ABSTRACT

Title of Document: PROCESSING OF SPEECH IN COMPLEX LISTENING ENVIRONMENTS BY INDIVIDUALS WITH OBSCURE AUDITORY DYSFUNCTION

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Obscure auditory dysfunction (OAD) is a disorder characterized by patient report of excessive amounts of difficulty understanding speech in the presence of background noise, despite relatively normal hearing sensitivity. It has been hypothesized that OAD may be the result of mild cochlear dysfunction, central auditory processing deficits, and/or psychological disorders. To evaluate auditory processing aspects of this disorder, speech recognition was measured in complex listening conditions for 10 normal-hearing persons with self-reported problems understanding speech in noisy environments. Ten normal-hearing listeners without reported difficulty hearing speech in noise served as controls. Each participant completed a standard audiometric evaluation, the QuickSIN test (standard clinical test of speech recognition in noise), and experimental speech recognition measures in simulated background environments, which included a range and combination of competitor stimuli presented in monaural and binaural conditions. The results show that the OAD participants had poorer overall speech recognition abilities in noise than did control participants for the experimental speech recognition tasks. The pattern of performance deficits suggests that the speech-understanding problems of these OAD participants are not attributable to abnormally poor binaural hearing or to a reduction in masking release. Further, performance deficits exhibited by listeners with OAD were not identified by a standard clinical speech-in-noise measure.

PROCESSING OF SPEECH IN COMPLEX LISTENING ENVIRONMENTS BY INDIVIDUALS WITH OBSCURE AUDITORY DYSFUNCTION.

By

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Dedication

I would like to dedicate this Doctoral dissertation to my family and friends for their continued love and support, especially:

To my husband, Andrew, for making me laugh when I wanted to cry, and holding me up when I was ready to fall. *"You are simply my best time. You are simply my sweetest laughter. Always you will have my hand to hold. Always." (Unknown).*

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Chapter 1: Introduction

Introduction to Obscure Auditory Dysfunction

All individuals experience increased difficulty communicating in the presence of background noise, regardless of their hearing acuity. For some, this difficulty becomes so intrusive that they seek help for their problems from professionals such as audiologists or otologists. Patients who have audiometrically normal hearing sensitivity, but complain of excessive amounts of difficulty understanding speech in the presence of background noise, are classified as suffering from “Obscure Auditory Dysfunction” (OAD; Saunders & Haggard, 1989). Other names commonly used to describe this disorder are “Auditory Disability with Normal Hearing” (ADN; Stephens & Rendell, 1988), and “King-Kopetzky Syndrome” (KKS; Hinchcliffe, 1992).

Obscure auditory dysfunction (OAD) is a disorder characterized by patient report of excessive amounts of difficulty understanding speech in the presence of background noise, despite relatively normal hearing sensitivity. Investigators estimate that 5-10% of patients who are evaluated for aural problems have audiometric findings and complaints consistent with OAD (Higson, Haggard, & Field, 1994; Saunders & Haggard, 1989). OAD has been speculated to be a multifactorial disorder, the result of mild cochlear dysfunction, central auditory processing deficits, and/or psychological disorders (Saunders & Haggard, 1989; Shaw, Jardine, & Fridjhon, 1996). Otologic history also may play a role in the difficulties experienced by individuals with OAD. When questioned, patients with OAD have been up to five times more likely to report a history of childhood middle ear dysfunction and/or a family history of hearing impairment than their non-OAD normal-hearing counterparts (King & Stephens, 1992; Saunders & Haggard, 1989; Stevens & Zhao, 2000). Previous studies also have shown that individuals with OAD have poorer average pure-tone thresholds compared to individuals without OAD, while still remaining within normal limits (King & Stephens, 1992; Middelweerd, Festen & Plomp, 1990; Saunders & Haggard, 1989; Zhao & Stephens, 2000).

Statement of the Problem

While a basic speech recognition deficit among patients with OAD has been documented in single noise competitor conditions, a comprehensive study of the effects of specific environmental factors, such as competitor type, competitor locations, and number of competitors has not been conducted. These variables, which are known to influence speech recognition performance in predictable ways among young listeners with normal hearing who do not have OAD, are useful for examining underlying processing mechanisms. For this reason, the following study was developed to assess speech recognition abilities among patients with OAD in a range of simulated listening environments. Selected test conditions allowed us to explore the effects of spatially separating the target signal from the competitor, monaural versus binaural listening, temporal properties of the competitor, and linguistic content of the competitor on speech recognition. The comparison of performance between patients with OAD and normal hearing controls for the complex listening conditions should permit an improved understanding of the nature and scope of OAD. This new information may lead to better diagnostic and identification tools for the clinical assessment of OAD. The findings from this study also will help to delineate the contributions of central auditory processing deficits and mild cochlear dysfunction within OAD, and to establish ways in which normal hearing listeners with OAD perform differently than listeners without OAD on speech-in-noise tasks.

Chapter 2: Review of Literature

Possible Mechanisms behind Obscure Auditory Dysfunction

Kopetzky first described Obscure Auditory Dysfunction (OAD) in 1948. At that time, OAD was categorized as a form of "psychogenic deafness," and was defined further as a "loss of the capacity for discriminative listening" (King, 1954). Recent literature has focused on the possible structural reasons for the problem of OAD, focusing on central auditory processing and cochlear disparities.

OAD is thought to be a multifactorial disorder involving mild dysfunctions of cochlear function, central auditory processing, and psychological factors (Saunders & Haggard, 1989; Shaw, Jardine, & Fridjhon, 1996). Mild cochlear dysfunction is believed to be a likely contributor to OAD because of slightly elevated pure tone audiometric thresholds and evidence of subtle cochlear outer hair cell deficits. However, the evidence that individuals with OAD have worse average thresholds at all or most frequencies tested when compared to normal-hearing listeners (normal-hearing average from .25-8 kHz = 7.9 dB HL, OAD average = 10.9 dB HL, Saunders & Haggard, 1989; similar findings found by King & Stephens, 1992; Middelweerd, Festen, & Plomp, 1990; Zhao & Stevens, 2000) is not especially compelling. While this difference is significant for most cases, audiometric thresholds for participants with OAD remain within normal limits. Subtle threshold differences in the absence of an abnormal otologic history have been hypothesized to be associated with cochlear dysfunction.

Zhao and Stephens (2006) examined the relationship between OAD and mild cochlear dysfunction. These authors evaluated transient-evoked otoacoustic emission (TEOAE) and distortion-product otoacoustic emission (DPOAE) results for 82 OAD participants and 70 control participants. Results indicated TEOAE amplitudes between OAD and control listeners did not differ if TEOAEs were found present, however, the prevalence of TEOAEs were significantly reduced ($p < .0005$) for the OAD listeners (77% prevalence) compared to control listeners (96% prevalence). Analysis of DPOAE data revealed that OAD listeners had significantly reduced DPOAE amplitudes when compared to control listeners ($p < .001$), even with pure-tone thresholds held as a co-variable.

Central auditory problems also are suspected in patients with OAD. Fermen, Vershuure and van Santen (1993) hypothesized that poor speech intelligibility in noisy situations may be related to deficits in central auditory function. To test their theory, they evaluated 37 participants with OAD using a series of central auditory listening tests, including a dichotic discrimination test, filtered speech reception test, and alternating speech reception test. Results showed that 65% of the participants (24 of 37) in their study had abnormal results on at least one of the tests. Zhao and Stephens (2000) evaluated the central auditory processing performance of 110 patients with OAD. They used the Staggered Spondaic Word Test (SSW), which consists of 50 overlapping pairs of spondee words presented at a suprathreshold level, one word to each ear. Eighteen of their 110 (16%) patients had an abnormal score on the SSW. Deficits in central auditory processing also have been indicated in some patients with OAD on a dichotic listening test that measures focused attention (Higson, Haggard, & Field, 1994). Findings from a sentence completion task also suggest some patients with OAD have a lower linguistic ability when compared to listeners without OAD (Saunders & Haggard, 1989).

The psychological and personality-related intricacies that exist among individuals with OAD have been replicated over a series of studies conducted during the past two decades. The most common finding among OAD patients is an increased anxiety level when compared to normal-hearing controls. This finding has often been captured using the Crown-Crisp Experiential Index (CCEI). Significant differences were reported between OAD patients and normal-hearing controls on the CCEI sub-scales for free-floating anxiety, somatic anxiety, and depression (Saunders & Haggard, 1989; King & Stephens, 1992; Higson, Haggard, & Field, 1994). Significant discrepancies between subjective and objective scores on the Pseudo-Free-Field in Noise Test (PFFIN) also have revealed increased psychological disturbances among OAD patients (Saunders & Haggard, 1989; Higson, Haggard & Field, 1994). Results from these various psychologically based studies support the idea that speech discrimination in noise exacerbates communication difficulty, leading to increased anxiety, isolation, and depression among individuals with OAD. However, these personality and psychological characteristics may not be related to the individual's speech recognition in noise ability, and may be pre-existing in nature.

Speech Recognition in Noise by Listeners with OAD

Individuals with OAD suffer the greatest disability comprehending speech when in noisy environments (King & Stephens, 1992; Saunders & Haggard, 1989;

Stephens & Rendell, 1988). Since the late 1980s, researchers have quantified the speech recognition deficits reported by individuals with OAD. Zhao and Stephens (2000) evaluated 110 patients with OAD and 70 individuals with normal-hearing sensitivity and no signs of OAD using the BKB (Bamford-Kowal-Bench) Speech-in-Noise test (SiN, Bench & Bamford, 1979). Sentences were presented in the free-field with background speech-spectrum noise presented at two separate signal-to-noise ratios (SNRs) of 0 and -5 dB. The mean speech recognition thresholds (SRTs) for the patients with OAD were on average more than 2 SD above the mean for the control listeners in both SNR conditions. In another study of 37 patients with OAD (Ferman, Vershuure & van Santen, 1993), 95% of the participants showed elevated SRTs in noise on a sentence recognition task in both monaural and binaural conditions. Each participant had been documented to have normal hearing in quiet. A reduced gain from binaural listening when compared to monaural listening was also noted in 19 of the participants. Middelweerd, Festen, and Plomp (1990) used steady-state versus fluctuating noise and various presentation modes (headphones, speakers, monaural, binaural) to examine the effect of competitor type and mode of presentation on speech recognition thresholds in a group of patients with OAD. Fluctuating masking noise proved the most challenging listening condition for participants with OAD in all listening presentations, especially monaurally under headphones and when listening in the sound field. Significant differences in SRTs in noise for the participants with OAD compared to the control group were observed in all listening conditions ($p<0.05$).

Binaural Processes for Speech Recognition in Noise

Two variables can determine an individual's ability, or inability, to recognize speech in the presence of background noise. First, the "head shadow effect" is the loss of transmission of sound around the head and body, mainly affecting the mid- and high-frequency content of acoustic stimulation. The basic effect of the head shadow is that a signal directed to the non-listening ear is attenuated as it travels around objects in its path, specifically, the head and body. This attenuation effect is approximately 6 dB in the mid-frequencies and up to 15 dB for high-frequency acoustic information (e.g., Staab, 1988; Tillman *et al*., 1963), and can result in either a favorable or unfavorable listening condition. A favorable condition results when competing noise is attenuated before reaching the listening ear, which reduces the masking effect of the competing noise. An unfavorable listening condition may result when noise is presented to the listening ear and speech is presented to the non-listening ear. For this adverse listening condion, speech is reduced in intensity when it reaches the listening ear, creating a poor (low) SNR.

The second variable is the listener's ability to compare the signals presented at the two ears. A properly functioning auditory system performs an autocorrelation of signals at the two ears to take advantage of the interaural time delay and/or the interaural intensity difference. Two specific binaural processes are the binaural squelch and the masking level difference (MLD). Binaural squelch refers to the listener's ability to extract target stimuli from the competitor(s) with greater effectiveness when listening binaurally versus monaurally (Carhart, 1965). The MLD reflects a person's ability to detect and/or identify a binaural signal in the presence of a binaural masker when the phase or level of either the signal or masker differs at the two ears relative to their ability to detect the signal when the phase and level of the stimuli are the same at the two ears (Hirsh, 1948). The effects resulting from the binaural squelch and MLD phenomena can greatly enhance a person's ability to suppress the effects of noise in many listening situations.

Carhart (1965) examined the head shadow effect on speech recognition performance by evaluating listeners with normal hearing. Monosyllabic words were presented in various levels of competing sentence background noise for both monaural and binaural listening conditions in the sound field. Monaural speech recognition ability for the speech signal presented to the non-listening ear was poorer by approximately 25% at a SNR of –12 dB than for the speech signal presented directly to the listening ear. To assess the binaural squelch effect, Carhart compared monaural performance to binaural performance in noise for competing sentences presented to the non-listening ear (90° azimuth) and target words presented directly in front of the listener (0° azimuth). The advantage of binaural listening due to the binaural squelch effect was on average 4.8 dB – 10.6 dB.

The number of competitors used in an experiment can also have an effect on a person's ability to recognize speech. Carhart, Nicholls, and Kacena (1972) investigated the effect of competitor number on spondee thresholds. Carhart and his colleagues utilized masker complexes of up to 15 competitors, composed of combinations of two female and three male talkers reading English prose. Competitor level was controlled so that increasing the number of talkers did not yield an increase in overall SPL. Carhart *et al.* reported that the masking effect increased with increasing number of competitors. For example, when using one competitor the spondee threshold was 50.5 dB, however, when using five competitors the spondee threshold increased to 66.3 dB. Carhart *et al.* also found that the greatest incremental increase in masking occurred with the presentation of two competitors versus one (9.1 dB increase, $p < 0.05$), with each additional competitor yielding a smaller incremental amount of masking than that produced by the preceding smaller sets of maskers. This increase in masking by the overlapping time spectrum, leaving fewer gaps in the masking stimuli for the target speech to be heard, most likely causes the increased masking effect with increased number of maskers.

In 1983, Duquesnoy investigated the effect of spatial separation on speech recognition ability. To measure the advantage gained from spatial separation of the target stimuli from the competing stimuli, Duquesnoy tested listeners in two speech recognition conditions using coincident versus separated stimuli. The first condition was arranged so that the sentences and competing noise were presented from the same speaker located in front of the listener (0° azimuth). In the second condition, the sentences were presented from the front speaker only, while the competing noise was presented from a speaker arranged 90° off to the listener's side. For both conditions, the SNR was determined that corresponded to 50% correct sentence recognition. The difference in SNR for the spatially coincident versus the spatially separate conditions was evidence of the advantage obtained by the listener when the stimuli were separated. Elderly listeners with hearing loss in Duquesnoy's study were not able to take advantage of the spatial separation to the same extent as young listeners with normal hearing. However, it was unclear whether the minimal benefit from spatial separation for the older group was associated with listener age, presence of hearing loss, or an interaction between the two factors.

Gelfand, Ross, and Miller (1988) evaluated the effect of age and hearing loss on the advantage of spatial separation by assessing the speech recognition abilities of young, middle-aged, and older individuals with normal hearing sensitivity, and that of elderly individuals with hearing loss. Each group was evaluated while listening to spatially coincident versus spatially separate stimuli. Gelfand and his colleagues used SPIN target sentences (Kalikow, Stevens, & Elliott, 1977) and 12-talker babble as the competitor. SRTs and babble detection thresholds were measured for each condition. The participant groups with normal hearing sensitivity all gained similar listening advantages from spatially separate target speech and babble; however, the participant group with hearing loss showed significantly less advantage. Based on these findings, it seems that age alone does not influence an individual's ability to take advantage of spatial separation when recognizing speech. However, hearing loss does impair a person's ability to benefit from signal/competitor separation.

The type of competitor can also affect speech recognition ability. Competitors that have been used include, but are not limited to, white noise, speech-shaped noise, nonsense speech, a single talker, and multiple talkers. Different competitor types have different temporal properties, allowing for varying amounts of the target speech to be masked. For example, speech-shaped noise is white noise that has been filtered to resemble the average long-term spectrum of speech. It is not modulated like speech; however, it has a constant level of energy present, making it a more powerful masker than those maskers with fluctuating spectra. Speech-shaped noise is a broad spectrum steady-state noise that has no linguistic or semantic content. It is an example of an energetic masker. Speech-shaped noise is typically more effective than speech-shaped modulated noise maskers. The latter are characterized by gaps and fluctuations that make them less effective maskers of speech. In contrast, speech competitors consist of time-varying frequency components that vary in amplitude from moment-to-moment, potentially allowing for “windows” of time where the target speech may be heard by the listener. Although speech competitors may produce less energetic masking than steady-state noise, speech has linguistic content that may create additional interference in masking the speech signal. This linguistic-induced interference is known as ‘informational masking” (Lufti, 1990; Pollack & Pickett, 1958) or “perceptual masking” (Carhart, Tillman, & Greetis, 1969a). To determine the contribution of the linguistic content to the masking effect, researchers have compared masking produced by speech competition to masking produced by nonsense speech or reversed speech. For these latter masker types, spectral, temporal, and amplitude characteristics of the speech masker are preserved but informational content is lacking. Carhart *et al.* (1969a) found normal-hearing listeners exhibited 6.6 dB more masking with two speech competitors compared to a modulated which noise competitor on a speech recognition task. In contrast, when only one speech competitor and one noise competitor (either modulated or unmodulated white noise) were employed, 3.2 dB of additional masking was observed relative to that for modulated white noise. Carhart and his colleagues surmised that the additional masking was caused by semantic interference when speech competitors were used.

Hawley, Litovsky, and Culling (2004) evaluated multiple environmental factors in various combinations and their detrimental effects on speech recognition to obtain more realistic estimates of binaural hearing benefit for listeners with normal hearing sensitivity. Specifically, Hawley *et al.* evaluated multiple conditions involving monaural versus binaural listening, coincident versus separated stimuli, single versus multiple competitors, and noise versus speech and speech-like competitors.

To mimic realistic noise environments, Hawley *et al.* (2004) used various noise competitors presented over headphones in spatial patterns that replicated sound sources coming from different locations around the listener. Harvard IEEE sentences (Rothauser, *et al*., 1969) were presented in front of the listener as the target (0° azimuth), while one, two, or three competitor complexes were presented simultaneously from various simulated spatial locations in front or to the sides of the listener (-30°, 0°, 60°, and 90° azimuth). Four types of competitors were used: speech-spectrum shaped noise, modulated speech-spectrum shaped noise, time-reversed speech, and sentences spoken by the same talker used for the target sentences.

Measurements of speech intelligibility were made by Hawley *et al* in both binaural and monaural listening conditions to isolate the two main components that aid speech intelligibility in noise, namely head shadow and binaural processing effects. The dependent measure for all of these conditions was the SRT, defined as the signal-to-noise ratio needed for 50% correct speech recognition. The binaural interaction was estimated for a given individual by subtracting the monaural advantage (monaural coincident SRT – monaural separated SRT) from the total advantage (binaural coincident SRT – binaural separated SRT) for a given condition. Evaluating these components of speech intelligibility allowed Hawley *et al.* (2004) to obtain a representation of the normal hearing listener's speech recognition ability in noise. They found that the monaural advantage due to the head shadow effect was not dependent upon competitor type for one, two, or three competitors. However, the binaural interaction due to binaural processing was dependent on competitor type for two or three competitors, but not for one competitor. Specifically, the binaural interaction for all competitor types was 2-4 dB when only one competitor was used. However, the binaural interaction for speech-based competitors (speech and reversed speech) was 6-7 dB, while the binaural interaction for noise-based competitors (speech-shaped steady-state noise and speech-shaped modulated noise) was only 2-4 dB for two or three competitors. These results indicate that a realistic estimate of the binaural advantage for listeners with normal hearing sensitivity using multiple speech competitors is approximately double the magnitude of the original binaural advantage effect of 3 dB (Keys, 1947; Shaw, Newman, & Hirsh, 1947).

Chapter 3: Research Aims

Purpose of this Study

The primary purpose of this study is to determine whether individuals with OAD experience monaural and binaural speech processing difficulties in the presence of background noise and to delineate those listening situations that are particularly problematic. Because listeners with OAD report difficulty understanding speech in everyday noisy environments, and because reducing the effects of noise on speech recognition in everyday listening situations is thought to be related to normal binaural processes, it is possible that listeners with OAD have deficits in binaural processes. These difficulties may be more evident in challenging listening environments comprised of multiple background noise sources (competitors) compared to a single background noise source (competitor). A previous study showed that the advantage of binaural information for listeners with normal hearing is greater in multiple-competitor environments than in single competitor environments (Hawley, Litovsky, & Culling, 2004).

Speech recognition deficits among patients with OAD have been well documented in background noise conditions. Previous studies, however, have had participant groups that vary appreciatively in the ranges of their pure-tone thresholds, possibly confounding the obtained speech recognition results. Further, the specific environmental factors that contribute to the reported problems of listeners with OAD have not been delineated. Most studies of OAD have used speech-in-noise measures with only one noise competitor. Typically the competitor has been a speech-shaped noise originating from the same location as the speech target. While such speech-in-noise measures can detect differences in speech recognition ability in noise for listeners with OAD and those without OAD, they do not provide insight into the underlying nature of the subjective condition of OAD. This limitation has hampered the development of rehabilitation protocols to compensate for OAD deficits.

The purpose of this study is to gain further insight into the mechanisms that may underlie OAD. These mechanisms may include mild cochlear dysfunction and central auditory processing problems. For example, if listeners with OAD do not show a reduced binaural advantage, but require higher intensity signals to recognize the speech signal, it may be inferred that a mild cochlear dysfunction is contributing to their problems. Pure-tone thresholds from previous studies have revealed that listeners with OAD have somewhat reduced hearing sensitivity compared to listeners with normal-hearing sensitivity and no complaints of OAD. This evidence is consistent with a contribution to the OAD condition from mild cochlear dysfunction. It is unknown whether listeners with OAD have reduced benefit from spatial separation of target and competitor signals, or if they experience reduced binaural advantages (monaural versus binaural listening). If these problems do exist, however, then an auditory processing problem may be inferred.

This research evaluates the speech recognition deficits present for individuals with OAD when listening in complex noise environments. The data will help to clarify the underlying mechanism of OAD as it relates to a binaural processing problem, and, ultimately, to develop intervention and compensation strategies for persons with OAD. The protocol is designed to establish whether individuals with OAD can utilize binaural information in speech recognition tasks as efficiently as do most persons with normal hearing. Hearing sensitivity and middle ear function are controlled and neutralized as confounding factors in this study. In addition, a standardized speech-in-noise test is administered for comparative purposes to the experimental speech-in-noise measures. Ultimately, we show that this standard test provides no diagnostic utility for identifying OAD.

Research Questions

This research will address the following set of related questions:

1. Do participants with OAD exhibit poorer pure tone thresholds than those of participants without OAD?
2. Do patients with OAD exhibit poorer speech recognition abilities in noise than those of listeners without OAD on the QuickSIN, speech-in-noise task?
3. Do patients with OAD exhibit poorer speech recognition abilities on the experimental measures of speech recognition in complex listening tasks?
4. Do patients with OAD demonstrate less binaural benefit than do participants without OAD on experimental measures of speech recognition in complex listening environments?
5. Do patients with OAD derive less benefit from spatial separation of the target and competitor source when compared to the corresponding benefit achieved by listeners without OAD?

6. Do patients with OAD derive an improvement in SRT with a background of reversed speech compared to a background of forward speech (i.e., benefit from informational masking release)?
7. Do patients with OAD derive an improvement in SRT with a background of modulated speech-noise compared to a background of steady-state speech-noise (i.e., benefit from modulated masking release)?

Research Hypotheses

The data collected from this study will test the following hypotheses:

H_1: Participants with OAD will have poorer audiometric thresholds compared to those of listeners without OAD as measured by pure-tone air conduction testing.

H_2: Results from a standard clinical test of speech recognition in noise will not show a significant difference in performance between the two test groups as measured by the QuickSIN evaluation.

H_3: Participants with OAD will show significantly poorer performance than the listeners without OAD on the experimental measures of speech recognition in complex listening environments.

H_4: Participants with OAD will exhibit reduced benefit for of listening binaurally versus monaurally in the presence of single or multiple competitors when compared to benefits achieved by listeners without OAD.

H_5: Participants with OAD will exhibit reduced benefit for target and competitor spatial separation when compared to the benefit achieved by listeners without OAD.

H_6: Participants with OAD will show a reduction in masking release for competitor backgrounds of speech versus reversed speech when compared to the masking release obtained by listeners without OAD.

H_7: Participants with OAD will show a reduction in the masking release for competitor backgrounds of modulated noise versus steady-state speech-spectrum noise when compared to the masking release obtained by listeners without OAD.

Summary

In total, 10 OAD participants were tested and their performances compared with a set of 10 control listeners on a battery of standardized and experimental speech recognition measures to evaluate the above hypotheses. The purpose of this study was to measure the potential impact of complex listening environments on listeners with self-reported difficulty hearing in noise compared to listeners without reported difficulty. The study was designed to provide evidence that a deficit in binaural processing ability and/or mild cochlear dysfunction contributed to the reported speech recognition problems. While individuals with OAD are able to function in everyday society, their complaints and concerns are often dismissed. The results of this study were expected to elucidate or rule out possible underlying mechanisms contributing to the speech understanding deficits for persons with OAD. The findings may be useful in guiding the development of treatment options for individuals with OAD.

Chapter 4: Methodology

Participants

Participants with self-reported problems of speech recognition in noise were recruited from two sources: 1) the patient population of the Division of Otolarylangology at the University of Maryland, Baltimore (UMB), and 2) the patient population of the University of Maryland at College Park (UMCP) Hearing and Speech Clinic. Participants meeting the criteria for OAD were drawn from either the active caseloads at each clinic or from the clinic's database of prior patients. Recent patients meeting the criteria for this study were contacted via a letter of recruitment. The control participants were recruited from the UMB community using a recruitment flyer posted in public areas on the campus. The University Institutional Review Board (IRB) for both UMB and UMCP approved all mechanisms of subject recruitment and the corresponding materials used for this project. In all, 20 paid participants, ranging in age from 19-54 years old, participated in this study.

All participants for this study met the following inclusion criteria:

1. Normal audiometric hearing sensitivity as defined by pure-tone thresholds of ≤ 20 dB HL (re: ANSI, 2004) from 500 – 4000 Hz and ≤ 25 dB HL at 250, 6000, and 8000 Hz
2. ≥ 90% word recognition in quiet (NU-6, AUDiTEC of St. Louis, revised #2)

3. Normal middle ear function as assessed by tympanometry (Margolis & Heller, 1987)
4. Ages 19 – 55 years
5. Native speakers of English
6. No reported history of neurological disorder

Group 1 consisted of those individuals who reported difficulty understanding speech when in the presence of background noise or in group listening situations. Each member of Group 1 pursued an audiological evaluation for help with his or her problem at either the UMB or UMCP clinic. This group will be referred to as the OAD listening group. Group 2 was the control listening group. Individuals in Group 2 had normal-hearing sensitivity and no reports of difficulty hearing in noisy or group listening situations. Each group consisted of 10 participants. The screening form utilized for this study can be seen in *Appendix A*.

Individuals of all races, ethnic origins, socioeconomic levels, religions, and genders were eligible for participation in this study. However, only native speakers of American English were selected for participation. People listening in a language that is not their native language tend to perform more poorly than native speakers of the test language, even if they are fluent in the tested language and perform well in quiet conditions (van Wijngaarden, Steeneken, & Houtgast, 2002).

Preliminary Measures

Demographic and case history information was documented for each participant who completed the *Hearing and Health History* Questionnaire (see *Appendix B).* This questionnaire was developed for this study in consultation with the UMB staff. The questionnaire includes questions regarding personal and family otologic history, current listening environments, and reading/learning development. The administration of this questionnaire took approximately 10-15 minutes.

Routine audiological measures were conducted using an audiometer (Grason Stradler, model GSI-10) audiometer and a middle ear analyzer (Grason Stradler, model GSI-33). Participants were tested in a double-walled sound-attenuating booth. Tonal and speech stimuli were presented by insert earphones (Etymotic, model ER-3A) for the routine audiological assessment and QuickSIN task. Audiometric testing was performed with pure-tone stimuli ranging from 250-8000 Hz, and a modified Hughson-Westlake procedure (Carhart & Jerger, 1959) for threshold estimation. Measurements of tympanic membrane mobility, middle ear pressure (tympanometry), and acoustic reflex thresholds also were measured. Tympanometry was measured with a 226 Hz probe tone and an air pressure sweep from + 200 to – 400 daPa. Acoustic reflex thresholds were measured using a 226 Hz probe tone and 500, 1000, 2000, and 4000 Hz stimulus tones in both the ipsilateral and contralateral conditions. Monaural speech recognition in quiet was measured utilizing Northwestern University Speech Test No. 6 (NU-6) wordlists (Tillman & Carhart, 1966) presented at 60 dB HL (compact disc recording, AUDiTEC, Revision 2). The comprehensive audiological evaluation took approximately 30 minutes to complete.

The QuickSIN (Speech-in-Noise, *Etymotic Research,* 2001) test is a standard clinical measure of speech recognition in noise. This measure provides a quick method by which to assess a person's speech recognition ability, or disability, in noise. The QuickSIN test consists of sentence lists of six IEEE (Rothauser *et al*., 1996) sentences (five keywords) each, presented bilaterally at 70 dB HL in a background of 4-talker babble. The level of background babble was adjusted automatically from +25 to 0 dB SNR with each subsequent sentence. One point was added to the participant's score (out of 30) for each keyword repeated correctly. The average score for two lists was then taken as the participant's total score. To determine the listener's signal-to-noise ratio loss (SNR loss), the total score was subtracted from 25.5, the average standardized performance of normal hearing listeners (Killion & Niquette, 2000). The SNR loss indicates how much more intense the target speech level must be relative to a normal SNR to recognize the target sentences with 50% accuracy (Killion & Niquette, 2000). Administration of this measure in the binaural listening mode took approximately 5 minutes.

Experimental Measures

Stimuli.

The experimental measures utilized a subset of materials and listening conditions reported in a study of the cocktail party effect (Hawley *et al*., 2004**.** Test material consisted of 32 10-sentence lists of IEEE sentences (Rothauser *et al*., 1996). These materials were supplied for this study by M. Hawley (2004, originally obtained by P. Zurek of MIT). Each list contained different sentences for a total of 320 sentences. The test sentences featured two male talkers, each contributing approximately one-half of the sentences.

Four types of competitors were paired with the target stimuli: speech, reversed speech, speech-spectrum noise, and modulated spectrum noise. The competitor stimuli were developed using four of the longest IEEE sentences, chosen because their length ensured that the target sentences were always shorter in length than the competitor(s). One or two competitors of the same type were played simultaneously with the target speech sentence. The speech competitors were made of spoken IEEE sentences pre-selected for use as the competitors. The speech competitor sentences were reversed in time to create the reversed speech competitors. This type of competitor is useful because it provides a competitor condition with the same temporal and spectral structure as speech, but lacks linguistic information. Noise and modulated-noise competitors were constructed based upon the speech envelope for each male talker, and matched in length to the competitor speech samples.

The recorded target stimuli and competitors were developed to simulate varying source locations in realistic listening environments. The recording method utilized head-related transfer functions (HRTFs). HRTFs represent measurements from different locations in space through small microphones housed within a mannequin’s (or person’s) ears. HRTFs can be measured in any desired environment. For the target and competitor stimuli used for this study, HRTFs were selected from the AUDIS catalogue (Blauert *et al*., 1998). The stimuli were measured from the HMS III mannequin head (*HEAD Acoustics;* Herzogenrath, Germany) in an anechoic chamber at specific spatial locations. By processing a desired stimulus with the HRTF, stimuli are perceived by a listener through supra-aural earphones as originating from a specific location of interest.

Conditions.

The virtually processed stimuli portrayed spatial patterns (source of the sound(s)) and interactions (sound reflection) that occur in realistic communication environments. The competitors were presented in conditions simulating two spatial situations, incident with the target sentence and separated from the target sentence. A schematic drawing of the listening configurations is shown in Figure 1. Each of the 4 configurations (incident or separated source locations; 1 or 2 competitors) was used for binaural and monaural listening conditions, with each of four competitor types, for a total of 32 total conditions.

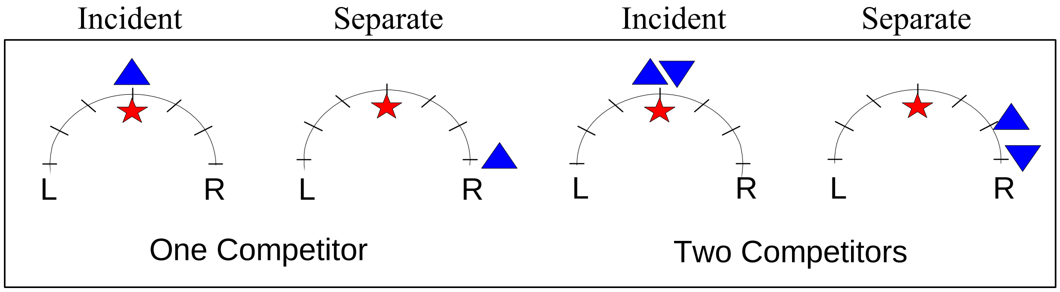

Figure 1. Schematic depiction of the four target sentence (red star) and competitor (blue triangle(s)) spatial configurations. (Figure adapted with permission from Hawley *et al.*, 2000).

The experiment included 32 listening conditions. Sixteen of the 32 listening conditions were presented binaurally, and 16 were presented monaurally. Target stimuli were fixed at 0˚ azimuth, while the competitors were presented in front (0˚

azimuth) or were spatially separated from the target sentence at 60˚ and/or 90˚ azimuths. One-half of the binaural and monaural conditions used only a single competitor, while the other half used two competitors. For the monaural listening mode, target and competitor stimuli were perceived at the listener's left ear only. The stimulus for this condition mimicked the expected attenuation level caused by the head shadow effect. A complete list of the 32 listening conditions is shown in Table 1. Each listening condition involved presentation of one list of 10 sentences each.

Procedures.

During each condition, the target and competitor stimuli were played from separate portable compact disc players and turned on manually at the same time. The speech stimuli were fed into the external input of an audiometer (Grason-Stradler, model GSI-10) so that the target sentence level could be controlled manually throughout testing. The target was then combined with the fixed-level competitor using an audio mixer (TDT, model SM3 Summer) and presented to headphones (Telephonics, model TDH-50) through a headphone buffer (TDT, model HB6). The average level of each competitor presented at 0˚ azimuth was calibrated to 62 dBA. Calibration was performed for each competitor type and a target sentence at the beginning of each test day using a sound level meter (Brüel & Kjær, model 2260) and artificial ear coupler (NBS 9A, 6-cm^3). The sound level meter was set to the slow time constant to calibrate the sentence stimulus.

Table 1. Summary of the 32 listening conditions used in the experimental procedures.

	Competitor Type	BINAURAL (Competitors perceived as originating from the following spatial locations)	MONAURAL (HRTFs recorded using the following spatial locations)
Single Competitor	Speech	0°	0°
	Reversed Speech	0°	0°
	Speech-shaped noise	0°	0°
	Modulated speech-shaped noise	0°	0°
	Speech	90°	90°
	Reversed Speech	90°	90°
	Speech-shaped noise	90°	90°
	Modulated speech-shaped noise	90°	90°
Two Competitors	Speech	0°, 0°	0°, 0°
	Reversed Speech	0°, 0°	0°, 0°
	Speech-shaped noise	0°, 0°	0°, 0°
	Modulated speech-shaped noise	0°, 0°	0°, 0°
	Speech	60°, 90°	60°, 90°
	Reversed Speech	60°, 90°	60°, 90°
	Speech-shaped noise	60°, 90°	60°, 90°
	Modulated speech-shaped noise	60°, 90°	60°, 90°

The listener's speech recognition threshold (SRT) was measured for each of the 32 listening conditions. The SRT was defined as the level (dB) of the target speech signal required for the listener to achieve 50% correct recognition of the target words while listening simultaneously to the fixed-level competitor(s). Participants were instructed to repeat as much of each target sentence as they heard following stimulus presentation. Scoring was based on the correct recognition of target words in the sentence. Signal level was varied adaptively based on the 1-up/1-down adaptive tracking paradigm (Levitt, 1971). The first target sentence of each list was presented approximately 30 dB below competitor level and increased in 4 dB steps until the listener was able to identify at least three key words correctly. The level of the target sentence was then adjusted in 2 dB steps. Following the listener's verbal response, the examiner determined if the target words were repeated correctly or incorrectly. Therefore, if the listener correctly identified three or more of the target keywords in a target sentence, than the level of the target stimuli was decreased by 2 dB. If the participant was unable to identify 3 or more of the keywords, than the level of the target stimuli was increased by 2 dB. For speech competitor conditions, the competitor text was supplied to the listener to avoid listener confusion with the target sentence.

The presentation order of the listening conditions was randomized across subjects for each group. Prior to commencing the experimental conditions, four practice lists were presented to allow each listener the opportunity to learn the nature of the listening task. Participants were also asked to give an anecdotal response regarding the approximate spatial locations of the target and competitor stimuli for a binaural listening separated condition to verify appropriate perception of spatial location. Administration of the experimental speech recognition measures took approximately two hours, which included the four practice lists completed prior to commencement of the actual measure. Listeners were required to take a break after each set of 12 lists.

Chapter 5: Results

Preliminary Measures

Hearing sensitivity.

The mean pure-tone thresholds at each frequency are shown in Figure 2 for each group. Comparison of the means using independent samples t-test analyses revealed no significant difference in pure-tone thresholds between the two groups at each frequency, except at 3 kHz for the left ear ($t(18) = 2.23$, $p < .05$). Listeners with OAD had an average threshold at 3000 Hz that was 4 dB poorer than that of listeners in the control group. Immittance measures revealed that all participants had normal middle ear pressure and tympanic membrane mobility, and acoustic reflex thresholds elicited at normal levels from 500-2000 Hz.

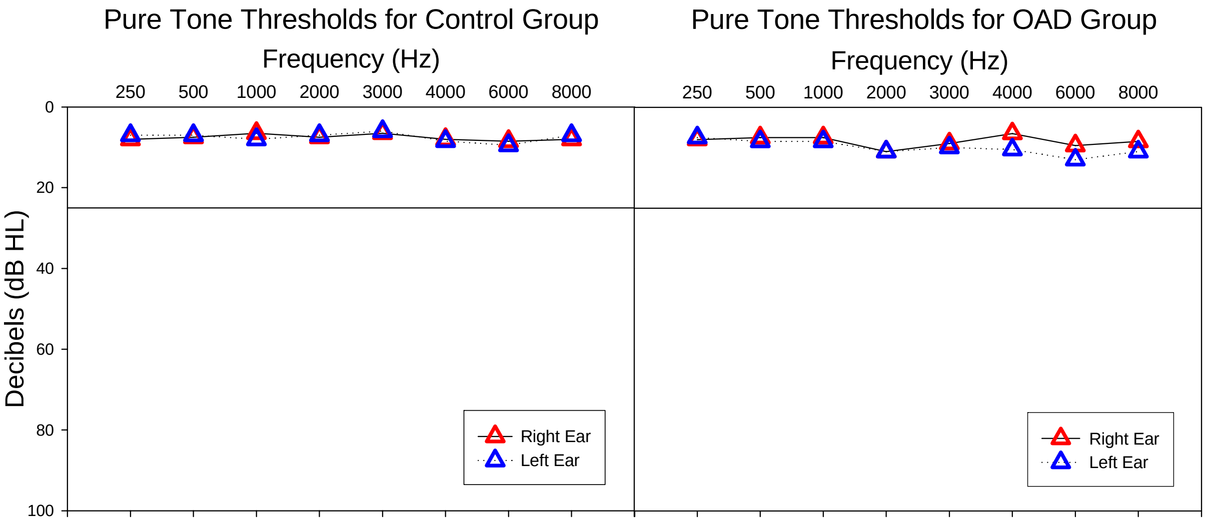

Figure 2. Mean pure tone thresholds (in dB HL, re: ANSI, 2004) by group for the left and right ears.

QuickSIN.

The mean SNR loss by group for the QuickSIN test is shown in Table 2. Comparison of the means using an independent samples t-test revealed no significant difference in performance between the two groups (t(18)=.161, p=.874). Both groups performed within the normal range of 0-2 dB SNR loss (Killion & Niquette, 2000) on the QuickSIN test. The average SNR loss (dB) for control and OAD listeners was 0.5 dB and 0.45 dB, respectively.

Table 2. Mean SNR loss, in dB, and corresponding standard deviations for the two listening groups on the QuickSIN measure.

	Mean SNR loss (dB HL)	Std. Deviation
Control Group	.50	.782
OAD Group	.45	.599

Experimental Measures of Speech Recognition in Noise

In the first set of analyses, the one and two competitor conditions were analyzed for the incident and separated locations for each competitor type. Raw SRT data for the four configurations (i.e., (1) one competitor incident with the target location, (2) one competitor separated from the target location, (3) two competitors incident with the target location, and (4) two competitors separated from the target location) were analyzed using an analysis of variance (ANOVA) with a split-plot factorial design. For each analysis, there were one between-subjects factor (group: OAD vs. control), and two within-subject factors (listening mode: monaural, binaural;

and, competitor type: speech, reversed speech, steady-state noise, and modulated noise). Mean data for the two groups collapsed across listening mode and competitor type are shown in Figure 3 for each of the four listening configurations. The collapsed data are presented to provide an overview of the results. Low (-) SNR values reflect good performance, whereas high (+) SNR values indicate relatively poor performance. Initial inspection of the mean data shown in Figure 3 reveals a consistent trend of poorer performance (less negative) by the OAD participants compared to performance of normal control listeners across these four conditions. Furthermore, as expected, the two competitor incident condition is the most difficult condition for both groups, while the one competitor separated condition shows the best performance for both groups.

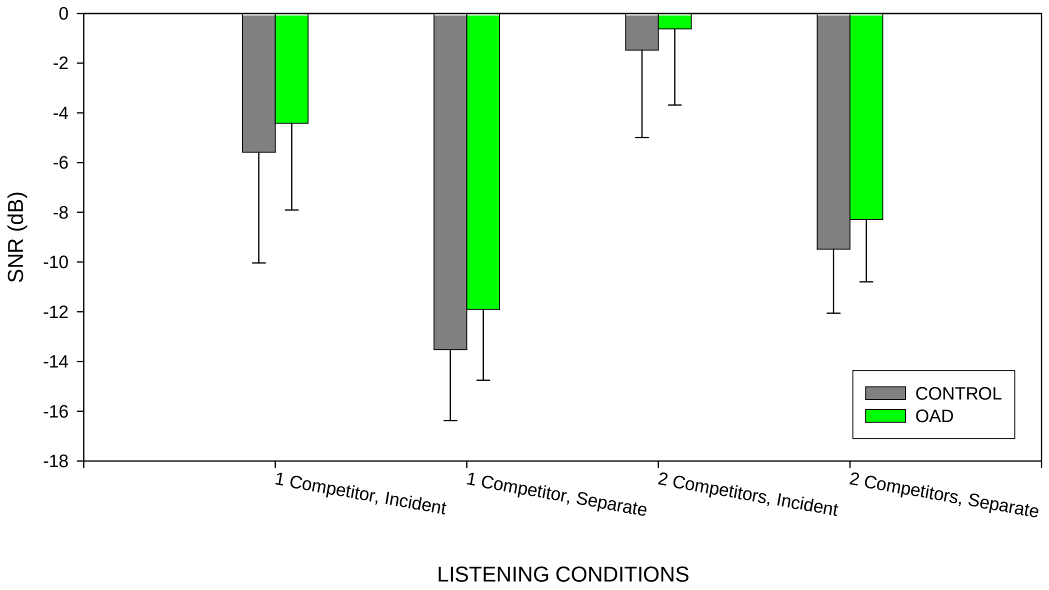

Figure 3. Mean SRT performance expressed as SNR (dB) for listeners in the control and OAD groups for the four listening configurations.

Effect of group, listening mode, and competitor type for one-competitor conditions.

The effects of group (control vs. OAD), listening mode (monaural, binaural), and competitor type (speech, reversed speech, noise, modulated noise) were examined for the single competitor conditions with the competitor located at 0° azimuth. The mean group data for this listening configuration across competitor type and listening mode are shown in Figure 4. Listeners in the OAD group performed more poorly than those in the control group for conditions with speech and reversed speech competitors. An analysis of variance was conducted and revealed significant main effects of group [$F(1,18) = 5.9$, $p < .05$], listening mode [$F(1,18) = 26.9$, $p < .001$], and competitor type [$F(3,54) = 11.0$, $p < .001$], as well as significant interactions between listening mode and competitor type [$F(3,54) = 132.2$, $p < .001$] and group, listening mode, and competitor type [$F(3,54) = 3.0$, $p < .05$]. Simple main effects analysis revealed significantly poorer performance for the OAD group compared to the control group for the monaural listening condition with a speech competitor ($p < .01$). No significant group differences were revealed for the remaining conditions ($p > .05$). A significant effect of listening mode for speech and reversed speech competitors was revealed for both groups, but there was no effect of listening mode for noise and modulated noise competitors ($p > .05$). For speech competitor conditions, monaural listening produced better performance than binaural listening ($p < .001$) for both groups. For reversed-speech competitor conditions, binaural listening produced significantly better performance than monaural listening conditions (*p* < .001) for both groups. Finally, a significant effect of competitor type was shown for both listening mode and group (*p* < .001). *Post hoc* analysis using the

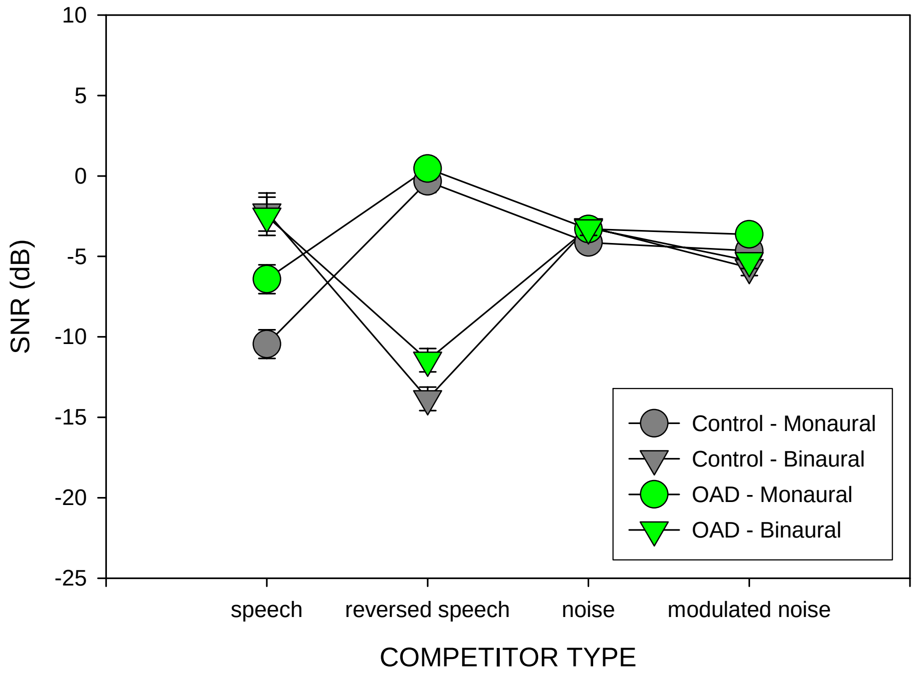

Figure 4. Mean SNR (dB) data for the control and OAD groups as a function of competitor type and listening modes for the one-competitor incident conditions (0˚ azimuth).

Scheffe statistic showed that in the monaural mode, control listeners had significantly better thresholds in the speech competitor conditions (*p*< .001), and significantly poorer thresholds in the reversed-speech competitor conditions (*p*< .001), when each is compared to the remaining three competitor conditions. For listeners with OAD, the monaural speech condition produced significantly better thresholds than the reversed speech competitor condition (*p* < .001). None of the other comparisons of means for this group in the monaural mode were significant (*p* > .05). For binaural conditions, *post hoc* analysis revealed that control listeners performed significantly better in the reversed speech competitor condition (*p*< .001) compared to the remaining three competitor types. For the OAD group in the binaural listening condition, listeners also achieved significantly better thresholds with a reversed speech competitor ($p < .001$) compared to the remaining three competitor types. None of the other comparisons of competitor type were significant in the binaural mode.

The effects of group, listening mode, and competitor type for one-competitor conditions also were examined for conditions with the competitor located at 90˚ azimuth (separated). The mean data for the control and OAD groups for the one-competitor separated condition is shown in Figure 5. An analysis of variance was conducted on the SRT data. Significant main effects of group [$F(1,18) = 8.0$, $p < .05$], listening mode [$F(1,18) = 184.8$, $p < .001$], and competitor type [$F(3,54) = 10.4$, $p < .001$], as well as a significant interaction between listening condition and competitor type [$F(1,18) = 84.4$, $p < .001$] were obtained. The main effect of listener group

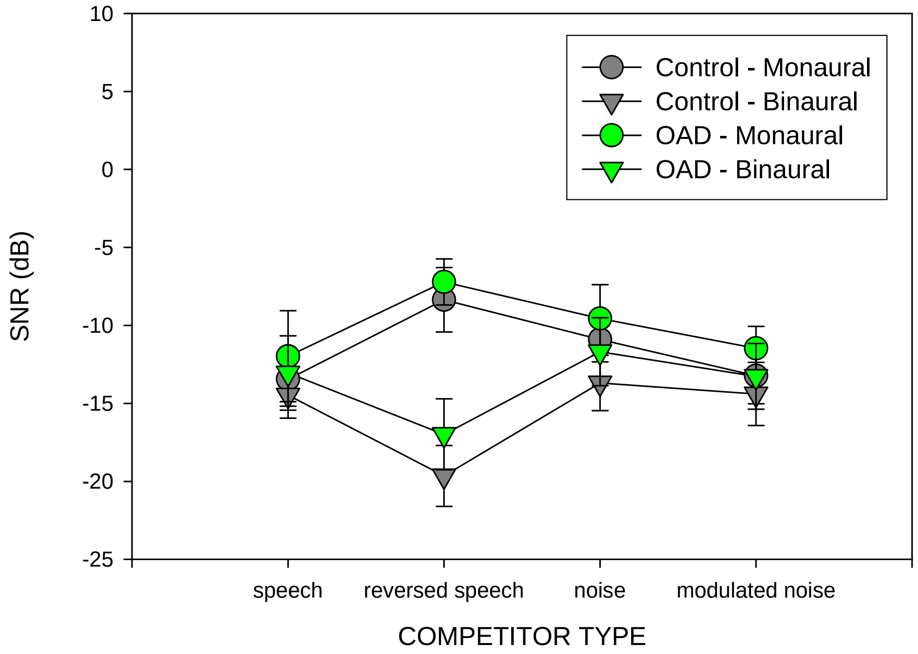

Figure 5. Mean SNR (dB) data for the control and OAD groups as a function of competitor type and listening modes for the one-competitor separated conditions (90˚ azimuth).

indicates that OAD listeners performed significantly poorer than control listeners in all conditions. The simple main effects analysis revealed that binaural listening produced significantly better thresholds than monaural listening across the competitor types ($p < .05$) for both groups. The magnitude of this difference, however, varied across competitor type with the largest difference in listening mode noted for reversed speech competitor conditions. Finally, a significant effect of competitor type was shown for both monaural and binaural listening ($p < .001$). *Post hoc* analysis using the Scheffe statistic showed that in the monaural conditions, listeners performed significantly poorer with a reversed speech competitor than with any of the remaining three competitor types ($p< .01$). For binaural listening conditions, listeners obtained significantly better SRTs with the reversed speech competitor ($p < .001$) than with any of the remaining three competitor types. None of the other comparisons across competitor type were significant.

Effect of group, listening mode, and competitor type for two-competitor conditions.

The effects of group, listening mode, and competitor type also were examined for the two-competitor conditions. First, an analysis was conducted for those conditions with the competitors located incident to the target (0˚, 0˚ azimuth). The mean data for the control and OAD groups are shown in Figure 6 for the two-competitor incident condition as a function of competitor type and listening mode. An analysis of variance revealed significant main effects of listening mode [$F(1,18) =$

46.8, *p* < .001] and competitor type[*F*(3,54) = 143.3, *p* < .001], as well as a significant interaction between listening mode and competitor type

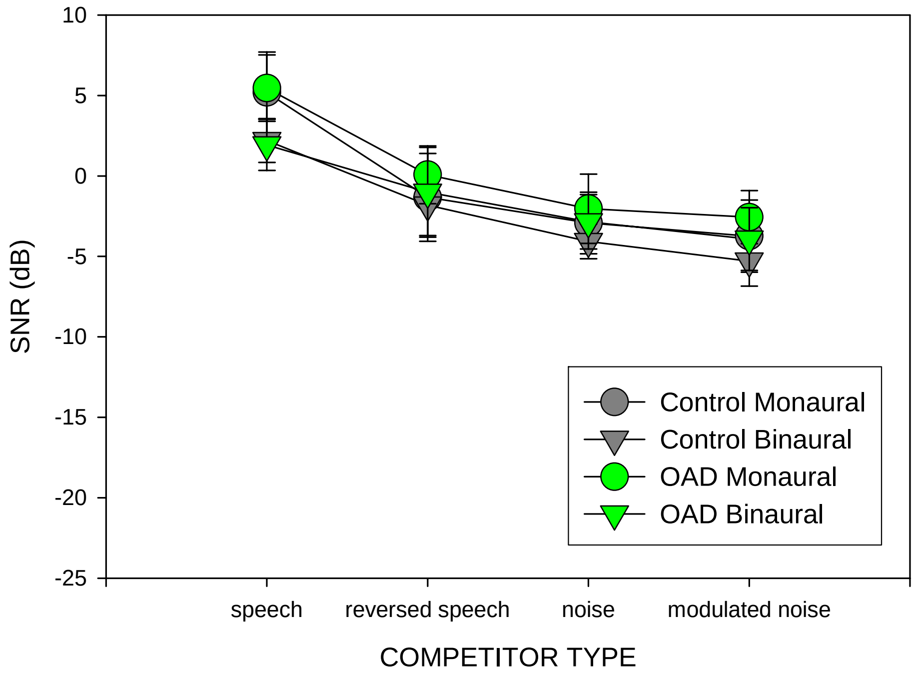

Figure 6. Mean SNR (dB) data for the control and OAD groups as a function of competitor type and listening modes for incident two-competitor conditions (0˚, 0˚ azimuth).

[*F*(3,54) = 6.4, *p* = .001]. The effect of listener group was not significant [*F*(1,18) = 2.1, *p* > .05]. Simple main effects analysis of the listening mode by competitor-type interaction for the two-competitor incident condition revealed that binaural listening produced significantly lower thresholds compared to monaural listening for speech (*p* < .001), noise (*p* < .05), and modulated noise (*p* < .01) competitors, but not for reversed speech competitors (*p* > .05). Simple main effects analysis also yielded a significant effect for competitor type in the monaural listening condition (*p* < .001) and in the binaural listening condition (*p* < .001). Listeners obtained significantly better thresholds with modulated noise and noise competitors (*p* < .001) than with the reversed-speech and speech competitor conditions for both monaural and binaural listening. Additionally, listeners performed significantly more poorly in monaural and binaural listening conditions with speech competitors ($p < .001$) than with the reversed-speech competitors.

The effects of group, listening mode, and competitor type in the two-competitor conditions also were examined for conditions with the competitors separated from the target (60°, 90° azimuth). The mean data for the control and OAD groups are shown in Figure 7 as a function of competitor type for the parameter of listening mode. An analysis of variance revealed significant main effects of group [$F(1,18) = 5.5$, $p < .05$], listening mode [$F(1,18) = 97.4$, $p < .001$], and competitor type [$F(3,54) = 53.4$, $p < .001$], and a significant interaction between listening condition and competitor type [$F(3,54) = 7.7$, $p = .001$]. The main effect of group indicates that listeners with OAD performed more poorly than the normal controls in all conditions. Simple main effects analysis revealed significantly better performance for binaural listening conditions compared to monaural listening conditions for reversed speech ($p < .001$), noise ($p < .001$), and modulated noise ($p < .001$) competitor conditions, but not for the speech competitor ($p > .05$). A significant effect of competitor type was shown for both monaural and binaural listening conditions ($p < .001$). Listeners obtained significantly better thresholds for the monaural listening conditions with reversed-speech competitors ($p < .05$) than with each of the remaining competitor types. Binaural listening yielded significantly different listener performance for each competitor type ($p < .05$), with best performance achieved for

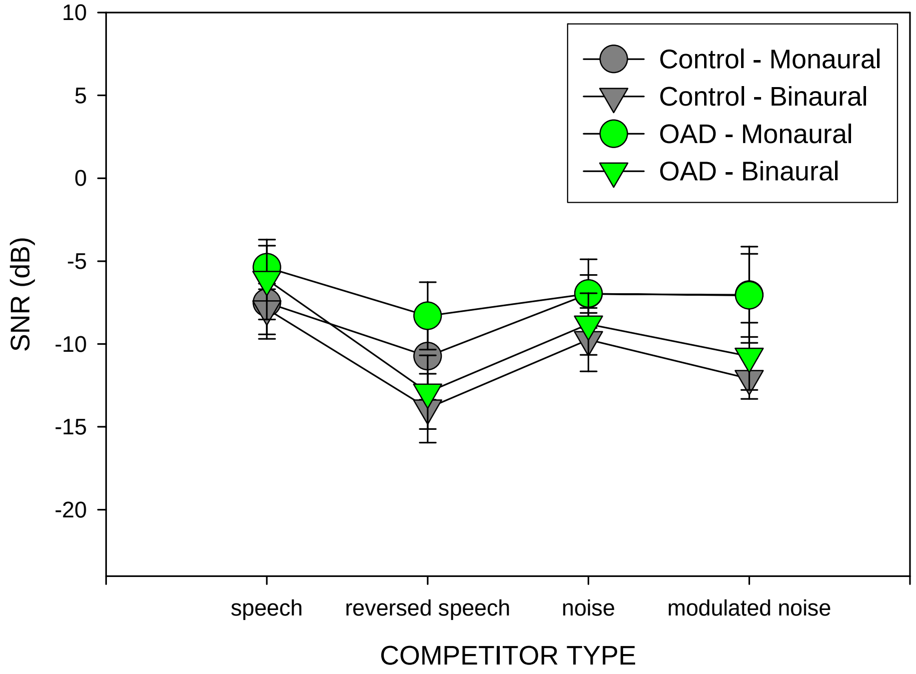

Figure 7. Mean SNR (dB) data for the control and OAD groups as a function of competitor type and listening modes for the separated two-competitor conditions (60˚, 90˚ azimuth).

conditions with reversed-speech competitors, and worst performance documented for conditions with speech competitors.

Effect of linguistic content.

An analysis was conducted for the incident-one and two-competitor binaural listening conditions to assess the overall effect of linguistic content on speech recognition in noise for the two groups. Mean performance for the speech and reversed-speech competitor conditions are reported in Figure 8. Analysis of variance was performed using a split-plot factorial design with one between-subjects variable (group) and two within-subjects variables (number of competitors, competitor type).

Each factor has two levels. The ANOVA revealed significant main effects of number of competitors ($F(1,18) = 214.27$, $p < .001$) and competitor type ($F(1,18) = 936.7$, $p < .001$), as well as a significant interaction between number of competitors and competitor type ($F(1,18) = 227.51$, $p < .001$).

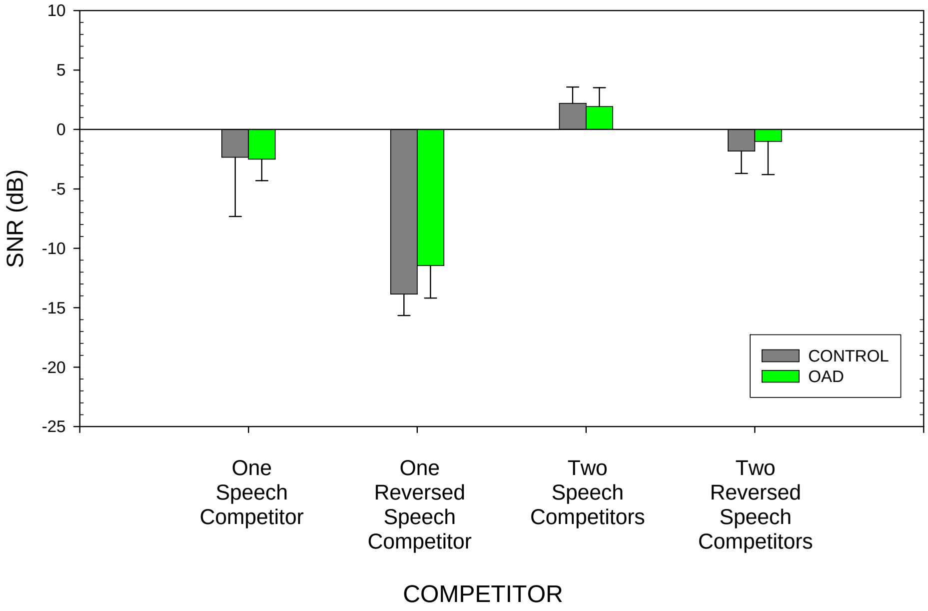

Figure 8. Effects of linguistic content for speech versus reversed-speech competitors, number of competitors (one versus two), and listener group (control versus OAD) for the binaural listening condition.

The effect of group was not significant ($F(1,18) = .940$, $p > .05$). Simple main effects analysis revealed a significant effect of competitor type in the one-competitor condition ($p < .001$), in which a significantly better threshold was measured with the reversed-speech competitor than with the speech competitor. No difference in performance by competitor type was revealed in the two-competitor condition ($p > .05$). Simple main effects analysis also revealed a significant difference between thresholds obtained for one versus two-competitor conditions for both competitor types ($p < .001$). For the speech and reversed-speech conditions, thresholds were significantly better for one-competitor conditions than for the two-competitor conditions. In addition to these analyses, the linguistic masking release was computed by taking the mean difference in performance by group for speech and reversed-speech competitor conditions. The mean masking release values for control and OAD subjects were 7.8 dB and 5.9 dB, respectively. An independent t-test revealed no significant difference in linguistic release between the two listening groups (t (18) = 1.49, $p > .05$).

Effect of noise modulation.

Analysis of noise modulation was conducted for the incident one and two-competitor binaural listening conditions to assess the overall difference in performance between the two groups with modulated-noise compared to steady-state noise competitor conditions. Mean performance for the control and OAD groups for the steady-state noise and modulated-noise competitor conditions is shown in Figure 9. An ANOVA was performed using a split-plot factorial design with one between-subjects variable (group) and two within-subjects variables (number of competitors, competitor type). Each factor has two levels. The analysis revealed a significant main effect of competitor type ($F(1,18) = 61.91$, $p < .001$). The effects of group (F (1,18) = 2.6, $p > .05$), number of competitors (F (1,18) = .68, $p > .05$), and all interactions, were not significant. The main effect of competitor type indicates that listeners obtained significantly better thresholds with the modulated-noise competitor conditions than with the steady-state noise conditions ($p < .001$). In addition, the modulated-masking release was computed by taking the mean difference in performance by group for steady-state noise and modulated-noise competitor conditions. The mean masking-release values for control and OAD subjects were 1.9 dB and 1.6 dB, respectively. An independent samples t-test revealed no significant difference in modulated masking release between the two listening groups (*t* (18) -.749, *p* > .05).

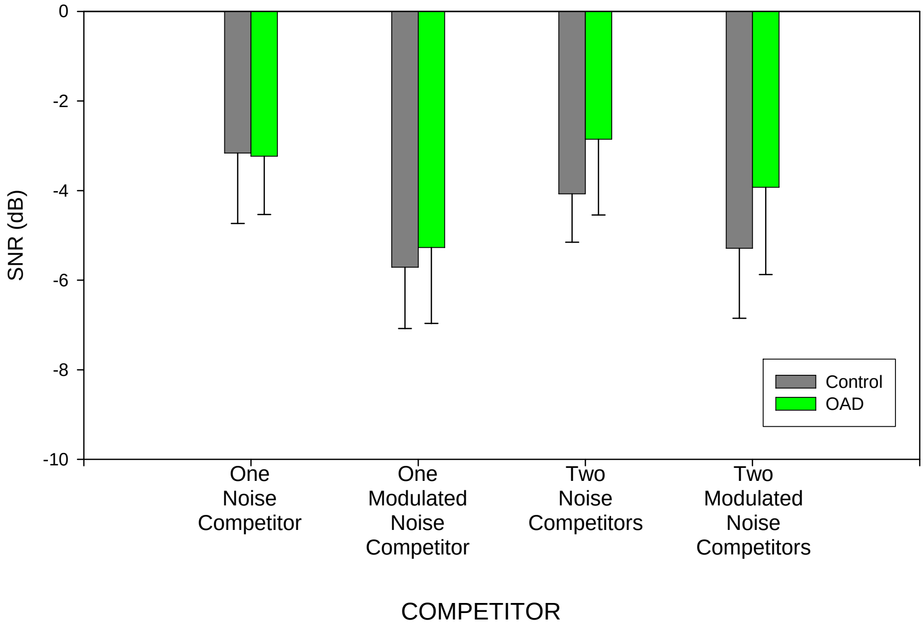

Figure 9. Effects of steady-state noise and modulated-noise on the speech recognition threshold by competitor number (one versus two) and listener group (Control versus OAD).

Advantages of separation and binaural listening.

The final analyses examined the effect of spatial separation of the target and competitor(s) on group performance. The data were analyzed using the assumption that observed differences in SRTs for differing spatial configurations are the result of best-ear listening and binaural processing. Therefore, the raw SRT data for each condition were used to calculate the monaural advantage, total advantage, and binaural interactions for both one and two-competitor conditions. As defined by

Hawley *et al.* (2004), the monaural advantage of separation for each listener in each condition is defined as the difference between listening in each monaurally spatially separated condition and the corresponding unseparated (incident) condition. Therefore this calculation examines the effect of "better-ear" listening in the conditions where the competitor originates from the side of the non-listening ear versus those conditions with the competitor located incident to the target sentence. The monaural advantage of separation therefore reflects solely the advantage afforded by the head shadow effect under conditions of spatial separation. The total advantage is defined as the difference between the binaurally spatially separated condition and the corresponding binaural unseparated (incident) condition. This condition examines the effect of binaural processing, in addition to the effect of the head shadow effect. Finally, the binaural interaction is defined as the portion of the total advantage (binaural processing and head shadow effect) not accounted for by the monaural advantage (head shadow effect), which is computed by taking the difference between the total and monaural advantages. Thus, the binaural interaction reflects binaural processing abilities such as the masking-level difference and binaural squelch.

The computed monaural and total advantages of separation and the binaural interaction were calculated for each listener separately for the one- and two-competitor conditions. Separate analyses were conducted for the computed advantages in the one and two-competitor conditions using a split-plot factorial design with one between-subjects factor (group) and one within-subjects factor (competitor type). The mean monaural advantage, total advantage, and binaural interaction as a function of competitor type are shown in Figure 10 for the one-competitor conditions. A value of zero or less on the figure represents no advantage.

Analysis of the monaural advantage for the one-competitor conditions (Figure 10, top panel) revealed a significant main effect of competitor type (F (3, 54) = 10.30, p <.001), and a significant interaction between competitor type and group (F (1,18) = 4.86, p < .05). Simple main effects analysis revealed that the control group obtained significantly less advantage of separation for the speech competitor condition than did the OAD group (p< .001). Further, listeners in the control group obtained significantly less advantage in the speech-competitor condition compared to the advantages measured for the remaining three competitor conditions (p < .05). Analysis of the total advantage (Figure 10, middle panel) for the one-competitor conditions revealed a significant main effect of competitor type (F (3, 54) = 13.68, p < .001), but no effect of listener group (F (1,18) = 2.47, p > .05). Listeners also obtained significantly greater advantage of separation for conditions with speech competitors compared to conditions with a reversed-speech or modulated-noise competitor (p < .05). Analysis of the binaural interaction (Figure 10, lower panel) revealed a significant main effect of competitor type (F (3, 54) = 22.63, p < .001), but no significant effect of listener group (F (1,18) = 2.47, p > .05). *Post hoc* analysis (Scheffe) showed listeners obtained a significantly greater advantage in the speech competitor conditions compared to the other competitor conditions (p < .05). Furthermore, an advantage of binaural interaction was not obtained for the reversed-speech competitor conditions.

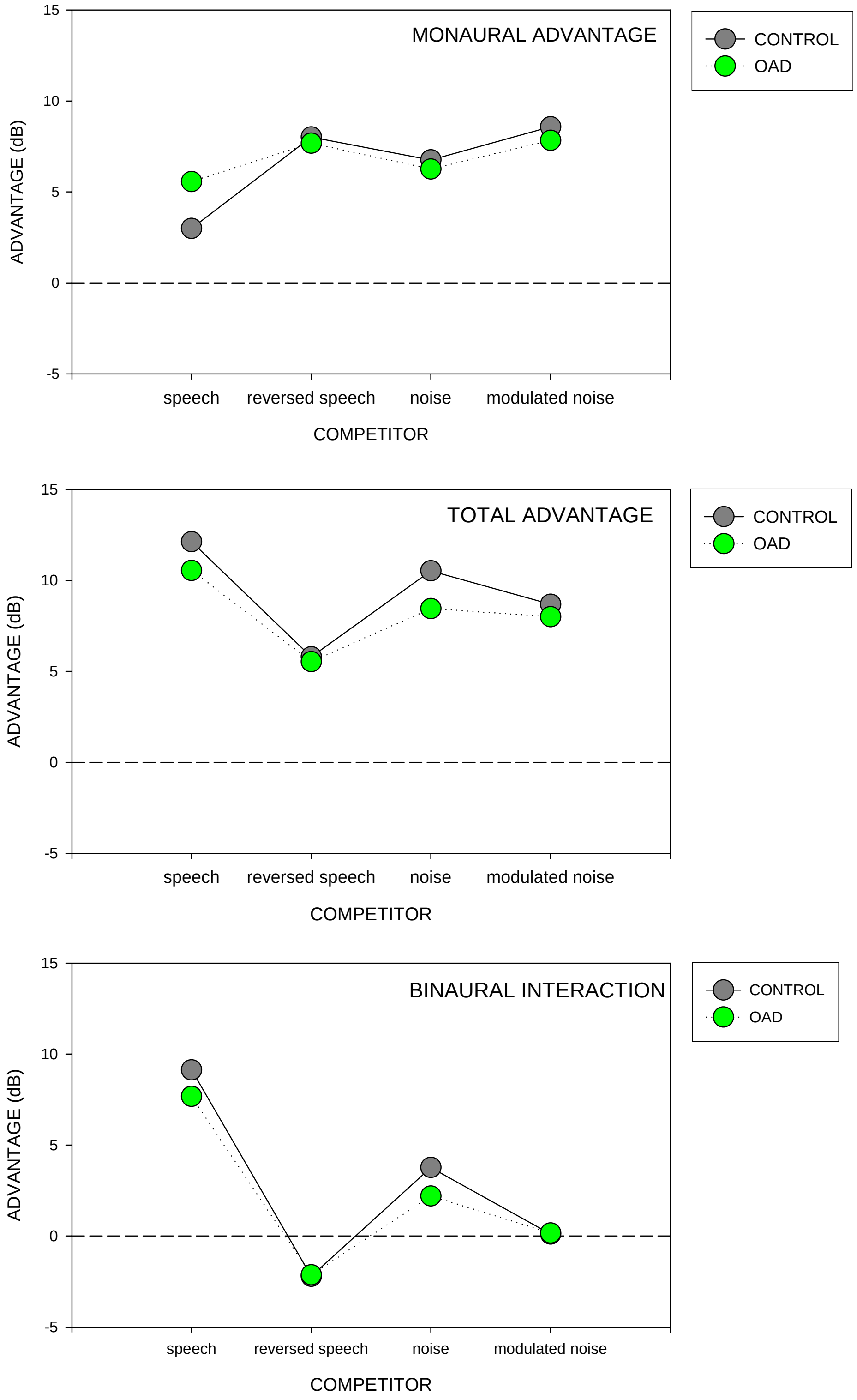

Figure 10. Monaural advantage (top panel), total advantage (middle panel), and binaural interaction (lower panel) data by group and competitor type for one-competitor conditions.

The mean monaural advantage, total advantage, and binaural interaction as a function of competitor type are shown in Figure 11 for the two-competitor conditions. Analysis of the monaural advantage for the two-competitor conditions (Figure 11, top panel) revealed a significant main effect of competitor type (F (3, 54) = 31.61, p <.001), but not a significant effect of listener group (F (1,18) = .152, p > .05). Listeners obtained a significantly greater advantage of separation for the speech competitor conditions compared to the remaining three competitor types (p < .05). None of the other comparisons across competitors were significant. Analysis of the total advantage (Figure 11, middle panel) revealed a significant main effect of competitor type (F (3, 54) = 29.18 dB, p < .001), but no significant effect of listener group (F (1,18) = 1.45, p > .05). Listeners obtained a significantly greater advantage of separation for conditions with the reversed-speech competitor compared to the advantages measured for the remaining three competitor types ($p \leq .001$). Analysis of the binaural interaction for two-competitor conditions revealed a significant main effect of competitor type (F (3, 54) = 9.168, p < .001), but no significant effect of listener group (F (1,18) = .16, p > .05). Listeners obtained significantly less advantage of binaural interaction in the speech competitor condition than in the reversed-speech, modulated-noise, and noise competitor conditions (p < .05).

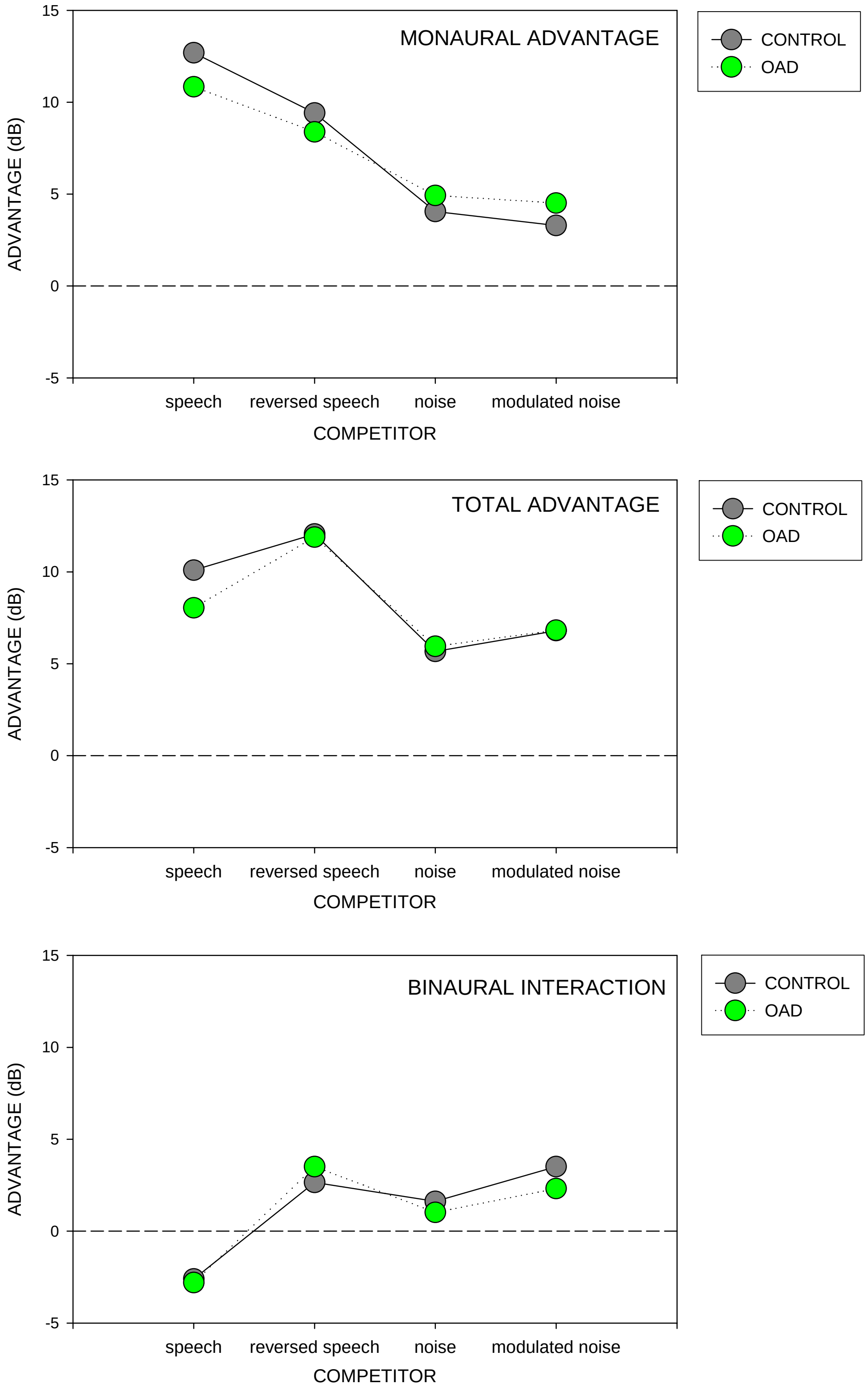

Figure 11. Monaural advantage (top panel), total advantage (middle panel), and binaural interaction (lower panel) data (dB) by group and competitor type for two-competitor conditions.

Chapter 6: Discussion

General Discussion

OAD is an often-overlooked problem in audiological and ENT clinics because audiological findings are unremarkable and cannot explain the symptoms. The overall objective of this study was to investigate the hypothesis that patients with OAD exhibit subtle deficits on complex speech recognition in noise tasks compared to listeners without OAD, but do not exhibit such deficits on a standardized clinical speech-in-noise measure. Additional goals were to identify the possible mechanisms that may contribute to this speech recognition deficit, particularly a reduction in the ability to take advantage of binaural cues.

Preliminary Measures

Hearing sensitivity.

There were no significant differences in pure-tone hearing thresholds between the two listener groups, except at a single frequency, 3 kHz, in the left ear. These results contrast with those previous studies of OAD participants, which have shown significantly poorer pure-tone sensitivity at most or all frequencies tested between .25- 8 kHz for both ears (King & Stephens, 1992; Middelweerd, Festen & Plomp, 1990; Saunders & Haggard, 1989; and Zhao & Stephens, 2000). Previous findings suggest that differences in pure-tone thresholds likely do not explain the speech recognition differences between patients with OAD and normal-hearing control listeners. In previous studies, thresholds were within normal limits for both groups. However, covariate analyses were not pursued to rule out the impact of subtle but disparate pure-tone thresholds between groups on recorded speech recognition in noise; therefore, this confounding factor cannot be ruled out as an explanation for the performance differences on speech recognition tasks. The current study, however, did show poorer speech recognition in listeners with OAD compared to the control listeners, despite equivalent thresholds between the two groups. Therefore, the speech recognition problems exhibited by listeners with OAD in the current investigation appear to be independent of hearing loss and cannot be attributed to mild cochlear dysfunction.

QuickSIN.

One objective of this investigation was to determine if patients with OAD exhibit deficits on a clinically routine speech recognition measure in noise. Results of the QuickSIN measure revealed no significant differences between listener groups. Furthermore, results for both groups fell within the normal range of 0 dB to 2 dB SNR. This result indicates that each listener would require a SNR of approximately 0 to 2 dB to understand 50% of words in a sentence. Normative results for the QuickSIN evaluation have shown a single QuickSIN list provides an estimate of SNR loss accurate to +/- 2.7 dB at the 95% confidence level (Killion *et al*., 2004). The current results thus suggest that this standard clinical measure of speech recognition in noise (QuickSIN) is not adequate for revealing the speech recognition deficits reported by patients with OAD.

Experimental Measures

Group effects on speech recognition in noise.

Performance of the two listener groups was compared on a complex speech recognition task performed under multiple listening conditions, including variations in listening mode (monaural, binaural), spatial configuration (incident, separated), number of competitors (one, two), and competitor type (forward speech, reversed speech, noise, modulated noise). Results of this intensive study of speech recognition in complex listening conditions revealed that OAD listeners performed significantly more poorly than the control listeners for many of the listening conditions, especially those with separated target and competitor stimuli.

The overall findings presented in the current investigation are not consistent with those reported by Saunders and Haggard (1992). Their results showed a 2.5 dB performance difference between their OAD and control listening groups for speech recognition of sentence materials presented in steady-state noise. For the current investigation, an overall average difference between control and OAD listeners for conditions with steady-state noise was less than 1 dB. There are several possible reasons for this discrepancy. First, the hearing sensitivity of the listeners with OAD in the Saunders and Haggard investigation had significantly poorer pure-tone thresholds than those of their control listeners. This difference may have contributed to the reported poorer speech recognition performance in noise than was observed for the

OAD participants in the current investigation. Secondly, the speech-in-noise task presented by Saunders and Haggard used two noise sources coming from simulated speakers located at 135˚ and 215˚ azimuth, with the target speech source presented at 0˚ azimuth. Although these researchers used headphone administration, the noise set-up for the experiment is considerably different than that employed for the current study, which may have had an effect on the SRT outcomes. Furthermore, it is possible that Saunders and Haggard evaluated listeners that were affected by OAD with greater severity than those evaluated here.

In this current study, a significant group difference in performance was noted for the monaural one-competitor incident condition (speech competitor only), the one-competitor separated conditions (all competitors, both modes), and the two-competitor separated conditions (all competitors, both modes). These conditions proved most difficult for the listeners with OAD. The spatial configuration that did not show any significant performance differences between the listener groups was the two-competitor incident conditions. This spatial configuration is the most challenging of the four listening configurations because the three signals were presented from the same spatial location. This was a difficult listening condition for every listener. Overall performance across conditions showed that both groups performed best in the one-competitor separated condition, and most poorly in the two-competitor incident condition. This outcome is consistent with that found by Hawley *et al.* (2004).

Overall, listeners achieved better SRTs in the binaural listening conditions; however, there was one condition for which listeners performed more poorly in the binaural listening mode than in the monaural listening mode. This condition was the incident one-speech competitor condition. It is not clear why this occurred. All listeners heard the same specific target and competitor pairs for each individual condition. This inexplicable result might be related to list dependency and the relative complexity of the assigned stimuli and competitor for each of these conditions (i.e., the masking effectiveness between the target and competitor may have been greater in the binaural condition than in the monaural condition).

Effect of linguistic content.

To establish the effect of the linguistic content of competitor stimuli on speech recognition ability, performance was measured for speech and reversed-speech competitor conditions for incident and target and competitors in the binaural listening mode. Linguistic masking refers to a decrease in performance caused by an intelligible speech masker relative to a corresponding masking condition that is missing linguistic content (i.e., reversed speech). Direct comparisons between listener groups revealed no significant differences in performance in these conditions. Therefore, no group differences in masking release were observed with variations in linguistic content. This finding reflects the hypothesis that the OAD group would yield less linguistic masking release than would the control group. There was, however, a significant difference in performance for both groups that was dependent upon competitor type for the one-competitor condition. Both groups performed significantly poorer in the presence of the speech competitor than in the presence of the reversed-speech competitor. However, a significant difference in performance by competitor type was not present for the two-competitor condition. One possible explanation for this outcome is that the presence of two speech competitors confounded the listener’s ability to recognize linguistic information and, thus, reduced the speech competitors’ masking effectiveness. Thus, the effect of linguistic masking is attenuated perhaps because multiple competitors provide additional energy that fills in the intermittent temporal and spectral gaps apparent in one-competitor conditions. The resulting release from masking therefore is similar to that obtained with a reversed speech competitor obsolete.

Effect of noise modulation.

Historically, research has shown that normal-hearing listeners are able to obtain better SRTs in conditions with modulated-noise (dips, or reductions in energy across the time course of the competitor) compared to steady-state noise competitors (e.g., Festen & Plomp, 1990). For this study, listener performance by group was compared for the noise versus modulated-noise competitor conditions in the binaural mode with target and noise presented from the same speaker (incident). It was hypothesized that participants with OAD would show a reduction in modulated masking release relative to the release obtained by listeners in the control group. Direct comparisons revealed no significant differences in group performance in these conditions. That is, there was not a significant difference in the magnitude of modulated masking release between listener groups. However, there was a significant effect of competitor type, indicating that listeners obtained significantly better SRTs in modulated noise competitor conditions compared to SRTs measured in steady-state noise competitor conditions. This result is consistent with findings in previous studies that have shown modulated masking provides “dips” through which listeners can listen to the target stimuli for improved threshold results when compared to steady-state noise conditions (Festen & Plomp, 1990; Hawley *et al*.,2004; Takahashi & Bacon, 1992). Masking release due to modulation is a temporally mediated phenomenon that can be significantly decreased by the addition of multiple competitors or the decrease of modulation depth (Bronkhorst & Plomp, 1992; Takahashi & Bacon, 1992). Furthermore, research has indicated that poor speech recognition associated with decreased temporal resolution is observed among individuals with sensorineural hearing loss (Souza & Turner, 1994; Takahashi & Bacon, 1992). Therefore, results of this present study are consistent with findings that normal hearing individuals (i.e., OAD and control listeners for this study) maintain normal temporal resolution allowing them to take advantage of the dips in modulated noise and in-turn, obtain superior performance for the modulated noise conditions compared to steady-state noise conditions.

Effect of spatial separation and binaural processing..

Speech recognition performance improves when speech and competitor signals are separated in space, thus providing a “spatial release from masking” (Bronkhorst and Plomp, 1992; Hawley *et al.*, 1999; Plomp and Mimpen, 1981). In general, interaural differences of time and level provide this improvement. For this study, group differences in the advantage of spatial separation and binaural listening were evaluated. It was hypothesized that listeners with OAD would show reduced advantage for binaural listening, determined by evaluating speech recognition for incident and separated conditions for the monaural and binaural listening modes. The only significant effect of group was observed for the monaural advantage (monaural separated SRT – monaural incident SRT) single-speech competitor condition, for which control listeners obtained significantly less advantage than did listeners in the OAD group. No other significant effects of group were observed for the advantage data for either one or two competitor conditions.

Previous studies did not assess the contribution of spatial configuration or binaural interaction for speech recognition results of listeners with OAD. However, a similar study of normal-hearing listeners, who presented without complaints of difficulty hearing in noise, revealed a binaural interaction that was greatest for multi-competitor conditions using speech and reversed-speech competitors (Hawley *et al*., 2004). This difference was more than double the 3 dB benefit expected for single-competitor conditions. This current study did not reveal the binaural interaction that was obtained by listeners in Hawley's study for the speech and reversed speech multiple-competitor conditions. Rather, in this study, multiple competitor conditions produced a 2-3 dB binaural interaction (total advantage – monaural advantage) for the reversed speech, modulated-noise, and steady-state noise conditions, while no binaural interaction was observed for the speech competitor condition. This finding, however, is similar to the results of Hawley's study for single-competitor conditions with all competitor types, and for multiple competitor conditions in the modulated-noise and steady-state noise conditions. This discrepancy is likely due to differences in randomization procedures used in the two studies. Hawley *et al.* used a Latin-square design to minimize an order effect. Therefore, each sentence list was paired with each condition only once and the order of presentation of conditions was not repeated. In this study, the order of conditions was varied across listeners, but the sentence lists were fixed to a single condition.

Investigators have suggested that OAD is a multifactorial disorder caused by mild cochlear deficits, central auditory problems, and personality-related factors. This investigation consistently revealed a speech recognition deficit in noise among patients with OAD, despite the presence of normal hearing sensitivity. This difference is most significant for the one and two-competitor separated conditions across competitor types and monaural and binaural listening modes. Analysis of monaural advantage (monaural separated SRT – monaural incident SRT), total advantage (binaural separated SRT – binaural incident SRT), and binaural interaction (total advantage – monaural advantage) did not show significant deficits for the OAD listeners. Thus, despite the overall speech recognition deficit, patients with OAD do not appear to exhibit deficits in non-linguistic masking release, modulated masking release, or binaural advantage. Furthermore, it is clear that peripheral auditory function, as measured by pure-tone hearing sensitivity, was normal in all listeners. Nevertheless, the listeners with OAD exhibited significant deficits for speech recognition in noise for spatially separated conditions. This pattern of results suggests that listeners with OAD may not be able to compare and interpret contrasting acoustic cues associated with spatial separation. To the extent that this deficit is related to central auditory mechanisms, the speech recognition deficit in patients with OAD may reflect dysfunction at the central levels of the auditory nervous system. Therefore, the present findings are tentatively consistent with the notion that listeners with OAD may have a deficit in central auditory processing.

Clinical Implications

The listener group with OAD can be differentiated from the control group using complex listening measures, but not by using a standard, simplified, speech in noise measure. However, the protocol for the experimental speech-in-noise measurements is too complex and cumbersome to be a realistic measure for clinical application. Rather, the use of a subset of these measures may be sufficient for identification of reduced speech recognition abilities in these individuals. Based on the limited data collected in this investigation, it is tentatively suggested that the best conditions to assess OAD listeners would be (1) a speech competitor presented incident to the target sentence in the monaural listening mode, or (2) a monaural or binaural listening condition with a single competitor of any type presented at 90˚, and the target presented at 0˚. Differences in performance between groups were observed for the separated two-competitor condition, but performance for both groups was generally depressed because of the additional difficulty of the task. Consequently, one-competitor conditions are probably better than two-competitor conditions for the identification of listeners with OAD.

A diagnostic test for OAD should reveal the patient's report of excessive difficulty understanding speech in noise. Such a test potentially would aid in counseling of patients with OAD and in the selection of an appropriate treatment protocol. Patients with OAD who seek to confirm the problem of OAD often do not receive objective verification of their reported symptoms through standard assessment tools. Because these patients do not exhibit significant hearing loss they are not typical candidates for amplification or other augmentative communication devices. However, for certain individuals with specific listening needs, an assistive listening device (ALD) may be an appropriate and effective treatment option. ALDs include telephone amplifiers and personal or group FM (frequency modulated) systems used for improving the signal-to-noise ratio for listeners functioning in difficult communication environments. These devices would not be a practical treatment option for every patient, however ALDs may be considered as a treatment option for those individuals with more severe deficits associated with OAD.

A more universal treatment option for individuals with OAD would be counseling. Through counseling, audiologists may allow these patients to experience an improved quality of life as it relates to hearing. Counseling should focus on the hypothesized nature of OAD and aural rehabilitative strategies for coping with the perceived problem of hearing in noise. Coping strategies such as the use of contextual cues, facial expressions, and environmental positioning should be discussed with the patient. If affected patients are made aware of factors that they may be able to control within their environments, then they will be better able to manipulate listening conditions to achieve a more favorable SNR. For example, rehabilitative strategies could focus on activities strengthening the patient’s selective attention because separated target and competitor conditions are most difficult for listeners with OAD. A previous study demonstrated that by constructing a correct expectation of the location of competitor source, listener performance can be improved for both selective attention (attending to a single source in the presence of competing sources) and divided attention (attending to multiple sources; Shinn-Cunningham & Ihlefeld, 2004). Thus, if listeners always require the target signal to come from in front at 0° azimuth, then their speech recognition performance will likely improve relative to situations where no such requirements are made. Such rehabilitative strategies may therefore be appropriate for implementation in counseling of listeners presenting with OAD. Previous research also has suggested that the basis and severity of OAD varies between listeners, therefore counseling should be directed to address the observed and reported problems dictated by the patient (Saunders & Haggard, 1989; Saunders & Haggard, 1992). Reassurance that the patient has normal hearing sensitivity is a necessary first step to move beyond the issue of hearing loss and to focus him or her on the sub-clinical deficits or attentional issues.

Recommendations for Further Research

Based on the current findings, it appears that further research into OAD should focus on alternative diagnostic approaches and cost-effective treatment plans for these patients (i.e., counseling, ALDs). Further research into the underlying cause(s) of OAD should be directed to studies of central auditory processing. These may include electrophysiologic studies to evaluate differences in central auditory function between normal-hearing listeners both with and without reported OAD. To date the evaluation of listeners with OAD has not examined electrophysiologic responses in the auditory pathway beyond the auditory brainstem. A task that would elicit endogenous potentials, such as the P_{300} response, would be important to provide information regarding the nature of higher brain functions (Downs *et al.*, 2001). An endogenous task relies on the patient to perform a psychological or cognitive task for the response to be recorded. Previous research has suggested that the response is correlated with many centrally linked processes such as short-term memory, stimulus discrimination, and processing of information in a sequential order (Donchin, 1981; Squires *et al.*, 1976). Furthermore, an abnormal P_{300} response has been observed in cases of central auditory processing disorders (Jirsa & Clontz, 1990), making it a viable test for assessment of patients with OAD.

Conclusion

This study is the first to show a significant speech recognition deficit in noise for listeners with OAD who were matched audiometrically with normal-hearing control listeners. The results of this study suggest that listeners with OAD have a general performance deficit when compared to listeners without OAD for detection of speech in complex listening conditions, particularly for one and two-competitor separated conditions. These findings validate the speech recognition difficulties reported by the OAD group when listening in background noise. While the deficit exists, its cause cannot be linked to a deficit of binaural performance, non-linguistic masking release, or modulated masking release.

Appendices

Appendix A: Participant Screening

Subject No. ________ Date: ___________

PURETONE THRESHOLDS (Eligibility: 500 – 4000 Hz ≤ 20 dB HL, and ≤ 25 dB HL at 250, 6000, and 8000 Hz)

Ear / METHOD	250 Hz	500 Hz	1000 Hz	2000 Hz	3000 Hz	4000 Hz	6000 Hz	8000 Hz
Right / AIR								
Left / AIR								

PTA Right - _____ PTA Left - _____

WORD RECOGNITION IN QUIET (Eligibility: ≥ 90%)

	Stimulus/Masker (dB HL)	**List #**	**Percent Correct**
Right	60 / 40		
Left	60 / 40		

TYMPANOMETRY

Normative values (Margolis & Heller, 1987; ASHA, 1990): Peak pressure @ 0.3 – 1.4 ml; EC volume of 0.6 – 1.5; and, peak pressure no more negative than –100 daPa

Right tympanogram		Left tympanogram	
Peak admittance		Peak admittance	
Ear canal volume		Ear canal volume	
Peak pressure		Peak pressure	

CHIEF COMPLAINT

Participant notes excessive difficulty understanding speech in the presence of noise?
YES or NO

CANDIDACY:
Participant is a candidate for participation in this research study? YES __ NO __

If yes, the participant will be assigned to the following group: OAD ___ CONTROL ___

Participant's Signature: ____________________________ Date: __________

Experimenter's Signature: __________________________ Date: __________

Appendix B: Hearing & Health History Questionnaire

Please answer these questions to the best of your ability. Some of the questions may not be relevant to you or you may not wish to answer them. You can ignore these questions.

Section A:

1. Age: _______

2. Is English your native <u>and</u> primary language? Yes / No

3. What is the highest degree of education you have completed?
____

4. Are you employed? Yes / No

   If yes, what is your occupation?

   Please describe your work environment (i.e., quiet office, factory).

5. Please describe your lifetime noise exposure (occupational/ recreational).

6. Please describe your current living situation (i.e., number of people living with you, is it relatively quiet, etc.)

7. Do you feel you are able to control the noise level in your home and at work?

8. Are you aware of having had difficulty learning to read or write as a child? Yes / No

9. Have you ever been diagnosed with a language or learning disorder? Yes / No

   If yes, please describe.

10. Has any family member, past or present, experienced similar reading, writing, or language problems?

    If yes, please describe.

Section B:

1. Do you have excessive difficulty understanding speech in the presence of background noise or when in group situations? Yes / No

   (If yes, please answer questions a – e)

   a. When did this difficulty first occur? (i.e., how many years ago, at what age)

   b. At time of onset, were there any notable events that occurred around the same time?

   c. Has your difficulty become progressively worse over time?

   d. Are you concerned that your hearing sensitivity is decreasing?

   e. Do your family or friends ever comment on your difficulty hearing speech in certain situations?

2. Do you experience tinnitus (i.e., ringing/buzzing in your ears) on a regular basis? Yes / No

   If yes, how often?

3. Do you ever experience vertigo (i.e., dizziness)? Yes / No

   If yes, how often?

4. Do you feel you are sensitive to loud sounds or certain sounds? Yes / No

   If yes, please describe.

5. Do you have a history of ear infections? Yes / No

   If yes, please describe (when, estimated number of infections, treatment if known).

   Have you ever had tubes in your ears?

6. Have you ever had any head trauma? Yes / No

   If yes, please describe.

7. Does anyone in your family have hearing loss? Yes / No

If yes, please fill in the below chart:

Relation	Onset (child/adult)	Do they use hearing aids?

Section C:

1. Please rate your health status: Poor / Average / Excellent
2. Please list any medications you are currently taking.
3. Please note any previous illnesses/disorders?
4. Have you, or any member of your family, ever been diagnosed with a neurological or psychological/psychiatric disorder? Yes / No

   If yes, please note your diagnosed disorder.

5. Do you tend to worry about your health? Yes / No

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