PREDICTING BENEFIT FROM A SIGNAL-TO-NOISE RATIO HEARING AID INTERVENTION BASED ON INDIVIDUAL DIFFERENCES IN HEARING AND COGNITION WITHIN AN OLDER ADULT POPULATION

by

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As members of the Dissertation Committee, we certify that we have read the dissertation prepared by James Shehorn, titled Predicting Benefit from a Signal-to-Noise Ratio Hearing Aid Intervention Based on Individual Differences in Hearing and Cognition within an Older Adult Population and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

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Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copies of the dissertation to the Graduate College.

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DEDICATION

This dissertation is dedicated to my wife, the hardest working person I know, and to my son, my biggest source of inspiration.

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ABSTRACT

Difficulty perceiving speech in noise is a common complaint for individuals with hearing loss, even while wearing hearing aids. Current clinical test measures are limited in their ability to predict potential benefit from hearing aid interventions such as directionality. If speech in noise interventions provide an SNR boost, then the slope of a speech in noise psychometric function or rate of improvement could help to predict the corresponding intelligibility benefit due to an improved SNR. Recent research highlights the association between cognition, hearing loss, and speech perception in noise. We hypothesized that the rate of improvement, which is likely associated with both auditory and cognitive factors, may be a source of the variable benefit observed from directionality.

Our study revealed that more intelligibility benefit due to hearing aid directionality was measured in a listening condition which resulted in steeper rate of improvement (babble background) than a listening condition which resulted in a shallower rate of improvement (competing speech). Additionally, the rates of improvement between our most relevant SNRs were significantly associated with directional benefit. These results confirm that the rate of improvement for a given range of SNRs could help in predicting potential benefit from an SNR intervention within a hearing loss population. Our results confirmed that hearing loss severity of negatively associated with rate of improvement and working memory capacity was positively associated with rate of improvement. Our findings support the involvement of cognition in addition to the auditory pathway for the perception of degraded speech signals within a population with hearing loss. Measuring cognitive factors such as working memory capacity could improve our understanding of patient variability for aided speech in noise outcomes and provide a patient-specific approach to hearing loss interventions.

CHAPTER ONE: INTRODUCTION

The Speech-in-Noise Problem

More than 38 million adults in the United States have at least a mild hearing loss in both ears (Goman & Lin, 2016), leaving many listeners, particularly older adults, with limited audibility and reduced speech intelligibility. A common complaint of adults with hearing loss is difficulty perceiving speech in noise. Listeners with hearing loss not only experience reduced audibility but also often exhibit a significant disadvantage compared to listeners with normal hearing when listening in noisy environments (Bronkhorst, 2000; Kochkin, 2012; McCormack & Fortnum, 2013; Moore et al., 2014; Plomp, 1986). This disadvantage can make adverse listening conditions more aversive to individuals with hearing loss which may contribute to the reduced social activity and reduced quality of life observed in this population (Arlinger, 2003; Ciorba et al., 2012; Dalton et al., 2003).

Additionally, speech perception performance in noise is highly variable within the population of adults with hearing loss, even when wearing hearing aids (Heinrich et al., 2015; Humes, 2007). Much of the observed variability in speech perception in noise performance is unexplained, even when accounting for common audiologic measures such as pure tone thresholds and word recognition scores in quiet (Holube & Kollmeier, 1996; Humes et al., 1986; Killion & Niquette, 2000; Pavlovic, 1984; Pavlovic et al, 1986). It is therefore necessary to look beyond the audiogram for potential contributors to speech perception in noise performance.

Speech perception in noise is a complex task in which individuals utilize cognitive processes to compensate for an unclear speech signal, especially when a speech signal is already distorted due to a hearing loss. Adverse listening conditions often introduce distortion to the speech signal. As a result, listeners must maintain the signal within short term memory for its repair. Further, listeners must maintain attention on the task and inhibit distracting stimuli. Therefore, it is probable that cognitive factors in addition to auditory factors contribute to speech perception in noise performance. Indeed, a growing number of studies have found links between cognition and speech perception in noise performance (Akeroyd, 2008; Besser et al., 2013; Dryden et al., 2017; Pichora-Fuller, 1995; Rönnberg et al., 2010; Wingfield et al., 2005). Recent evidence has also demonstrated links between cognitive factors and aided listening as well (Arehart et al., 2013; Arehart et al., 2015; Cox & Xu, 2010; Ellis & Munro, 2013; Gatehouse et al., 2003, 2006; Ng et al., 2013; Rudner et al., 2011; Sarampalis et al., 2009; Souza et al., 2015). For example, Arehart and colleagues (2013, 2015) found that speech perception in noise performance while wearing hearing aids with frequency compression was associated with working memory capacity, and this association was strongest when the compression settings were set to the highest level of compression. The authors hypothesized that older adults with good working memory capacity are less susceptible to alterations of an acoustic signal due to hearing aid signal processing strategies like frequency compression.

For the purposes of this dissertation, I will be focusing on bilateral, symmetrical, sensorineural hearing loss, which is a common presentation for age-related hearing loss. Bilateral hearing aids are the most common intervention for individuals with bilateral hearing loss, but a lack of perceived benefit from hearing aids, particularly in noise, causes many individuals to stop wearing their hearing aids or to not purchase them at all (Kochkin, 2007; McCormack & Fortnum, 2013; Meyer & Hickson, 2012). Hearing aids can amplify sounds to potentially restore audibility to individuals with hearing loss, but hearing aids are limited in their ability to differentiate between speech signals and noise, resulting in amplification of both the signal and background noise. There are, however, hearing aid strategies intended to improve listener outcomes in difficult listening conditions.

Hearing Aid Strategy: Directionality

Several hearing aid program strategies are used to improve listener outcomes in noise such as digital noise reduction, remote microphones, or directional microphones. The focus of this dissertation is on directional microphones since they are a very common strategy to aid speech perception in noise. Directional signal processing is a common hearing aid strategy that makes use of multiple microphones in an array to attenuate sounds arriving from behind or beside a listener. Dual microphone signal processing attenuates sounds coming from behind and the sides of the listener by applying a time delay to the acoustic signal arriving at the rear microphone port and subtracting that from the acoustic signal arriving at the front microphone port. This subtraction process can attenuate sounds arriving at the rear microphone port first and on average provides about a 3-6 dB boost in the signal-to-noise ratio (SNR) when a listener's head is oriented to the speech signal (Ricketts, 2001). The angles of maximum attenuation are called the "nulls" of the directivity pattern. A further advancement of directionality called adaptive directionality functions by analyzing input sound sources, estimating the directions of a speech signal and background noises, and adjusting the nulls to the angles from which the noise is arriving. This strategy is most useful when the noise source is consistently arriving from a single direction (Ricketts et al., 2005).

Variability in Outcomes with Hearing Aid Directionality

One might expect that when the SNR is improved by a given amount through a hearing aid strategy such as directionality, hearing aid users should receive similar levels of objective (e.g. intelligibility score) and subjective benefit (e.g. effort rating). However, both subjective

(Bentler, 2005; Cord et al., 2002) and objective benefit from directional processing (Galster & Rodemerk, 2013; Killion et al., 1998; Ricketts, 2000; Ricketts & Mueller, 2000) are highly variable between individuals, with some listeners receiving a large boost in intelligibility and self-reported benefit, while other listeners report little to no benefit from directional processing. Moreover, the large variability in patient performance in response to hearing aid directionality is not well predicted by an individual's hearing sensitivity as measured by pure tone audiometry (Ricketts & Mueller, 2000). The real-ear directivity index has been found to be a good predictor of directional benefit for speech recognition in noise (Dhar et al., 2004; Dittberner & Bentler, 2007), however this finding cannot explain why individuals who receive the same acoustic benefit in SNR can have highly variable recognition benefit.

Significance of the Variability Problem

The variable outcomes in objective and subjective benefit from directionality for speech perception in noise makes the hearing aid selection, fitting, and counseling process challenging for audiologists and limits their ability to make evidence-based individualized decisions regarding hearing aid options. Even though it is difficult for clinicians to anticipate their patients' potential benefit from speech in noise interventions, the top factor for hearing aid selection by audiologists is the perceived level of need for speech in noise management (Gioia et al., 2015). The authors concluded that this judgment made by audiologists likely relies on opinions and preferences for fitting various hearing aid strategies as well as their patient's level of hearing acuity/activity level rather than evidence provided by either research or a clinical test result which could help to predict individual benefit from various hearing aid strategies. Given the variability in objective and subjective outcomes for directionality, further study is critical to determine which listeners could potentially benefit from the intervention in order to guide patient-centered hearing aid feature selection. Counseling patients regarding their expectations for potential benefit from hearing technology in noisy listening environments would be improved through a better understanding of the key factors contributing to the unpredictability of patient outcomes with hearing aid speech in noise interventions.

Predicting Hearing Aid Outcomes

There is a long history of research directed toward predicting individual speech perception in noise ability and hearing aid outcomes. Early attempts to predict speech perception in noise made use of the pure tone audiogram. The articulation index and speech transmission index were developed to be acoustical indices derived from pure tone thresholds for the prediction of speech intelligibility (Fletcher & Galt, 1950; Steeneken & Houtgast, 1980). These measures were shown to have limited ability in predicting speech perception in noise ability for individuals with hearing loss given that much of the variance was not explained the articulation index or speech transmission index calculations (Holube & Kollmeier, 1996; Humes et al., 1986; Pavlovic, 1984; Pavlovic et al, 1986). Individuals with similar pure tone thresholds often exhibit vastly different speech recognition in noise performance (Dirks et al., 1982; Killion & Niquette, 2000). Measures of speech recognition in quiet were also found to only weakly relate to both unaided and aided speech perception in noise (Plomp, 1986; Plomp, 1994), as well as aided satisfaction (Killion & Gudmundsen, 2005). Therefore, a standard clinical test battery of pure tone audiometry and word recognition testing in quiet do not appear to be particularly useful predictors of unaided and aided speech perception in noise.

Because speech perception in quiet performance is an inadequate predictor of unaided or aided speech recognition in noise, it was clear that it was critical to directly measure speech perception in noise for patients with hearing loss. Several clinical measures have been developed to test speech perception in noise abilities at a fixed signal-to-noise ratio (SNR; e.g., Revised Speech in Noise test, Bilger et al., 1984) and to find the signal-to-noise ratio needed for 50% correct performance (e.g., QuickSIN, Killion, et al., 2004), reported as SNR loss relative to a population with normal hearing sensitivity. These test methods are helpful for assessing deficits in speech perception in noise which determines the need for an intervention to improve the SNR, such as hearing aid directionality or an assistive listening device. However, the measures do not inform the clinician or patient regarding potential speech perception improvement due to an SNR intervention.

The QuickSIN test measures speech recognition performance across a broad range of SNRs. Performance can be tracked across the range of SNRs, and the data points can be fit with a psychometric function, although the QuickSIN protocol only reports the 50% performance SNR (as either threshold or 'SNR Loss,' the threshold relative to normative data). Within the field of psychoacoustics, the psychometric function describes the relation between an acoustic variable and a perceptual variable. Psychoacousticians commonly measure the relation between changes in absolute signal intensity or intensity changes relative to a competing noise (e.g., dB SNR) and the effect of those changes on intelligibility. This function fit to behavioral data typically takes the shape of a sigmoid (see Figure 1).

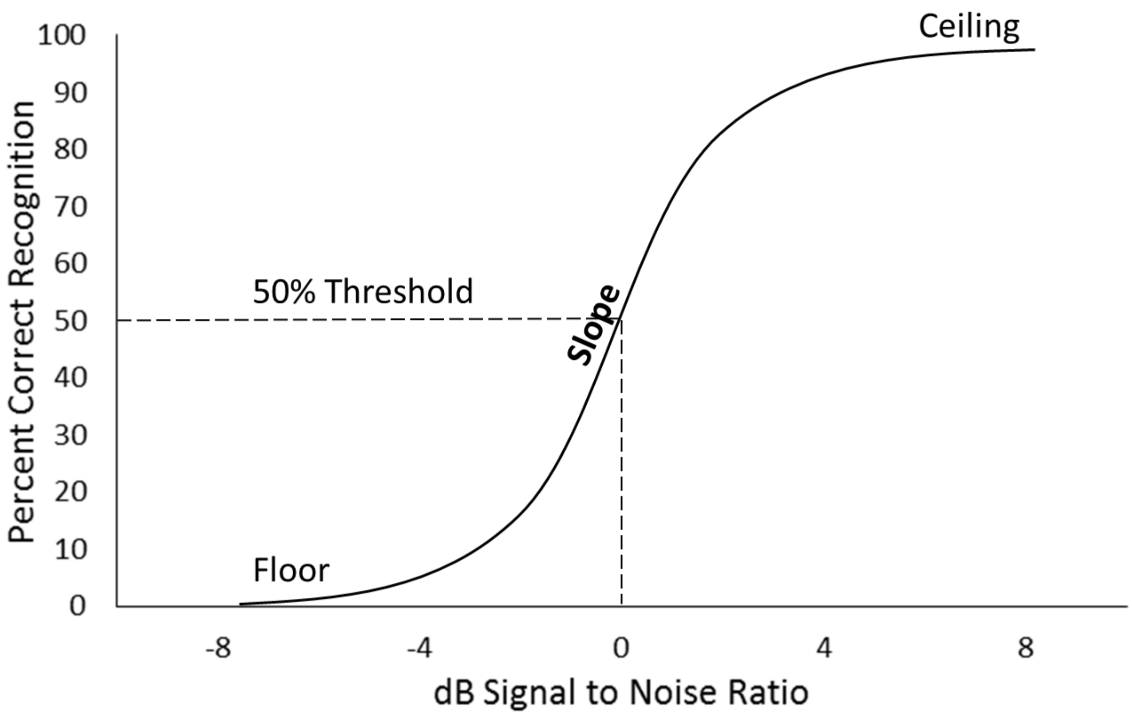

Figure 1. Psychometric function. An example of a psychometric function, plotting percent correct recognition as a function of dB SNR.

The fitted psychometric function provides several pieces of information including ceiling performance, floor performance, a threshold (typically set at the 50% or 75% point) and the slope of the function (rate of improvement). The slope of the psychometric function describes the rate of intelligibility improvement as a signal becomes more intense either by itself or relative to a competing noise or masker. If speech perception benefit from an SNR intervention is quantified as increased intelligibility due to an improved SNR, then the unaided rate of improvement across SNRs (i.e. slope of the SNR psychometric function) should effectively predict intelligibility benefit due to an SNR intervention (MacPherson & Akeroyd, 2014). In other words, measuring the rate of improvement would help to inform how much speech perception benefit a listener would experience from an improved SNR, which will be the focus of this dissertation. For example, an individual with a shallow rate of improvement would receive less of an intelligibility boost from a given improvement in signal-to-noise ratio than an individual with a steeper rate of improvement, even if they were to have the same threshold (50% point; see figure 2).

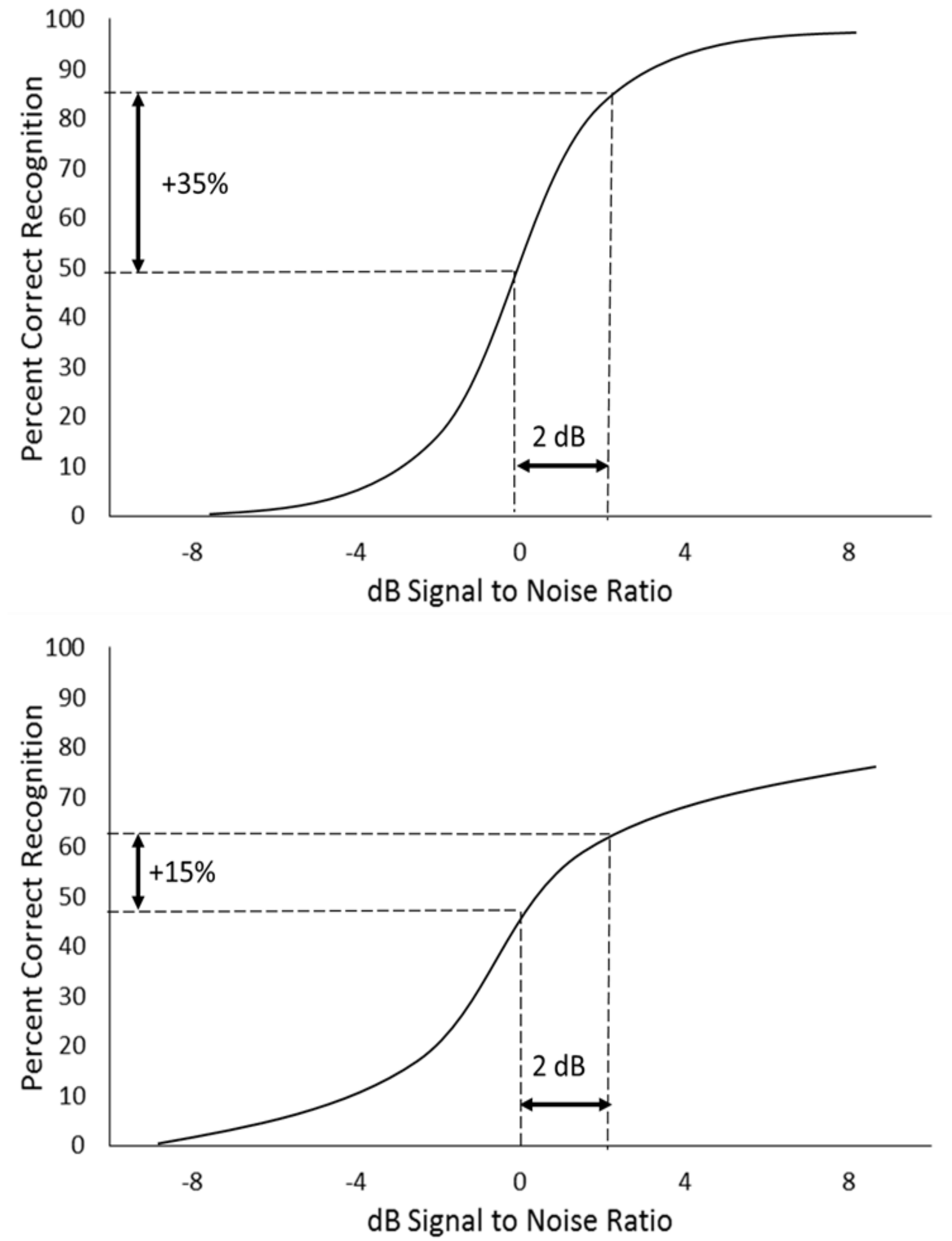

Figure 2. Slope of psychometric function and recognition. Example psychometric functions representing a steep psychometric function (upper panel) vs. a shallow psychometric function (lower panel) and their different gains in recognition due to an increase in the SNR despite having the same 50% threshold.

Individuals with steeper functions would have an advantage for potential objective and subjective benefit from an SNR intervention. Generally speaking, objective aided performance in noise positively correlates with subjective ratings for difficult listening conditions (Cox & Alexander, 1992; Humes et al., 1996; Mendel, 2007; Peeters et al., 2009), although several studies have also noted significant objective benefit but no subjective benefit due to directionality (Bentler et al., 2006; Gnewikow et al., 2009; Palmer et al., 2006; Ricketts et al., 2003; Walden et al., 2000). Therefore, if an individual has a steep rate of improvement in noise, one could expect objective benefit and possibly subjective benefit from an SNR intervention.

Factors Influencing Rate of Improvement on Speech Perception in Noise Tasks

The studies that have measured the rate of speech perception in noise improvement across SNRs for individuals with hearing loss have found significant variability in the rates of improvement even when accounting for hearing loss severity and configuration (Bosman & Smoorenburg, 1995; McArdle, et al., 2005; Wagener & Brand, 2005; Wilson et al., 2007). The variability in rate of improvement could be a potential source of the variability observed in speech recognition benefit from SNR interventions. Since the rate of intelligibility improvement is likely an accurate method to quantify the expected benefit from an improved SNR, it is critical to better understand the factors that contribute to its variability.

Individual differences in cognitive function. Real-world acoustic environments often become demanding listening conditions due to multiple, competing sound sources, requiring listeners to determine which stimuli are significant and to fill in missing information from the signal with top-down processing. These processes likely rely on the function of the cognitive domains of working memory and executive function. Working memory is a limited capacity cognitive domain responsible for the manipulation and short-term storage of incoming information (Baddeley, 2000). Working memory has been the most commonly measured variable for the hearing aid studies that have intended to measure cognition (Souza et al., 2015). Working memory would be necessary for speech perception in noise, particularly for individuals with hearing loss, because both hearing loss and noise result in an attenuated and degraded speech signal, which requires explicit processing and manipulation (see figure 3). Hearing aids can help to overcome the attenuation of the message by applying gain but cannot overcome the distortion of a speech signal created by a sensorineural hearing loss and further degraded through the mixing of the noise with the encoding of the signal. A degraded message must then be held within short-term memory for further processing, which would require working memory function. Easily recognizable speech is likely implicitly processed and does not require further processing to arrive at the meaning of the message.

Executive function enables individuals to allocate cognitive resources for a task, shift attention between tasks, update items being held in working memory with new relevant information, and inhibit distractor stimuli (Miyake et al., 2000). When an individual is holding a conversation or multiple conversations in a noisy environment (classic cocktail party effect; Cherry, 1953), he/she has to firstly maintain attention on the current conversation and avoid attending to any background conversations (competing speech). This person may also have to divide attention to multiple conversations at once, maintaining and updating information coming from multiple speakers, essentially juggling tasks. Rapid task switching between listening, speaking, drinking, etc. would take place in this scenario. Another executive function in the form of inhibition would be necessary as well to limit wandering thoughts, responses to background conversations, or prepotent responses to the current conversation that may have been primed by prior conversations.

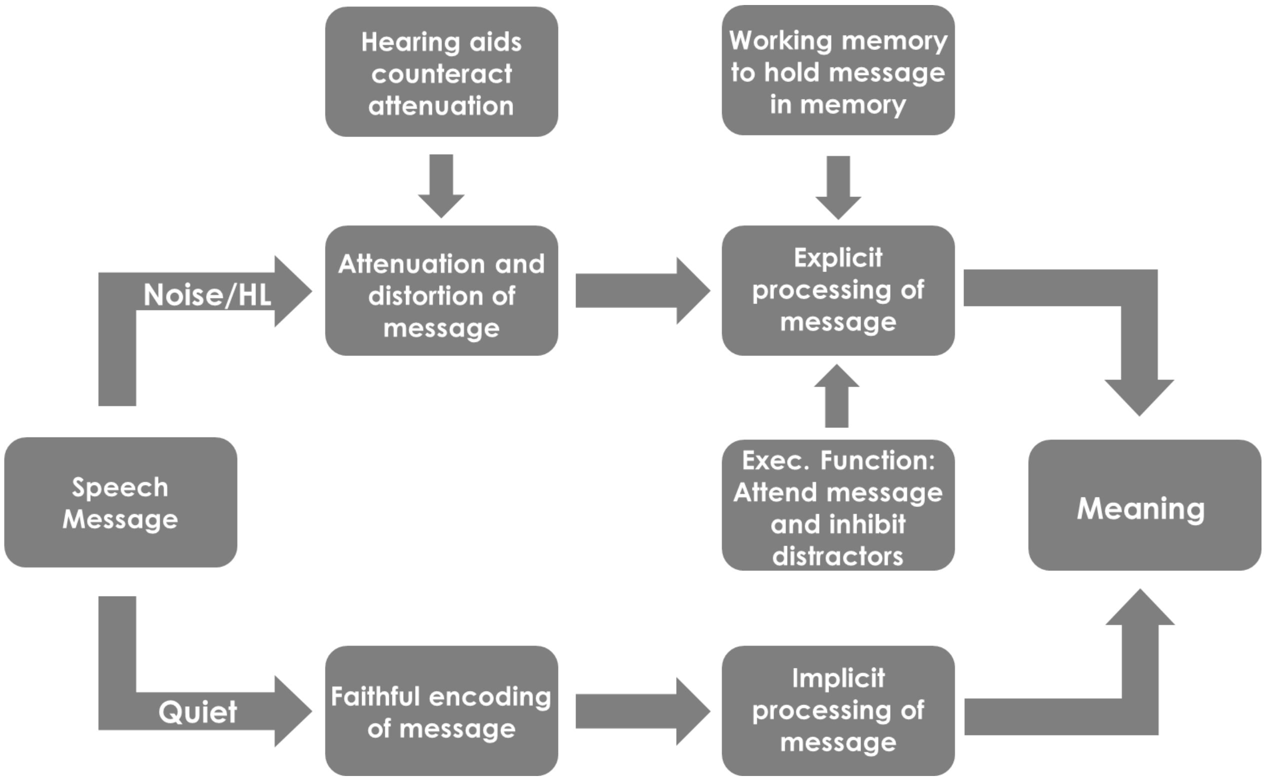

Figure 3. Model of speech recognition in noise vs. quiet. This model demonstrates the conceptual difference in explicit/implicit processing of a speech message in noise vs. quiet. It also incorporates hearing loss (HL), hearing aids, and working memory and executive (exec.) function as speech perception in noise factors.

Working memory and executive function allow individuals to mentally juggle multiple pieces of information from multiple sensory modalities in order to determine which sensory information is significant and allow for the complex processing of that information. For individuals with hearing loss, particularly in the presence of background noise, distortion of speech signals may result in a mismatch between phonological encoding in short-term memory and lexical representations in long-term memory (Rönnberg et al., 2013). The cognitive domains of working memory and executive function are responsible for the maintenance and manipulation of incoming auditory information to explicitly process speech stimuli into the likeliest lexical representation. Additionally, if an individual with hearing loss is wearing hearing aids, the spectral and temporal components of speech signals are being distorted both by the cochlea and hearing aid. This would result in an altered phonological encoding, potentially leading to lexical mismatch. Individuals with hearing loss must exert even more effort than listeners with normal hearing in order to accommodate frequent lexical mismatches, which can often lead to miscommunication (McCoy et al., 2005). These listeners must rapidly attend to and make use of any additional phonological cues that the hearing aids may be providing. If they are distracted by competing tasks, lose attention due to fatigue, or fail to inhibit distracting external and internal sources, then any benefit potentially provided by the directional microphones may be lost.

In light of studies that have found links between speech perception in noise and measures of working memory (Akeroyd, 2008; Besser et al., 2013; Pichora-Fuller, 1995; Rönnberg et al., 2010; Wingfield et al., 2005), the hypothesis for this dissertation is that cognitive factors of working memory and executive function in addition to auditory factors affect the rate of intelligibility improvement as SNR increases. It is predicted that listeners with better working memory and executive function would more efficiently resolve mismatch between phonological encoding and lexical representations, resulting in a higher rate of improvement due to an increasing SNR. It is predicted that individuals with better cognitive function would make better use of these additional cues, resulting in more benefit at the given SNR for the individuals with better cognitive function than the individuals with worse cognitive function. By testing multiple SNRs, you would then begin to see a steeper performance function for the individuals with better cognitive function, because as the phonological cues become available, they are better able to utilize those cues to predict lexical matches.

Additionally, variable patient outcomes for speech perception in noise with hearing technology strategies, such as noise reduction and non-linear frequency compression, have recently been described as being influenced by cognitive factors in addition to auditory factors (Rönnberg et al., 2013; Souza et al., 2015). These reviews claim that individual variability in auditory and cognitive factors plays a key role for the aided perception of speech in competing noise. An increasing number of hearing aid studies have found correlations between aided speech perception in noise with factors of cognition for various hearing aid programming strategies (Arehart et al, 2013, 2015; Cox & Xu, 2010; Ellis & Munro, 2013, 2015; Gatehouse et al., 2003, 2006; Humes, 2002; Humes, 2007; Ng et al., 2013; Rudner et al., 2011; Sarampalis et al., 2009; Shehorn et al., 2018). It seems probable that both auditory and cognitive factors play key roles in the aided rate of improvement for speech perception in noise as well.

Individual differences in auditory function.

Aging and hearing loss: Peripheral and Central Factors. One potential source for the variability observed in speech in noise intervention outcomes and the rate of improvement is age related hearing loss. Shallower slopes have been found for older listeners with hearing loss than younger listeners with normal hearing for multi-talker babble maskers (Wilson et al., 2007) but not for static/modulated noise maskers (Bosman & Smoorenburg, 1995; Wagener & Brand, 2005). These studies did not have an older adult group with normal hearing or a younger adult group with hearing loss to separate out factors of aging and hearing loss, so it is yet unclear how the two factors affect the slope of the psychometric function independently. Age-related hearing loss is associated with reduced hearing sensitivity and spectral/temporal distortion at the peripheral level which is commonly attributed to hair cell loss or damage. These effects likely contribute to the speech-in-noise deficit for this population.

Other potential sources for the variability in rate of improvement are temporal and spectral processing. Houtgast and Festen (2008) conducted a review of the auditory factors that contribute to speech perception in noise ability and identified temporal resolution as a key contributor. Temporal resolution is the ability to process rapid fluctuations in the amplitude of a sound. Reduced temporal resolution causes a distorted encoding of the sound signal being sent to auditory cortex, resulting in a poorer approximation of the signal. This can lead to greater difficulty in perceiving a speech signal and in separating speech signals from background noise (Drechsler & Plomp, 1985; Moore, 1985). It is likely that individuals with superior temporal resolution are able to more faithfully encode features of a signal as they become available due to an increasing SNR, resulting in a steeper rate of improvement. In summary, it is likely that the variability in speech perception in noise performance within the older adult population is related to both peripheral and central auditory factors.

Factors related to auditory ecology. Auditory ecology is a term that refers to the listening environments and listening demands that an individual regularly encounters. The rate of speech perception improvement is affected by factors related to the acoustic signal(s) and listening environment. As such, there is no single psychometric function that spans all listening conditions. As discussed in Gatehouse, Elberling, and Naylor (2003), listener performance, benefit from amplification, and sound quality judgments are multidimensional constructs that can vary greatly based on signal, masker, amplification, and task types. A signal is what a listener intends to hear and a masker is a stimulus that competes with the signal. Because listener performance is affected by signal and masker types, it is critical to measure multiple listening conditions when assessing listener performance and potential benefit from amplification strategies. It is also critical to interpret any findings within the context of the parameters of the test conditions. Therefore it is important to explore how parameters of the stimulus (signal and masker sources) and listening task may affect a rate of speech perception improvement.

Message context. One way that the rate of speech perception improvement may be affected is by the level of context provided for the listening task. Auditory stimuli that provide more context, such as sentences, typically result in a steeper rate of improvement for a psychometric function than stimulus types that lack context such as single words or phonemes (Miller et al., 1951; Pichora-Fuller et al., 1995). Within the context of a sentence the listener can make use of the contextual cues for the top-down manipulation of the signal and fill in any gaps or distortions in the signal that may have occurred. Stimulus set size can also affect the rate of improvement. Word recognition tests with larger set sizes result in shallower psychometric functions since the listener is more reliant on the encoding of the acoustic signal itself and cannot predict the target word (Bernstein et al., 2012; Miller et al., 1951).

Characteristics of background noise. Different masker types also result in different rates of intelligibility improvement. The general rule is that the more similar the masker is to the signal, the shallower the rate of improvement. For example, amplitude modulated noise results in a shallower rate of improvement than static noise (Festen & Plomp, 1990). Static noise is an example of an energetic masker, and its effectiveness as a masker is associated with the degree of spectral overlap and relative presentation levels between the stimulus and masker. An energetic masker is a sound that masks a signal by occupying the same neural pathways as the signal, combining the signal and masker in the neural code in the auditory periphery (Kidd et al., 1998). Purely energetic maskers like static noise result in a very steep rate of improvement because once the masker's amplitude and spectrum matches that of the signal, occupying the same auditory filters at the periphery, then intelligibility diminishes significantly.

Maskers that are intelligible, such as competing speech, also provide informational masking, which is a higher level masking effect that occurs when a listener confuses the signal talker with a competing talker and is unable to segregate their information (Kidd et al., 2008). The key factors influencing the amount of informational masking are signal-masker similarity and stimulus uncertainty (Durlach et al., 2003). Speech maskers which provide both informational and energetic masking result in shallower rates of intelligibility improvement than purely energetic maskers (Arbogast et al., 2002; Brungart, 2001). A meta-analysis conducted by MacPherson and Akeroyd (2014) also found that speech perception in competing, intelligible speech results in shallower rates of improvement of the psychometric function than babble maskers which are mostly unintelligible.

Hypothesis and Predictions

The grand challenge question is then: What are the sources of variability for speech perception in noise benefit from hearing aid interventions and how can clinicians measure them? Knowing that aided speech in noise outcomes (objective and subjective) are affected by both auditory and cognitive factors, our hypothesis is:

If the rate of improvement for speech perception in noise is affected by a combination of auditory and cognitive factors, then the rate of improvement may contribute to the variable benefit observed from a hearing aid SNR intervention.

Given this hypothesis, it is predicted that:

1) Listeners with better auditory and cognitive function will exhibit steeper rates of intelligibility improvement (absolute speech recognition scores in noise) than individuals with poorer auditory and cognitive function.
2) Listeners with steeper rates of improvement will receive more objective and subjective benefit from hearing aid directionality in comparison to omnidirectional performance.
3) In listening conditions which result in steeper rates of improvement (babble) more objective and subjective benefit will be received from hearing aid directionality in comparison to omnidirectional performance than in listening conditions which result in shallower rates of improvement (competing speech).

Dissertation Study

The dissertation study will measure speech perception in noise performance across a range of SNRs to determine the rate of improvement in an unaided listening condition in order to predict potential speech perception benefit from a hearing aid SNR intervention (directionality). The data collected for this dissertation will directly measure the potential speech perception benefit and subjective benefit from an improved speech signal due to a speech in noise intervention. The rate of improvement will be directly manipulated by using two different masker types: two-talker competing speech and 20-talker babble. Based on the literature reviewed, the 20-talker babble should result in a steeper rate of improvement function than the two-talker competing speech. It follows then according to our hypothesis that participants should receive significantly more benefit from the speech in noise interventions with a 20-talker babble masker than with a two-talker competing speech masker.

The findings would contribute to establishing the utility of a novel test method application that helps to predict patient variability in speech perception performance outcomes from SNR interventions. The results of the dissertation will also provide an evidence-base for the development or adaptation of a clinical measure to guide SNR intervention selection, fitting, and counseling. A clinical measure that better accounts for patient outcomes for SNR interventions will contribute to a more patient-centered approach to hearing technology selection, resulting in improved perceptual outcomes and increased intervention value to the patient. Lastly, by measuring the contribution of auditory factors and cognitive factors to the rate of speech perception improvement as SNR increases, this dissertation will provide critical theoretical contributions toward understanding inter-individual variability for speech perception in noise and its interaction with hearing aid interventions.

CHAPTER TWO: METHODS

General Methods

The study utilized a within-subjects design with repeated measures for a behavioral auditory perception experiment to address our hypothesis. The data includes audiologic evaluation, cognitive measures, and assessment of speech perception in noise psychometric functions. All auditory testing was conducted in a 12’ x 12’ double-walled sound booth with a reverberation time (RT60) of 0.2 seconds, using stimuli presented via loudspeakers or insert earphones with a PC-based audiometer calibrated according to the American National Standards Institute (ANSI S3.6-2004). Cognitive testing was conducted either in the sound booth or at a computer desk in a quiet room, free from distractions. Listening checks and daily calibration with a sound-level meter were conducted at the estimated position of the listener’s head in the soundfield.

Participants

Thirty older adults with sensorineural hearing loss were recruited and tested for the purposes of this dissertation. Fourteen male and sixteen female participants had an average age of 77.4 years with an age range from 65 to 87 years. The mean four frequency pure-tone-average (500, 1000, 2000, and 4000 Hz) was 47 dB HL with a range of 28 to 68 dB HL. Their mean pure tone thresholds and highest/lowest thresholds at each octave test frequency are charted in figure 4.

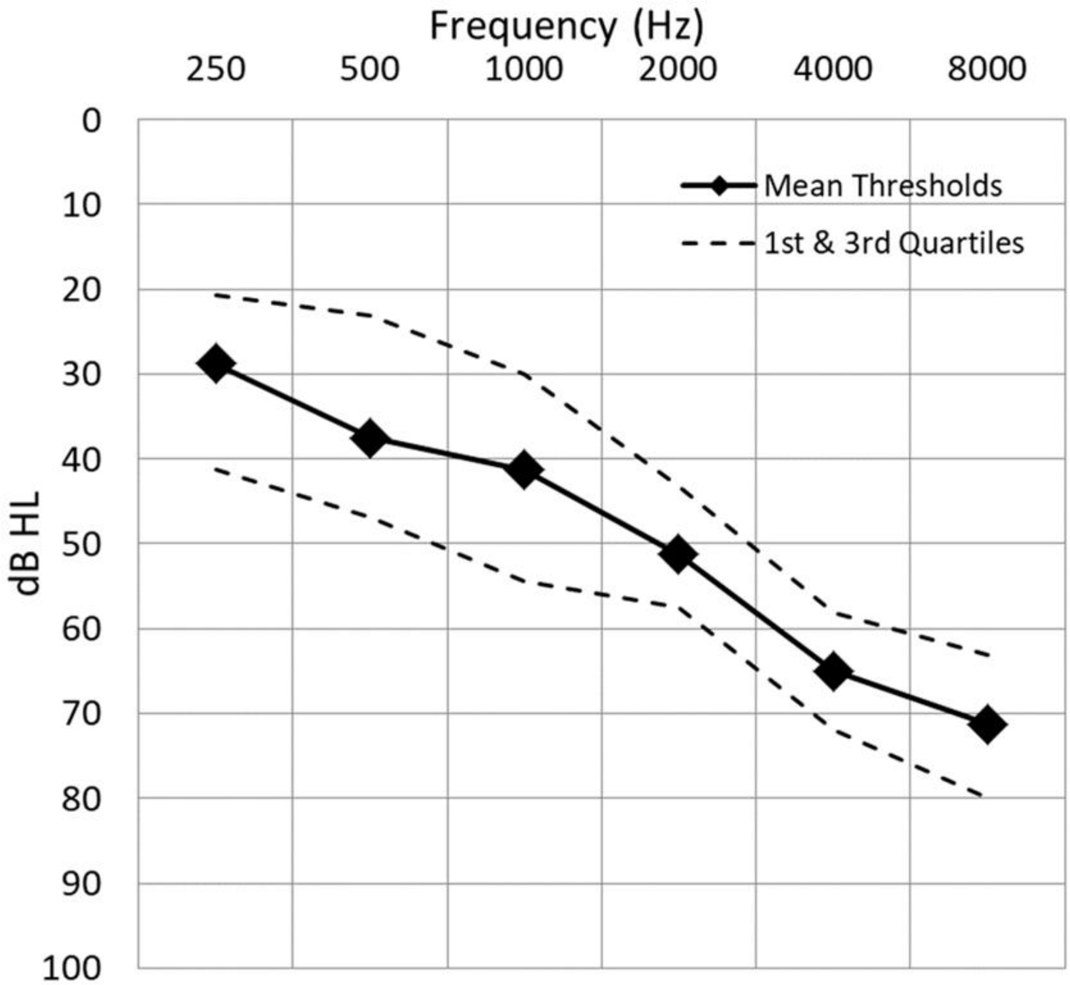

Figure 4. Average audiogram. Mean audiometric pure tone thresholds (dB HL) and 1st and 3rd quartiles.

Using the slope calculations from a pilot study with directionality, a sample size of 19 was calculated to provide a power level of 0.80 at a two-tailed alpha of 0.05**.** We had chosen to recruit thirty adults to protect against attrition across two test sessions. Adults over the age of 65 years were chosen for the proposed studies based upon findings that significant age-related changes in cognitive function can be observed for this population (NIH Toolbox Cognition Battery, Weintraub et al., 2013), and also that the greatest number of people with hearing loss are older adults (Goman & Lin, 2016). All participants completed a cognitive test battery for a collaborative study between the Listening in Multisource Environments Lab and the Aging and Cognition Lab at the University of Arizona. Participants were reimbursed $10/hour for their time. One participant did not complete the second test session.

Audiologic inclusion criteria. All participants completed a comprehensive hearing and tinnitus case history. Following otoscopy and immittance testing, air and bone conduction thresholds (250-16000 Hz) were measured at octave frequencies and at 3000 and 6000 Hz using a diagnostic PC-based audiometer (Otometrics Astera). Inclusion criteria for the study were bilateral, symmetrical sensorineural hearing loss, ranging in degree from mild to moderately-severe (25-70 dB HL four-frequency average of air conduction thresholds) and no air-bone gaps greater than 10 dB HL at two or more consecutive frequencies. All participants had at least six months of experience wearing bilateral hearing aids. To ensure adequate audibility of the stimuli presented in the experiment, individuals who had a pure tone threshold greater than 90 dB HL at any frequency from 250-4000 Hz or a conductive hearing loss were excluded from the study. Individuals were also excluded from the study if they had a history of neurological insult or disorder (self-report), were a non-native English speaker, or failed a screening for cognitive impairment (score less than 26 on the Mini-Mental State Examination, MMSE, Folstein et al., 1975). No participants exhibited signs of active ear disease on otoscopy or abnormal middle ear function on immittance measures.

Procedures (Test Session #1)

We hypothesized that speech perception in noise rate of improvement is influenced by individual differences in cognitive function in addition to auditory function. If true, then individuals with better auditory function (e.g. better spectral/temporal resolution, lower thresholds, etc.) and better cognitive function (e.g. working memory and executive function) will have higher rates of speech perception in noise improvement from an increasing SNR than individuals with poorer auditory and cognitive function. In order to test that hypothesis, we used the following test battery.

During the first test session, participants completed auditory testing and speech in noise testing to measure psychometric functions (See table 1). Participants recruited for this study had already completed the cognitive testing at a prior test session for a different research study.

Table 1
Summary of test measures for test session #1

Auditory Tests	Pure Tone Thresholds (Peripheral) Dichotic Digits (Central) Gaps in Noise (Central) QuickSIN (Peripheral and Central)
Cognitive Tests	Working Memory Capacity: Reading Span Frontal Factor: Mental Arithmetic, Phonemic Verbal Fluency, Backward Digit Span, Mental Control, Modified Wisconsin Card Sorting Task
Experimental Task	Soundfield amplified (SL +30 dB) speech perception in noise using Coordinate Response Measure

Auditory tests. The auditory tests included a combination of commonly used clinical measures and psychoacoustic measures. Pure tone air and bone conduction thresholds (250-16000 Hz) were measured under insert earphones using a diagnostic PC-based audiometer (Otometrics Astera).

The Dichotic Digits test was used to assess central auditory function (Musiek, 1983). The Dichotic Digits test is a divided attention task that assesses the ability to perceive dichotic speech information between ears that is presented at the same time. For this task participants hear two numbers in each ear, which they repeat in any order. This requires participants to attend to each ear separately. Performance on this task is scored independently for each ear. This test has been shown to be sensitive to binaural integration deficits, central auditory processing disorder, and cortical lesions.

We used the Gaps in Noise Test to measure temporal resolution, which is the ability to perceive changes in the envelope for a given sound stimulus (Musiek et al., 2005). This task estimates a listener's time window duration which indicates how long of a window a listener's auditory system averages sound stimuli together. A narrower time window would enable a listener to better resolve and separate multiple stimuli and detect onsets and offsets of speech sounds. The Gaps in Noise Test has been found to be sensitive to central auditory processing disorder, hearing loss, aging effects, and brainstem/cortical lesions. It is composed of six second sound clips of white noise with zero to three silent intervals ranging in duration from 2 msec to 20 msec. Participants press a button whenever they detect a temporal gap in white noise. Gap detection threshold is defined as the gap length at which the listener correctly detects 4/6 of the presentations for each ear separately. Performance on the Gaps in Noise test is also scored as the percent correct detection of all presented gaps. Participants completed one list per ear.

The QuickSIN (Killion et al., 2004) was used to assess each participant's SNR loss, calculated as the average of three equivalent QuickSIN lists. The SNR loss value is used by clinicians to determine patient speech perception performance in noise relative to a normally-hearing population and to guide hearing aid directionality and/or FM system recommendations. This is a sentence perception test with a background of four-talker babble that involves the entire auditory pathway. It also likely draws from cognitive resources given the evidence that working memory and executive function aid in the perception of degraded speech. For this test, participants are tasked to repeat full sentences. Each list is composed of six sentences ranging in signal-to-noise ratio from +25 dB SNR to 0 dB SNR in step sizes of 5 dB SNR. Each sentence has five scored keywords, resulting in 30 scored keywords per list. SNR loss is calculated by subtracting the total number of keywords correctly repeated from 25.5. We averaged together performance on three lists. Three lists provide a 95% confidence interval of ±1.6 dB.

Cognitive tests. The group of cognitive measures used for this study was developed in collaboration with Elizabeth Glisky, PhD, Professor of Psychology at the University of Arizona and Director of the Aging and Cognition Laboratory. The selected tests make use of minimal auditory instructions and are not tested in the auditory domain, avoiding the confound of hearing loss on cognitive test administration. Further, none of the participants that completed the cognitive test battery had significant, untreated visual loss which could have affected performance on these tests, verified by participant self-report.

Working memory capacity. The cognitive test battery included two versions of the Reading Span Test (Lyxell & Rönnberg, 1989; Waters & Caplan, 2003;). This test measures working memory capacity through a dual-task measure with a primary task of assessing the plausibility of a block of sentences and then repeating the subject or object of the sentences in the order that they were presented. The Waters and Caplan version of the test requires participants to recall the last word of each sentence, while the Rönnberg version of the test requires recall of either the first or last word of each sentence. The test produces two scores: percent of target words correctly recalled and percent of the target words correctly recalled in the order in which they were presented. Plausibility judgments are not scores, although participant plausibility judgments are monitored to ensure that they are attending to the plausibility task. The Reading Span test likely taxes both working memory and executive function and has been found to correlate with speech perception in noise performance (Rönnberg et al., 2010).

Frontal Factor. Several measures of executive function and working memory were included in the cognitive test battery (Mental Arithmetic, Wechsler, 1997; Phonemic Verbal Fluency, Spreen & Benton, 1977; Backward Digit Span, Wechsler, 1997; Mental Control, Wechsler, 1997; Modified Wisconsin Card Sorting Task, Nelson, 1976), which combined assess an individual's ability to update presented information, shift attention between tasks, and inhibit distractor stimuli. The executive function and working memory measures were grouped into a "frontal factor" composite score, which is the combination of performance on Mental Arithmetic, Phonemic Verbal Fluency, Backward Digit Span, Mental Control, and the Modified Wisconsin Card Sorting Task (Glisky et al., 1995).

Mental arithmetic is composed of a series of brief story problems which test distractibility, concentration ability, and problem-solving ability. Phonemic verbal fluency tasks participants to list as many words as possible that begin with the letter F, A, or S. This task measures an individual's ability to search and retrieve words and has been linked with frontal lobe function. Backward Digit Span requires participants to recall numbers in reverse order of the presentation order, which measures verbal working memory. Mental Control requires participants to recite and mentally manipulate over-learned sequences, such as the alphabet or numbers 1-20, which measures retrieval ability and working memory. The Wisconsin Card Sorting Task requires participants to make matches of cards without being told how they are supposed to be matched. Participants are required to learn the matching rule during the task. Additionally, the rule changes during the task, which once again forces participants to learn the new matching rule. This task measures participant ability to form novel strategies and overall cognitive flexibility.

Soundfield speech recognition in noise psychometric functions. Psychometric functions were measured for soundfield speech recognition in noise using the Coordinate Response Measure (Bolia et al., 2000). The Coordinate Response Measure is a closed-set, low-redundancy, recorded multi-talker corpus which was developed to test speech intelligibility in multi-talker spatial environments. Each trial is structured as: “Ready CALL SIGN go to COLOR NUMBER now.” The signal talker was the same female for each trial and can be identified by the call sign, “Charlie”. The listener was tasked to verbally identify the color and number given by the signal talker. Each trial performance was scored as correct only if the listener correctly identifies both the color and number. The signal was presented at 0° azimuth from a distance of 1 meter from the participant’s head (see figure 4). The signal sound level was presented at 30 dB sensation level (SL) above each participant’s 50% SRT for the CRM to ensure audibility. 30 dB SL was unattainable for one participant due to output limitations of the loudspeakers, and the level was set to the highest possible SL, which was +20 dB SL.

In order to manipulate the rate of improvement, two types of maskers were used for this experiment: two-talker competing speech and 20-talker babble. The two-talker competing speech, which should result in a shallower SNR rate of improvement function, was composed of two female talkers from the CRM corpus as the signal talker. The two competing female talkers spoke call signs, colors, and numbers drawn from the corpus at random without replacement, meaning the competing talkers did occasionally state the same sign, color or number as the signal talker. The 20-talker babble (Auditec, St. Louis, MO) was mostly unintelligible and maintains a stable level over time. The maskers were presented at 135° and 225° degrees azimuth (see figure 5), which are the angles of the nodes for the hearing aid directionality (supercardioid) being used for this experiment. The masker level was adjusted to create SNRs of +8, +4, +0, -4, and -8 dB. Participants were excluded from further participation if the +8 dB SNR masker would not be audible given their pure tone thresholds. Participants completed two test blocks of 25 trials per block for each SNR and masker condition.

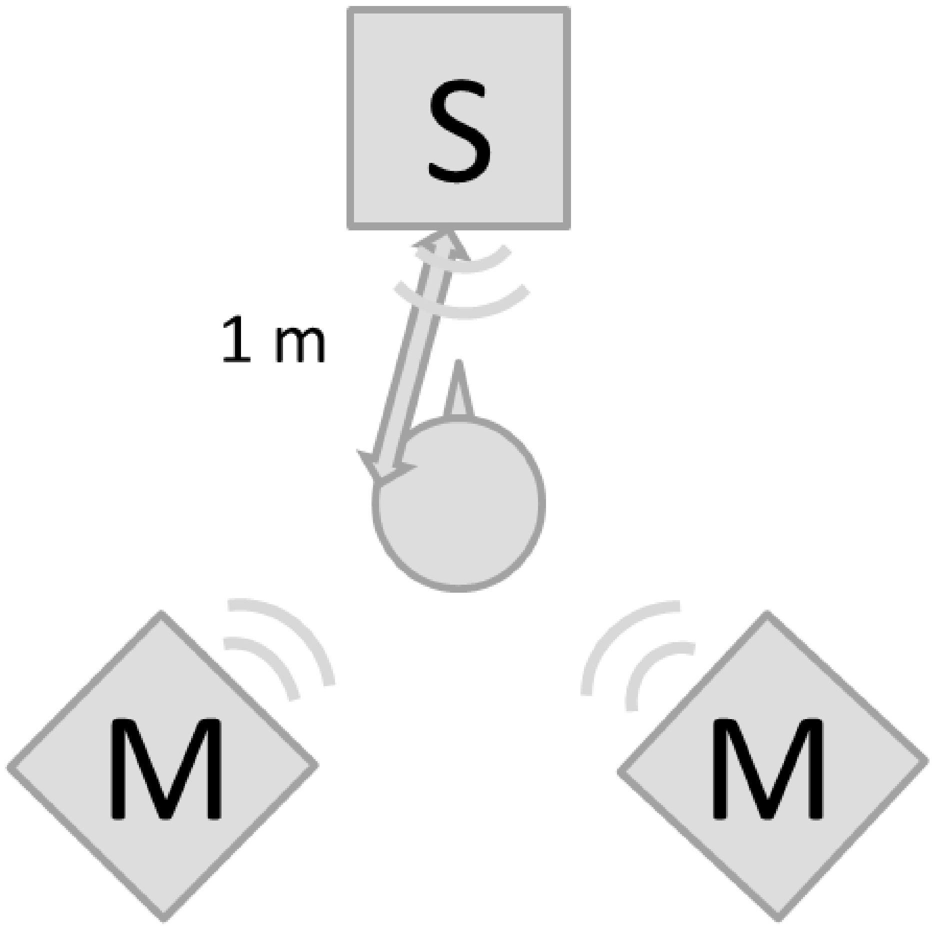

Figure 5. Spatial arrangement for experimental tasks. The signal was presented via loudspeaker at 0° azimuth at one meter from the participant's ear. The two maskers were presented from 135° and 225° at one meter from the participant's ears.

Procedures (Test Session #2)

The basic premise of this second part of the study is that the aided (omnidirectional) soundfield rate of improvement for speech perception in noise will predict the amount of improvement in intelligibility from hearing aid directionality. An innovation of the current study is to directly measure the rate of improvement (slope of the SNR psychometric function) in order to better understand potential benefit from an improved signal-to-noise ratio across the range of signal-to-noise ratios that are prevalent in real world listening conditions. In order to directly manipulate the speech perception in noise rate of improvement, two masker types were used to create one masking condition which would result in a shallower rate of improvement (two-talker competing speech) and another masking condition which would result in a steeper rate of improvement (20-talker babble; Brungart, 2001). Speech perception and subjective benefit from hearing aid directionality could then be compared within subjects for the different rate of improvement conditions to determine how omnidirectional rate of improvement interacts with hearing aid directionality benefit.

Participants attended one additional session in the laboratory for experimental testing to measure aided performance (see **Table 2**).

Table 2
Summary of test measures for test session #2

Aided Performance Measures	1) Hearing aid fitting and real ear verification of NAL-NL2 targets 2) Test box verification of directionality 3) Aided omnidirectional and directional testing using CRM

Hearing aid fitting procedures. A pair of commercial behind-the-ear hearing aids (Unitron Flex:Trial Quantum Pro 10) provided to the laboratory by Unitron (Plymouth, MN) for research purposes were used for this study. The hearing aids were coupled to the ear canal using foam Comply™ Canal Tips (Hearing Components, Oakdale, MN) . Aided output was matched to NAL-NL2 output targets (+/- 5 dB SPL) using real ear measures (Aurical Freefit, Otometrics, Taastrup, Denmark) and the directionality was verified using test box measures (see figure 6; Aurical HIT, Otometrics, Taastrup, Denmark). Averaged across frequency, the signal-to-noise ratio for the omnidirectional mode was +1.67 dB SNR and +10.33 for the directional mode. All noise management other than directionality was disabled as well as feedback suppression and volume control.

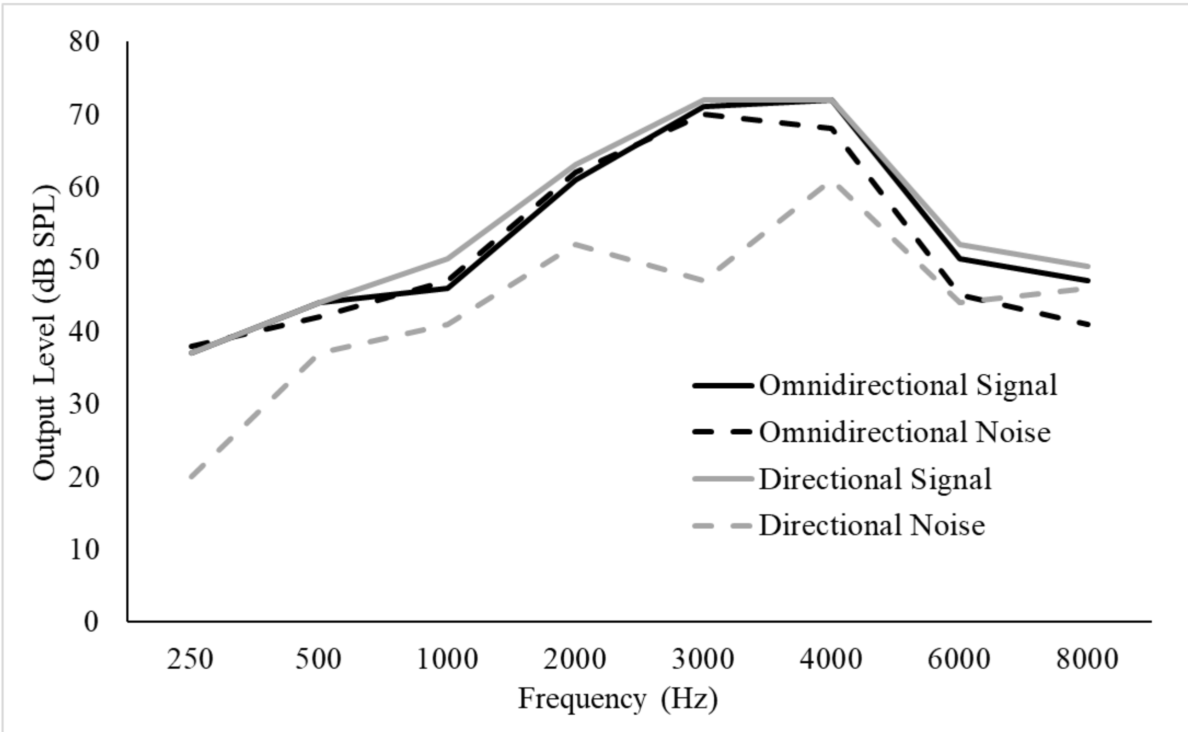

Figure 6. Directionality verification. Test box hearing aid output for signal and noise comparing omnidirectional and directional modes.

Aided speech recognition in noise. Once again we used the CRM for the aided speech recognition in noise testing (see test session #1 procedures for CRM procedures). Hearing aids were set to either omnidirectional or directional modes bilaterally, which was randomized and counterbalanced for each participant.

NASA Task Load Index. After each test block, participants completed a subjective rating form. The NASA Task Load Index is a subjective rating form that is widely used to measure perceived workload for a given task (Hart, 2006; Hart & Staveland, 1988). After each test block, participants filled out a modified NASA Task Load Index. This form requires participants to mark on a line (scale: 0-100) how mentally demanding the task was, how much effort they exerted, how well they believe they performed, and how frustrated they were while completing the task. Temporal and physical demand scales were excluded from the subjective rating form because they were irrelevant to the task.

Data Analysis

Performance on the experimental speech in noise tasks was calculated as percent correct for each SNR, both masking types, and both aided and soundfield (SL +30 dB) conditions. The soundfield rate of improvement (slope of the SNR psychometric function) was calculated using a Weibull fit (Wichmann & Hill, 2001). We used multiple linear regression to determine which auditory and cognitive factors are potentially driving the observed variability for the soundfield rate of speech perception in noise improvement in a hearing loss population. Speech perception and subjective benefit from directionality was calculated as the difference between performance in the omnidirectional condition and the directional condition. Repeated measures of analysis were used to compare speech perception benefit between the two-talker competing speech condition and the 20-talker babble condition. Correlational analyses were conducted between the rate of improvement in the omnidirectional condition and the speech perception benefit from directionality within each masker condition. All statistical analyses were conducted using SPSS Version 23 (IBM Corp.).

Because our participants had a broad range of ages (65-87 years), it is possible that the differences in age between our participants could result in significantly difference aging effects for cognition and hearing. However, there were no significant correlations between age and our dependent variables of rate of improvement in competing speech ($r=.11$, $p=.577$), rate of improvement in babble ($r=-.13$, $p=.479$), directional benefit in competing speech ($r=.00$, $p=.989$), and directional benefit in babble ($r=-.23$, $p=.223$). Therefore all planned analyses were calculated without grouping by age.

CHAPTER THREE: RESULTS

Individual Data: Slope of the Psychometric Functions with Soundfield Amplification

During the first test session, participants were tested in the soundfield without hearing aids at 30 dB SL. Individual rates of recognition improvement were calculated using a Weibull fit to the intelligibility scores across SNR. The rates of improvement varied significantly within the participant pool and ranged from 3.05% per dB SNR to 22.24% per dB SNR for the competing speech condition (mean: 9.68%, SD: 4.29%) and from 5.18% per dB SNR to 24.2% per dB SNR for the babble condition (mean: 12.77%, SD: 4.92%). The variability in rates of improvement was evident in both competing speech and babble backgrounds. To demonstrate individual variability within the data set, Figure 7 illustrates examples with high and low rates of improvement in intelligibility across a range of ecologically valid SNRs in the soundfield listening conditions (SRT+30). Because it is hypothesized that rate of improvement affects potential directional benefit, the individual variability observed here in unaided (soundfield SL +30) rates of improvement may be a source of the variability seen in directional benefit to listeners.

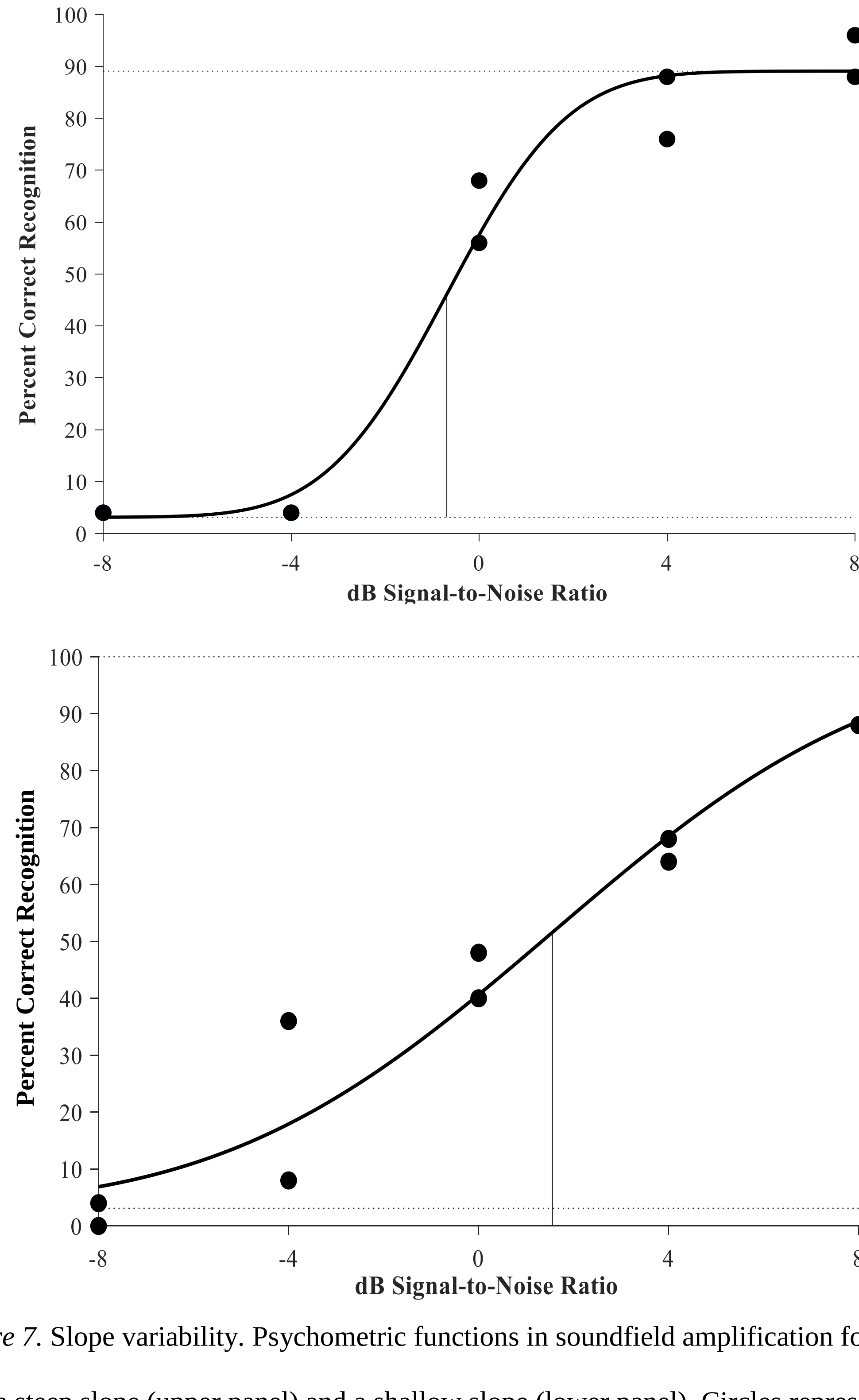

Figure 7. Slope variability. Psychometric functions in soundfield amplification for a participant with a steep slope (upper panel) and a shallow slope (lower panel). Circles represent raw data, dashed lines represent upper and lower asymptotes, and the vertical line represents 50% threshold.

Effect of Masker Type

Soundfield amplification. As illustrated in Figure 8, there was a steeper rate of improvement with a babble masker (mean: 12.77% per dB SNR, SD: 4.92) than with a two-talker competing speech masker (mean: 9.68% per dB SNR, SD: 4.29) in the soundfield amplified condition without hearing aids (SRT+30). Using repeated measures of ANOVA, a significant effect of masker type was observed for the rate of improvement ($F(1,29)=8.82$, $p=.006$, $\eta^2=.233$), with babble masking resulting in steeper rates of improvement than the competing speech masking. Based on our hypotheses, we could then expect greater directional benefit with a background of babble than a background of competing speech. This prediction was tested by measuring speech intelligibility with babble and competing speech masker types across a range of ecologically valid SNRs (-8 dB to +8 dB SNR) in SRT +30 dB, omnidirectional and fixed-directional listening conditions.

Omnidirectional amplification. The steeper rate of improvement for the babble masker (mean: 12.13% per dB SNR, SD: 3.93) in comparison to the two-talker competing speech masker (mean: 10.91% per dB SNR, SD: 6.83) held true in the omnidirectional listening condition (See figure 9). However, the difference in rates of improvement for the masker types was not statistically significant ($F(1,29)=.90$, $p=.351$). Given the similarity in rates of improvement between the soundfield and omnidirectional listening conditions, we will use the omnidirectional performance in comparison to directional performance to calculate directional benefit.

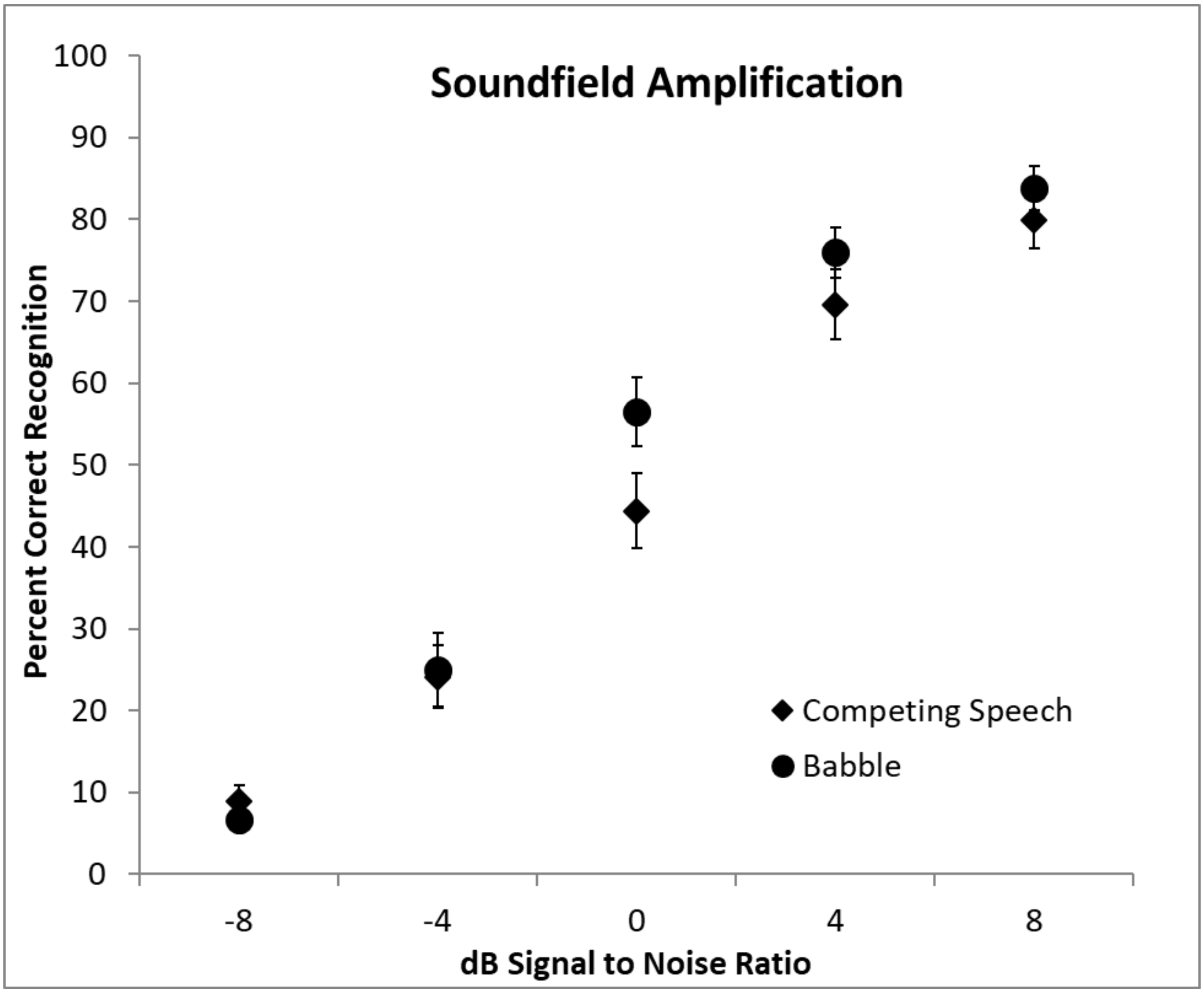

Figure 8. Soundfield amplification recognition. Mean soundfield percent correct recognition at each test SNR for masker types of competing speech vs. babble. The error bars represent ±1 standard error of the mean.

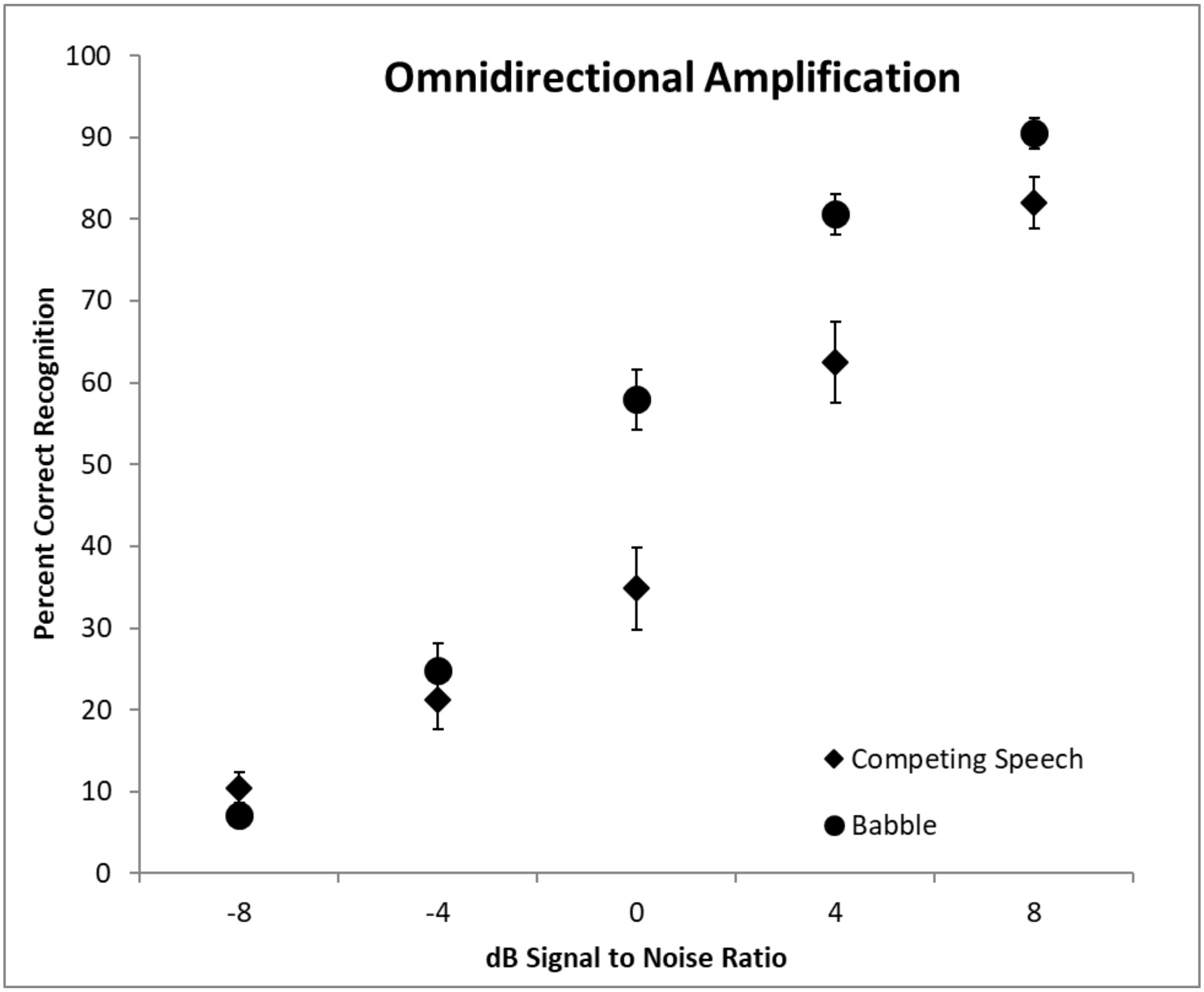

Figure 9. Omnidirectional amplification recognition. Mean omnidirectional percent correct recognition at each test SNR for masker types of competing speech vs. babble. The error bars represent ±1 standard error of the mean.

Directional Amplification. There was more benefit from directionality for intelligibility scores in babble than in two-talker competing speech (see Figure 10). Intelligibility scores were unchanged from omnidirectional with the addition of directionality in the competing speech condition, whereas a small boost in intelligibility scores can be observed in the babble condition. Mean directional benefit across SNRs was greater in the babble condition (mean: 4.05%, SD: 8.45%) than in the competing speech condition (mean: -0.39%, SD: 8.62%). A 2 x 2 repeated measures ANOVA was used to determine the difference in intelligibility scores between omnidirectional and directional listening conditions for backgrounds of babble and competing speech. There was a significant main effect of masker type ($F(1,28)=14.32$, $p=.001$, $\eta^2=.338$) but no significant main effect of directionality ($F(1,28)=2.13$, $p=.155$). There was a significant interaction between masker type and directional effect ($F(1,28)=5.21$, $p=.030$, $\eta^2=.157$), meaning the effect of directionality was different for the two types of maskers. Therefore separate ANOVAs were calculated to determine the effect of directionality for the two masker conditions. As predicted, there was a significant main effect of directionality for the babble background ($F(1,28)=6.65$, $p=.015$, $\eta^2=.192$) but not for the competing speech background ($F(1,28)=.06$, $p=.809$). These findings support the prediction that greater intelligibility benefit can be expected due to directional amplification in a background of babble than in a background of competing speech.

Because directional effects were likely minimal at -8 and +8 dB SNR due to floor and ceiling performance, another 2 x 2 repeated measures ANOVA was calculated to determine if the main effects in the initial ANOVA would change when only including SNRs of -4 to +4 dB SNR. The results of the analysis were the same as for the initial analysis including all SNRs. There was a significant main effect of masker type ($F(1,28)=39.12$, $p<.001$, $\eta^2=.583$) but no significant main effect of directionality ($F(1,28)=2.20$, $p=.149$). There was once again a significant interaction between masker type and directional effect ($F(1,28)=5.49$, $p=.026$, $\eta^2=.164$)

By taking the difference between the babble and competing speech functions, we were able to calculate the mean level of informational masking for each condition which was 2.47% (SD: 11.11) in the soundfield condition, 8.98% (SD: 15.96) in the omnidirectional condition and 13.27% (SD: 18.03) in the directional condition.

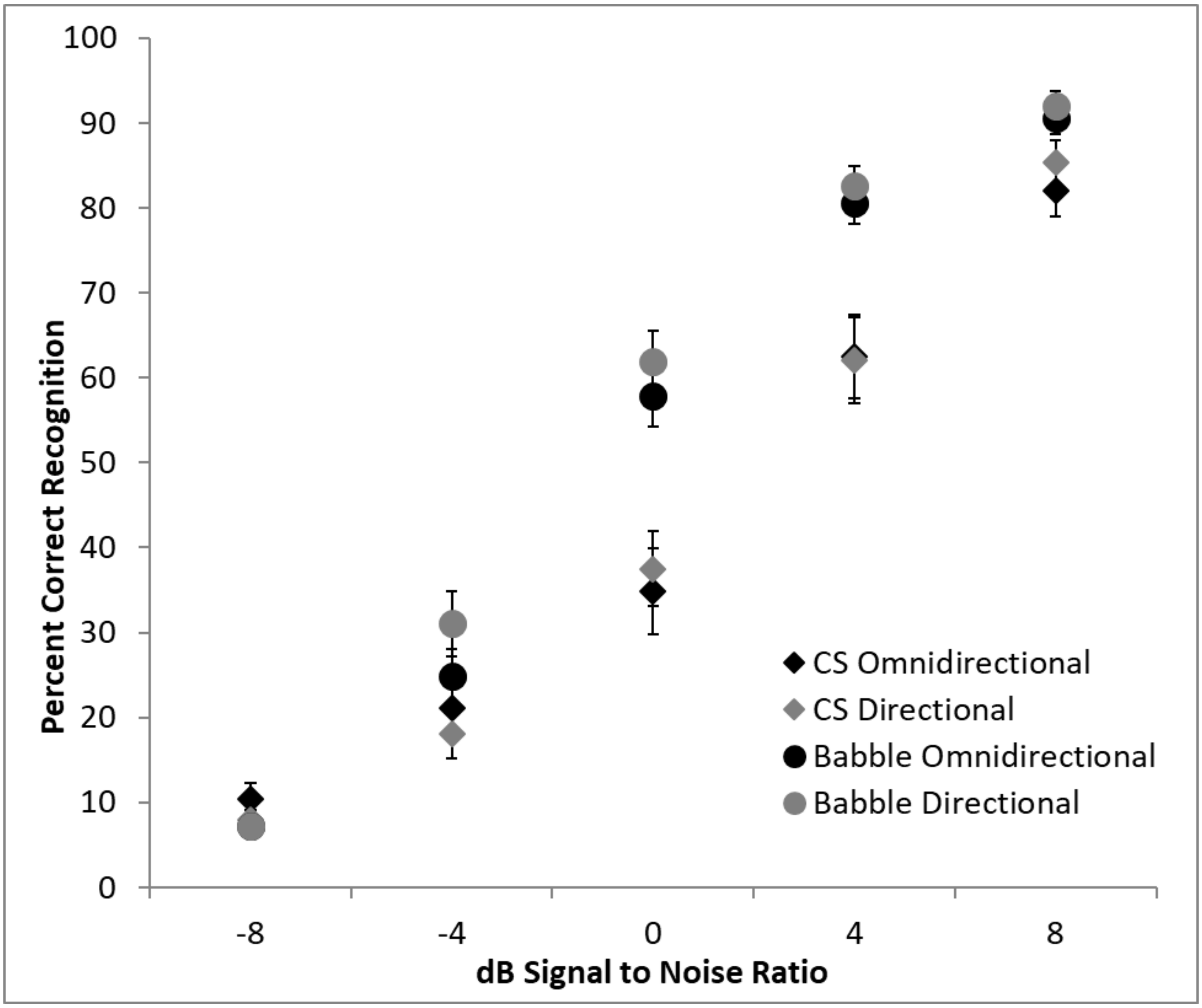

Figure 10. Omnidirectional and directional amplification recognition. Mean percent correct recognition at each test SNR for omnidirectional and directional conditions for masker types of competing speech (CS) vs. babble. The error bars represent ±1 standard error of the mean.

As discussed in the introduction, previous studies of directional benefit for speech perception in noise have demonstrated a great amount of variability in recognition benefit, which is difficult to predict. Our participants also demonstrated a high level of variability in recognition benefit in both the competing speech and babble masking conditions (see Figure 11). Even though the grouped data in Figure 10 shows little effect of directionality, the individual directional benefit/detriment in Figure 11 is quite variable. Directional recognition outcomes appear especially variable for the competing speech background, with some participants showing directional detriment and others showing significant directional benefit, whereas in the babble background much less directional detriment is observed.

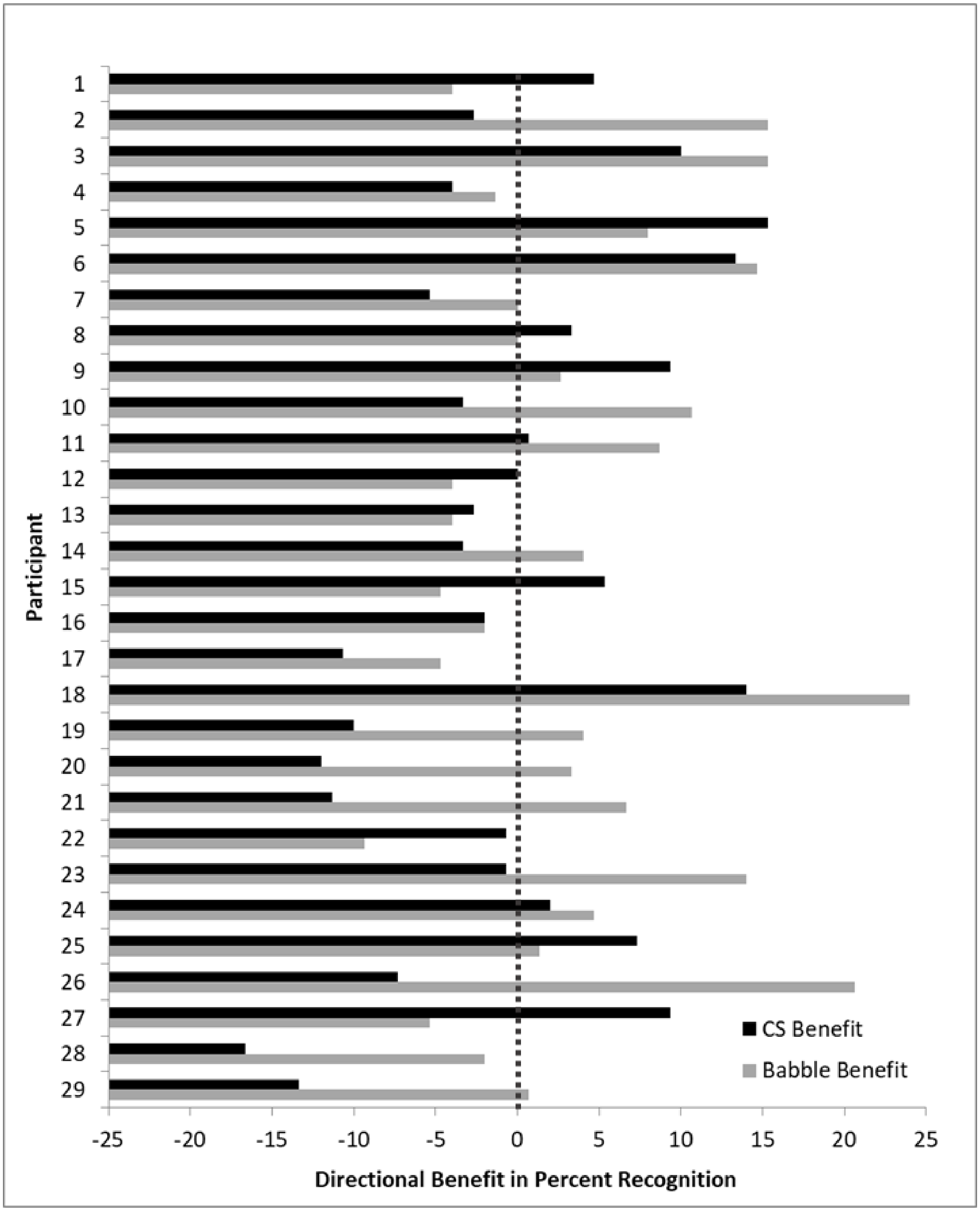

Figure 11. Individual directional benefit. Directional benefit/detriment in percent recognition for each participant in the competing speech (CS) background and babble background averaged across SNR..

Predicting the Rate of Improvement

Simultaneous multiple linear regression modeling was conducted separately for the two masker types (competing speech and babble) to determine which listener variables were associated with each individual's soundfield rate of improvement (slope of the psychometric function) given the particular background noise. Initially all six predictor variables (Gaps in Noise threshold, Dichotic Digits score, Frontal Factor, Reading Span score, QuickSIN SNR loss, and 4-frequency PTA (see figure 12 for correlations between predictor variables) were entered into a standard multiple regression model for both competing speech (see Tables 3 & 4) and babble background (see Tables 5 & 6) rates of improvement.

For the competing speech model, Dichotic Digits was removed due to a *p* value greater than the inclusion criterion of $p<.25$. After Dichotic Digits scores were removed, the five factor model yielded a significant regression equation ($F(5,29)=5.05$, $p=.003$) with all variables being either significant predictors or nearing significance (see Table 4). This finding supports the prediction that the rate of improvement with a background of competing speech is likely associated with both auditory (peripheral and central) and cognitive factors. Reading span scores and QuickSIN performance were positively associated with the rate of improvement. As expected, hearing loss severity (4 PTA) was negatively associated with the rate of improvement. However, in contrast to our prediction, better Gaps in Noise and Frontal Factor scores were associated with shallower rates of improvement.

In order to further examine the association between Frontal Factor scores/Gaps in Noise thresholds and rate of improvement, participants were split into high and low performance groups for the two cognitive measures (see figures 13 and 14). A 2 x 5 repeated measures ANOVA was calculated to compare recognition performance for high vs. low Frontal Factor scores at each test SNR. There was no main effect of Frontal Factor group, but there was a significant interaction between Frontal Factor group and SNR ($F(4,11)=3.03$, $p=.025$), due to the fact that individuals with high Frontal Factor scores performed better at worse SNRs, but performed similarly to the low Frontal Factor group at more advantageous SNRs. Another 2 x 5 repeated measures ANOVA was calculated to compare recognition performance for high vs. low Gaps in Noise scores at each test SNR. There was no main effect of Gaps in Noise group nor was there a significant interaction between Gaps in Noise group and SNR. Recognition was generally better across SNR for the high Gaps in Noise scoring group relative to the low scoring group, but this difference was not significant.

Multiple linear regression was again calculated to predict the rate of improvement with a background of babble using the same predictor variables as for the previous regression model (see Table 5). The initial model yielded high p values for all predictor variables except for Frontal Factor, Reading Span scores, and hearing loss severity (4 PTA). Given these findings, all variables were removed from the model except for Frontal Factor, Reading Span scores, and hearing loss severity. The model yielded a significant regression equation ($F(3,29)=3.17$, $p=.041$). Once again Reading Span scores were significantly and positively associated with rate of improvement. Frontal Factor was not a significant predictor variable in the final model, and hearing loss severity trended toward a significant negative correlation with rate of improvement (See table 6). Reading Span scores were positively associated with rates of improvement in both masking conditions.

		4 PTA	Gaps in Noise	Dichotic Digits	QuickSIN	Frontal Factor	Reading Span
4 PTA	Pearson r	1	0.10	-0.35	0.32	-0.31	0.22
	p	--	0.61	0.06	0.08	0.09	0.24
Gaps in Noise	Pearson r		1	-0.24	0.20	0.12	-0.09
	p		--	0.21	0.28	0.55	0.63
Dichotic Digits	Pearson r			1	-0.526**	0.57**	.22
	p			--	0.00	0.00	.24
QuickSIN	Pearson r				1	-0.01	-0.11
	p				--	0.958	0.56
Frontal Factor	Pearson r					1	0.08
	p					--	0.69
Reading Span	Pearson						1
	p						--

Figure 12. Correlations for individual predictor variables. The figure displays Pearson r correlation values and p values between 4 frequency pure tone average, Gaps in Noise, Dichotic Digits, QuickSIN, Frontal Factor, and Reading Span. * p < .05, ** p <.01

Table 3

Initial regression model for competing speech rate of improvement

Variable	*B*	*SE B*	*Beta*	*t*	*p*
(Constant)	19.93	25.16		.79	.443
4 PTA	-.14	.07	-.34	-2.00	.058
Gaps in Noise	.76	.23	.52	3.29	.003
Dichotic Digits	-15.95	24.84	-.16	-.64	.527
QuickSIN	-.46	.23	-.39	-2.00	.057
Frontal Factor	-2.07	1.47	-.29	-1.41	.173
Reading Span	**.28**	**.13**	**.33**	**2.13**	**.045**

Table 4

Final regression model for competing speech rate of improvement

Variable	*B*	*SE B*	*Beta*	*t*	*P*
(Constant)	3.97	3.80		1.04	.307
4 PTA	-.13	.07	-.34	-1.99	.058
Gaps in Noise	.80	.22	.55	3.69	.001
QuickSIN	-.38	.19	-.32	-2.02	.055
Frontal Factor	-2.69	1.10	-.38	-2.45	.022
Reading Span	**.26**	**.13**	**.32**	**2.07**	**.050**

Table 5

Initial regression model for babble rate of improvement

Variable	***B***	***SE B***	***Beta***	***t***	***P***
(Constant)	-10.14	33.25		-.31	.763
4 PTA	-.12	.09	-.26	-1.31	.205
Gaps in Noise	.23	.30	.14	.75	.462
Dichotic Digits	21.54	32.84	.18	.66	.518
QuickSIN	-.32	.30	-.23	-1.04	.309
Frontal Factor	-2.46	1.94	-.30	-1.27	.218
Reading Span	**.39**	**.17**	**.40**	**2.22**	**.037**

Table 6

Final regression model for babble rate of improvement

Variable	***B***	***SE B***	***Beta***	***t***	***P***
(Constant)	12.33	4.15		2.97	.006
4 PTA	-.17	.08	-.38	-2.05	.051
Frontal Factor	-1.82	1.45	-.23	-1.23	.220
Reading Span	**.46**	**.17**	**.48**	**2.73**	**.011**

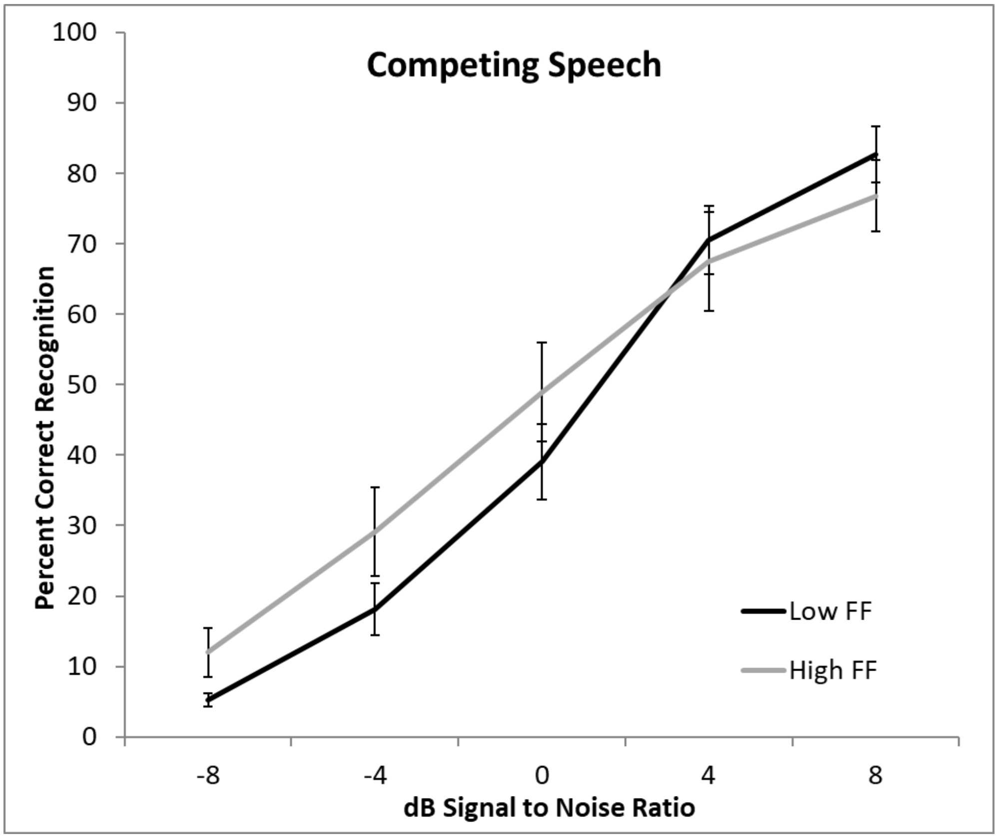

Figure 13. Grouped performance by Frontal Factor scores. This figure displays mean recognition at each test SNR in competing speech. Participants were split into high (High FF) and low (Low FF) performing groups for the Frontal Factor.

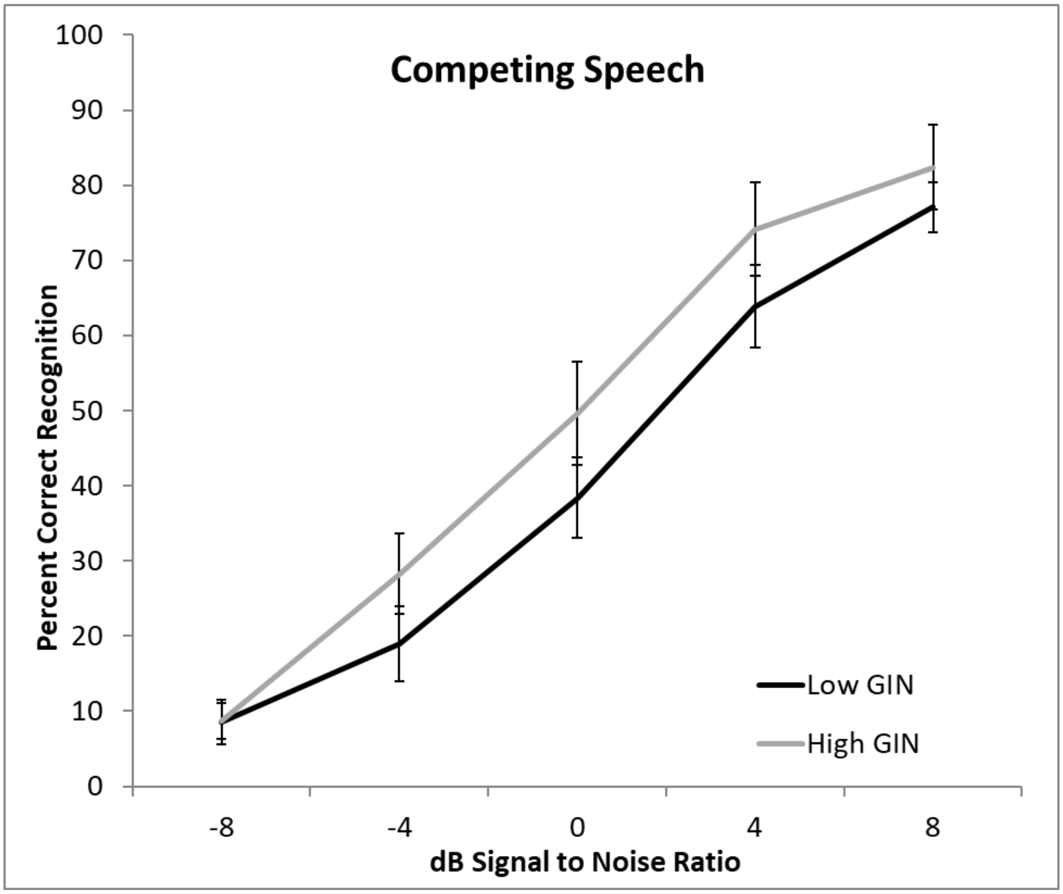

Figure 14. Grouped performance by Gaps in Noise thresholds. This figure displays mean recognition at each test SNR in competing speech. Participants were split into high (High GIN) and low (Low GIN) performing groups for the Gaps in Noise test.

Predicting Directional Benefit

It was predicted that omnidirectional rate of improvement would be significantly associated with directional benefit. Bivariate correlational analysis was used to test this prediction. Individual directional benefit was calculated as the difference in intelligibility at a given SNR between the omnidirectional and directional listening conditions for both masking types, yielding two benefit scores for each participant. These directional benefit scores were used to determine if there was an association between omnidirectional rate of improvement and directional benefit. So as to avoid ceiling and floor effects for the rate of improvement within our pool of participants, we focused on SNRs of 0 and +4 dB to calculate our rates of improvement. For the SNR step from 0 dB to +4 dB, the omnidirectional rate of improvement significantly correlated with directional benefit for both the competing speech background (r=.39, p=.040) and the babble background (r=.42, p=.027). This significant and positive association between slope and directional benefit (see figure 15) again supports the prediction that benefit from an improved SNR is associated with the rate of improvement for a given range of SNRs.

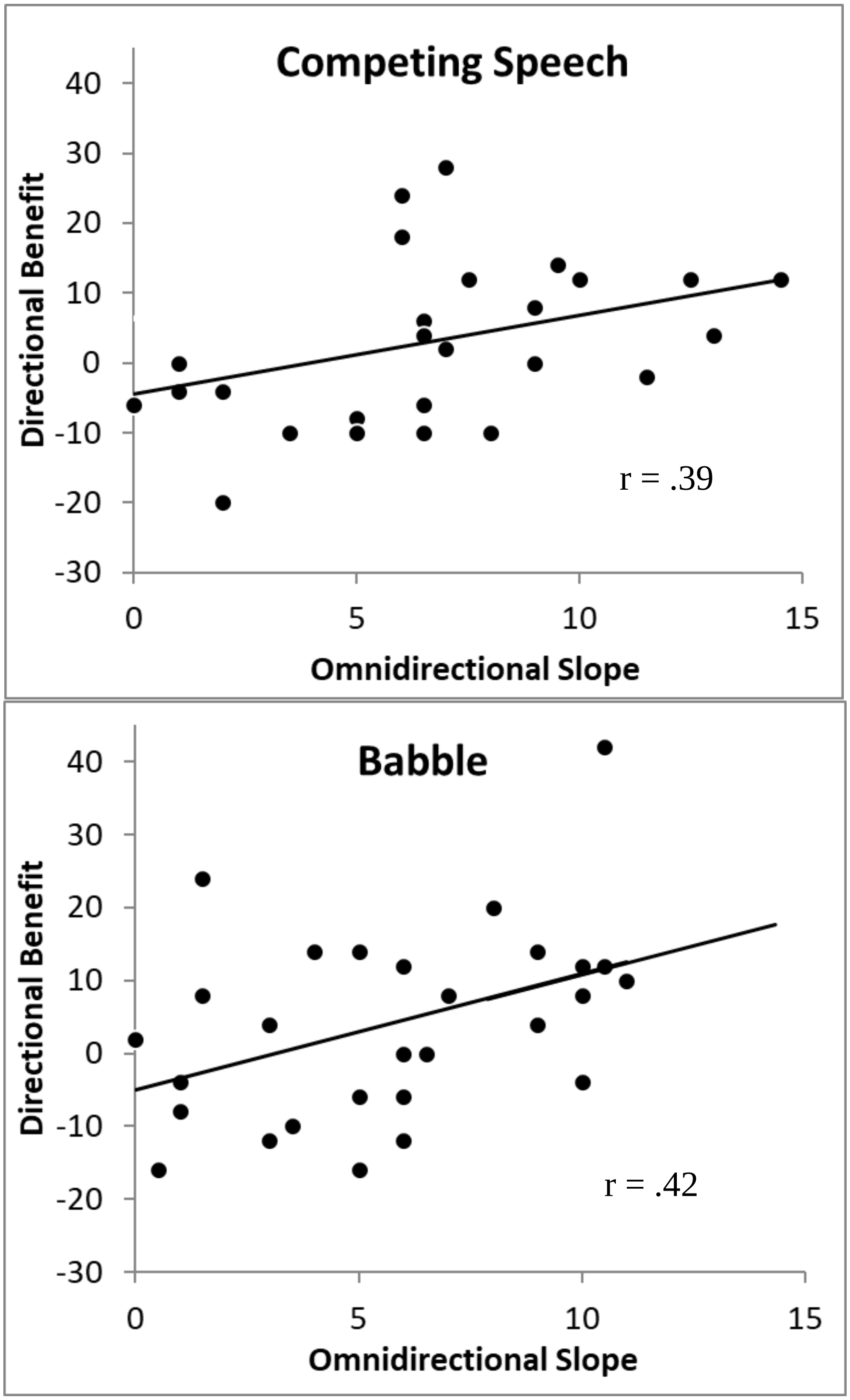

Figure 15. Slope and directional benefit scatter plots. This figure displays the scatter plots between omnidirectional slope from 0 dB SNR to +4 dB SNR and directional benefit at 0 dB SNR for competing speech (upper panel) and for babble (lower panel).

Subjective Outcomes

Participants completed a questionnaire (NASA Task Load Index) after each listening condition in order to measure outcomes in the subjective domains of self-rated mental demand, performance, effort, and frustration.

Subjective vs. Objective Performance. For comparison of the subjective performance rating and objective performance, bivariate correlational analyses were calculated on scores at 0 dB SNR in order to avoid ceiling and floor effects on the performance data (see figure 16). In the soundfield amplified listening condition, objective performance correlated significantly with subjective performance rating for both the competing speech (r= -.48, *p*=.007) and the babble background (r= -.47, *p*=.009). In the omnidirectional hearing aid listening condition, objective performance correlated significantly with subjective performance rating for babble background (r= -.48, *p*=.007) but not for competing speech (r= -.30, *p*=.116). In the directional hearing aid listening condition, objective performance correlated significantly with subjective performance rating for competing speech (r= -.44, *p*=.016) but was only nearly significant for the babble background (r= -.37, *p*=.051).

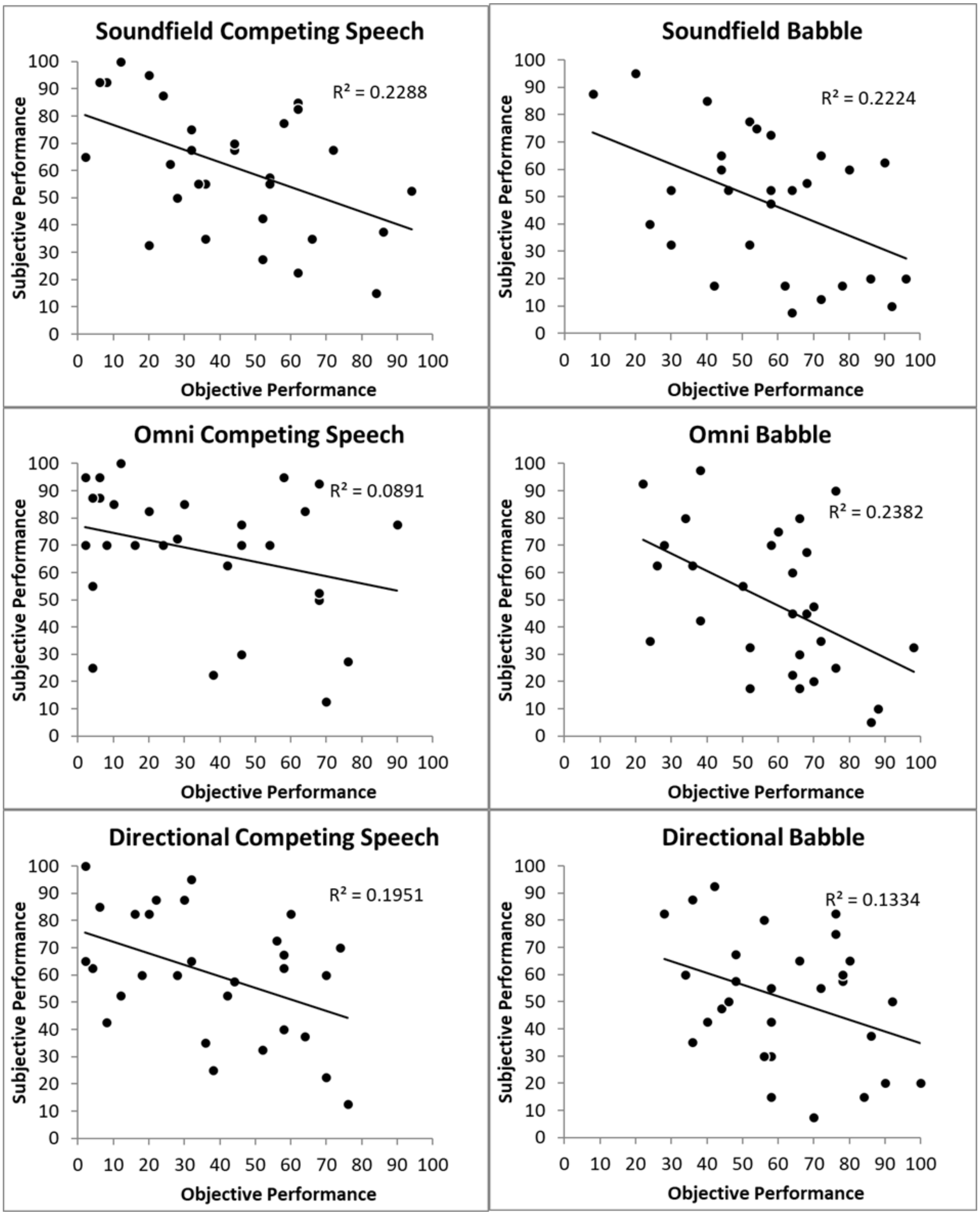

Figure 16. Objective vs. subjective performance scatter plots. This figure displays the scatter plots comparing objective and subjective performance for both masker types in soundfield, omnidirectional (omni) and directional listening conditions.

Mental Demand. Averaged across SNRs, participants rated mental demand as slightly higher, though not statistically significant, with the addition of directionality for both competing speech and babble backgrounds (See figure 17). Note that higher workload ratings correspond with higher mental demand. For the competing background, mean self-rated mental demand was 67.41% (SD: 18.98%) for the omnidirectional listening condition and 69.28% (SD: 19.09%) for the directional listening condition, meaning that participants rated the omnidirectional condition as slightly more mentally demanding than the directional condition. For the babble background, mean self-rated mental demand was 60.74% (SD: 20.72%) for the omnidirectional listening condition and 62.86% (SD: 18.80%) for the directional listening condition. A 2 x 2 x 5 repeated measures ANOVA was used to determine the difference in mental demand ratings between omnidirectional and directional listening conditions for backgrounds of babble and competing speech at each test SNR. There was a significant main effect of masker type ($F(1,28)=11.36$, $p=.002$, $\eta^2=.289$) but no significant main effect of directionality (($F(1,28)=1.22$, $p=.278$). There was not a significant interaction between masker type and directional effect ($F(1,28)=0.02$, $p=.898$), but there was a significant interaction between masker type and SNR ($F(4,25)=5.93$, $p=.002$, $\eta^2=.487$). There was no significant three way interaction ($F(4,25)=1.29$, $p=.302$). In summary, participants rated the competing speech background as more mentally demanding than the babble background, however mental demand ratings were unaffected by directional processing.

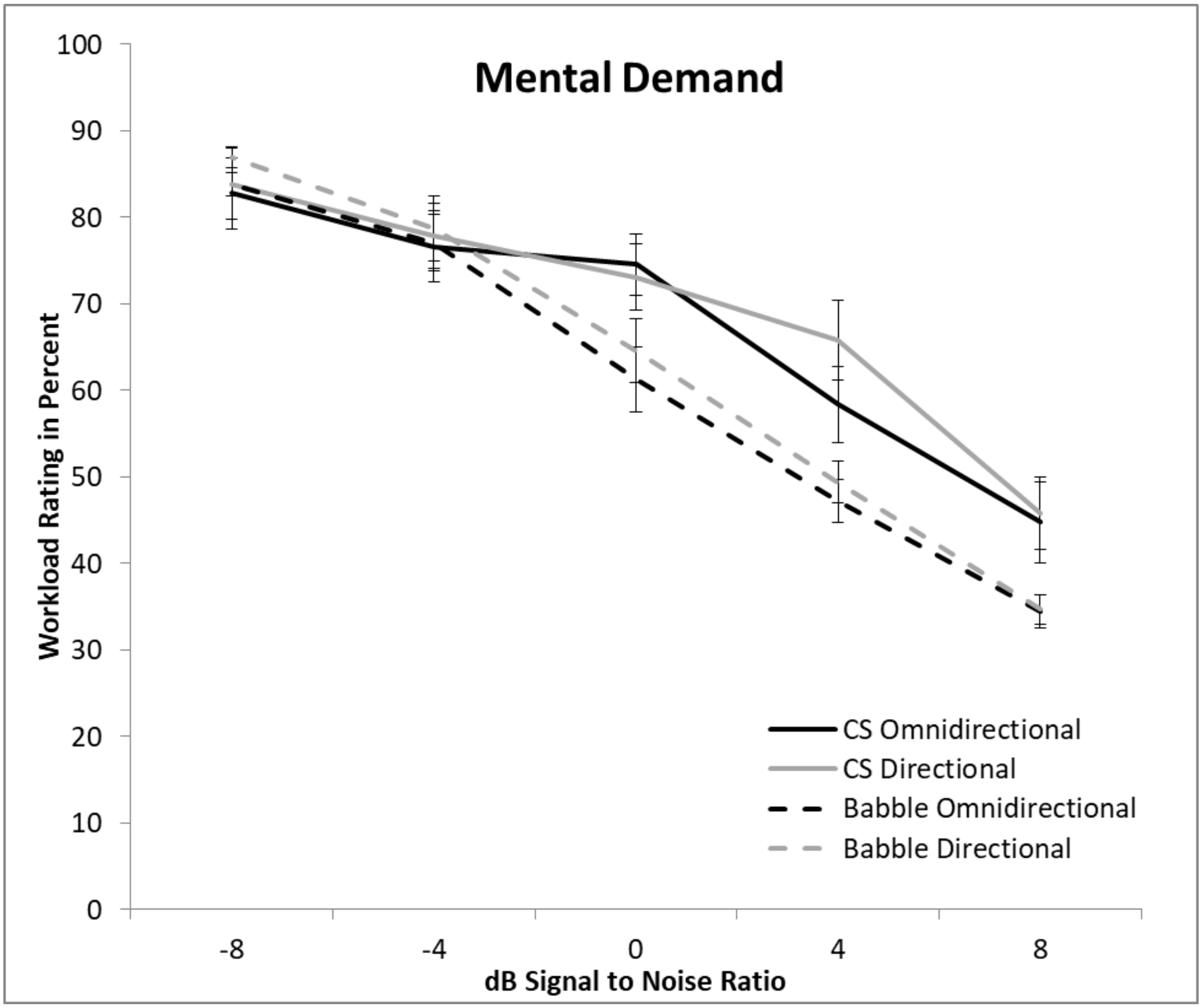

Figure 17. Subjective mental demand functions. Workload rating in percent for mental demand across SNR with a background of 2-talker competing speech (CS) and 20-talker babble. Lower scores would indicate a lower workload, meaning the task was easier.

Performance. Averaged across SNRs, participants rated their own performance similarly between competing speech and babble backgrounds (See figure 18). For the competing background, mean self-rated performance was 60.16% (SD: 19.31%) for the omnidirectional listening condition and 57.79% (SD: 16.50%) for the directional listening condition. For the babble background, mean self-rated performance and was 55.31% (SD: 15.56%) for the omnidirectional listening condition and 55.93% (SD: 14.72%) for the directional listening condition. A 2 x 2 x 5 repeated measures ANOVA was used to determine the difference in performance ratings between omnidirectional and directional listening conditions for backgrounds of babble and competing speech at each test SNR. There was no significant main effect of masker type ($F(1,28)=3.26$, $p=.082$) and no significant main effect of directionality (($F(1,28)=0.55$, $p=.464$). There was no significant interaction between masker type and directional effect ($F(1,28)=2.63$, $p=.116$), but there was a significant interaction between masker type and SNR ($F(4,25)=18.50$, $p< .001$, $\eta^2=.398$). There was no significant three way interaction ($F(4,25)=1.13$, $p=.346$). In summary, masker type and directional processing did not significantly affect subjective performance ratings.

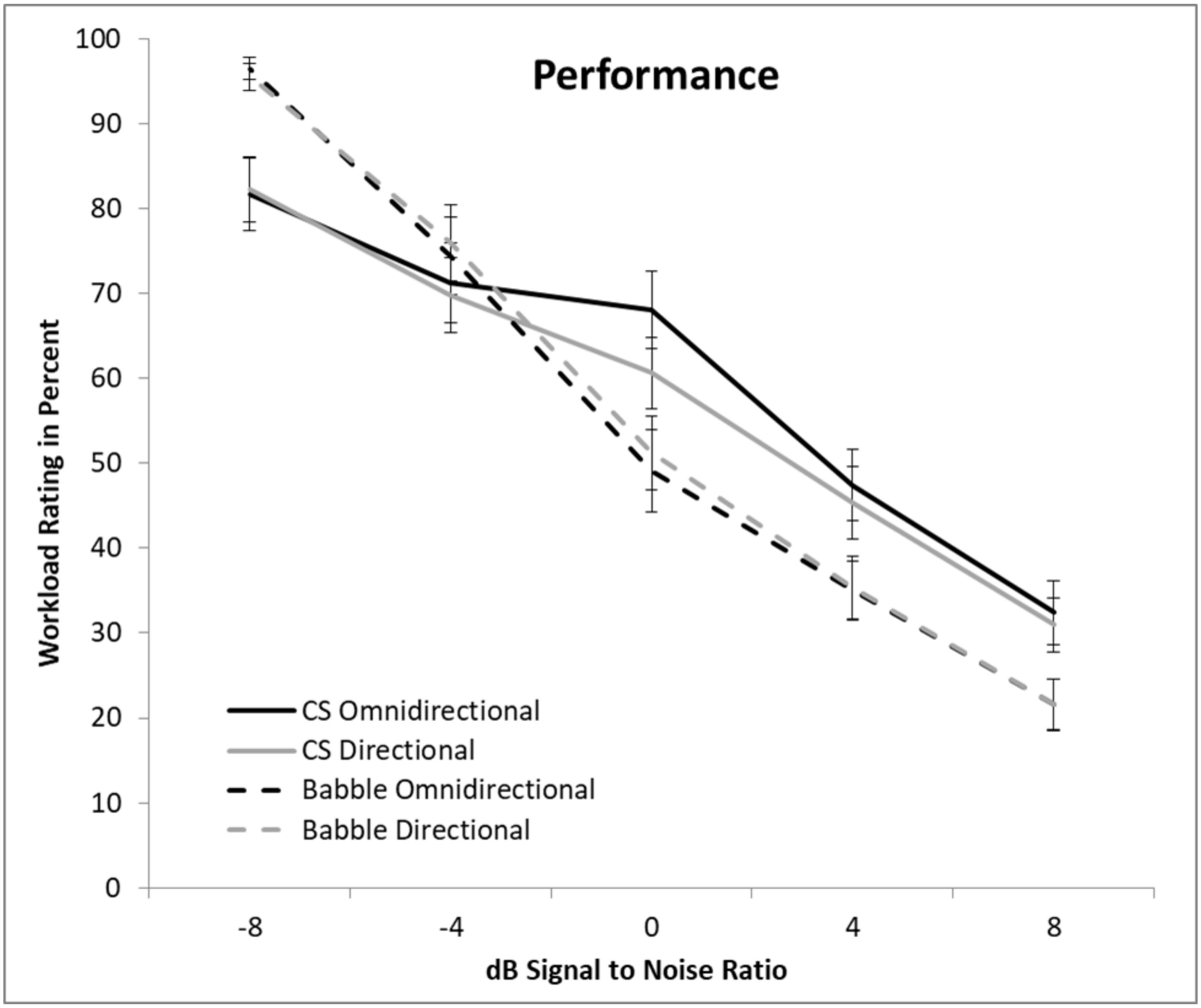

Figure 18. Subjective performance functions. Workload rating in percent for performance across SNR with a background of 2-talker competing speech (CS) and 20-talker babble. Lower scores would indicate a lower workload, meaning the task was easier.

Effort. Averaged across SNRs, participants rated the level of effort similarly between competing speech and babble backgrounds (See figure 19). For the competing background, mean self-rated effort was 70.22% (SD: 19.11%) for the omnidirectional listening condition and 70.57% (SD: 18.71%) for the directional listening condition. For the babble background, mean self-rated effort was 63.35% (SD: 17.91%) for the omnidirectional listening condition and 64.48% (SD: 18.60%) for the directional listening condition. A 2 x 2 x 5 repeated measures ANOVA was used to determine the difference in effort ratings between omnidirectional and directional listening conditions for backgrounds of babble and competing speech at each test SNR. There was a significant main effect of masker type ($F(1,28)=9.81$, $p=.004$, $\eta^2=.259$) but no significant main effect of directionality (($F(1,28)=0.23$, $p=.636$). There was no significant interaction between masker type and directional effect ($F(1,28)=0.16$, $p=.688$), but there was a significant interaction between masker type and SNR ($F(4,25)=7.45$, $p< .001$, $\eta^2=.210$). There was no significant three way interaction ($F(4,25)=.98$, $p=.420$). In summary, participants rated the competing speech background as requiring more effort than the babble background, however effort ratings were unaffected by directional processing.

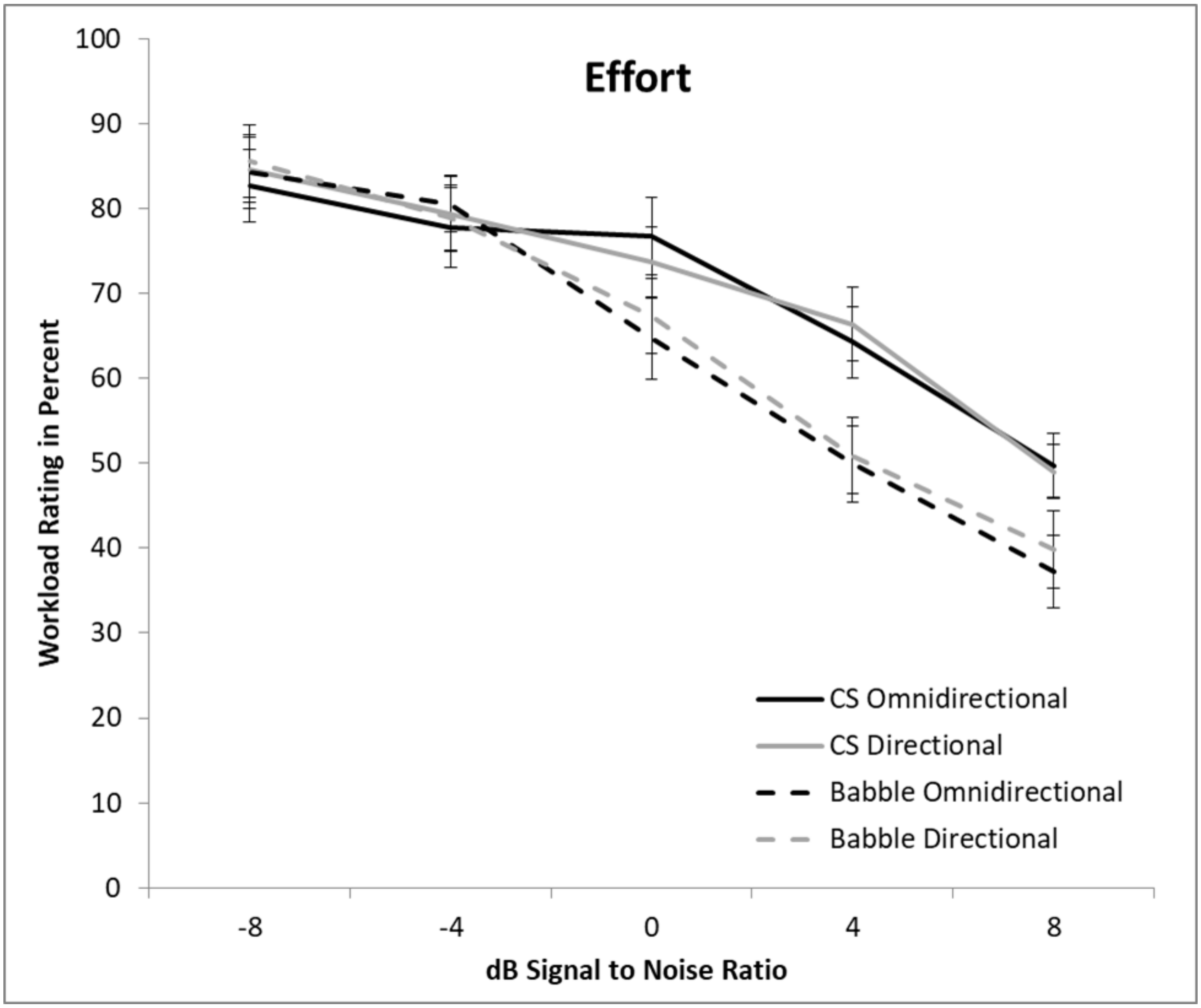

Figure 19. Subjective effort functions. Workload rating in percent for effort across SNR with a background of 2-talker competing speech (CS) and 20-talker babble. Lower scores would indicate a lower workload, meaning the task was easier.

Frustration. Averaged across SNRs, participants rated the level of frustration similarly between competing speech and babble backgrounds (See figure 20). For the competing background, mean self-rated frustration was 57.78% (SD: 24.45%) for the omnidirectional listening condition and 58.05% (SD: 23.73%) for the directional listening condition. For the babble background, mean self-rated frustration was 53.59% (SD: 21.73%) for the omnidirectional listening condition and 52.90% (SD: 23.11%) for the directional listening condition. A 2 x 2 x 5 repeated measures ANOVA was used to determine the difference in frustration ratings between omnidirectional and directional listening conditions for backgrounds of babble and competing speech at each test SNR. There was a significant main effect of masker type ($F(1,28)=5.72$, $p=.024$, $\eta^2=.170$) but no significant main effect of directionality (($F(1,28)=0.212$, $p=.915$). There was no significant interaction between masker type and directional effect ($F(1,28)=0.17$, $p=.682$), but there was a significant interaction between masker type and SNR ($F(4,25)=11.31$, $p< .001$, $\eta^2=.288$). There was no significant three way interaction ($F(4,25)=1.13$, $p=.347$). In summary, participants rated the competing speech background as more frustrating than the babble background, however effort ratings were unaffected by directional processing.

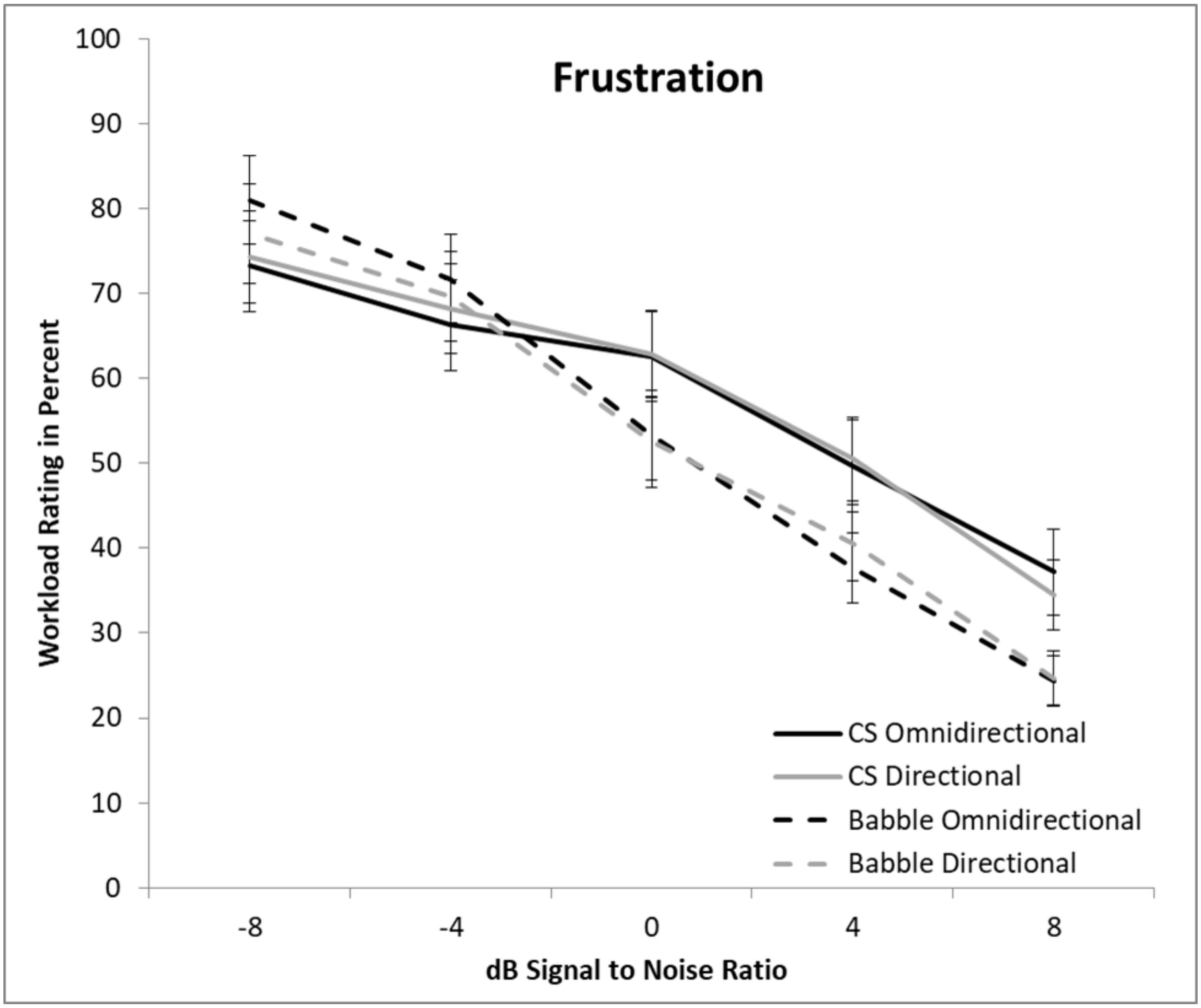

Figure 20. Subjective frustration functions. Workload rating in percent for frustration across SNR with a background of 2-talker competing speech (CS) and 20-talker babble. Lower scores would indicate a lower workload, meaning the task was easier.

To summarize, there was no effect of directionality for the subjective rating scales. However, there was a significant main effect of masker type for mental demand, effort, and frustration, indicating that participants found the competing speech masker more taxing than the babble background. This effect was not observed for the subjective performance rating.

Test-Retest Reliability

Objective Testing. Each listening condition was repeated for every participant to allow for test-retest reliability calculations. Pearson correlation coefficients were calculated for all three listening conditions and for both masker types at 0 dB SNR to avoid ceiling and floor effects. All correlation coefficients were equal to or greater than .77, and most coefficients were greater than .8 suggesting good reliability for all test conditions.

Subjective Ratings. Participants completed their subjective ratings twice to allow for test-retest reliability calculations. Pearson correlation coefficients were calculated for each NASA task load index subscale, all three listening conditions and for both masker types at 0 dB SNR to avoid ceiling and floor effects. Most correlation coefficients were once again greater than .7, however a few of the several conditions were of questionable reliability (between .6 and .7), two conditions were of poor reliability (between .5 and .6) and one condition (Directional subjective performance in babble) was of unacceptable reliability (less than .5). In summary, most of the subjective ratings for the listening conditions were of acceptable reliability, but there were a few conditions with poor or unacceptable reliability. Pearson correlation coefficients were consistently higher for objective performance than for subjective ratings. This means that the participants' objective performance was more reliable than their subjective ratings.

CHAPTER FOUR: DISCUSSION

Individuals with hearing loss often report difficulty understanding speech in noisy listening environments, and hearing aids are the most common treatment for hearing loss. Hearing aids employ multiple strategies like directional microphones to improve speech perception in noise, however objective and subjective outcomes are highly variable within this population and are difficult to predict even when using reliable test measures. The slope of the psychometric function or the rate of improvement as SNR increases is a measure that could help to predict speech recognition benefit from an improved SNR with directional microphones. We hypothesized that the rate of improvement is a significant source of patient variability when listening via directional processing through their hearing aids and that the rate of improvement is associated with both auditory and cognitive factors.

Rate of Improvement and Masker Type

In this study, we measured soundfield amplified, omnidirectional aided, and directional aided speech perception in competing speech and babble using the Coordinate Response Measure (Bolia et al., 2000). We tested across a range of SNRs in order to calculate the rates of improvement for the two masker conditions. It was predicted that the babble masker condition would result in a steeper rate of improvement than the competing speech condition, and therefore more objective and subjective benefit would be observed for the babble condition. Our results confirmed that the recognition rate of improvement was significantly steeper for the babble background than the competing speech. The results also revealed a significant amount of informational masking, calculated as the difference in recognition performance between the babble and competing speech masker conditions, for our aided listening conditions.

A steeper rate of improvement or slope of the psychometric function for babble than competing speech fits with previously published studies which also have found shallower rates of improvement for backgrounds of competing speech than for purely energetic maskers (Arbogast et al., 2002; Brungart, 2001) and for babble maskers (MacPherson & Akeroyd, 2014). This is likely due to the intelligible maskers providing informational masking in addition to energetic masking. Additionally, signal/masker confusion is more likely when the masker is similar to the signal (Kidd et al., 2008). With competing talkers of the same sex, listeners are more likely to experience signal/masker confusion than if competing talkers were of the opposite sex (Brungart, 2001) as was the case in our study. With a background of babble, as SNR improves to more advantageous SNRs where spectral cues become more salient, listeners are less likely to confuse the signal with the masker and intelligibility will improve more rapidly than it will for a background of competing speech. This finding in our study was not surprising, but it was necessary for our prediction that in the babble background more directional benefit would be observed due to a steeper rate of improvement than in the competing speech condition.

There is potential clinical impact for the finding that babble maskers result in a steeper rate of improvement than intelligible, competing talkers. Clinicians could make use of this information to educate patients regarding the unique difficulties than can be anticipated by the type of background noise. When there is a purely energetic masker, such as a fan or air conditioning, it is most helpful to be near to the individual(s) with whom patients are communicating in order to preserve an advantageous SNR. By maintaining a positive SNR, spectral cues can be preserved and the intended message is more likely to be understood.

The situation in which there are multiple background talkers appears to be a bit more complicated, particularly if the background talkers are of the same sex as the individual(s) with whom the patients are communicating. It would be beneficial to manipulate the talkers/listening environment in such a fashion that the signal becomes more dissimilar from the maskers. For example, if a patient were going out to eat with a group of only one sex, the patient could look around the restaurant and request a table where most of the competing talkers were of a different sex. We did observe near ceiling intelligibility performance for most of our participants once the SNR was high enough (+8 dB SNR), albeit our measure was closed-set, so it would be helpful once again to have the most advantageous SNR possible. With the difficult task of perceiving speech in a background of competing talkers, it may be more appropriate for use of assistive listening devices such as remote microphones or an FM system to get a larger SNR boost.

Directional Benefit for Intelligibility

Because the rate of improvement was steeper for the babble background than the competing speech background, we predicted that more directional benefit would be observed in the babble background than in the competing speech background. There was a statistically significant difference in directional benefit between the two masking conditions, with more directional benefit in the babble background as predicted. When using rate of improvement between the dB SNR steps that did not approach ceiling or floor performance (0 dB to +4 dB SNR), directional benefit was significantly associated with the omnidirectional rate of improvement for both babble and competing speech conditions. This finding confirms that benefit due to an SNR boost is likely associated with the rate of improvement for applicable SNRs where ceiling and floor effects are not present (i.e. SNRs surrounding 50% intelligibility).

We had hypothesized that due to a steeper rate of improvement with a background of babble, listeners should receive more intelligibility benefit from directional processing in the babble background than in the competing speech background. Although the effect was small, listeners did receive significantly more intelligibility benefit due to directional processing in the babble background than in the competing speech background. On average, there was nearly no difference between omnidirectional and directional performance in the competing speech background.

This is a novel finding in the amplification literature, as no articles were found in the literature review comparing directional performance between competing speech and babble backgrounds. In 2007, Hornsby and Ricketts reported directional benefit for speech recognition in noise, measured as the change in SNR 50% threshold using the Hearing in Noise Test (Nilsson et al., 1994), with backgrounds of either four maskers or seven maskers. The maskers were composed of forward speech, reversed speech, or modulated noise. The masker type and number manipulations were intended to alter the amount of informational masking. In contrast to our findings, they did not find a significant interaction between microphone type and masker type nor the number of maskers. However, Macpherson & Akeroyd (2014) conducted a meta-analysis of psychometric function slopes and the number of competing talkers and reported that once three or four maskers are present, the addition of more maskers does not affect slope of the psychometric function. Therefore, it may be the case that informational masking was limited due to the number of maskers and therefore no interaction between microphone type and number of maskers was found.

These findings are applicable to audiologic practice considering directionality is a common strategy used in hearing aids to help patients perceive speech in background noise. The lack of intelligibility benefit in the competing speech background should temper expectations for aided directional benefit in certain listening conditions. However, only one spatial arrangement was used along with a single speech corpus for this study, so it would be inappropriate to broadly conclude that directionality does not provide benefit in a competing speech background, but in our specific listening conditions no benefit was observed when there were competing talkers. A statistically significant, although relatively small boost in intelligibility was observed in the babble background. This finding could contribute to the discussion of patient expectations for intelligibility outcomes in noisy environments while wearing their hearing aids and also which listening environments hearing aid directionality may help most. Because our study did not find directional benefit in a competing speech background, an intervention that can provide a larger boost in SNR than hearing aid directionality may be recommended to a patient, especially if the patient is consistently struggling to communicate in multi-talker listening environment despite the proper use of their hearing aids.

Since rate of improvement was a significant predictor of intelligibility benefit from directionality, it could also be helpful to make use of a speech-in-noise test that measures performance across a range of SNRs and reports rate of improvement, as well as the SNRs where intelligibility performance changes most rapidly. The QuickSIN (Killion et al., 2004) tests across a range of SNRs to estimate the 50% intelligibility SNR, which would help to identify which SNR environments would be most affected by an SNR intervention because the rate of improvement is usually steepest around the 50% performance point. However, this measure does not calculate or report rate of improvement, making the amount of anticipated benefit from an SNR boost difficult to predict. A measure that calculates both 50% SNR and rate of improvement would help a clinician discuss with his/her patients in which noise levels they might expect more intelligibility benefit from hearing aid directionality and how much benefit they could potentially anticipate.

Individual Variability for Rate of Improvement

The statistically significant improvement across our test SNRs due to directional processing was modest on average (4%), but individual outcomes, as expected, were quite variable. We found that rate of improvement significantly correlated with directional benefit at 0 dB SNR. In order to better understand individual variability in rate of improvement, several auditory and cognitive measures were utilized to explore which individual factors may contribute to listener variability. It was hypothesized that a combination of cognitive and auditory factors would be associated with the rate of improvement, which could help to explain some of the variability observed in directional benefit.

Multiple linear regression modeling revealed that for a background of competing speech, the soundfield rate of improvement was associated with hearing loss severity, Gaps in Noise threshold (temporal processing), QuickSIN (SNR loss), Frontal Factor (executive function and working memory), and Reading Span (working memory capacity). Better QuickSIN SNR losses were associated with steeper rates of improvement. This would suggest that individuals who perform better at more difficult SNRs would generally also experience a greater intelligibility benefit from an SNR boost. Using a variety of clinically-available speech-in-noise measures, Wilson and colleagues (2007) found that older listeners with hearing loss generally exhibited worse SNR losses and shallower rates of improvement than younger listeners with normal hearing. Similarly, our study revealed hearing loss severity was negatively associated with rate of improvement, meaning individuals with greater hearing loss severity had shallower rates of improvement.

Better Reading Span scores were associated with steeper rates of improvement, however, Frontal Factor scores were associated with shallower rates of improvement, contrary to what was predicted. Given the likely relationship between frontal processes and working memory capacity, it is surprising that their associations with the rate of improvement are in opposite directions. However, for our participants, Frontal Factor and Reading Span scores were not significantly associated with each other. Given the complexity of the Reading Span test, it is difficult to determine which specific cognitive processes are involved in the task and how performance relates to other frontal processing tasks (Miyake, 2001; Whitney et al., 2001). It is possible that the positive correlation between Reading Span and rate of improvement is driven broadly by task complexity rather than specific cognitive processes. It is possible that individuals with better frontal processing performed better at the most difficult SNRs, resulting in a shallowing of their slope functions. By grouping the data into high and low Frontal Factor scores, it was confirmed that the individuals with better Frontal Factor scores did indeed perform better at the most difficult SNRs, but did not exhibit a benefit at the easiest SNRs, resulting in a shallowing of their psychometric functions.

Also contrary to our prediction, better temporal processing (Gaps in Noise threshold) was associated with a shallower rate of improvement. Further analysis revealed that individuals with better temporal processing performed better at the at most SNRs which would likely not affect the rate of improvement. In a meta-analysis, MacPherson (2013) reported that in listening conditions in which the masker is modulated, adults with poor temporal processing may exhibit steeper rates of improvement because they are unable to listen in the dips of the masker and therefore their psychometric functions may resemble functions for continuous noise (steeper). This may have been the case for our participants since it could have been possible for them to listen in the dips of the competing speech. This would not have been possible for the babble background, and indeed, there was no association between rate of improvement with a babble background and Gaps in Noise thresholds.

For the babble background, multiple linear regression modeling yielded a positive association between Reading Span scores and rate of improvement and a nearly significant negative association between hearing loss severity of rate of improvement. There was no association with temporal processing and rate of improvement for the babble background likely because the amplitude of the babble was relatively stable, and therefore there was minimal potential to listen in the gaps of the masker, which would have been possible with competing speech. Frontal factors were also not associated with rate of improvement for a babble background likely due to the reduced target/masker similarity, demanding fewer inhibitory and attentional resources. However, once again Reading Span scores were associated with rate of improvement, which may be due once again to underlying task complexity and participant effort levels.

The rate of improvement was significantly associated with both auditory and cognitive factors for both masker types. As expected, hearing loss severity was associated with a shallower rate of improvement, suggesting that deterioration of the sensory component of the auditory periphery does influence the rate of improvement. However, temporal processing was also associated with the rate of improvement, suggesting a central component in addition to a sensory component. Working memory capacity was also associated with rate of improvement for both masker types, suggesting that higher-level cognition is also associated with the rate of improvement. These findings demonstrate that the entire auditory pathway as well as higher-order cognition can all affect the rate of improvement independently and may contribute to variable perceptual benefit provided by SNR interventions like directionality.

We had hypothesized that individual rates of improvement would be associated with both auditory and cognitive factors. This was especially true for the competing speech masking condition in which all predictor variables except for Dichotic Digits scores were included in the final regression model. The contribution of cognitive factors in addition to auditory factors to the rate of improvement advocates for importance for audiologists to consider and incorporate measures of cognition in order to better understand patient performance in noise and potential benefit from an improved SNR. This information could contribute to improved patient education, particularly regarding hearing aid expectations and their utility in noisy listening environments. These findings can also contribute to the evidence supporting patient-specific device selection to best suit the listening needs of patients, while also considering potential to benefit from aided interventions. Fewer associations were found for the babble background, but listeners are more likely to encounter situations in which informational masking is present, making the competing speech masker more ecologically valid.

Subjective Outcomes

In the subjective domain, directional processing did not result in any significant changes in self-reported mental demand, performance, effort, or frustration levels. Previous studies have demonstrated variability in the subjective outcomes for directional hearing aids (Bentler, 2005; Cord et al., 2002; Palmer et al., 2006). In a large study comparing objective and subjective benefit for directional hearing aids, Gnewikow and colleagues (2009) measured both objective and subjective outcomes for directional hearing aids in comparison to omnidirectional aids in 94 participants and similarly found significantly improved recognition performance in noise for the directional aids but this objective benefit was not reflected on the subjective domain. Other studies comparing objective and subjective benefit have also measured consistent benefit in the objective domain for directional aids compared to omnidirectional aids, but inconsistent benefit in the subjective domain (Bentler et al., 2006; Palmer et al., 2006; Ricketts et al., 2003; Walden et al., 2000).

The previous studies measuring subjective directional benefit typically used measures that were designed to measure subjective hearing aid benefit (e.g. Profile of Hearing Aid Benefit; Cox et al., 1991) which have not demonstrated directional benefit consistently. It is possible that in real-world listening conditions in which reverberation or various signal and noise spatial relationships may occur, directional processing does not provide benefit and therefore is not present in self-report. It is also possible that these subjective measures are not sensitive to directional benefit in the specific listening situations in which intelligibility benefit may be expected or the patients may not be able to properly recall their performance in those listening scenarios. For our study, we required participants to fill out a subjective rating form (NASA Task Load Index; Hart & Staveland, 1988) immediately after each listening condition, eliminating the need for delayed recall of the listening scenario. However, as noted in previous studies comparing objective and subjective benefit, we did not find the same significant effect of directionality in the subjective domain that we did in the objective domain. It appears likely that patients have difficulty in detecting the small objective benefit that is being measure in the objective domain.

Our participants did rate competing speech to be more mentally demanding, effortful, and frustrating than babble, particularly at SNRs greater than -4 dB SNR. Once the SNR was reduced to -4 dB SNR and -8 dB SNR, subjective ratings of the maskers were somewhat similar, suggesting that energetic masking was driving their subjective ratings at the most difficult SNRs. Once the SNR was 0 dB or greater, it appears that spectral information was available to most participants, and the subjective ratings increased quickly for the babble background. The rate of improvement in the subjective domain for competing speech was not as steep, likely due to the informational masking provided by the competing talkers, making the listening task more demanding. One potential clinical implication for this finding is that patients can expect to be more frustrated and exert more mental effort when there are competing talkers that are intelligible. It may be advantageous to have as much distance as possible between conversation partners and competing talkers, not only for the SNR benefit, but also in an effort to make the competing talkers less intelligible.

Despite the lack of significant improvement in the subjective domain due to directionality, our participants' subjective ratings generally correlated well with objective performance. Participants were able to determine when they were objectively performing quite well or very poorly due to the change in SNR for our listening conditions. While they were able to subjectively report large changes in performance, the small intelligibility improvement due to directional was likely too small of the change for the participants to recognize and report.

Study Limitations

There are some limitations to the generalization of this study given that only a single type of directionality within a single hearing aid model was used to test speech perception in noise. It is possible that there are small manufacturer differences that could affect directional outcomes. We also tested only in a single spatial arrangement. Our findings do not generalize to all of the potential listening environments in the real world. It is likely that objective and subjective benefit would vary with a different spatial arrangement of signal of maskers. We chose our specific spatial arrangement in an attempt to elicit a directional effect so we could then determine whether rate of improvement is a good predictor of directional benefit.

Participants were not given an acclimatization period with the study hearing aids. All participants were experienced hearing aid users, but it is likely that they received different levels of gain for our testing than the amount of gain in their own hearing aids. Several participants did remark that our hearing aids were louder than their own hearing aids. With regard to hearing aid directionality, it is probable that our participants have had exposure to hearing aid directionality within their own hearing aids since it is a very common hearing aid strategy. Additionally, acclimatization effects are likely minimal with regard to directionality (Ricketts et al., 2003).

We used the CRM test for our speech perception in noise task in order to limit contextual effects. This test measure is a closed-set test with a consistent sentence structure, which is not typical for every day dialogue. However, some advantages of this measure are that there are limitless trials and the consistent structure provides effective informational masking. The CRM corpus also has recordings of eight different talkers, four males and four females, which makes it useful for testing various spatial arrangements of signals and maskers in order to simulate spatial listening with competing speech rather than babble or broadband noise. While the sentences may not resemble typical speech, this corpus allowed us to control for context, set size, and target/masker similarity.

Our participants had a range of hearing losses which meant that each participant had unique gain settings programmed in the hearing aids, which could have interacted with the directional processing of the hearing aids. However, Dhar and colleagues (2004) measured a real ear aided response to swept pure tones from 180°, 135°, and 225°. They did not find a significant correlation between Hearing in Noise test results and the in situ directivity measured using real ear. This finding would suggest that other listener variables beside the inter-individual variability in level of directionality being provided are affecting perceptual outcomes with directionality.

Directionality has also been demonstrated to significantly improve intelligibility for the range of hearing losses that our participants had (Gnewikow et al., 2009). The range of hearing losses allowed us to better assess the contribution of hearing loss severity to directional performance and the rate of improvement.

Lastly, all directional hearing aid testing was completed with noise reduction turned off. Typically, hearing aid noise management combines both noise reduction and directional processing to aid listening in background noise. For this purposes of our study, we wanted to isolate the SNR intervention of directionality to measure its effect on intelligibility in noise and to determine the interaction between an SNR boost provided by directionality and the rate of improvement. We were also concerned that the noise reduction may engage differently and on a different time scale for our babble vs. competing speech maskers.

Future Directions

The present study demonstrated the utility of measuring listener rates of improvement in order to better predict intelligibility benefit due to directional processing. Currently clinical speech in noise testing does not report rate of improvement but instead reports either the 50% recognition SNR or intelligibility scores for a fixed SNR. These data points can help a clinician determine how a patient might perform given a certain SNR, but they are limited in their ability to predict potential benefit from an SNR intervention. A measure which not only estimates the 50% SNR recognition point but also the rate of improvement around that SNR would better enable a clinician to inform his/her patients regarding which listening environments they could expect to receive directional benefit in and how much benefit may be provided by directional processing or any other intervention which improves the SNR. This information could also help to inform the hearing aid selection process and whether a patient could stand to receive an intelligibility benefit from a greater degree of noise management, which has large cost implications for the patient.

Our study provided novel evidence, to our knowledge, that directional benefit for intelligibility is on average present for a background of babble, but there appears to be no significant benefit for a background of competing talkers. Because it is a novel finding, it is important to further research to explore the interaction between hearing aid speech-in-noise strategies and ecologically valid masker types such as competing speech and babble. While informational masking has been studied within a population with hearing loss (Arbogast et al., 2005; Kidd et al., 2002; Marrone et al., 2008), there is less evidence for or against the utility of hearing aid noise management when informational masking is present. Further studies regarding hearing aid noise management and masker types could support recommendations regarding listening environment management and hearing aid feature selection based on listening environment.

We had hypothesized that the slope of the psychometric function or the rate of improvement would be associated with cognitive factors in addition to auditory factors. Reading Span scores and hearing loss severity were included in the regression models for both the competing speech and babble maskers. The Reading Span test measures working memory capacity and was associated with a steeper rate of improvement for our listeners. Working memory has been used in a number of amplification studies and has repeatedly been found to be associated with speech perception in noise (Akeroyd, 2008; Besser et al., 2013; Pichora-Fuller, 1995; Rönnberg et al., 2010; Wingfield et al., 2005). Because speech perception in noise is a common complaint for hearing aid users, it would be helpful for clinicians to measure working memory in addition to speech perception in noise to have a better understanding of the sources of difficulty for patients. A clinical assessment has recently been developed to measure working memory while testing speech perception in noise and could be useful to audiologists in the future (Smith et al., 2016).

Conclusion

Speech perception in noise continues to be a challenging scenario for individuals with hearing loss, even while wearing hearing aids. Current clinical test measures are limited in their ability to predict potential benefit from hearing aid interventions such as directionality. If speech in noise interventions provide an SNR boost, then the slope of a speech in noise psychometric function or rate of improvement could help to predict the corresponding intelligibility benefit due to an improved SNR. Indeed, our study revealed that more intelligibility benefit due to hearing aid directionality was measured in a listening condition which resulted in steeper rate of improvement (babble background) than a listening condition which resulted in a shallower rate of improvement (competing speech). Additionally, the rates of improvement between our most relevant SNRs were significantly associated with directional benefit. These results confirm that the rate of improvement for a given range of SNRs could help in predicting potential benefit from an SNR intervention within a hearing loss population.

We hypothesized that the slope of the psychometric function or rate of improvement is associated with both auditory and cognitive factors. Our results confirmed that hearing loss severity of negatively associated with rate of improvement and working memory capacity was positively associated with rate of improvement. Our findings support the involvement of cognition in addition to the auditory pathway for the perception of degraded speech signals within a population with hearing loss. Measuring cognitive factors such as working memory capacity could improve our understanding of patient variability for aided speech in noise outcomes and provide a patient-specific approach to hearing loss interventions.

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