) bandwidths. The interaction between carrier bandwidth and intensity was not significant [F (9, 180) = 1.88, p = 0.11, $\eta_p^2 = 0.09$].

Are Individuals With Normal Hearing More Resistant to the Negative Effects of High Intensity Sounds and Bandwidth Changes?

Figure 3.3 shows mean SMD thresholds and ±1 standard error for people with normal hearing and hearing loss. SMD thresholds were slightly lower (i.e., better) in normal hearing listeners (mean = 9.6 dB, SE = 0.9 dB) than in listeners with hearing loss (mean = 9.7 dB, SE = 1.4 dB). A mixed-model repeated measures ANOVA was used to assess whether individuals with normal hearing were more resistant to the harmful effects of high intensities. This difference was not statistically significant [F (1, 28) = 0.006, p = 0.94, $\eta_p^2 < 0.001$].

We also compared thresholds with 1 octave-wide carrier bandwidths versus 2, 3 and 4 octave-wide carrier bandwidths. Normal hearing listeners were expected to have enhanced inhibitory mechanisms, allowing them to perform better with the wider bandwidth (i.e., 4 octave) signal at the highest intensity than the narrowest bandwidth signal (i.e., 1 octave). Our findings revealed that normal hearing listeners had better SMD thresholds for the highest intensity and widest


2 cpo 1 Oct
SMD Threshold (dB)
0
2
4
6
8
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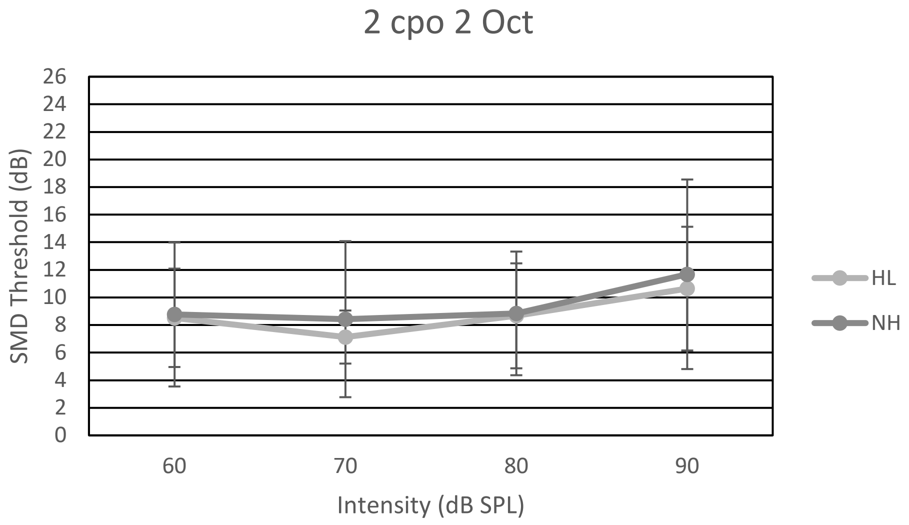
14
16
18
20
22
24
26
60
70
80
90
Intensity (dB SPL)
HL
NH


2 cpo 2 Oct
SMD Threshold (dB)
0
2
4
6
8
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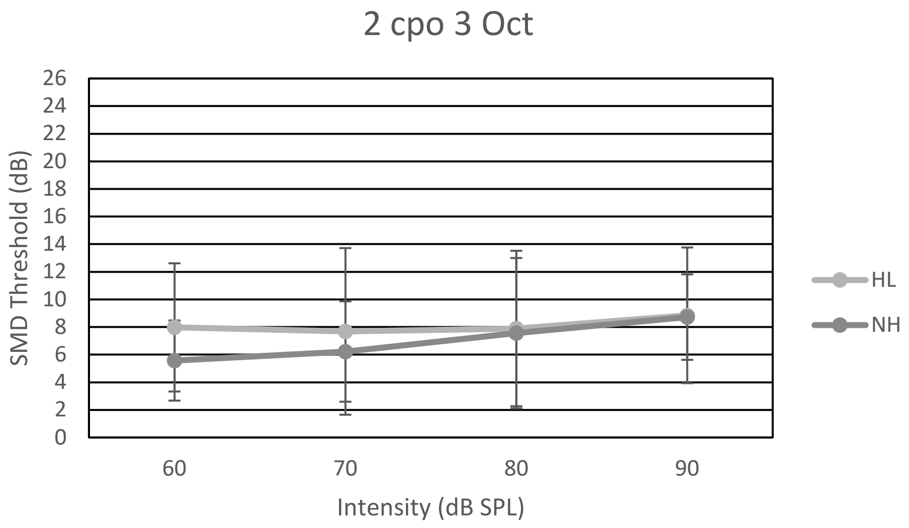
20
22
24
26
60
70
80
90
Intensity (dB SPL)
HL
NH



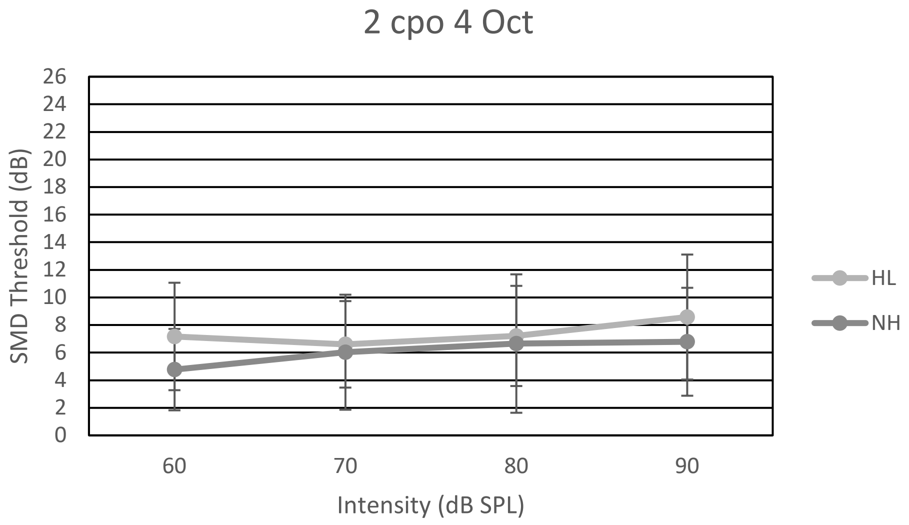


Figure 3.3. Mean and ±1 standard error of the mean for SMD thresholds for the four bandwidths and intensity levels for the hearing loss (HL) and normal hearing (NH) groups.

bandwidth signal, but this difference in SMD thresholds between normal hearing and listeners with hearing loss was not statistically significant (*p* = 0.21).

Discussion

This study measured SMD thresholds for narrow and wider bandwidth carriers in low, moderate, and high intensity rippled noise signals. The direct goal was to compare the effects of high intensity levels on broadband spectral processing in people with normal hearing to those listeners with hearing loss. Our findings revealed that input level and signal carrier bandwidth had a significant main effect within each group, but not across groups. SMD thresholds were highest for high intensity narrowband signals and lowest for moderate intensity broadband signals. These findings suggest that, as expected, individuals with hearing loss had poorer broadband spectral processing than those with normal hearing. These results are comparable to those reported by Eddins and Bero (2007), who also reported better SMD thresholds for bandwidths ranging from 2 to 4 octaves. This study's findings also revealed improved SMD thresholds with wider bandwidths.

Second, as signal intensity increased, all listeners' spectral processing abilities deteriorated. These findings are consistent with previous research on spectral processing (Dreisbach et al., 2005; Møller, 1983). Finally, people with hearing loss were slightly more vulnerable to the harmful effects of high intensity on their spectral processing abilities than people with normal hearing. The relationship between carrier bandwidth and signal intensity was inversely related to hearing status. For all individuals, the negative effects of high intensities were more detrimental for narrow carrier bandwidth signals. The results differed from

Dreisbach et al. (2005) in that the SMD thresholds for the normal hearing group were slightly poorer at 70 dB SPL compared to 60 dB SPL. The results for the hearing loss groups were similar, as the SMD thresholds improved from 60 dB SPL to 70 dB SPL. However, the results did not differ significantly between groups. These findings build on Dreisbach et al. (2005), revealing that SMD thresholds do not improve with an increase in audibility beyond 70 dB SPL, but rather worsened with a further increase in signal intensity. This finding is not surprising because as signal intensity increases, human auditory filters are known to broaden (Liberman & Dodds, 1984).

This study has some limitations to consider. The first limitation is whether the rippled noise was audible. Some hearing loss group participants had moderate hearing loss in the high frequencies. It is possible that 60 dB SPL rippled noise was not audible across the entire frequency range, and thresholds were elevated. Although there were no significant differences between the groups, this merits further investigation in a future study using either an open-source or a traditional hearing aid.

A second limitation is that only 2 cpo were studied. While this has been reported to have the most robust results, it may be worthwhile to look at other cpos, such as 1, 3, and 4, to see if there are any differences between the hearing loss and normal hearing groups. Finally, the group with hearing loss was smaller than the group with normal hearing, and some of the individuals with hearing loss could not tolerate the 90 dB SPL listening conditions. It may be beneficial to recruit a larger group of hearing loss participants to see if the difference observed remains.

Conclusions

Results revealed a significant difference in bandwidth and level within the hearing loss and normal hearing groups, but not across groups. Future work should examine this effect using audibility-controlled conditions across the listener groups, such as simulating a hearing aid in these situations to determine the impact of amplification on SMD thresholds.

Chapter 4: An exploratory investigation of objective and subjective factors that influence individual variance in noise tolerance levels

Introduction

Hearing aids have been shown to provide improvement in speech understanding (Cox, Johnson, et al., 2014; Johnson et al., 2016) and quality of life (Chisolm et al., 2007; Ciorba et al., 2012; Cohen et al., 2004; Kitterick & Ferguson, 2018). Despite these benefits, approximately one-third of those who could benefit from a hearing aid use one (NIDCD, 2021). This is a multi-faceted problem that includes access to care, hearing aid cost/insurance coverage, stigma of hearing loss, and post-hearing aid issues, such as the ability to use and perceive benefit with a hearing aid. All these factors influence hearing aid uptake, but the focus of this research will be on the post-hearing aid concerns of background noise, specifically noise tolerance.

Adult hearing aid users frequently report difficulty understanding speech in noise and difficulty listening comfortably in noise (Kochkin, 2000). Although hearing aid features such as directional microphones and noise reduction help to alleviate these complaints, speech understanding and listening comfort in noise are still problematic for hearing aid users. According to MarkeTrak X (Picou, 2020), while hearing aid users are more satisfied with their hearing than non-users in a variety of listening environments, common concerns still revolve around the hearing aid’s ability to provide listening comfort in noise and improve on speech intelligibility in noise. Hearing in a large group and following conversations in noise were two of the lowest rated environments for hearing aid satisfaction (Picou, 2020).

Gatehouse and colleagues (Gatehouse, 1992, 1993; Robinson & Gatehouse, 1996) noted that simply using amplification can improve speech understanding. Despite this natural acclimatization, hearing aid users still report problems with speech recognition and listening comfort in noise. One example of this can be seen when hearing aid outcome measures are evaluated using the Abbreviated Profile of Hearing Aid Benefit (APHAB; Cox & Alexander, 1995). Oftentimes, benefit is reported for the aided condition compared to unaided for the ease of communication, background noise, and reverberation subscales (Cox & Alexander, 1995;Johnson et al., 2010). This is not true for the aversiveness of sounds subscale.

Hearing aid users perceive sound as less aversive unaided than when aided, although this has improved slightly with digital technology (Cox & Alexander, 1995; Johnson et al., 2010). Cox et al. (2003) noted that the aversiveness subscale did not correlate with pure-tone air conduction thresholds. It was hypothesized that this was due to how thresholds and aversiveness are measured with thresholds being the softest level that can be heard, while aversive sounds are loud. There was no correlation either with speech in noise thresholds (Cox et al., 2003). Often benefit that is obtained objectively in a laboratory setting is not aligned with the hearing aid user’s real-world perceptions of benefit (Cord et al., 2000; Lawrence et al., 2018; Walden et al., 2000; Wu et al., 2019). Cox et al. (2003) hypothesized that aversiveness may be due to features like personality, emotion, etc. rather than auditory variables like hearing loss and suggested using suprathreshold loudness perception measures (Cox et al., 2003). This mismatch reflects the limitations of our current hearing aid fitting practices and the need for more sensitive measures.

Current Hearing Aid Fitting Practices

The evidence-based guidelines for fitting adults with hearing aids from AAA (Valente et al., 2006) and ASHA (Valente et al., 1998) provide some guidance on how to optimally fit hearing aids. Real-ear measures are advocated, but one drawback is that the targets are based on speech understanding in quiet and not in noise. The AAA guidelines (Valente et al., 2006) suggest some methods in evaluating advanced features in hearing aids like noise reduction and directional microphones, by using tools such as electroacoustic measures. Modern hearing aid analyzers include testing protocols that are specific to that analyzer that will examine whether these two features are working properly. While these measures are important for serving as a quality control and to troubleshoot whether the device is working, there are no standards as to how much reduction in gain is considered within specifications and this testing does not assess whether adjustments have improved speech recognition in noise.

The guidelines also suggest unaided and aided speech recognition testing, but the AAA guidelines (Valente et al., 2006) caution that there are limitations when performing in-clinic measures using a single loudspeaker to estimate real-world benefits (Valente et al., 1998, 2006). A diffuse listening environment has been shown to be more accurate at simulating a real-world environment (Compton-Conley et al., 2004). Anderson et al. (2018) note that there is lack of guidance for fitting and adjusting these advanced features, with the majority of clinicians relying on default settings.

Individual Factors That Might Influence Noise Tolerance

In order to provide guidance on programming hearing aids for individuals, it is important to understand what factors impact different hearing aid use factors. Some studies have tried to evaluate hearing aid users' perception of speech quality and intelligibility (Preminger & Van Tasell, 1995a, 1995b). Preminger and Van Tasell (1995a, 1995b) examined ratings of loudness, intelligibility, noisiness, listening effort, pleasantness, and total impression using sentences with varied frequency responses in adults with normal hearing and hearing loss. The intelligibility of the sentences was maintained to determine what other factors impact sound quality. Results revealed that pleasantness had the most variability and that listening effort, noisiness, and overall impression were also unique across individuals and should be measured when making adjustments.

Preminger and Van Tasell's (1995a, 1995b) studies help establish qualities that are relevant for perceptions of speech in quiet. While most hearing aid users do well in quiet, there are often more complaints of hearing in background noise, both for understanding speech and tolerance of noise. It would be of interest to determine what factors impact a hearing aid users' perception of speech in noise and tolerance of noise.

Skagerstrand et al. (2014) evaluated what sounds are aversive to adult hearing aid users. In addition to looking at these sounds, other factors, such as age, hearing loss, gender, years of hearing aid experience, and the signal processing (simple or complex) were evaluated. Hearing aid users kept diaries and sounds could be placed into 18 categories. The top five most mentioned bothersome sounds were verbal human sounds, TV/radio, vehicles, machine tools, and household appliances. Results overall were similar when grouped by age, hearing loss, gender, years of hearing aid experience, and signal processing. Some hearing aid users reported taking their hearing aids out in these situations or just coping with the situation. Skagerstrand et al. (2014) note that future studies should consider examining the characteristics, such as frequency and intensity, of these sounds.

Similarly, Gygi and Hall (2016) completed a scoping review to examine adult hearing aid users and the impact of background sounds. Their results indicated that interference and annoyance was usually due to two factors, either the acoustical properties of the sound itself or the interference that it caused with a target signal.

One way to measure noise tolerance is the acceptable noise level test (ANL; Nabelek et al., 2004). The ANL examines a person's ability to tolerate background noise and uses this information to predict whether the person will be a successful hearing aid user. Thus, improving a person’s score on the ANL could increase their likelihood to use their hearing aid(s) when needed. Franklin et al. (2014) examined whether there was a relationship between the amount of time spent in certain environments and a person’s ANL threshold in adults with normal hearing. Results did reveal a trend that those with higher (poorer) ANLs spent less time in noisy environments. Freyaldenhoven et al. (2006) also examined normal hearing adults and the relationship between self-report of being in background noise and their ANLs. Results revealed no significant correlation between self-report of being in background noise and the ANL. If individual factors are found to correlate with the ANL, we could determine which hearing aid users possess those factors and use this information to fine-tune their hearing aids or provide tailored aural rehabilitation. Some studies have suggested factors that may have a relationship with a person’s noise tolerance.

Mackersie et al. (2021) evaluated differences in noise tolerance in adults with normal hearing. Four categories of noise tolerance were evaluated: loudness, annoyance, distraction, and speech interference. A modified ANL called the noise tolerance threshold (NTT; highest SNR that can be tolerated), paired comparisons and an absolute measure (scale of 0-100) of these four categories using the NTT, and the Weinstein noise sensitivity questionnaire (Weinstein, 1978) were completed. Results revealed that noise distraction and speech interference were the most important determinants of noise tolerance and loudness was the least important category. The participants could be broken into three main groups of those who were bothered most by either annoyance, distraction, or interference. NTTs were highest (high SNR) for the annoyance group, followed by the distraction group and the speech interference group. There was no group effect for the Weinstein questionnaire, but those with higher NTT scores had higher scores on the questionnaire as did those who rated annoyance the highest.

Mackersie et al. (2021) also noted that noise seems to be the dominant feature for noise tolerance versus the speech. This research suggests that questionnaires such as the Weinstein noise sensitivity scale may provide information on who is less tolerant to noise and will have higher ANLs. Paired comparisons may also be a tool that can be used to group hearing aid users into different categories for noise tolerance. Mackersie et al. (2021) note that their study is limited to normal hearing adults and that other factors like working memory may play a role in noise tolerance. In a study examining speech intelligibility and ANL, Recker and Micheyl (2017) noted that speech intelligibility was an important factor for determining ANLs for adults with normal hearing, but not for adults with hearing loss.

Personality may also play a role in acceptance of noise. Huber & Johnson (2021) evaluated the potential relationship between sound acceptability and emotional reactivity and personality in young normal hearing adults. The International Mini Marker questionnaire (Thompson, 2008) and Perth Emotional Reactivity Scale (Becerra & Campitelli, 2013) were used to determine relationships with the Sound Acceptability Test (Johnson, 2012). The Sound Acceptability Test evaluates non-speech sounds of varying duration (transient, episodic, and continuous) and level (soft, average, and loud). Results revealed a relationship between negative reactivity and loud transient sounds and agreeableness and loud transient, average episodic, and loud episodic sounds. Huber and Johnson (2021) reported that negative reactivity and agreeableness accounted for a small amount of variance for sound acceptability scores (range of 9-14% depending on the non-speech sound). This suggests that personality factors such as negative reactivity and agreeableness may be related to noise tolerance.

Franklin et al. (2013) also evaluated how personality related to the ANL test using the Big Five Inventory (John et al., 1991; BFI) and the Myers-Briggs Type Indicator (Briggs, 1987) test. The BFI evaluates the personality traits of openness, neuroticism, conscientiousness, extroversion, and agreeableness. The Myers-Briggs Type Indicator evaluates the personality dimensions of judging-perceiving, extroversion-introversion, sensing-intuition, and thinking-feeling. Results revealed a weak, but significant inverse relationship between ANL and conscientiousness and openness. These results suggest that people who are more open to new experiences and who are more conscientious have lower ANL scores. This also indicates that personality may play a role in noise tolerance.

Another potential aspect of personality that could impact noise tolerance is self-control. Nichols and Gordon-Hickey (2012) examined the relationship between self-control and ANLs in young adults with normal hearing. Results revealed a significant negative relationship between the self-control scale and ANL. These results suggest that as self-control increases, ANL scores decrease. This study suggests that there may be a relationship between self-control and ANL that should be further explored.

Cognition could also play a role in a person’s ability to tolerate noise, specifically working memory. Working memory capacity is a person’s ability to hold information for a short period of time. Someone that has a smaller capacity would be expected to perform poorer in noise than someone with a larger capacity. Brännström et al. (2012) examined the ANL and its relationship with working memory capacity in adults with normal hearing. Results revealed a significant relationship between working memory capacity and background noise levels and working memory capacity and the overall ANL score. This suggests that those that had higher background noise levels on the ANL and those with lower (better) ANLs had larger working memory capacity. This suggests a potential cognitive factor for noise tolerance.

Factors of the hearing aid itself could also play a role in a person’s ability to tolerate noise. Schwartz and Cox (2012) examined how accurately questionnaires such as the DOSO’s use subscale predict hearing aid use compared to the ANL. Results revealed that the DOSO use subscale provided the most accurate measure of successful hearing aid use compared to the ANL. This suggests that questionnaires such as the DOSO could be used to predict the noise tolerance of a hearing aid user.

While the described research hints at several factors that could predict noise tolerance, there is little research evaluating preferences for noise tolerance in adults with hearing loss. Based on these varied studies, there are many variables that may contribute to an individual's tolerance of background noise, including personality, working memory, and device factors. The goal of this study is to integrate this previous research into a multi-dimensional evaluation of noise tolerance in adults with hearing loss as the majority of these studies have laid the groundwork for some of these variables mainly in normal hearing adults. When we have a better understanding of what the factors are that impact noise tolerance, we can better determine if these characteristics can be changed/are plastic. This information could also be used to improve customization of hearing aid features and interventions for hearing aid users including individualized programming and aural rehabilitation.

Research Questions

The purpose of this study was to build off of previous research examining factors that could impact noise tolerance in a group of adults that have hearing loss and that use hearing aids. This study examined:

1) the impact of individual factors such as personality, preferences for background noise, working memory, device factors, hearing thresholds,

and speech in noise thresholds and their relationship with a hearing aid user’s noise tolerance.

2) Based on these relationships, are there any variables that can be grouped together than can explain a hearing aid user’s tolerance for background noise?

Methods

Participants

Twenty-one adult hearing aid users were recruited using methods approved by the ethical review board at the University of Minnesota – Twin Cities. Inclusion criteria included adults with hearing aids that were between the ages of 18-85 years and could read English. There were 10 males and 11 females with a mean age of 72.4 years (SD = 12.5 years). The average length of hearing loss was 19.6 years (SD = 15.8 years), and the average time of hearing aid use was 10.4 years (SD = 11.3 years). The potential etiologies for participants’ hearing loss are shown in Table 4.1. All participants were bilateral hearing aid users.

Table 4.1. Patient reported potential causes of hearing loss.

Health Condition	**N**
Noise exposure	9
Genetics	9
Ear infections	3
Presbycusis	5
Concussion	1
Sudden hearing loss	1
Ménière’s disease	1
Unknown	3

Note: Some participants reported more than one potential cause of hearing loss

Equipment and Outcome Measures

The research study measures were completed remotely due to COVID-19. A remote study method was chosen due to restrictions on in-person research at the University of Minnesota. Equipment was provided using CDC guidelines and all equipment was disinfected prior to and after use by the participant. A research toolkit with all the equipment needed for the research study and a comprehensive step-by-step guide (see Appendix A) on how to complete the study was provided to the participant. The research toolkit included the tablet and headphones for the hearing test and digits in noise test, a tablet for the ANL and reading span task, a tape measure, a loudspeaker, a binder of instructions, a pen, and sanitizing wipes. All demographic questions and questionnaires were compiled into Qualtrics to be completed by the participant on their own electronic device.

Audiogram and Digits in Noise Testing

Hearing thresholds were tested using a hearX® Self Test Kit portable audiometer. The Self Test Kit included a Samsung Galaxy Tab A tablet with pure-tone audiometry using the hearTest™ software (V10116) and a speech in noise test called hearSpeech, which is a digits in noise task. Sennheiser HD 280 Pro headphones were used for all testing. All equipment was calibrated, and a listening check was performed prior to testing. Participants followed step-by-step instructions on how to self-test their hearing at home. The order of tests was counter balanced.

Participant hearing was tested bilaterally from 500-8000 Hz. The participant read through the instructions and the software evaluated if the environment was quiet enough to ensure an accurate test. If the environment was noisy, the participant either removed the noise source or completed testing in another room. Then tones were presented, and the participant tapped a button on the screen whenever they heard the tone. If they pressed the button too much the software alerted them. Participants also read the instructions for the digits in noise task. The participant listened for three numbers in background noise and entered what the numbers were on the tablet. The result was the signal-to-noise ratio (SNR) at which the digits could be heard. A lower SNR indicated better performance as the person could have more noise present and hear the numbers.

Acceptable Noise Level (ANL) Test

The Unitron uHear app on an Apple™ iPad™ (8th generation) was used to test noise tolerance using their version of the ANL test. The ANL is the highest level of noise a listener is willing to put up with while listening to speech at a comfortable volume (Nabelek et al., 1991). This version of the ANL has been shown to be equivalent in results to the traditional ANL test in young normal hearing adults (Barnett et al., 2021). Testing was completed unaided and aided using a JBL Flip 5 portable Bluetooth loudspeaker. This loudspeaker has a bandwidth of 65-20,000 Hz and was chosen for its easy setup with the tablet. A tape measure was provided to ensure the loudspeaker was three feet in front of the participant. The participant read the instructions in the app and performed the ANL task by first adjusting the speech to their most comfortable listening level. Then the noise came on and the participant adjusted the noise to a level that was loud, but still tolerable while listening to the speech. The participant performed this task three times unaided and three times aided and the three trials were averaged. A lower ANL indicated greater tolerance of noise (the noise can be higher than the speech signal and still be tolerable).

Working Memory

Working memory was assessed using a reading span task (Conway et al., 2005; current URL: https://ubiq-x.gitlab.io/rspan/). This task required participants to read sentences and to indicate on the iPad if the sentence was correct (the subject of the sentence made sense) or incorrect (it was nonsensical). Then a letter would appear. The participant had to remember the letter while making judgements of the sentences. There were 18 trials and the participant had to remember two to seven letters after the trial. Participants read the instructions and completed three practice tests. One practice test consisted of judging sentences, one practiced remembering letters, and the last practice test put the two tasks together. Results were scored using the partial-credit unit score. This score examines the percentage of letters correctly recalled in the correct position (Conway et al., 2005). The partial-credit unit score is averaged across trials. A higher partial-credit unit score indicated better working memory.

Big five inventory – 2 (BFI-2)

The Big Five Inventory – 2 (BFI-2; Soto & John, 2017) evaluates personality traits of extroversion, agreeableness, conscientiousness, negative emotionality, and open-mindedness. This inventory uses a 5-point scale ranging from 1 = disagree strongly to 5 = agree strongly. There are a total of 60 questions, with 12 questions for each of the big five personality categories. Of these 12 questions, six questions are positive in nature and six questions are negative (reversed). An overall score was calculated in addition to scores for each of the five personality traits. A higher score indicated a stronger presence of that trait.

Self-control measures

The Adult Temperament Questionnaire (Evans & Rothbart, 2007; ATQ) evaluates aspects of personality that include effortful control, negative affect, extroversion/surgency, and orienting sensitivity. The effortful control section of the questionnaire was chosen for this study. Within the effortful control section, there are three areas that are examined: attention control, inhibitory control, and activation control. There were a total of seven questions for activation control, five for attentional control, and seven for inhibitory control. Participants were asked to use a 7-point scale ranging from 1 = extremely untrue of yourself to 7 = extremely true of yourself to answer questions about their personality in these areas. An overall score is calculated for each section. A higher score indicated higher self-control in that respective category.

The self-control scale (Tangney et al., 2004) was also assessed and consists of 36 questions that evaluate general self-control. The participant rated how much the statement reflected who they are using a 5-point scale that ranged from 1 = not at all to 5 = very much. The overall score was calculated and a higher score indicated higher self-control.

Device Oriented Subjective Outcome Scale (DOSO)

The device oriented subjective outcome scale (DOSO) by Cox et al. (2014) assesses hearing aid satisfaction across subscales of speech cues, listening effort, pleasantness, quietness, convenience, and use. This questionnaire was designed to examine hearing aid outcomes based on device performance rather than personality traits. There are a total of 28 questions across six subscales. Each participant was asked to rate how well their hearing aids performed across various tasks, using a 7-point scale ranging from 1 = not at all to 7 = tremendously. In addition to the average score for each of the six subscales, an overall rating was also computed. A higher score indicated improved device benefit/outcomes for the respective category.

Weinstein Noise Sensitivity Scale

The Weinstein Noise Sensitivity Scale (Weinstein, 1978) evaluates a person’s ability to tolerate noise in everyday situations. Participants rated a variety of situations for a total of 21 questions using a 6-point scale that ranged from 1 = agree to 6 = disagree. A total score was calculated, and a higher score indicated greater sensitivity to everyday noise.

Procedures

This study was completed remotely due to COVID-19. Prior to the start of the study, the informed consent form was signed either in person when the equipment was dropped off or digitally. Demographic information along with the BFI-2, DOSO, self-control questionnaire, Weinstein Noise Sensitivity Questionnaire, and the ATQ were completed in Qualtrics via a personal link sent by the researcher. The questionnaire took about 1 hour to complete.

The researcher and participant agreed on a time to drop off the equipment for remote testing at their home or a convenient location. The equipment was cleaned and checked prior to the drop off. The following safety precautions were taken to prevent the spread of COVID-19. The headphones had disposable earphone covers to make cleaning easier. The tablet and headphones were disinfected. The participant was screened by their preferred method (email, Zoom, or phone) prior to dropping off the equipment for COVID-19 symptoms. Social distancing was maintained when dropping off the equipment.

Instructions were provided to participants in a written format (see Appendix A). The instructions were personalized for each participant with their participant number and the order of testing. Remote testing included the audiogram, digits in noise test, the reading span task, and the ANL test. The researcher was available by Zoom or phone and also by email to answer any questions about the study. Remote testing, on average, took about 1.5-2 hours. After completing remote testing, the participant was contacted to schedule a pick-up time for the equipment. Each participant was paid $10/hour for their time.

Data Analysis

The data was placed into an Excel spreadsheet and was analyzed using RStudio (version 2022.07.0). Initial analysis using linear regression revealed multicollinearity among the independent variables (see Appendix B for the variance inflation factor). A least absolute shrinkage and selection operator (Lasso) regression was therefore used due to the multicollinearity and small sample size compared to predictors in the model. A Lasso regression analysis using the glmnet package in R (Helwig, 2017) was used to determine which variables may play a role in a person's ability to tolerate background noise (see

Appendix C for R code). Aided ANL was the dependent variable and the remaining 20 variables were the independent predictor variables (see Table 4.5 for the 20 independent variables). The model was cross-validated on five folds of the dataset. The optimal lambda was determined to be 1.57. The Lasso regression was then completed using the optimal lambda and the r-squared was calculated.

Results

Hearing Thresholds and Digits in Noise

The mean right and left pure-tone air conduction thresholds and ± one standard deviation are shown in Figure 4.1. The mean, ± one standard deviation, and the range of hearing thresholds of the participants is also reported in Table 4.2. The average participant had a moderate hearing loss in the right ear at 44.17 dB HL (SD = 15.09 dB HL) and in the left ear at 44.17 dB HL (SD = 14.73 dB HL). There was a wide range of digits in noise abilities, with a range of -11.2 dB to a +9.2 dB SNR.

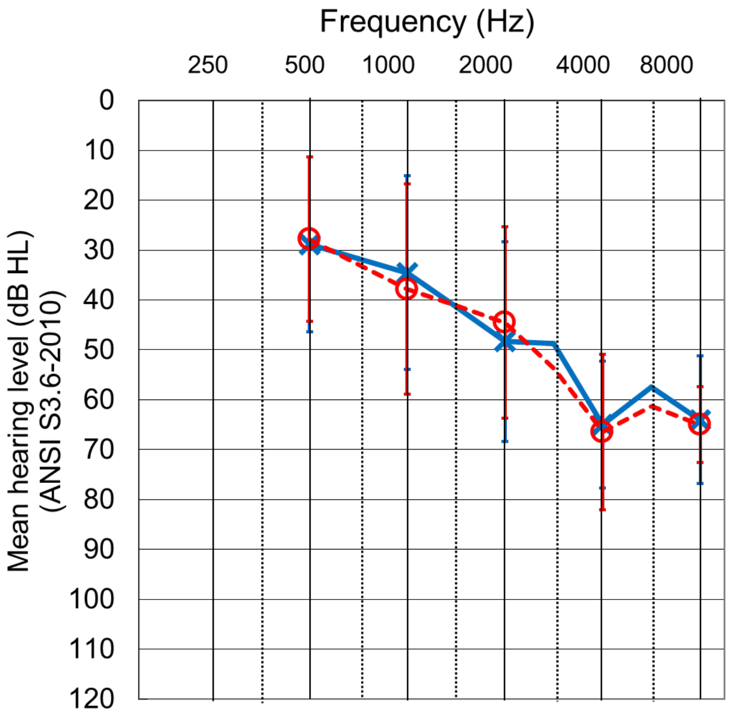


Figure 4.1. Mean right and left ear hearing thresholds and ± 1 standard deviation for the at home hearing test.

Acceptable Noise Level (ANL) Test

The ANL was completed unaided and aided (Table 4.2). Results revealed an average score around 5.81 dB (SD = 6.31 dB) unaided and 4.51 dB aided (SD = 4.69 dB). Note that these scores were an average of three trials as this is the standard protocol for the ANL.

Working Memory

The reading span task was completed and the average score of the percentage of letters correctly recalled is reported in Table 4.2. This reading span task tracks the accuracy of stating if the sentences are sensical or nonsensical.

The average accuracy was 87% suggesting that participants did not rush through the sentences in order to remember just the letters. The overall percentage of letters that were correctly recalled in order was 56% (SD = 21%).

Table 4.2. Mean, SD, and range of remote testing data.

Measure	**Mean**	**SD**	**Range**
Hearing thresholds (Right ear in dB HL)	44.17	15.09	21.25 – 75.00
Hearing thresholds (Left ear in dB HL)	44.17	14.73	22.50 – 78.75
Digits in noise (in dB SNR)	-5.23	4.54	-11.20 – 9.20
Unaided ANL (in dB)	5.81	6.31	-1.33 – 19.00
Aided ANL (in dB)	4.51	4.69	-4.33 – 14.00
Working memory (in partial-credit unit)	0.56	0.21	0.09 – 0.83

Questionnaires

The results from the BFI-2, DOSO, self-control questionnaire, ATQ, and Weinstein Noise Sensitivity Scale are reported in Table 4.3. As can be seen, the group had a wide range of responses across the questionnaires. This indicates there was a wide range of personality characteristics amongst the participants.

Table 4.3. Mean, SD, and range of questionnaire data.

Questionnaire	Mean	SD	Range
Overall BFI-2	218.05	14.09	198 – 252
BFI-2 agreeableness	50.10	5.59	39 – 59
BFI-2 negative emotionality	28.10	9.09	16 – 47
BFI-2 open-mindedness	48.9	5.75	34 – 59
BFI-2 extraversion	42.81	7.37	32 – 60
BFI-2 conscientiousness	48.14	6.92	36 – 59
ATQ – activation control	5.43	0.61	4.29 – 6.71
ATQ – attentional control	4.47	1.19	1.8 – 6.6
ATQ – inhibitory control	4.91	0.81	2.86 – 6.14
Overall DOSO	4.85	1.08	3.27 – 6.7
DOSO – speech cues	4.46	1.43	1.71 – 6.71
DOSO – listening effort	5.32	1.12	3.2 – 7.0
DOSO – pleasantness	5.45	1.20	2.5 – 7.0
DOSO – quietness	4.02	1.44	1.0 – 6.6
DOSO – convenience	5.74	1.16	2.5 – 7.0
DOSO – use	4.13	1.04	2.0 – 5.0
Self-control	135.29	18.07	84 – 163
Weinstein	74.95	21.34	44 – 116

Pearson Correlations Between the Dependent Variable and Predictors

Pearson correlations were calculated between the dependent variable of aided ANL and the 20 predictor variables and the unaided ANL (Table 4.4). Only two variables were significantly related to the aided ANL: the DOSO listening effort subscale and the unaided ANL. The correlation with the unaided ANL demonstrates that the two ANL measures are related. These results are consistent with previous findings that unaided and aided ANL scores are related (Nabelek et al., 2004).

Table 4.4. Pearson correlations of the predictor variables with the dependent variable of aided ANL.

Predictor	**Correlation With Aided ANL**
ATQ: activation	0.06
ATQ: attention	-0.257
ATQ: inhibition	-0.081
BFI-2: agreeableness	0.152
BFI-2: conscientiousness	0.123
BFI-2: extraversion	-0.222
BFI-2: negative emotionality	-0.07
BFI-2: open mindedness	-0.234
DOSO: convenience	-0.244
DOSO: listening effort	-.453*
DOSO: pleasantness	-0.306
DOSO: quietness	-0.395
DOSO: speech cues	-0.294
DOSO: use	0.068
Unaided ANL	.755**
Self-control	0.116
Weinstein	0.132
Working memory	-0.031

Digits in noise	0.429
Pure-tone average (Right)	0.363
Pure-tone average (Left)	0.309

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

Least Absolute Shrinkage and Selection Operator (Lasso) Regression Analysis

A Lasso regression analysis was completed and results revealed a relationship between aided ANL and the listening effort subscale of the DOSO and the digits in noise test (see Table 4.5). No other model predictors were included in the model. These results suggest that with a one unit increase in the listening effort subscale (improved listening effort with the hearing aid), the aided ANL decreases by 0.410 (gets better; see Figure 4.2). For digits in noise, a one-unit (1 dB SNR) increase (poorer performance in noise) would result in the aided ANL increasing by 0.070 (decrease in tolerance; see Figure 4.3). An adjusted r-squared revealed that the listening effort subscale of the DOSO and digits in noise test predicted 64.17% of the variance in predicting the aided ANL score.

Table 4.5: Lasso regression beta coefficients.

Predictor	**βLasso**
Intercept	7.052
ATQ: activation	--
ATQ: attention	--
ATQ: inhibition	--
BFI-2: agreeableness	--
BFI-2: conscientiousness	--
BFI-2: extraversion	--
BFI-2: negative emotionality	--
BFI-2: open mindedness	--
DOSO: convenience	--
DOSO: listening effort	-0.410
DOSO: pleasantness	--
DOSO: quietness	--
DOSO: speech cues	--
DOSO: use	--
Self-control	--
Weinstein	--
Working memory	--
Digits in noise	0.070
Pure-tone average (right)	--

Pure-tone average (left)	--
Adjusted R^2	64.17%

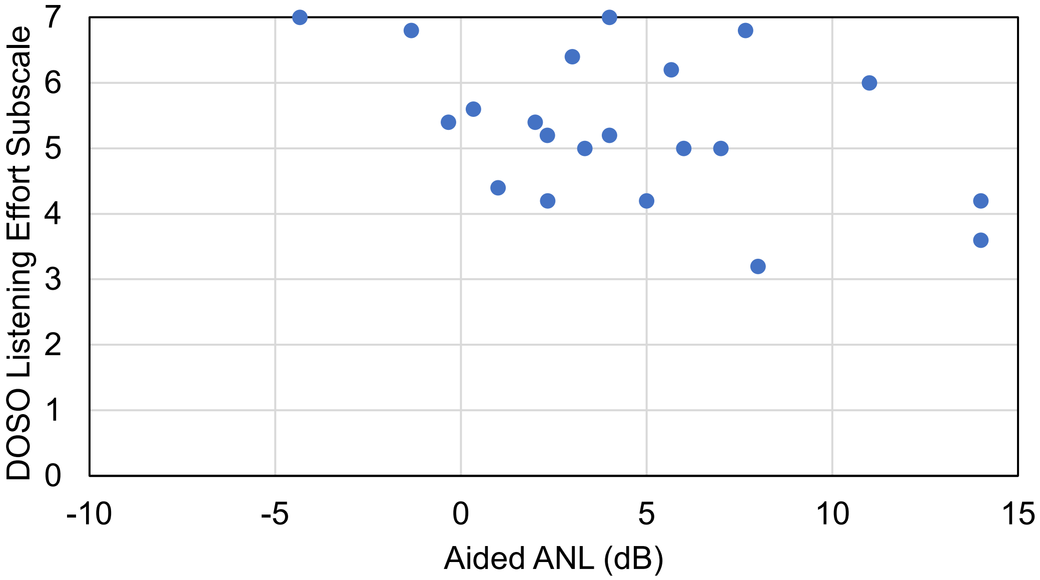


Figure 4.2. Scatterplot showing the relationship between the aided ANL and the DOSO listening effort subscale (7-point scale of 1 = not at all to 7 = tremendously).

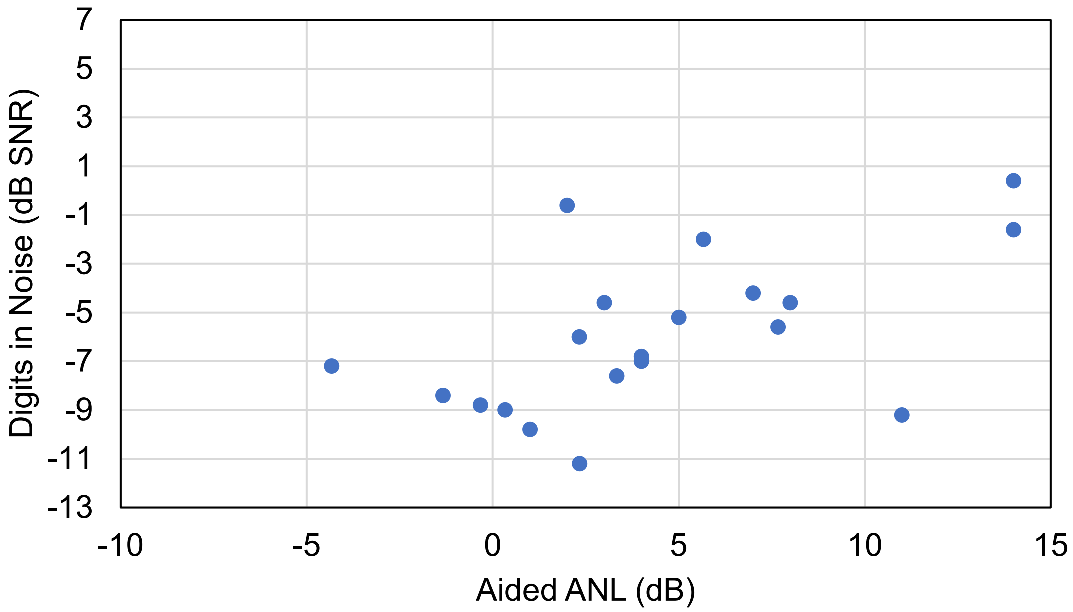


Figure 4.3. Scatterplot showing the relationship between the aided ANL and the digits in noise task (dB SNR).

As can be seen in Figure 4.2 examining the relationship between the aided ANL and the DOSO listening effort subscale, in general, as hearing aid users reported improved listening effort with the hearing aids, their ANL scores decreased. This indicates improved performance and more tolerance for background noise when listening effort improves. When examining Figure 4.3 and the relationship between aided ANL and the digits in noise task, in general, as hearing aid users had better digits in noise SNR scores, their ANL scores decreased. This indicates improved performance and more tolerance for background noise for this trait.

Discussion

This study sought to discover variables that impact a person's ability to tolerate background noise. Different facets of personality, hearing aid benefit, working memory, hearing loss, and speech in noise abilities were examined. Results revealed that of the 20 variables, only the listening effort subscale of the DOSO and the digits in noise test predicted ANLs in the participant population. This indicates that personality and cognitive factors in this population did not play a role in determining the ANL, but device factors and digits in noise abilities did.

While the DOSO use subscale was shown to be an accurate predictor of the ANL by Schwartz and Cox (2012), this differed from the results of this study. Instead of use, the listening effort subscale was shown to be inversely related to the aided ANL, with improved listening effort from device use causing a decrease (improvement) in ANL scores. It is important to note that Schwartz and Cox (2012) only examined the use subscale of the DOSO. The current literature has not evaluated the DOSO further and its potential relationship with the ANL. As noted in the fNIRS study, listening is difficult to define and measure as it is made up of many factors. Listening effort is defined as "the mental exertion required to attend to, and understand, an auditory message" (McGarrigle et al., 2014). It is possible that if a device decreases a person's listening effort to obtain the message of interest, this in turn would improve their tolerance to background noise. More research is needed to evaluate this potential relationship.

A relationship was also noted with the digits in noise test and the aided ANL. As the digits in noise test SNR increased (poorer performance), the ANL also increased (decreased tolerance of noise). Previous literature has not examined digits in noise, but a few studies reported that the Hearing in Noise Test (Hedrick et al., 2021) and the Speech in Noise Test (Nabelek et al., 2004) were not related to the ANL. A study completed by Gordon-Hickey and Morlas (2015) evaluated ANLs in adults with and without hearing loss and their speech perception abilities at their preferred ANLs and +5 and -5 dB SL. Results revealed better speech perception for those with higher ANLs than those with low ANLs. This suggests that those with lower ANLs may not have based their judgements on their speech recognition abilities, while the higher ANL group did. Further research should evaluate this potential relationship between the aided ANL and digits in noise test.

These results cannot be directly compared with Mackersie et al. (2021) who reported differences between groups for their measured noise tolerance threshold. Important factors found in Mackersie et al. (2021) for noise tolerance included annoyance, distraction, and speech interference. It is possible that these three factors could be related to listening effort and digits in noise abilities. This should be investigated in future research. Mackersie et al. (2021) used a different noise tolerance task than the traditional ANL task and that could account for some differences in results. Future studies should consider evaluating different noise tolerance tasks to see which one may be the most sensitive to a hearing aid users' real-world experiences.

Future studies should also seek to evaluate what aspects of noise tolerance are most important to each individual hearing aid user as loudness/annoyance to noise is as complex as listening effort. Mackersie et al. (2021) highlight this in their study noting that noise tolerance varied for each participant. Some participants reported annoyance, distraction, or speech interference impacted their tolerance for noise while loudness of the noise did not seem to impact noise tolerance. It is important to note that this study was completed on adults with normal hearing and hearing loss adds to the complexity, as it could add distortion to the signal.

In a different study conducted by Huber and Johnson (2021), they evaluated whether personality traits impacted sound acceptability in young, normal hearing adults. Results suggested a potential relationship between negative reactivity and agreeableness personality traits with tolerance for loud sounds. This again, differs from the current study, which did not find any significant personality traits related to the ANL. However, Huber and Johnson (2021) examined soft, average and loud sounds while this study only examined the ANL and it sets speech at a comfortable volume with noise at the person's most tolerable volume. Also, the test examined by Huber and Johnson (2021) uses non-speech environmental sounds. Future studies should consider evaluating louder stimuli to see how this would impact the relationship between ANL and personality characteristics.

Gygi and Hall (2016) noted that the acoustical properties and the interference with the target signal can impact a hearing aid listener's annoyance in background noise. This is an important consideration for this study as it is unknown what acoustical properties may have bothered each participant in this study. It is also important to note that the talker was someone that the listener did not necessarily have an investment in listening intently too. Futures studies could further probe what noises bother different hearing aid users and use speech that is relevant to that hearing aid user, such as a family member's voice. Many participants noted that the ANL test wasn't too bothersome because they were able to control the noise. Pushing this boundary of loudness tolerance may provide a more accurate picture of why some hearing aid users struggle in background noise.

Limitations

One big limitation of this study was the limited online and portable formats of tests that could be used for speech recognition and ANL testing. Due to COVID-19 and limited in-person testing, only measures that were readily available online could be used. While not ideal, these measures have been tested in other studies and have been shown to be accurate and provide similar results to the traditional ANL test (Barnett et al., 2021). Future studies should examine other noise tolerance tests to see which might be the most sensitive and accurate to the patient’s real-world experience. In addition, other tests that use more real-world stimuli, such as sentences, should be examined and compared to the digits in noise results.

The sample size was also a limitation. While twenty-one adults with hearing aids was reasonable during the pandemic, this group likely did not provide enough power to find differences between the examined variables. Future studies should examine a larger cohort of hearing aid users to determine if these results still hold true.

Another limitation is the sound clips that were used to assess noise tolerance. In the real-world, hearing aid users experience a variety of signals that change in frequency and level, and they have the context of the situation, emotion, mood, etc. Certain signals may be less tolerable than others based on hearing aid user preferences. While there is no way to assess all situations, future studies could consider more realistic situations. In addition to the limitations of the stimuli, the loudspeaker set up is also not reflective of the real-world. While speech and noise can be co-located, often noise is surrounding the hearing aid user. This could provide a different impression than the environment that was tested.

Another limitation is testing in the home environment. It is hard to determine what the participant’s attention level was and if background noise levels changed during testing. There was one control during hearing threshold testing where the tablet evaluated the noise in the room and told the participant if it was too loud. However, this doesn’t mean that the noise levels stayed quiet for the other tests as the noise was not monitored during other tests. While this was the best that could be done during COVID-19 lockdowns, this is an important variance to consider.

Lessons Learned From Remote Testing

COVID-19 has sparked more interest in performing auditory research remotely. While the pandemic forced us to pivot and think of creative ways to continue our research, there are distinct advantages to doing research remotely. First, a larger pool of participants could be reached. In addition, remote research could also make studies more inclusive. Sometimes it is difficult to obtain transportation to research sites or participation is limited due to working hours of participants and everyday activities. Remote research could be completed at any time at the convenience of the participant, opening more opportunities for those that want to participate to be able to. There would be limitations based on internet service, any special software or device requirements that would be needed, and technical capabilities of the participants.

Remote testing overall was easy for this study, but there were many lessons that were learned from completing remote research. The first hurdle was ensuring that you have the proper equipment to complete the study. For the dissertation, I needed to obtain a portable audiometer that would be easy to use, find a tablet that would be able to handle the reading span task and the uHear app, and a loudspeaker. Just like with a traditional research study, this took a lot of time and research to find the equipment that would meet the study’s goals. A colleague had previously used an online version of the reading span task in another study, and I had learned about the uHear app at a conference. I had initially explored other avenues for a more traditional ANL, but the time to create the materials and equipment needed would not have been feasible for a dissertation timeline. The uHear app had also been validated to be similar to a traditional ANL, which ensured accuracy of the test (Barnett et al., 2021). The uHear app required an Apple tablet and would not work with the tablet for the audiometer, so two pieces of equipment were needed.

The most difficult element for finding appropriate equipment was the loudspeaker for aided ANL testing. I consulted with several researchers who had started remote testing and with an electronics specialty store, but advice I received involved equipment that would be wired to a computer and required a complex setup. This lesson brings up the important factor that when doing remote research your participant population should have a simple, easy to follow protocol. With two tablets that already needed to be kept apart and explained to participants, adding a laptop would have been overly complex. I searched for simple Bluetooth speakers that could be paired with the Apple tablet so that a seamless on/off of the loudspeaker would be all that was needed for ANL testing. I chose the JBL Flip 5 portable loudspeaker due to this ease of use, its wide frequency range, and reasonable output (around 96 dB) for this study. While this is not a research level loudspeaker, remote research may require some compromises to create simplicity for the participant and the researcher. Some participants did note that if I hadn’t distantly shown them how to use the equipment and have a guidebook that the process would have been overwhelming and they likely would not have completed the study.

Remote research, just like in-person research, also requires frequent equipment checks. While critical for both types of research, this may be even more critical for remote research as any software updates or other technical issues may be hard for patients to troubleshoot. In particular, the hearX audiometer required several updates throughout the study. I checked this prior to the appointment, but for one participant the update occurred when I dropped off the equipment. Fortunately, the participant had strong technical skills to troubleshoot and update the equipment. I also had glitches with the reading span task where buttons would get highlighted when they were not precisely pressed, and it was difficult for participants to determine how to move forward when this happened. Sometimes this problem could be resolved remotely with troubleshooting, but sometimes I had to go to the participant’s house to resolve the issue.

Another barrier that I could not control was standardization of the home environment. While there is a safety mechanism built in for the hearing test that checks the environmental noise prior to testing and alerts the participant to move to a quieter area if it is too loud, I did not have this safeguard for the reading span task or the ANL test. Participants may have been distracted by things in their environment and one advantage of the lab is the ability to remove these distractions and to control the noise in the environment. It could be argued, however, that this is more representative of a real-world environment. Instructions about the importance of having a distraction free environment, while not a perfect solution, can be helpful in alerting participants of where and when they should consider completing the study tasks.

Finally, a comprehensive guidebook (see Appendix A) was needed for remote testing. It needed to have every single step required to complete the study so that participants did not become frustrated. One of my biggest concerns was whether participants could connect the tablet to the internet for the reading span task. Luckily, with clear instructions, everyone was able to complete this step successfully, with some minor delays in finding the password for their internet. Piloting the guidebook on others was the key to success, but there will always be one thing that is missed that will be caught by a participant. While this isn't asked in traditional research, asking participants at the end of the study if any step was unclear can ensure that the guidebook is clear and accessible to all participants. Also, if possible, being present during testing via Zoom or on the phone can help with troubleshooting any issues that arise, can ensure the patient accurately completes the tasks, and provides confidence to the participant when doing the study knowing they have someone to ask questions to if they have problems.

The more the research base is built around remote testing and tests are created for online utilization, the more remote research is feasible in auditory research. This will take time to create, but the more that we address these issues, the more opportunities we have of recruiting a more diverse participant pool, which in turn will make our research applicable to our diverse patient population.

Future Considerations

A larger pool of hearing aid users should be examined to validate the current results. While the aided ANL did have relationships with the listening effort subscale of the DOSO and the digits in noise test, it is important to note that the ANL may not the best test to use for examining noise tolerance. Other tests, such as that used by Mackersie et al. (2021) should be examined to determine if they are more sensitive to a hearing aid user’s experience.

One of the long-term goals of this study is to determine what individual factors influence speech in noise tolerance and whether these factors are modifiable. Since the factors noted in this study were device or speech in noise ability related, it may be possible that device modifications or aural rehabilitation may be an option to modify these factors and improve noise tolerance. Formby et al. (2003) proposed using sound tolerance training for patients with hyperacusis and for patients with hearing loss to see if their tolerance for noise could be increased and thus improve satisfaction in background noise. Bees et al. (2019) investigated whether an auditory training regimen would improve the ANL in adults with normal hearing. Results showed that auditory training improved ANLs. This is of interest to the audiology community because if we can increase ANLs, patients may find that wearing hearing aids in background noise is more tolerable. More research into who would benefit from auditory training and what type of auditory training would be most effective in improving ANLs is required.

In addition, other future considerations are to examine how these noise tolerance measures change with hearing aid features to determine how much these features improve a person's noise tolerance. While we have guidelines on how to fit hearing aids in general, we do not have guidance on what might be the best settings for individual patient profiles for background noise. More research is needed in this area to maximize our ability to improve our patients' experiences in difficult listening environments. While there will always be a limitation due to the hearing loss and limitations of hearing aids, trying to maximize the hearing aid settings would be beneficial. This is a complex area of study due to the many factors that could impact noise tolerance and satisfaction with hearing aids, but one worth pursuing to determine if there are factors that could be manipulated to improve a person's ability to wear their hearing aids in background noise.

Chapter 5: Conclusions and Future Directions

Summary of Results

These three studies aimed to examine different aspects of evaluating a person’s performance with hearing aids and individual factors that can impact noise tolerance. The first study indicated that fNIRS may be a potential tool for evaluating listening effort. This could be beneficial for researchers, but may not be a clinically applicable tool due to set up and the cost of equipment. fNIRS could potentially be used to examine whether different hearing aid features decrease listening effort for individuals and could help guide evidence-based fitting guidelines based on findings. More research is needed in evaluating fNIRS for its feasibility in this endeavor.

The SMD study evaluated how adults with normal hearing and hearing loss were impacted by bandwidth at different intensity levels using 2 cpo. Results revealed poorer performance for the hearing loss group, with a wider bandwidth being more beneficial. This information could be used in the future to evaluate how hearing aid users SMD thresholds change with different bandwidths and intensity levels. This information could be used to evaluate different hearing aid features to determine what settings would provide the lowest SMD thresholds and determine if this changes a person’s tolerance to noise and speech recognition abilities.

The final study evaluated different listener factors that could impact a person’s noise tolerance. Results revealed that listening effort and digits in noise abilities could be used to predict changes in the ANL. A larger sample size is needed to determine if these factors hold true. If these factors hold true, future research could evaluate ways to improve listening effort and speech in noise abilities to help improve a person’s noise tolerance so they can wear their hearing aids longer. Future research also needs to determine who would be most likely to benefit from this potential treatment.

Future Directions

Future studies should continue to evaluate SMD thresholds and fNIRS as potential tools to examine a person’s ability to listen in background noise. A portable SMD test has been created for auditory research called the Portable Automated Rapid Testing (PART; Lelo De Larrea-Mancera et al., 2020). PART can be downloaded on a tablet for easy access. It could be shipped to participants, dropped off/picked up, or potentially downloaded to a participant’s own laptop or tablet. This tool provides several auditory tests in addition to SMD thresholds, including temporal fine structure processing, temporal amplitude modulation, and noise tasks. Lelo De Larrea-Mancera et al. (2020) evaluated PART in a group of normal hearing adults and reported high validity and test-retest reliability. PART is promising as it provides an easy-to-use tool for auditory researchers interested in psychoacoustics and evaluating a person’s abilities in background noise. For fNIRS, continued evaluation of its utility in auditory research is warranted. Once this is determined, it could be a powerful tool to evaluate real-world environments by using the portable version of fNIRS.

Another potential future direction is to continue evaluating factors that impact noise tolerance and determine if those factors can be changed to improve a hearing aid user's tolerance for high intensity background noise, such as listening effort. If a hearing aid user is able to accept more background noise, this could improve their satisfaction and increase the use of their hearing aids (Nabelek et al., 1991). One potential method to improve noise tolerance is to decrease the sensitivity of the central auditory gain, which controls suprathreshold sensitivity, via sound enrichment. Sound enrichment, or background noise, has been used for patients with tinnitus and hyperacusis and has been shown to decrease sensitivity of central auditory gain by increasing tolerance to noise (Sheppard et al., 2020). Gordon-Hickey et al. (2020) examined whether sound enrichment would improve noise tolerance using the ANL in young, normal hearing adults. Participants listened to background noise (fan, music, etc.) and after two weeks, ANLs for the sound enrichment group improved (had improved noise tolerance) compared to the control group.

Another method that could potentially improve listening comfort in noise and also speech recognition and cognition is auditory training. Bees et al. (2019) examined changes in loudness discomfort levels and ANLs after auditory training in normal hearing adults. Results revealed a significant decrease in the ANL (improved tolerance) for the auditory training group compared to the control group. This suggests that auditory training could potentially improve noise tolerance. Sweetow and Palmer (2005) conducted a systematic review on the evidence of auditory training in improving communication skills. Results revealed the need for more evidence-based research, but trends noted speech recognition in noise improved as well as participants’ active listening strategies.

Humes et al. (2019) examined auditory training at home and whether it improved speech recognition in noise. While improvements were noted for speech recognition in noise for trained materials, this improvement did not translate to non-trained outcome measures, including hearing aid satisfaction and noise tolerance. The researchers noted that training with frequent words may not have been ideal, and the task should have been more interactive. These studies suggest auditory training might improve speech recognition in noise. Lawrence et al. (2018) examined the impact of auditory and cognitive training on cognitive function for adults with hearing loss. This systematic review revealed the need for more research with results reporting a small effect of auditory training on cognition. An improvement in cognitive processing was noted for one study that incorporated cognitive training with auditory training (Anderson et al., 2013). Overall results are mixed and suggest that further research is required to determine the impact of auditory training on noise tolerance, speech recognition in noise, and cognitive processing. The potential of aural rehabilitation should be examined in future studies once more individual factors that impact noise tolerance have been determined and whom this would benefit based on these factors.

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Appendix A.

Checklist and Guidebook for at Home Testing

In-home tablet testing

- Set-up tablet for the participant
  - Make sure Tablet is charged
- Check calibration
- Put items in bag for participant
  - Tablet (2 – audiogram and other tests)
  - Loudspeaker
  - Headphones
  - Instructions notebook
  - Cleaning wipes
  - Pen
  - Sheet for recording
- Set-up a time to drop off tablet and to do testing
    - Date/time of tablet drop off___________________________

☐ Drop off tablet

☐ Be there for tablet testing and answer questions

Instructions for At Home Testing

Thank you for agreeing to participate in my dissertation study! This book contains instructions on how to complete the final at home portion of this study. If at any time you have questions, please do not hesitate to contact me by phone at: #, by email at: oedi0004@umn.edu, or we can set up a Zoom meeting as well.

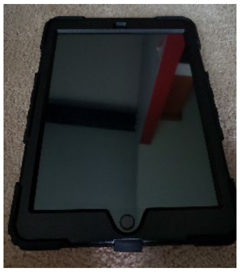
This final portion will consist of four tests:

1) A hearing screening
2) A listening in noise task where you will listen for numbers in background noise
3) A memory task
4) A noise tolerance task and make sound quality judgments

What is in the bag?

- A hearing screening kit (contains headphones and a tablet with a charger) – this will be used for the first part to test your hearing and listening in noise abilities

- A tablet to test your memory and noise tolerance abilities along with a charger



- A loudspeaker that will be used for the noise tolerance task along with a charger

- A blue instruction binder
- Sanitizing wipes

- A pen
- A tape measure

Instructions for hearing screening

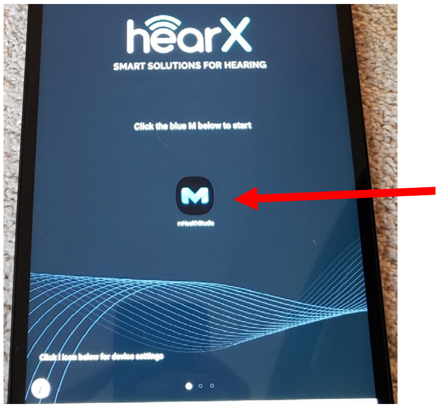
- You will complete this test without your hearing aids. The hearing screening equipment is in this bag.

- The headphones are on one side and the tablet is on the other side (in a pouch)

- To turn on the tablet press the power button on the side (top button). Hold the power button until the screen turns on. It will take the tablet a couple of minutes to warm up before proceeding. Then swipe anywhere on the screen to unlock the tablet.

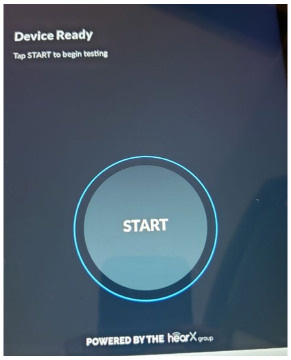
Power button

- Press the mHealthStudio icon on the screen

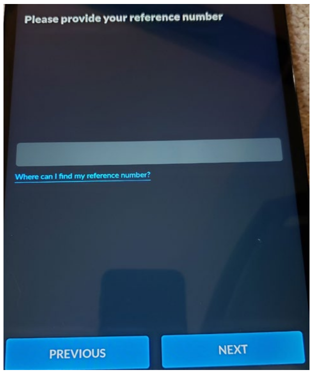


mHealthStudio icon

- Press the start button

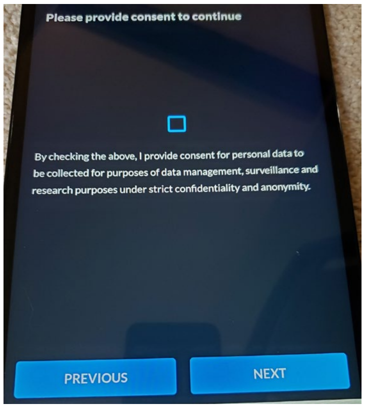


- On the next screen it asks for your reference number, put _________, and press next.



Please provide your reference number

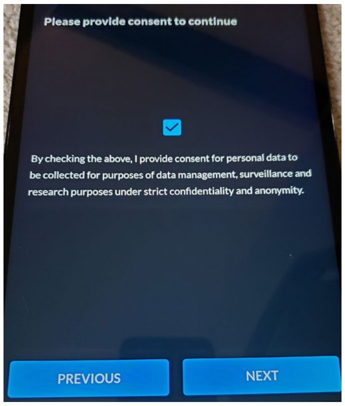
- On the next screen, press the box to check it and press next



Please provide consent to continue

☐

By checking the above, I provide consent for personal data to be collected for purposes of data management, surveillance and research purposes under strict confidentiality and anonymity.

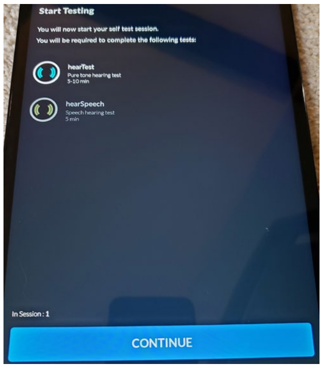


Please provide consent to continue

☑

By checking the above, I provide consent for personal data to be collected for purposes of data management, surveillance and research purposes under strict confidentiality and anonymity.

- This screen shows the tests you will complete, press continue



Start Testing

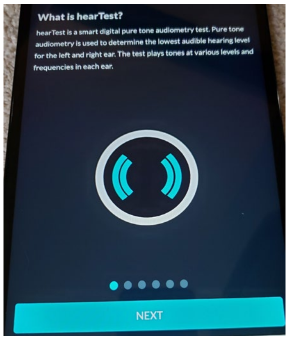
You will now start your self test session.
You will be required to complete the following tests:

hearTest
Pure tone hearing test
5-10 min

hearSpeech
Speech hearing test
5 min

In Session : 1

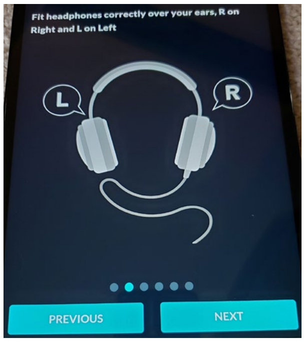
- Read through the instructions on the screen and press next



What is hearTest?

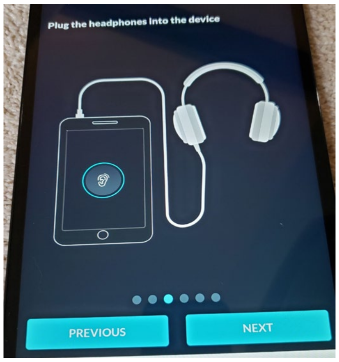
hearTest is a smart digital pure tone audiometry test. Pure tone audiometry is used to determine the lowest audible hearing level for the left and right ear. The test plays tones at various levels and frequencies in each ear.

- Next, put the headphones on your ears; note they are labeled R for the right ear and L for the left ear, then press next

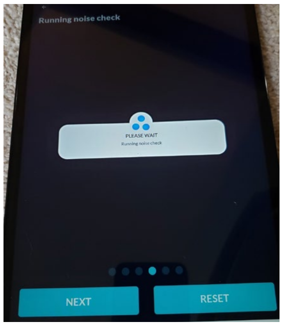

Fit headphones correctly over your ears, R on Right and L on Left

- Plug in the headphones in the headphone jack on top of the tablet and press next


Headphone jack


Plug the headphones into the device

- The tablet will run a noise test. If the room is quiet, it will let you know you are good to continue testing and can press next. If it is too noisy, it will let you know and you can click reset. When you move to a quieter place, press rest and run the test again. If it is good, press next.

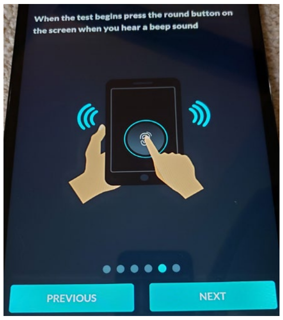


Running noise check

PLEASE WAIT

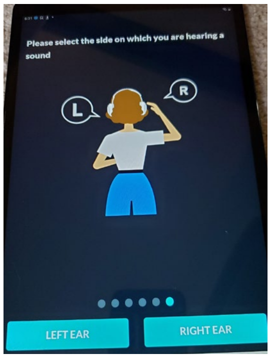
Running noise check

- Read through the instructions and press next



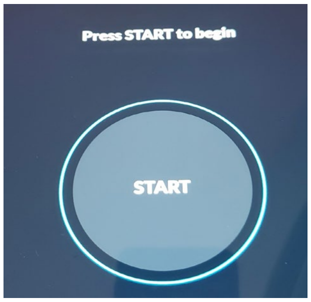
When the test begins press the round button on the screen when you hear a beep sound

- Read through the instructions and choose which ear you hear the sound in

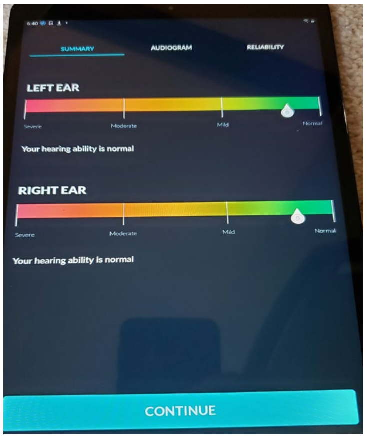


Please select the side on which you are hearing a sound

- Press start to start testing



- When the test is done you will see this screen. Press continue to go to the hearing in noise test

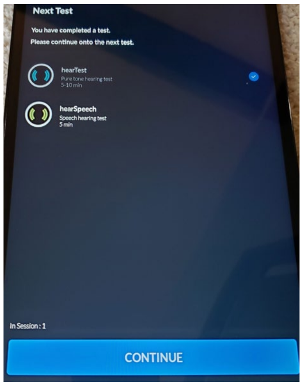


Your hearing ability is normal

Your hearing ability is normal

Instructions for hearing in noise test

- Press continue



Next Test

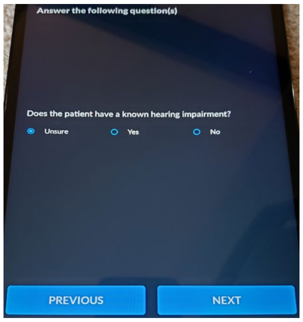
You have completed a test.
Please continue onto the next test.

hearTest
Pure tone hearing test
5-10 min ☑

hearSpeech
Speech hearing test
5 min

In Session : 1

- Answer the question on the screen by pressing your selection and press next

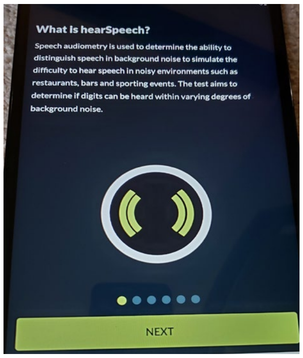


Answer the following question(s)

Does the patient have a known hearing impairment?

● Unsure ○ Yes ○ No

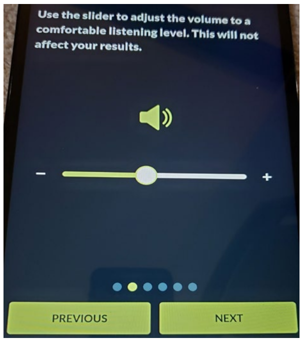
- Read the instructions and press next



What is hearSpeech?

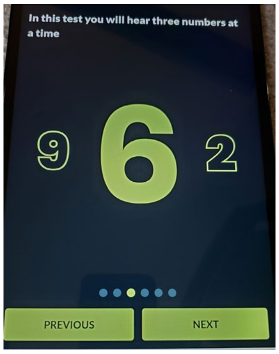
Speech audiometry is used to determine the ability to distinguish speech in background noise to simulate the difficulty to hear speech in noisy environments such as restaurants, bars and sporting events. The test aims to determine if digits can be heard within varying degrees of background noise.

- Read the instructions and adjust the volume by putting your finger on the circle on the line and moving it either to the right to make the speech louder or to the left to make the speech softer, then press next



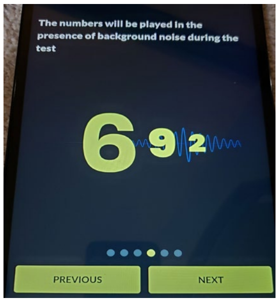
Use the slider to adjust the volume to a comfortable listening level. This will not affect your results.

- Read the instructions and then press next



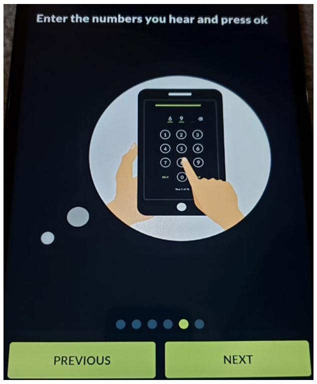
In this test you will hear three numbers at a time

- Read the instructions and then press next



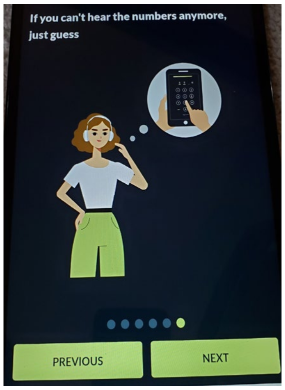
The numbers will be played in the presence of background noise during the test

- Read the instructions, then press next



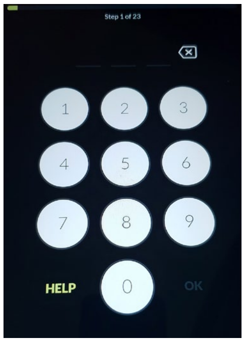
Enter the numbers you hear and press ok

- Read the instructions, then press next



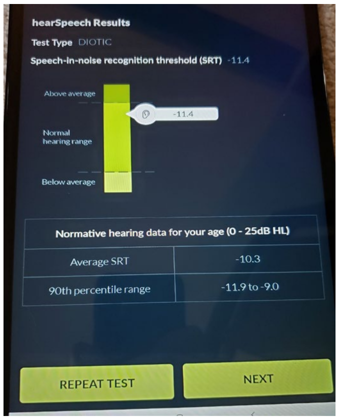
If you can't hear the numbers anymore, just guess

- The test will start (see screen below)



Step 1 of 23

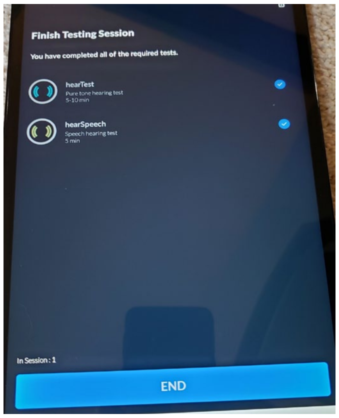
- When you are done you will see the following screens, press next and end and press the power button just to turn the screen off (you do not have to turn the tablet off)


hearSpeech Results

Test Type DIOTIC

Speech-in-noise recognition threshold (SRT) -11.4

Normative hearing data for your age (0 - 25dB HL)	
Average SRT	-10.3
90th percentile range	-11.9 to -9.0


Finish Testing Session

You have completed all of the required tests.

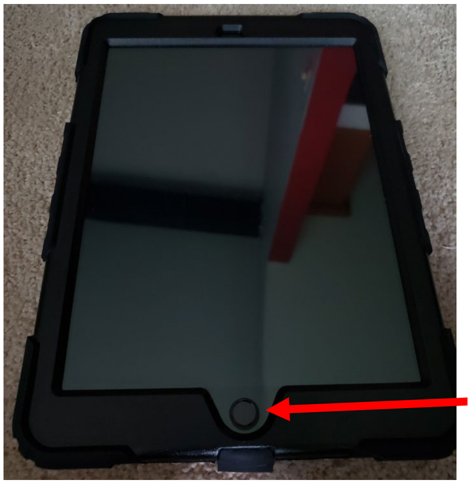
hearTest ✓
Pure tone hearing test
5-10 min

hearSpeech ✓
Speech hearing test
5 min

In Session : 1

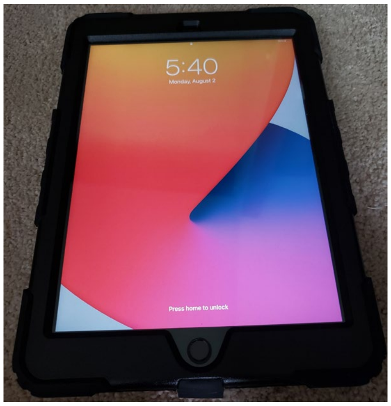
Instructions for working memory test (https://ubiq-x.gitlab.io/rspan/)

- You will not need your hearing aids for this test. You will use this tablet for testing. To turn on the tablet, press the home button on the bottom.

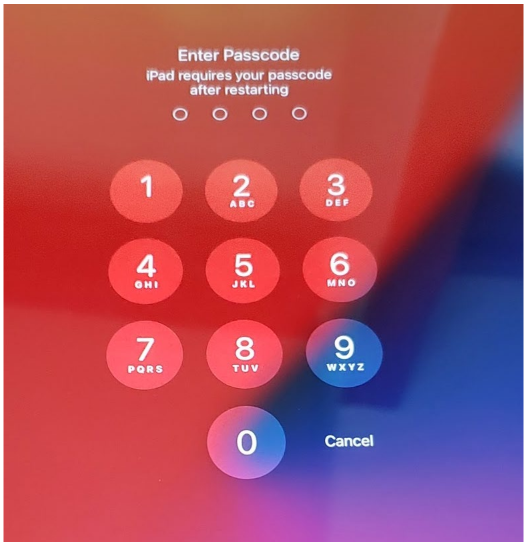


Home button

- Press the home button to unlock the screen



- A password screen will appear, **the password is #**



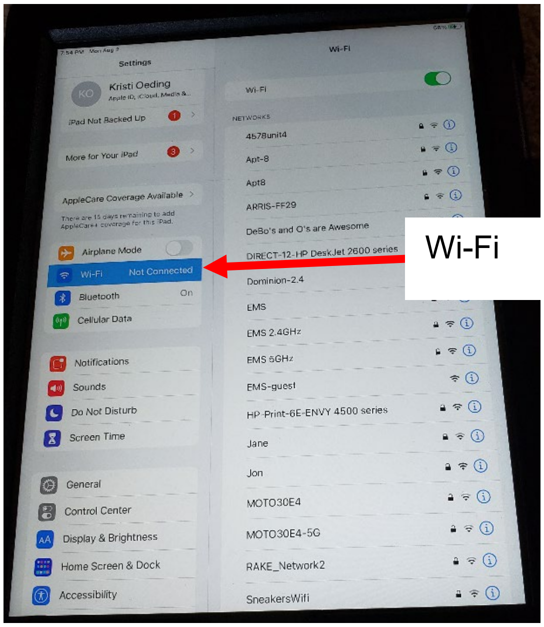
Enter Passcode

iPad requires your passcode after restarting

- To do this task, you will need to connect the tablet to the internet. You will need to know your password for your internet. If you do not know your password, let me know and I can send the link for the memory task to your email and you can complete it on a computer at home and send me the results.
- To connect to the internet, press the settings icon on the bottom right

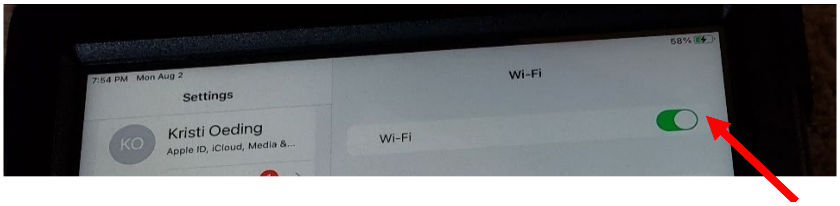
Settings icon

- On the left hand side of the screen, find Wi-Fi and press it



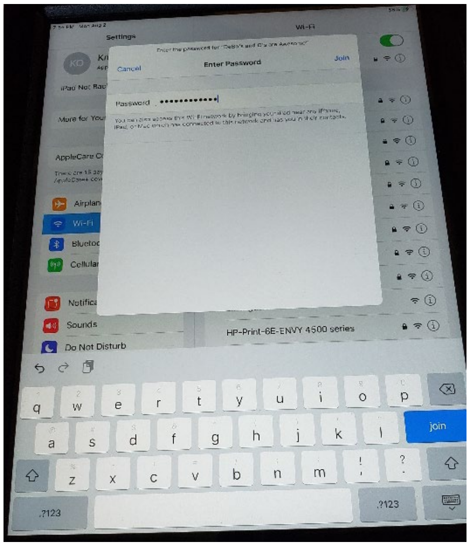
Wi-Fi

- The tablet will start searching for your internet. If you don't see it, turn the Wi-Fi off and on again by pressing the button near Wi-Fi on the top of the screen (it will turn grey when turned off and green when turned on again)

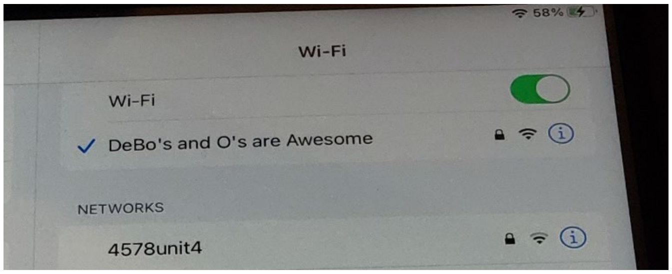


Wi-Fi on/off button

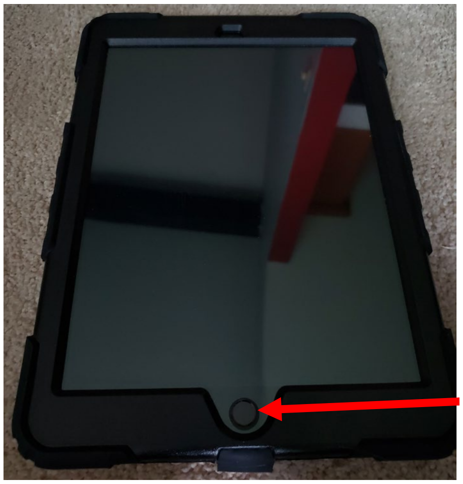
- When you see your internet in the list, press the name and it will prompt you to enter the password. When done entering your password, press Join



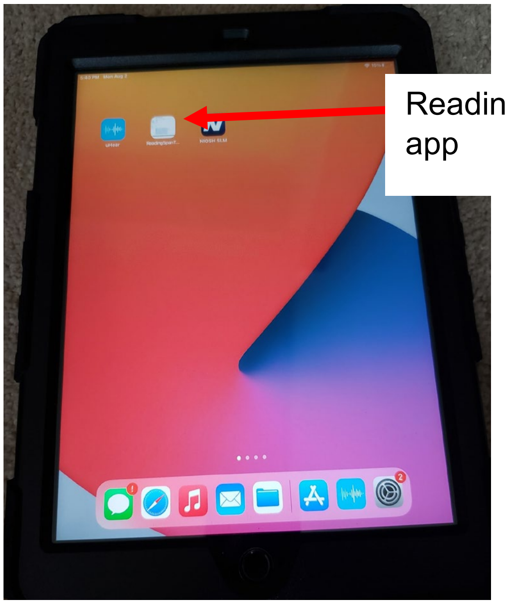
- When you are connected to the internet, you will see your internet below the on/off button on top with a check mark by the name.



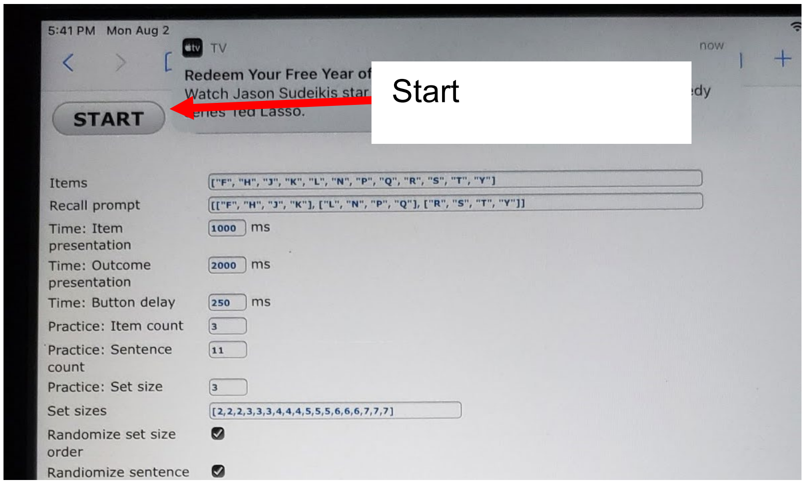
- To go back to the home screen, press the home button


Home button

- Press the ReadingSpanTest app to open the memory task


ReadingSpanTest app

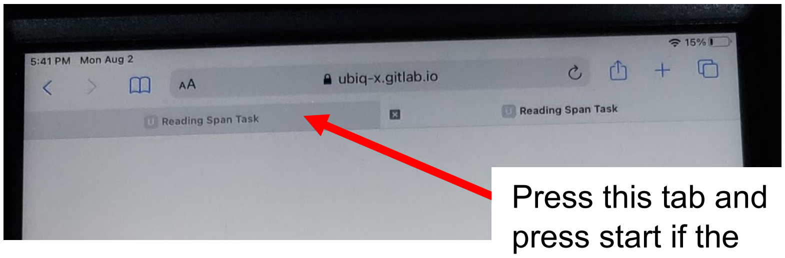
- Press start



Start

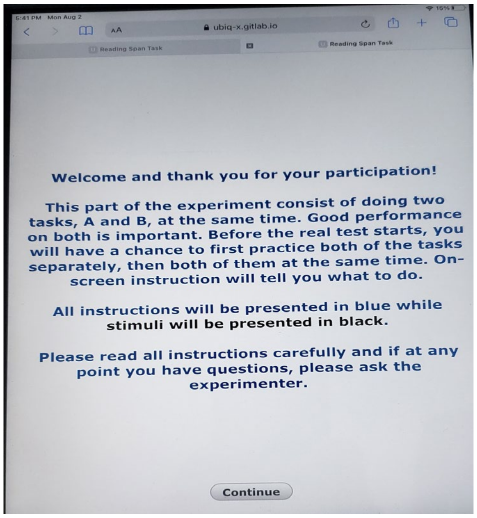
Items	["F", "H", "J", "K", "L", "N", "P", "Q", "R", "S", "T", "Y"]
Recall prompt	[["F", "H", "J", "K"], ["L", "N", "P", "Q"], ["R", "S", "T", "Y"]]
Time: Item presentation	1000 ms
Time: Outcome presentation	2000 ms
Time: Button delay	250 ms
Practice: Item count	3
Practice: Sentence count	11
Practice: Set size	3
Set sizes	[2,2,2,3,3,3,4,4,4,5,5,5,6,6,6,7,7,7]
Randomize set size order	☑
Randiomize sentence	☑

- If the memory task doesn't load, go back to the first Reading Span Task tab and press start again



Press this tab and press start if the task doesn't load

- Read through and follow the instructions on the screen. You will be taken through some practices tasks and then complete the memory task.



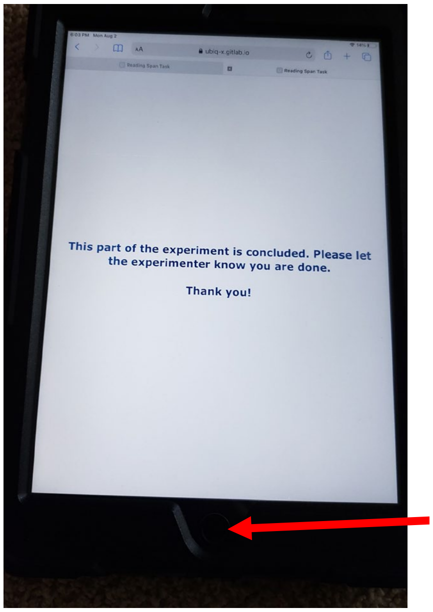
Welcome and thank you for your participation!

This part of the experiment consist of doing two tasks, A and B, at the same time. Good performance on both is important. Before the real test starts, you will have a chance to first practice both of the tasks separately, then both of them at the same time. On-screen instruction will tell you what to do.

All instructions will be presented in blue while stimuli will be presented in black.

Please read all instructions carefully and if at any point you have questions, please ask the experimenter.

- When you are done, you will see the following screen, press the Home button to close the screen.



This part of the experiment is concluded. Please let the experimenter know you are done.

Thank you!

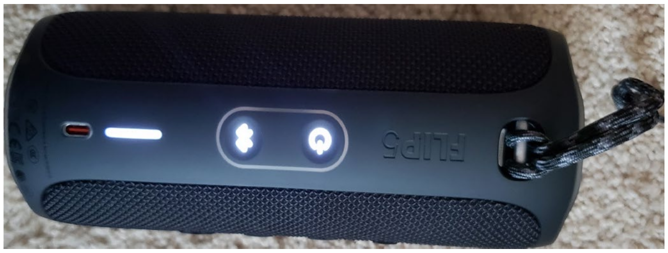
Home button

- You will use this tablet to complete the noise tolerance task

Instructions for Acceptable Noise Level test/sound quality ratings task

- You will use the loudspeaker with the tablet for this task
- To turn on the loudspeaker, press the power button until the loudspeaker turns on

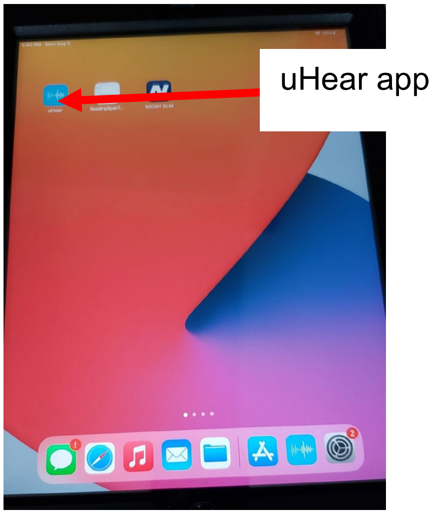
- You may hear the loudspeaker come on and you will see the light turn on as well



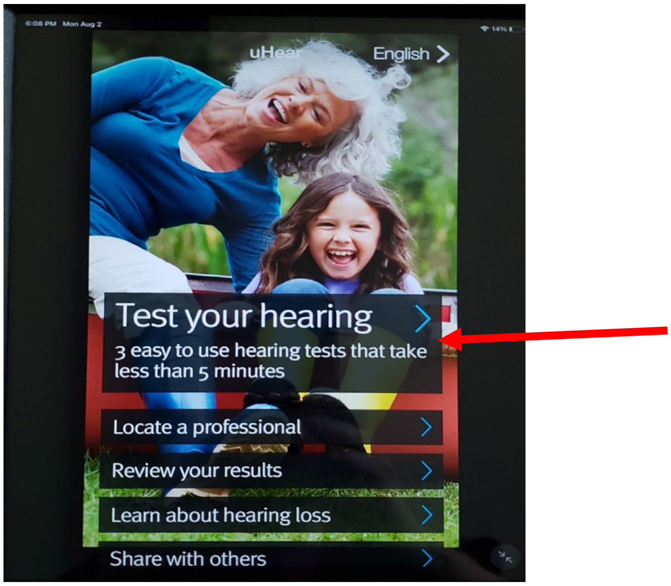
- The loudspeaker sits like this on a surface with the JBL label facing you. You will want to place the loudspeaker on a table facing you and sit about 3 feet from the loudspeaker (there is a tape measure you can use to estimate distance in the bag).

- <u>For the first part, you will wear your hearing aids.</u>

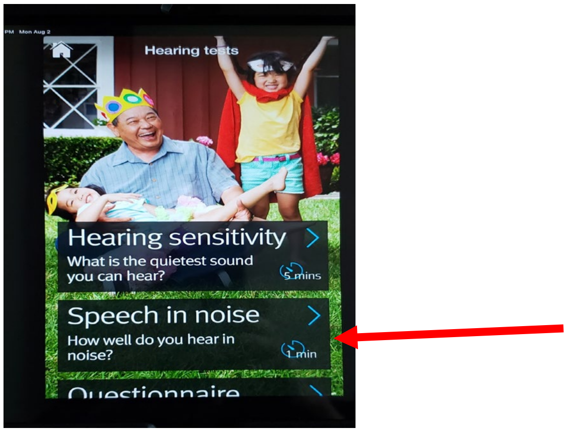
- Press the uHear app to open it



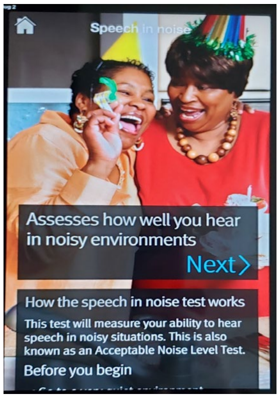
- Press the Test your hearing option



- You will be taking the speech in noise test three times. Press the speech in noise option to see the instructions.



- Read through the instructions (you will have to scroll down to read all of the instructions), then press next. NOTE: In the before you begin section, you can ignore the instructions about headphones as you will use the loudspeaker and about the tablet settings as this has been taken care of.



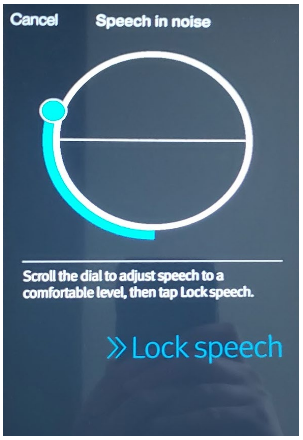
Assesses how well you hear in noisy environments

How the speech in noise test works

This test will measure your ability to hear speech in noisy situations. This is also known as an Acceptable Noise Level Test.

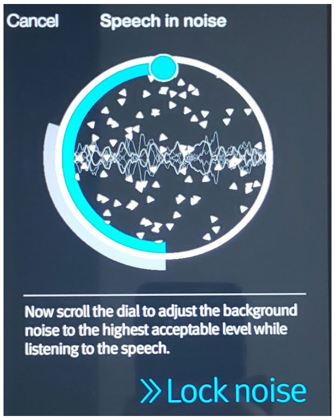
Before you begin

- The following screen will appear, follow the instructions (to turn the volume of the speech up, put your finger on the blue circle and move it clockwise, to turn the volume down, move the blue dot counterclockwise)



Scroll the dial to adjust speech to a comfortable level, then tap Lock speech.

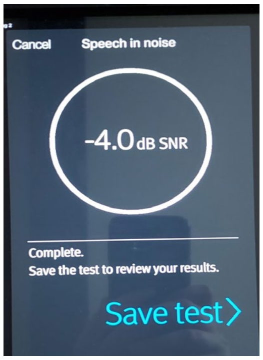
- When you find the volume that is comfortable, press lock speech
- The next screen will appear, follow the instructions (to turn the volume of the noise up, put your finger on the blue circle and move it clockwise, to turn the noise down, move the blue dot counterclockwise)



Now scroll the dial to adjust the background noise to the highest acceptable level while listening to the speech.

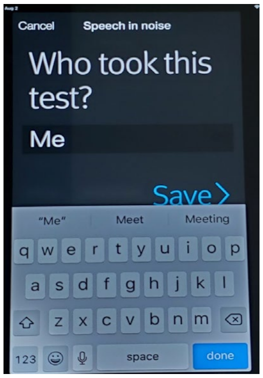
- When you find the volume that is the highest acceptable level when listening to speech, press lock noise

- The following screen will appear, press save test



Complete.
Save the test to review your results.

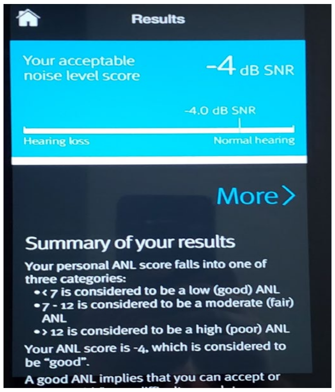
- On the next screen, you can leave the name as me and press save



Who took this test?

Me

- You are welcome to read the summary, but do not have to. Press more to move to the next screen.



Your acceptable noise level score -4 dB SNR

Summary of your results

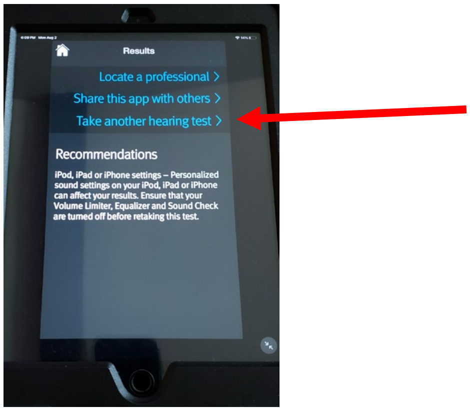
Your personal ANL score falls into one of three categories:

- < 7 is considered to be a low (good) ANL
- 7 - 12 is considered to be a moderate (fair) ANL
- > 12 is considered to be a high (poor) ANL

Your ANL score is -4. which is considered to be "good".

A good ANL implies that you can accept or

- Press take another test and do the test again (Speech in noise) for a second time



iPod, iPad or iPhone settings – Personalized sound settings on your iPod, iPad or iPhone can affect your results. Ensure that your Volume Limiter, Equalizer and Sound Check are turned off before retaking this test.

- <u>After the second time, complete the test a third time (a total of three tests).</u>
- When done, press lock noise and save the test (press save test, save as me, and then press more).
- <u>Now repeat the same task three times without your hearing aids.</u>
- You are now done with the test and can press the home button and the tablet will shut itself off.
- Press and hold the power button on the loudspeaker until it turns off.

Congratulations! You have completed the research study. When you are done, contact Kristi either by phone: # or by email: oedi0004@umn.edu to set-up a time for her to pick up the equipment.

She will bring a payment form for you to complete to receive your reimbursement for participating. If this study took you more than 4 hours, please let her know. Thank you again for your willingness to participate!

Appendix B.

Variance Inflation Factor

Independent Variables	Variance Inflation Factor
Activation	8.87
Attention	11.38
Inhibition	36.29
Domain A	242.32
Domain C	71.52
Domain E	9.92
Domain NE	425.83
Domain OM	85.93
Conv	279.93
Listen	45.57
Pleasure	377.22
Quiet	75.04
Speech	39.59
Use	8.24
SC	131.97
Weinstein	49.31
PU	76.02
Digits	176.81

PTA_R	232.77
PTA_L	25.81

Appendix C.

ANL Study R Code

```
### Load data and libraries ###
library(glmnet)
library(readxl)
Main_Use <- read_excel("C:/Users/ql3448wd/OneDrive - MNSCU/Desktop/Main_Use.xlsx")
View(Main_Use)

### Data Preprocessing ###
### Create response variable ###
y = Main_Use$ANL_A
n = length(y)

### Create model design matrix (without intercept) ###
X = model.matrix(~., data=Main_Use[,1:20])
X = X[,-1]

### Check size of X ###
dim(X)

### Create fold assignments for 5-fold CV ###
```

```
set.seed(819)

### 5-fold CV to estimate lambda ###
cvlasso = cv.glmnet(X, y, nfolds=5, alpha=1)

### Plot results ###
plot(cvlasso)

### Get the coefficients ###
lassocoef.min = coef(cvlasso, s="lambda.min")
lassocoef.1se = coef(cvlasso, s="lambda.1se")

### Find lambda ###
best_lambda <- cvlasso$lambda.min
best_lambda

### Find the best fitting model ###
best_model <- glmnet(X, y, alpha = 1, lambda = best_lambda)
coef(best_model)

modcoef = as.matrix(coef(best_model))
modcoef
```

```
### Find r-squared ###

y_predicted <- predict(best_model, s = best_lambda, newx = X)

sst <-sum((y = mean(y))^2)

sse <- sum((y_predicted - y)^2)

rsq <-1 - sse/sst

rsq
```