TOWSON UNIVERSITY
OFFICE OF GRADUATE STUDIES
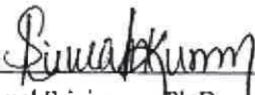
OBJECTIVE COMPARATIVE ANALYSIS OF PERSONAL SOUND

AMPLIFICATION PRODUCTS (PSAPs) IN THE PRESENCE OF

REVERBERATION

By:

Christina Downs

A Thesis

Presented to the faculty of

Towson University

in partial fulfillment

of the requirements for the degree

Doctor of Audiology

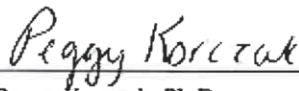**Department of Audiology, Speech-Language Pathology, and Deaf Studies**

Towson University
Towson, Maryland 21252

May, 2018

ii

ACKNOWLEDGEMENTS

This project would not have been possible without the guidance and support of the following people: Dr. Peggy Korczak, my thesis advisor and head of my committee, who consistently provided me with feedback and guidance, which helped me do my best and stay on track throughout the whole process; Dr. Nirmal Srinivasan, one of my committee members, who gave a lot of input into the methodology of the study and spent many hours setting up our sound proof booth with the necessary equipment; Dr. Frank Lin and Dr. Nick Reed, who took the time to share their expertise, opinions and research, which helped shape this project and guide it in the right direction; And finally, my family, who has supported me every step of the way. I greatly appreciate each and every one of you for everything you have done throughout this process.

ABSTRACT

OBJECTIVE COMPARATIVE ANALYSIS OF PERSONAL SOUND

AMPLIFICATION PRODUCTS (PSAPs) IN THE PRESENCE OF REVERBERATION

Christina Downs, B.S.

The purpose of this pilot study was to evaluate the performance of s a pair of traditional hearing aids (Oticon Nera2Pros) to a pair of high-end PSAPs (Soundworld Solutions Sidekicks) in the presence of reverberation. Three participants with mild to moderate sensorineural hearing loss were evaluated with each pair of amplification devices. Prior to the test session with each participant, electroacoustic analysis (EAA) was performed on each device and the results of this EAA were compared to the manufacturer's specifications to ensure proper functioning of the amplification devices. Fitting of the devices was done by the audiologist and was validated by comparing the participant's real ear measurements (REMs) to their NAL-NL2 targets. Each participant then performed two speech-in-noise tests, the AzBio test and the Coordinate Response Measure (CRM) test, in quiet and in the presence of reverberation.

Electroacoustic measures for both the Oticon HAs and the Sidekick PSAPs was relatively consistent with manufacturer's specifications. During REMs, the devices did a relatively good job of meeting NAL-NL2 targets for each test frequency. The only exception to this was at 4000 Hz, where both sets of devices undershot target by ~10-20 dB. Both the Oticon HAs and Sidekick PSAPs also undershot the NAL targets at most test frequencies for the third participant. Optimal fitting of both of these devices based on NAL targets could not be achieved for participant 3 as she complained that the signal was too loud at higher volume levels.

Results of the AzBio speech-in-noise task revealed that as expected the participants performed substantially worse in the reverberant environment compared to the quiet environment. Results of the CRM test revealed participants performed better when the target signal and the maskers were spatially separated versus co-located. The participants performed better in the quiet environment for approximately 50% of the CRM test conditions and better in the reverberant environment for the remaining 50% of the conditions. Lastly, in general participants performed better in aided conditions (Sidekick PSAPs and Oticon HAs) versus the unaided condition.

The analysis and interpretation of the results of this study are limited due to the small number of participants. Therefore, the results should be interpreted with caution and may not be representative of a larger population with mild to moderate hearing loss.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

KEY TO ABBREVIATIONS

3MS: Modified Mini-Mental State

AFFD: Auditory Fitness for Duty

AGC: Automatic Gain Control

ANSI: American National Standards Institute

ARHL: Age-related Hearing Loss

ASHA: American Speech, Language, and Hearing Association

BTE: Behind-the-ear

CES-D: Center for Epidemiologic Studies- Depression Scale

CIC: Completely-in-the-canal

CL: Co-located

CRM: Coordinate Response Measure

dB HL: Hearing loss in decibels

EAA: Electroacoustic Analysis

EIN: Equivalent Input Noise

FDA: United States Food and Drug Administration

fMRI: Functional Magnetic Resonance Imaging

HA: Hearing aid

HHIE: Hearing Handicap Inventory for the Elderly

HHTM: Hearing Health and Technology Matters

IOM: Institute of Medicine

ITC: In-the-canal

ITE: In-the-ear

LTASS: Long-Term Average Speech Spectrum

MPO: Maximum Power Output

NAL-NL2: National Acoustic Laboratories Non-Linear version 2

NIDCD: National Institute on Deafness and Other Communication Disorders

OTC: Over the counter

PCP: Primary Care Physician

PCAST: President's Council of Advisors on Science and Technology

PSAPs: Personal Sound Amplification Products

PTA: Pure tone average

REMs: Real-ear measurements

RIC: Receiver in the canal

RT: Reverberation Time

SIN: Speech-in-noise

SNR: Signal-to-noise ratio

SPL: Sound pressure level

SS: Spatially Separated

THD: Total harmonic distortion

UCL: Uncomfortable Loudness Level

VA: Veterans Affairs

VA-SLUMS: Veteran's Affairs St. Louis University Mental Status

WHO: World Health Organization

WWH: World Wide Hearing

CHAPTER 1

INTRODUCTION

Despite the large number of individuals with hearing loss world wide, hearing aid adoption rate remains low (Chien & Lin, 2012). This low adoption rate can be attributed to factors such as the high cost, lack of accessibility, and stigma associated with traditional hearing aids (Kochkin, 2007). Unfortunately, there are consequences associated with untreated age-related hearing loss, including cognitive decline, brain volume decline, increased cognitive load, social isolation and increased risk of falls (IOM, 2014; Kamil et al., 2016; Lin et al., 2013; Peelle, Troiani, Grossman, & Wingfield, 2011). Therefore, the low adoption rates of amplification devices in the current hearing aid market needs to be addressed. One way to address this issue is over-the-counter amplification devices.

Thanks to a recommendation from the Presidents Council of Advisors on Science and Technology (PCAST) to introduce more accessible and affordable treatment options for hearing loss, the U.S. Food and Drug Administration (FDA) is in the process of creating a category of over-the-counter (OTC) hearing aids (Abrams, 2017). While this legislation is in progress, Personal Sound Amplification Devices (PSAPs) have been investigated and compared to traditional hearing aids (HAs) in their ability to treat individuals with mild to moderate hearing loss (Oliver, 2017; Polyak, 2016). Currently, PSAPs are not approved by the FDA for treatment of hearing loss; rather, they are intended for recreational use to amplify environmental sounds. Until the FDA creates a category of OTC hearing aids, however, PSAPs remain a cheaper, more viable option for

many adults with mild to moderate hearing impairment when compared to traditional hearing aids.

While Polyak (2016) demonstrated that high-end PSAPs perform similarly to a traditional hearing aid in a quiet, sound proof booth, many hearing impaired listeners face more adverse listening conditions in their daily life. One common adverse listening condition is reverberation. Reverberation occurs when sound reflects off of walls and other surfaces, causing the listener to hear delayed versions of the original signal (Dillon, 2012). In the current study, one pair of high-end PSAPs (Soundworlds Solutions Sidekicks) were compared to a pair of traditional hearing aids (Oticon Nera2Pros) with and without reverberation. The amplification devices were compared using EAA, REMs, and two speech-in-noise measures, the AzBio test and the CRM test, which were performed both in quiet and in a reverberant environment.

Prior to discussing the details of the current study, a review of relevant literature will be provided. Topics in the following literature review include: prevalence of hearing loss, hearing aid usage, reasons for a low adoption rate of hearing aids, consequences of untreated age-related hearing loss, an overview of amplification devices (PSAPs and HAs), outcome measures used to evaluate benefit of amplification, past studies comparing PSAPs and HAs, and reverberation.

CHAPTER 2

LITERATURE REVIEW

Hearing Loss Demographics

Prevalence of hearing loss. Hearing loss is a condition that is highly prevalent worldwide. The World Health Organization (WHO) estimates that 360 million people

worldwide have a disabling hearing loss (WHO, 2017). Of the 360 million people with disabling hearing loss, 32 million are children and 328 million are adults. The WHO defines disabling hearing loss as a hearing loss > 40 dB HL in the better ear for adults and >30 dB HL in the better ear for children (WHO, 2017). The WHO (2017) estimates about one third of individuals over the age of 65 years have disabling hearing loss, with the majority of these individuals living in South Asia, Asia Pacific, and sub-Saharan Africa.

As seen with the dark bars in Figure 1, the prevalence of hearing loss increases with age, almost doubling each decade (Chien & Lin, 2012; Institute of Medicine (IOM), 2014). For example, about 12% of Americans ages 50-59 years have hearing loss, which then increases to approximately 80% of individuals over the age of 80 years. These numbers are predicted to increase, as Agrawal, Platz, and Niparko (2008) state: "The prevalence of hearing loss in the United States is predicted to rise significantly because of an aging population and the growing use of personal listening devices."
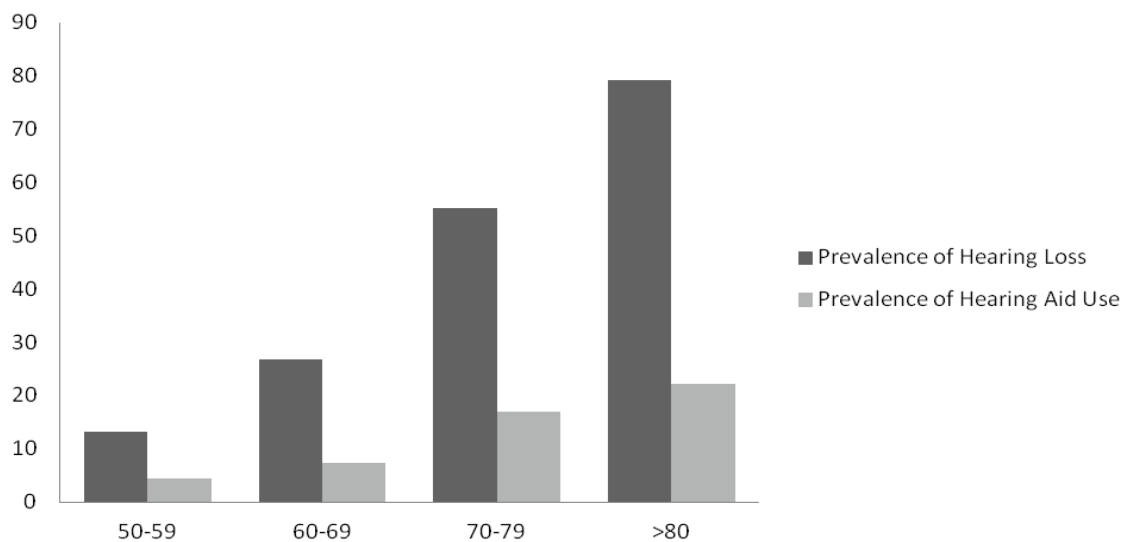
Figure 1. Prevalence percentage of hearing loss and hearing aid use in the United States by age. Adapted from the IOM workshop summary, 2014. Data from Chien and Lin, 2012.

3

Hearing Aid Usage. Given the high prevalence of hearing loss in the United States, especially among the elderly, it is surprising that hearing aid usage is low. In 2012, Chien and Lin analyzed data obtained from the 1999-2006 National Health and Nutrition Examination Survey to determine the prevalence of hearing aid usage in individuals ages 50 years and older. They reported that only 1 in 7 (14.2%) of American adults who are 50 years and older and who have a hearing loss wear hearing aids (Chien & Lin, 2012). Chien and Lin (2012) also reported that hearing aid use varies with age, gender, and severity of hearing loss, as seen in Table 1 (Chien & Lin, 2012). Specifically, hearing aid use increases with increasing age. For example, prevalence of hearing aid usage increases from 4.3% in individuals ages 50-59 years to 22.1% in individuals over the age of 80 years. Although the percentage of hearing aid use increases with age, the percentage of hearing aid users remains low among adults with hearing loss. Hearing aid usage also varies with gender; males had increased hearing aid usage compared to females for each decade age group 60 years and older. Lastly, their data suggests that the severity of the hearing loss increases with increasing age (Chien & Lin, 2012). The prevalence of moderate or greater hearing loss (>40 dB) increases from 11.8% in individuals ages 50-59 years to 35.7% in individuals ages 80 years and older (See Table 1).

Table 1

Prevalence and Number of Individuals 50 Years or Older With Hearing Loss Using Hearing Aids in the United States.

Table. Prevalence and Number of Individuals 50 Years or Older With Hearing Loss[a] Using Hearing Aids in the United States[b]

| | Prevalence of Hearing Aid Use Among Adults With Hearing Loss[a] ≥25 dB, % (95% CI)[c] | | | | | | No. With Hearing Loss[a] ≥25 dB (in Millions) |
| | Sex | | Hearing Loss Severity[d] | | Total | | |
Variable	Male	Female	Mild (25-40 dB)	Moderate or Greater (>40 dB)	Overall Prevalence of Hearing Aid Use	No. With Hearing Aids (in Millions)	
Age, y							
50-59	4.3 (0-9.5)	4.5 (0-13.5)	2.7 (0-6.6)	11.8 (0-27.5)	4.3 (0-8.8)	0.2	4.5
60-69	7.3 (2.5-12.1)	7.2 (1.4-13.0)	2.6 (0-5.2)	23.9 (10.6-37.2)	7.3 (3.6-10.9)	0.4	6.1
70-79	21.1 (14.5-27.6)	12.7 (6.0-19.5)	3.4 (0.3-6.5)	47.8 (37.0-58.6)	17.0 (12.4-21.6)	1.5	8.8
≥80	28.1 (20.3-35.9)	17.9 (11.2-24.7)	3.4 (0-7.7)	35.7 (28.7-42.7)	22.1 (18.5-25.8)	1.6	7.3
Estimated total No. of individuals with hearing aids and with hearing loss (in millions)						3.8[d]	26.7

[a] Hearing loss was defined as a speech frequency pure tone average of hearing thresholds at 0.5-, 1-, 2-, and 4-kHz tones presented by air conduction in the better hearing ear of 25 dB or greater.
[b] Data were derived from the 1999-2006 National Health and Nutrition Examination Survey.
[c] All values represent prevalence percentage unless otherwise noted.
[d] Numbers do not sum to group total because of rounding.

Note. Adapted from "Prevalence of hearing aid use among older adults in the United States," by W. Chien, and F. Lin, 2012, *Archives of Internal Medicine*, *172*(3), 292-293.

The prevalence of hearing aid use is not only low in the United States. The Institute of Medicine (IOM) estimated that only approximately 20% of adults with hearing loss in the United States and Europe use hearing aids (IOM, 2014). That number decreases to about 11% in Japan, 6% in Russia, 2% in China, and less than 1% in India (IOM, 2014). Even though the rate of hearing aid ownership is low, the number of individuals who use their hearing aids on a daily basis may be even lower. Specifically, Chia et al. (2007) surveyed 707 hearing impaired individuals and reported that 233 individuals owned hearing aids, but only 180 individuals (25.5%) habitually used them.

Possible Reasons Why Age-Related Hearing Loss Goes Untreated

Despite the high prevalence of hearing loss around the world as previously stated, hearing aid adoption rates remain low. There are many reasons why individuals with

hearing loss are not pursuing amplification options. These reasons include: accessibility, cost, and consumer opinions of hearing aids.

Accessibility. One reason individuals with hearing loss may not pursue hearing aids is their accessibility to the devices and/or hearing healthcare professionals. Hearing aids are regulated by the FDA; therefore, in order to obtain hearing aids, an individual is required to see an audiologist or a hearing aid dispenser (ASHA, n.d). Several studies have shown that there is a low number of hearing healthcare professionals on a global basis (Fagan & Jacobs, 2009; Goulios & Patuzzi, 2008). In developing countries, the ratio of hearing health care providers to hearing impaired patients ranges from one provider for every half a million hearing impaired patients to one provider for every 6.25 million hearing impaired patients (Swanepoel et al., 2010). That ratio somewhat improves in developed countries, with an average of one audiologist for every 20,000 people. These numbers, however, still demonstrate an extreme shortage of hearing health care professionals (Goulios & Patuzzi, 2008).

A second issue related to accessibility is that almost 80% of people with hearing loss reside in developing countries (Fagan & Jacobs, 2009). World Wide Hearing (WWH) states that, in the developing world, less than 1 in 40 individuals who need hearing aids have access to them. The majority of staff trained to provide hearing health care services in developing countries move to developed countries (McPherson, 2008, as cited in Swanepoel, et al., 2010). The majority of hearing health care providers reside in metropolitan areas (Swanepoel, 2010). Therefore, the hearing impaired population living in large, rural areas of developing countries are largely underserved (Swanepoel et al., 2010).

Goulios and Patuzzi (2008) reported that lack of government funding, public awareness, and training programs contributes to the shortage of health care professionals and services. Part of this lack of awareness stems from physicians and other health care providers who are not referring their patients to audiologists for testing (IOM, 2014). Lack of awareness also comes from individuals with hearing loss. Many of these individuals have reported they would not know where to go for hearing healthcare services (Abrams & Kihm, 2015; Kochkin, 2007). Specifically, Kochkin (2007) surveyed 2,169 non-adopters of hearing aids and reported almost half of respondents stated they lack knowledge about hearing loss and would not know where to have their hearing tested or where to buy hearing aids. Lastly, limited resources and geographical/natural barriers also contribute to lack of accessibility to audiological services (Margolis & Morgan, 2008; Swanepoel et al., 2010).

Cost. Aside from the need to have access to hearing health care providers, hearing impaired individuals must have the financial means to purchase hearing aids. Research suggests that cost is one of the primary reasons individuals who could benefit from hearing aids do not own them (Gopinath, Gourinchas, Hsieh, & Li, 2011). After surveying 3,000 hearing aid candidates, Kochkin (2007) reported that 76% of respondents stated the costs associated with visits to hearing healthcare professionals and the cost of hearing aids were factors preventing them from adopting hearing aids. One of the reasons for this may be that individuals with hearing loss are more likely to be retired and less likely to be employed (Kochkin, 2009; WHO, 2017).

Part of the reason hearing aids are expensive is the price of the device itself. The average hearing aid costs around $2,300 and, since hearing loss is typically bilateral,

most consumers pay an average of $4,600 for bilateral devices (Cassel & Penhoet, 2015). This cost is paid mostly out of pocket, since most insurance companies do not provide coverage for hearing aids (Cassel & Penhoet, 2015; Chien & Lin, 2012; Donahue, Dubno, & Beck, 2010; IOM, 2014). Kochkin (2009) reported third party sources including Medicare, unions, insurance, health maintenance organizations, veteran's affairs (VA), rebates, family members, etc. only provided financial assistance in 39.7% of hearing aid purchases in 2008.

The price of hearing aids goes beyond the initial price of the device. Consumers must also pay for maintenance of hearing aids, such as buying batteries, cleaning tools, and additional warranties after the initial manufacturer warranty expires. Moreover, most hearing impaired individuals will have to purchase several pairs of hearing aids in their lifetime, as the American Speech, Language, and Hearing Association (ASHA) reports hearing aids last four to six years on average (ASHA, n.d.). This will increase the amount spent over time.

In addition to paying for hearing aids and maintaining them, individuals have to pay for visits to see the audiologist, as well as their physician and/or an ear, nose, and throat (ENT) physician. As displayed in Figure 2, the process of obtaining hearing aids typically starts with an individual seeing their primary care physician (PCP), who will refer them to an audiologist for a hearing test. After confirming hearing aid candidacy, the patient will then need to obtain medical clearance from an otolaryngologist in order to be cleared for hearing aid use. Then, the patient goes back to the audiologist and purchases the hearing aids on the day of the fitting. Finally, the patient will have multiple follow-up visits with the audiologist. Not only does this process cost the patient a total of

around $3050-5050, but it also costs the patient their time (Lin, 2016). The whole process

lasts approximately 6 months, from the time the patient first sees their PCP to the time

they complete their post-fitting follow-up visits (See Figure 2).
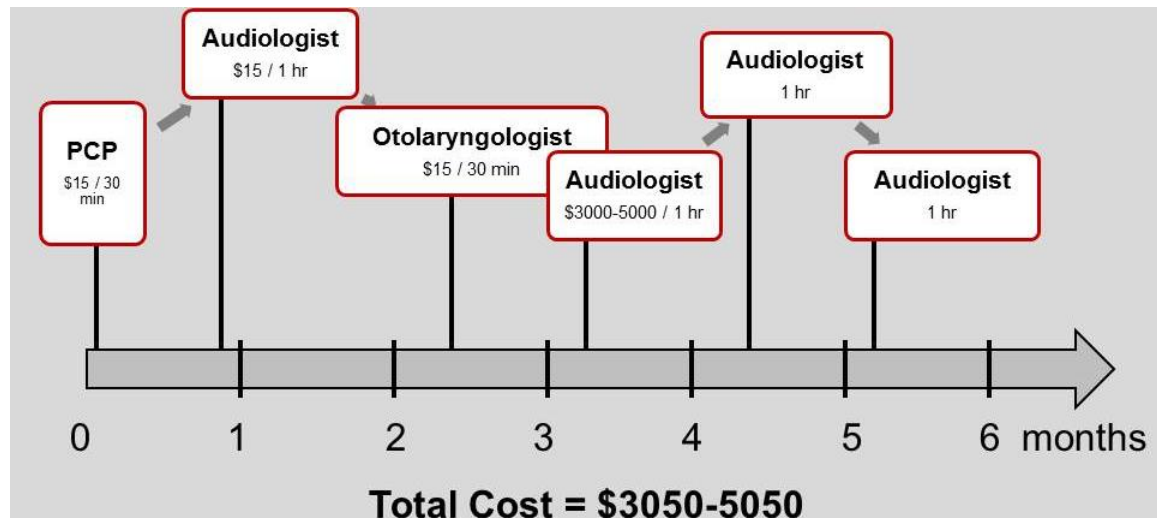
Figure 2. Costs associated with the "gold-standard model of hearing health care". Adapted
from "Hearing Loss in Older Adults: A Public Health Perspective." by F. Lin, 2016,
Towson University.

Consumer opinions. Although cost is a major complaint, there are some

individuals who report they would not use hearing aids even if they were free (Abrams &

Kihm, 2015). As a matter of fact, in Wales and England, where the cost of hearing aids is

covered by national health care, the prevalence of hearing aid usage is quite low, at

approximately 17% (IOM, 2014). Some of this non-adoption is due to consumer

opinions about their hearing loss or about hearing aids.

One reason consumers have a negative opinion of hearing aids is the stigma

effect. The stigma effect is described as individuals feeling hearing aids are unattractive

and/or associated with old age (Abrams & Kihm, 2015). Unfortunately, the stigma effect

is very common and individuals with hearing loss will reject hearing aids, because they

associate hearing aids with old age (Ross, 2015). Kochkin (2007) surveyed 2,169 non-

9

adopters of hearing aids. About one third of respondents reported they thought hearing aids were too noticeable, they would be embarrassed to wear them, or the devices would make them look disabled/old. In addition to associating hearing aids with old age, approximately 50% of respondents reported they heard bad reviews about hearing aids, such as: they do not work well in noise, they whistle, and they are a hassle (Kochkin, 2007). Therefore, in addition to the stigma effect, some consumers do not buy hearing aids because they have heard negative things about how they function.

Non-adoption of hearing aids is also linked to consumers' opinions about their hearing loss. After an individual develops hearing loss, it takes an average of seven years for them to try hearing aids (Ross, 2015). Ross (2015) suggested this is because that is how long it takes for the individual's hearing difficulties to be considered more important than their feelings toward hearing loss and/or hearing aids. The Kochkin survey in 2007 revealed that many individuals with hearing loss did not think their hearing loss is bad enough to pursue hearing aids or did not feel that purchasing a hearing aid was a priority (Kochkin, 2007). A little less than half (42%) of respondents reported their hearing loss "is not disruptive to their life" (Kochkin, 2007). Therefore, many individuals do not perceive the need to buy hearing aids on the basis that their hearing loss is not creating communication problems for them.

Consequences of Untreated Age-Related Hearing Loss

Individuals with untreated age-related hearing loss (ARHL) may face some related consequences. These consequences include: cognitive decline and dementia, physiologic changes in the brain, increased cognitive load, social isolation, depression, and vestibular changes.

Cognitive Decline and Dementia. The Alzheimer's association defines dementia as a decline in mental ability, which interferes with daily activities. Studies have suggested ARHL is associated with early-onset dementia and cognitive decline (Lin et al., 2011; Gallacher et al., 2012). Lin et al. (2011) evaluated hearing status in 639 individuals with Alzheimer's disease and dementia over a 12-year period. After evaluating participants several times over the 12-year period, a diagnosis of dementia was made by a multidisciplinary team, utilizing standard measures of dementia and Alzheimer's disease (i.e. the Diagnostic and Statistical Manual of Mental Disorders and the National Institute of Neurological and Communicative Disorders and Stroke-Alzheimer Disease Guideline). Researchers concluded hearing loss was independently associated with incident dementia (Lin et al., 2011). Additionally, Lin and colleagues reported that the greater the degree of hearing loss, the greater the risk for dementia (Lin et al., 2011).

Gallacher and colleagues (2012) conducted a longitudinal study in 1000 men to investigate the association of auditory threshold and cognitive decline. Participants were evaluated with standard measures of dementia as well as a comprehensive battery of cognitive testing (i.e. the Cambridge Cognitive Examination, the Mini Mental State Examination, the National Adult Reading Test, the Rivermead Memory Scales, a test of incidental memory, and the Alice Heim: a test of fluid intelligence and reaction time). After a 17-year period of evaluation, Gallucher et al. (2012) reported that behavioral audiometric thresholds were associated with incident dementia and cognitive decline. These researchers also reported that poorer auditory thresholds were associated with

poorer cognitive function. These findings are in good agreement with those reported by Lin et al. (2011).

In 2013, Lin and colleagues conducted a follow up study of 1984 older adults over a time period of six years. The participants were divided in to two groups: normal hearing individuals and hearing impaired individuals. All participants were given the following two tests: Modified Mini-Mental State Examination (3MS), which assesses orientation, attention, language, praxis, and memory (Folstein, Folstein, & McHugh, 1975); and the Digit Symbol Substitution Test, which assesses psychomotor speed and executive function (Wechsler, 1997). Each of these tests were administered four times over the duration of the study. Lin and colleagues reported ARHL is independently associated with dementia (Lin et al., 2013). Further, individuals in the hearing impaired group had a 24% increased risk for incident cognitive impairment and a 30-40% increased rate of cognitive decline compared to the normal hearing group (Lin et al., 2013). This risk increased linearly based on the severity of the hearing loss. Additionally, Lin et al. (2013) suggested a significant change in cognitive function occurs sooner in individuals with hearing loss compared to individuals with normal hearing. Specifically, these investigators reported it would take on average 7.7 years and 10.9 years to show a 5-point decrease on the 3MS for hearing impaired and normal hearing individuals, respectively (Lin et al., 2013).

Therefore, an increased risk of cognitive decline and/or dementia has been associated with hearing loss. In addition, the degree of the hearing loss impacts cognitive functioning, such that the more severe the hearing loss, the poorer the cognitive function.

Physiological Changes in the Brain. Another consequence of untreated hearing loss is physiological changes in the brain. Peelle, Troiani, Grossman, and Wingfield (2011) used functional magnetic resonance imaging (fMRI) to evaluate the effect of hearing impairment on neural processing of speech. Twenty-five individuals over the age of 60 years participated in the study, with hearing status ranging from normal hearing to mild sensorineural hearing loss. Participants listened to a variety of sentences, while researchers monitored their fMRIs to evaluate their level of brain activity. Their fMRI scans revealed decreased language-related neural activity in individuals with hearing impairment compared to normal hearing individuals (Peelle et al., 2011). The volume of gray matter in the auditory cortex was also decreased in hearing impaired participants (Peelle et al., 2011).

In 2014, Lin and colleagues conducted a study on 126 participants to evaluate brain volume in hearing impaired and normal hearing individuals. The hearing impaired group was mostly comprised of individual with mild hearing loss (78%). The remaining hearing impaired participants had moderate (18%) or severe (4%) losses. Lin and colleagues used magnetic resonance imaging (MRI) brain scans to study trajectories of brain volume change. These investigators reported individuals with hearing impairment had an increased rate of brain volume decline, especially in the right temporal lobe, compared to normal hearing individuals (see Figure 3).

HEARING LOSS x INTERVAL ON RAVENS GM
(Hearing Loss Interval > No Hearing Loss Interval)
T contrast, p < .001, cluster correction >= 50
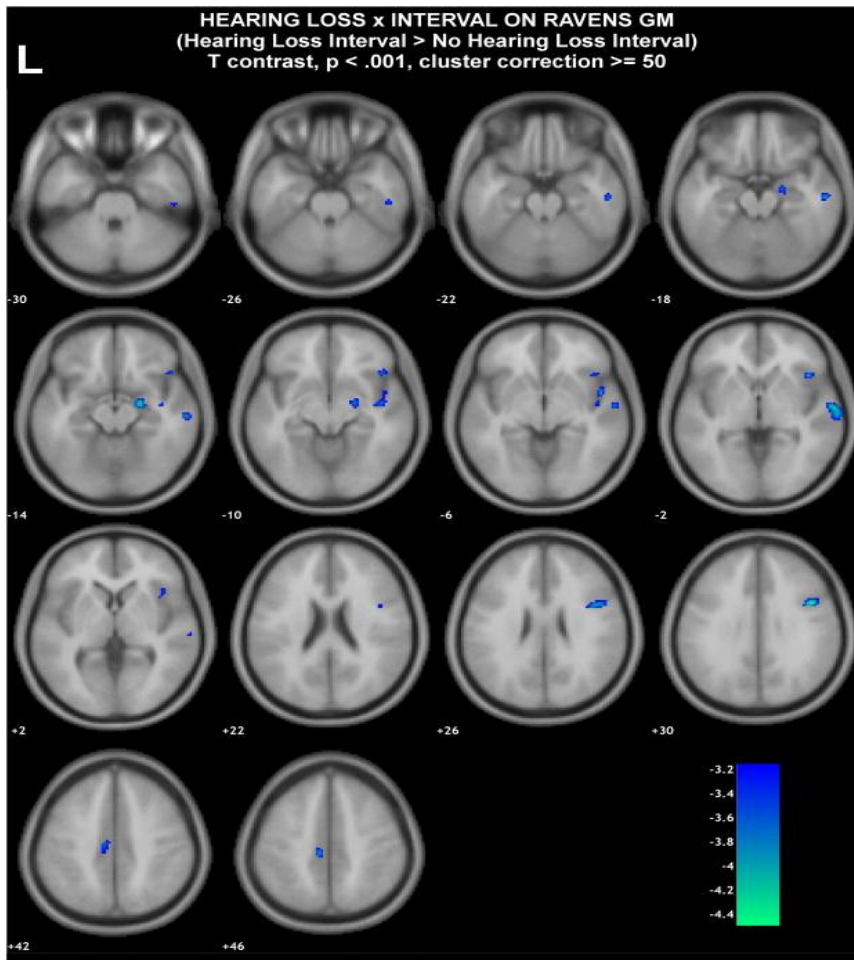
Figure 3. Difference in average slopes of RAVENS gray matter maps between hearing impaired and normal hearing individuals. Blue/green are areas in which individuals with hearing impairment had a higher rate of gray matter decrease compared to those with normal hearing. Color bars denote regression coefficient t-values. Adapted from "Association of hearing impairment with brain volume changes in older adults," by F.R. Lin, L. Ferrucci, Y. An, J.O. Goh, J. Doshi, E.J. Metter…and S.M. Resnick, 2014, *Neuroimage*, *90*, p. 84-92.

These two studies provide support for an association between untreated ARHL and physiologic changes in the brain, including decreased language-related processing and reduced brain volume, particularly in the right temporal lobe.

Increased Cognitive Load. Individuals with hearing loss may also experience increased cognitive load. Carrying out everyday bodily functions expends approximately 60 to 70% of the body's energy (IOM, 2014). Even more energy is expended to maintain

14

homeostatic equilibrium when someone is fighting disease or disability, leaving less energy for other simple activities such as movement or thinking. The brain must disseminate its resources to a variety of tasks, including, but not limited to: attention, motor function, hearing, and vision (IOM, 2014). During dual-tasks, such as walking while talking on the telephone, there is a competition for resources. If an individual has difficulty hearing, they must use more of their cognitive resources and energy to concentrate on hearing and less energy can be spent on simultaneous tasks, such as walking (IOM, 2014). Younger individuals have additional energy, which can be used to multi-task, while older individuals have more constrained resources (IOM, 2014). Therefore, both older individuals and individuals with hearing loss may experience functional cognitive consequences from having reduced energy or resources that can be dedicated to a variety of tasks. In the case of ARHL, individuals are experiencing effects of aging as well as hearing impairment, which may make performing certain tasks especially difficult.

Gosselin and Gagne (2011) conducted a study to investigate listening effort in 25 older adults, 64-76 years old, and 25 younger adults, 18-33 years of age. Participants each performed a sentence-recognition task in the presence of background noise and a vibrotactile pattern recognition task in quiet. The sentence recognition task consisted of closed-set sentences presented orally to the participant. The vibrotactile task required the patient to identify one of four vibrotactile pulse combinations (i.e., short-short, long-short, short-long, long-long). Participants performed these tasks separately and then concurrently. Results of both tasks revealed older adults exerted more listening effort compared to younger adults. Based on these objective measures, researchers concluded

older adults exert more listening effort and require more cognitive resources to understand speech than younger adults.

      Social Isolation, Depression, and Reduced Quality of Life. Other consequences associated with untreated hearing loss are social isolation, depression, and reduced quality of life. In 1999, the National Counsel on Aging surveyed 2000 adults with hearing loss and 2000 close friends and/or family members of an individual with hearing loss (IOM, 2014). The aim of the survey was to investigate the effects of untreated hearing loss (IOM, 2014). Responses to the survey indicated individuals with untreated hearing loss are more likely to experience decreased social activity and emotional stress, as well as exhibit symptoms of sadness, depression, anxiety, and paranoia, when compared to individuals with hearing loss who wear hearing aids (IOM, 2014).

      More recently, Pronk, Deeg, and Kramer (2013) conducted a four year longitudinal study with 960 participants to investigate the association between hearing loss and depression and loneliness. Investigators assessed participants with the De Jong-Gierveld Scale for emotional and social loneliness and the Center for Epidemiologic Studies Depression (CES-D) scale for depression. Results indicated social loneliness was more likely to be found in individuals with hearing loss who did not wear hearing aids compared to individuals who wore hearing aids (Pronk, Deeg, & Kramer, 2013). Likelihood of depression did not differ between hearing aid users and non-users this study (Pronk et al., 2013).

      However, other studies have suggested hearing loss has a strong association with depressive symptoms (MacDonald, 2011; Saito et al., 2010). MacDonald (2011) studied the link between hearing loss and depressive symptoms in 45 individuals over the age of

65 years. Each participant's hearing was evaluated using pure tone audiometry and otoacoustic emissions. Their depressive symptoms were evaluated using the Hearing Handicap Inventory for the Elderly (HHIE), the CES-D scale, and a self-assessment. Results revealed hearing loss and depressive symptoms had a significant relationship and depressive symptoms increased as severity of hearing loss increased (MacDonald, 2011). Similarly, Saito et al. (2010) studied the relationship between hearing handicap and depressive symptoms in 548 Japanese adults ages 65 years and older. Participants were evaluated using the HHIE and, based on the results, were divided into either the hearing handicap group or the group without a hearing handicap. When the Geriatric Depression Scale was used to assess depressive symptoms, researchers found a 19.6% incidence of depressive symptoms in the hearing handicap group. However, there was only an 8.0% incidence of depressive symptoms in the group without hearing handicap (Saito et al., 2010).

Another study, conducted by Chia and colleagues in 2007, evaluated health-related quality of life in 3000 older adults (Chia et al., 2007). Each subject was administered a questionnaire with 36 questions related to their physical, social, and mental health status. Responses to the questionnaires revealed individuals with bilateral hearing loss had lower scores in all categories compared to those with unilateral hearing loss. Two of the eight categories (physical functioning and role limitation due to physical problems) had a statistically significant difference (Chia et al., 2007). Compared to individuals with normal hearing, individuals with bilateral hearing loss had significantly lower scores in the four following categories: physical functioning and role limitations due to physical problems, social functioning, and emotional problems (Chia et al., 2007).

Lastly, Chia et al. (2007) reported poorer scores were associated with more severe hearing impairment.

Gopinath and colleagues (2012) conducted a similar study on 811 individuals. They used a shortened version of the HHIE to investigate hearing impairment and it's association with self-perceived handicap and health outcomes. Researchers found that ~67% of participants with hearing impairment at baseline audiometric testing had self-perceived handicap within five years (Gopinath et al., 2012). Additionally, individuals with self-perceived handicap were more likely to show depressive symptoms, low self-rated health, and poor quality of life (Gopinath et el., 2012). Gopinath et al. (2012) concluded hearing impaired individuals were more likely to experience emotional distress (i.e., frustration and embarrassment), and social engagement restrictions in comparison to their normal hearing peers.

Increased Risk of Falls. Hearing loss has also been associated with an increased risk of falls in older adults. Viljanen et al. (2009) conducted a study to examine the association between hearing loss and falls. Their study included 423 women from the Finnish Twin Study on Aging. Hearing was assessed with pure-tone audiometry and pure-tone averages (PTAs) of 500, 1000, 2000, and 4000 Hz were calculated. The PTA of the better ear was used for analysis, with mild hearing loss equating to a PTA of 21 dB or greater. Researchers assessed postural sway by examining the participant's postural stability as they stood in a semi-tandem stance on a force platform for 20 seconds. Additionally, participants marked the number of falls that occurred each day on a calendar for a year. Researchers found that 30% of participants in the poorest hearing group reported two or more falls per month, compared to 17% in the best hearing group.

Viljanen et al. (2009) concluded that poorer hearing loss was associated with a greater risk of falls and poor postural control played a partial role in this relationship.

Kamil and colleagues (2016) studied frailty and the number of falls that occurred in 2,000 older adults with varying degrees of hearing loss. These researchers utilized longitudinal data from the Health, Aging, and Body Composition study to measure these parameters. In this study, frailty was described as a gait speed of <6.0 ms and/or the subject needing their arm strength to rise from a chair. The number of falls on an annual basis were self-reported by participants. Researchers found that individuals with moderate or worse hearing loss had a 63% increased risk of frailty and a greater increase of annual falls over time in comparison to their normal hearing peers (Kamil et al., 2016). In summary, Kamil et al. (2016) concluded that hearing loss in older adults is independently associated with an increased risk of frailty and a greater number of falls over time.

In another study, Lopez et al. (2011) investigated the association between hearing difficulties and risk of falls in 5,354 adults, ages 76-81 years, over a six-year time span. Hearing impairment and falls were self-reported by participants in this study. Participants were considered to have a hearing impairment if they reported difficulty following a conversation. Falls were reported by the participants at multiple times over the ~6 year period. Results revealed hearing impairment was associated with a 77% and 82% increased risk of falls for males and females, respectively. Based on their results, Lopez et al. (2011) concluded that hearing loss was associated with an increased risk of falls.

Overall, research indicates that there are emotional and physiological consequences associated with untreated hearing loss. Further, some of these studies

suggest the importance of hearing aid use, as it decreases the likelihood of experiencing at least some of the consequences associated with age-related hearing loss (IOM, 2014; Pronk et al., 2013).

Amplification Devices

In general, there are two types of amplification devices for individuals that have difficulty hearing: traditional hearing aids and over-the-counter amplification devices, also known as personal sound amplification products (PSAPs). A hearing aid is an electronic, sound-amplifying device intended for individuals with a hearing loss (NIDCD, 2016). On the other hand, PSAPs are sound-amplifying devices that are intended to amplify environmental sounds, but are not traditionally intended to compensate for hearing loss. PSAPs are advertised for recreational use, such as listening to a lecture with a distant speaker, bird watching, or listening to other soft sounds that would be difficult for normal hearing individuals to hear (NIDCD, 2016).

Similarities and Differences Between Hearing Aids and PSAPs. Hearing aids (HAs) and PSAPs have notable similarities and differences. They can be compared based on the following categories: FDA regulation, internal components, style, cost, degree of hearing loss the device is appropriate for, and fitting technique.

FDA Regulation. The first thing that separates a traditional hearing aid from a PSAP is FDA regulation. The FDA categorizes hearing aids as Class I medical devices intended for individuals with hearing loss (FDA, 2016). Therefore, the FDA mandates that hearing aids must be labeled (model, serial number, etc.) and the patient must receive an instruction manual from the manufacturer at the initial fitting appointment. Hearing aid programming and maintenance following the initial fitting requires the patient to visit

a hearing healthcare professional, such as an audiologist. Additionally, a medical examination, completed within six months of the hearing aid fitting, must be signed by a physician and provided to the hearing healthcare professional in order for the patient to take home the hearing aids. If an individual is 18 years or older, they may sign a medical waiver, which signifies that they understand the risk of not receiving a medical examination prior to hearing aid purchase. Records of these documents must be kept on file by the hearing healthcare professional for at least three years after dispensing the hearing aids (FDA, 2016).

Up until very recently, PSAPs had not been regulated by the FDA and did not have to follow the specifications discussed previously (FDA, 2016). This means PSAPs did not have to be listed with the FDA and they had no regulatory classification, product code, or requirements for registration by the manufacturer. Instead, the FDA regulated sound amplification devices under the Radiation Control for Health and Safety Act of 1968 and PSAP manufacturers had to comply with applicable provisions of this act (FDA, 2016). Specifically, PSAP manufactures were required to report defects and adverse events associated with the device. There have also been rules in place for re-purchasing, repairing and replacing PSAPs (FDA, 2016). Unlike hearing aids, PSAPs did not need to be purchased, programmed, or maintained by a hearing health professional.

However, following recent announcements from PCAST, there will now be new regulations for PSAPs. PCAST is a team of scientists and engineers formed by President Obama in 2009 (Office of Science and Technology Policy, 2011). The aim of PCAST is to directly advise the president and to make recommendations about science, technology and innovation that will strengthen the economy and benefit the American people. In

reference to PSAPs, PCAST has recommended to improve the accessibility of amplification devices (Abrams, 2017). Therefore, the FDA is now adding a new OTC category to their regulation of amplification devices. On August 3, 2017 the US Senate passed the FDA Reauthorization Act, which included a provision directing the FDA to create an OTC category of hearing aids that would be available for adults with mild to moderate hearing loss (Hearing Health and Technology Matters (HHTM), 2017). The bill also requires the FDA to develop a website where they will discuss the quality, safety and effectiveness of the OTC devices. With the passing of this bill, the FDA will be encouraged to regulate safety and labeling requirements of OTC devices (HHTM, 2017).

Internal Components. Hearing aids and PSAPs are composed of the same basic components, including a microphone, amplifier, signal processor, and speaker (Dillon, 2012). The microphone picks up sounds in the environment, converts the sounds into an electrical signal, and sends the signal along to the amplifier. The amplifier makes the signal louder and sends the signal along to the speaker, which then converts the electrical signal back into an acoustic signal and sends the sounds into the ear of the person wearing the device. Most devices will also have signal processing, which further manipulates and optimizes the signal for the listener (Dillon, 2012).

Acoustic Features. The acoustic features available in traditional hearing aids and PSAPs vary. Traditional hearing aids have numerous acoustic features, including directional microphones, compression, feedback reduction, and multi-channel processing (Dillon, 2012). Volume controls and customizable programs for various listening environments are also options for traditional hearing aids. Telecoils are standard features in traditional hearing aids and facilitate listening on the telephone and/or in environments

22

with a loop system (Dillon, 2012). All of these features can be adjusted and customized for the patient by the hearing healthcare professional in the manufacturer's software for their traditional hearing aid.

PSAPs also have acoustic features, such as volume control and programs for various types of listening environments. However, these features are typically limited in their ability to be customized for the user and are generally being manipulated by the listener themself, rather than an experienced audiologist. Some PSAPs, similar to traditional hearing aids, have a telecoil feature (Bean, n.d.). Additionally, some PSAPs have Bluetooth capabilities and can connect to the hearing-impaired user's cell phone for programming and remote microphone purposes (Soundworld solutions, n.d.).

Styles of devices. Hearing aids are available in behind-the-ear (BTE) and custom styles (ASHA, n.d.). Traditional BTE hearing aids sit behind the ear and are coupled to tubing and custom ear molds. Custom ear molds are available in different materials, including acrylic, silicone, and vinyl (Dillon, 2012). Certain materials will be more advantageous than others for some patients, depending on their ear (Dillon, 2012). For example, individuals with particularly soft ears may find it easier to insert a mold made of a harder material, such as acrylic. Proper insertion is important, as it can impact the sound quality and amount of feedback produced by the device. (Dillon, 2012).

Another type of BTE hearing aid is a receiver-in-the-canal (RIC) hearing aid. RIC hearing aids are typically "open-fit", meaning they are coupled to dome pieces and allow some sound to pass into the ear naturally. However, RIC hearing aids can also be coupled with custom ear pieces. Custom ear pieces can be useful for retention and for amplifying sound for individuals with a more severe degree of hearing loss (Dillon, 2012).

Custom hearing aids are custom made for the patient's ear and can be manufactured into different styles. For example, in-the-ear (ITE) custom hearing aids sit in the concha of the ear, while invisible-in-the-canal (IIC) hearing aids sit deeper in the canal, making them invisible or nearly invisible in most ears. See Figure 4 for images of different hearing aid styles.

Figure 4. Styles of hearing aids from left to right: Behind-the-ear, receiver-in-the-canal, in-the-ear, invisible-in-the-canal. Adapted from "Different styles of hearing aids" by American Speech-Language-Hearing Association (n.d.). Retrieved from http://www.asha.org/public/hearing/Different-Styles-of-Hearing-Aids/

PSAPs also have a range of styles. However, unlike traditional hearing aids, they do not have styles that are custom-made for the patient's ear. Instead, they come with dome pieces of varying sizes, similar to the dome pieces used for RIC hearing aids. PSAPs are available in both BTE and ITE styles (See Figure 5).

Figure 5. Examples of PSAP styles. On the left: Behind-the-ear style called CS-50+ by Soundworld solutions. On the right: In-the-ear style called the Bean by etymotic research. Adapted from "CS50+ Specifications" by Soundworld Solutions (n.d.) and "Technical Specs" by Bean (n.d.).

Cost. Both PSAPs and traditional hearing aids are available in low-end and high-end devices, ranging in price. Low-end PSAPs retail for under $150, while high-end PSAPs retail for over $150 (Smith, Wilber, & Cavitt, 2016). Overall, PSAPs range in price from about $30 to $500 (Callaway & Punch, 2008). Traditional hearing aids are more expensive, with low-end hearing aids retailing for around $500 per aid, and high-end aids averaging around $3,200 per aid (Smith et al., 2016).

Degree of Hearing Loss. Sensorineural hearing loss can range in degree, from slight to profound, and in configuration, from flat to sloping to a rising hearing loss. Traditional hearing aids, with their range of styles, can be used to aid most degrees and configurations of hearing loss (Dillon, 2012). For example, Phonak SuperPower receivers for their line of Audeo Q hearing aids are capable of producing an output of 129 dB SPL (Phonak, n.d.). This would be appropriate for more severe hearing loss. On the other hand, PSAPs are generally appropriate for slight to mild hearing loss (Cheng & McPherson, 2000). For example, the maximum power output of the CS-50+ PSAP is 112 dB SPL (Soundworld Solutions, n.d.). Therefore, this device could be appropriate for individuals with approximately mild to moderate hearing loss. However, due to a lack of custom ear pieces, feedback could further limit the output of the device.

Fitting of the Device. Hearing aid programming requires the patient to visit a hearing healthcare professional, such as an audiologist or a licensed hearing aid professional (FDA, 2016). On the other hand, PSAPs can be fit for the user a few ways. First, they can be fit by the users themselves, following the instructions in the manual provided by the manufacturer. For the purposes of this literature review, this approach will be called an "out-of-the-box self-fit". Second, the user can fit the device by

following the instruction manual, as well as manipulating features on the cell phone

application associated with the device. For this literature review, this approach will be

referred to as "advanced-user self-fit". Lastly, PSAPs can be fit to the user by a hearing

healthcare professional. This is considered the gold standard fitting strategy. A pilot study

investigating the effects of these three fitting approaches on participants' speech-in-noise

performance has been conducted recently (Oliver, 2017). The results of this preliminary

study will be discussed later in this literature review.

In summary, there are a number of similarities and differences between hearing

aids and PSAPs regarding FDA regulations, internal components, acoustic features, styles

of the devices, cost, and degree of loss they are appropriate for. See Table 2 for an

overview of the primary differences between traditional hearing aids and PSAPs.

Table 2

Primary differences between PSAPs and hearing aids.

PSAPs	Hearing Aids
1. FDA regulated for mild to moderate hearing loss	FDA regulated: compensate for hearing loss
2. Basic PSAPs have limited acoustic features and programming options	More acoustic features and programming options
3. Ear pieces are not customizable	More styles and customizable ear pieces
4. Less expensive ($10-$500)	More expensive ($500-$3000 per aid)
5. Appropriate for limited degrees of hearing loss (mild to moderate)	Appropriate for all degrees of hearing loss
6. Purchased over-the-counter or online	Purchased and programmed through an audiologist or hearing aid dispenser

Functional Outcome Measures Used to Assess Hearing Aid Benefit

There are several functional outcome measures that can be used to verify the function of hearing aids and PSAPs and to assess the benefit of these devices. These measures are objective and include: electroacoustic analysis (EAA), real-ear measurements (REMs), and speech-in-noise measures. Below is a brief description of each of these outcome measures.

Electroacoustic Analysis. EAA is an objective measure of hearing aid function, which ensures that hearing aids are meeting standards set by the manufacturer (Dillon, 2012). EAA is performed inside a test box by attaching the hearing aid to a 2 cc coupler, which simulates the volume of the ear canal. Speakers within the test box will then

deliver a calibration signal to the hearing aid, while a microphone regulates the signal level (Dillon, 2012).

EAA consists of several measurements, including OSPL90, frequency range, equivalent input noise (EIN), and total harmonic distortion (THD). These are the objective measurements that were used in this study and they are defined below. The OSPL90 curve, represented by the top green line in Figure 6, corresponds to the limits of the hearing aid output with a 90 dB SPL input when the gain settings are full-on (Dillon, 2012). Additionally, the maximum OSPL90 is measured, which corresponds to the maximum point measured along the OSPL90 curve and is recorded on the side of the screen, labeled by the number "1" in Figure 6.

The bottom purple line in Figure 6 represents the hearing aid in reference test setting. During this setting, a mid-level (60 dB SPL) input signal is delivered and the frequency range of the hearing aid is determined, as shown by number "2". The frequency range represents range from the lowest to the highest frequency the hearing aid can amplify. The high-frequency average (HFA), number "3" in Figure 6, is the average gain at 1000 Hz, 1600 Hz, and 2500 Hz with a 60 dB SPL input (Audioscan, 2015).

Automatic gain control (AGC), number "4" in Figure 6, evaluates the compression capabilities of a hearing aid by measuring attack and release times. Attack time is the time it takes for the hearing aid to activate compression in response to a loud sound. Release time is the time it takes the hearing aid to eliminate compression once the loud sound has reduced in intensity.

EIN and THD are also measured during EAA. EIN, number "5" in Figure 6, corresponds to the amount of internal noise generated by the microphone and the receiver

of the hearing aid. THD, number "6" in Figure 6, is the percentage of distortion present in

the hearing aid output (Audioscan 2015; Dillion, 2012). THD is measured by analyzing

an amplified pure tone signal at 500, 800, and 1600 Hz. Distortion is identified if there is

any artifact as a result of the amplified sound. All of these measurements are then

compared to the manufacturer's specifications to confirm that the hearing aid is

functioning within the allowed range. It is useful to run EAA on a hearing aid before

dispensing and while troubleshooting to ensure the device is functioning properly.

Although traditionally preformed on hearing aids, EAA can be run on PSAPs as well.
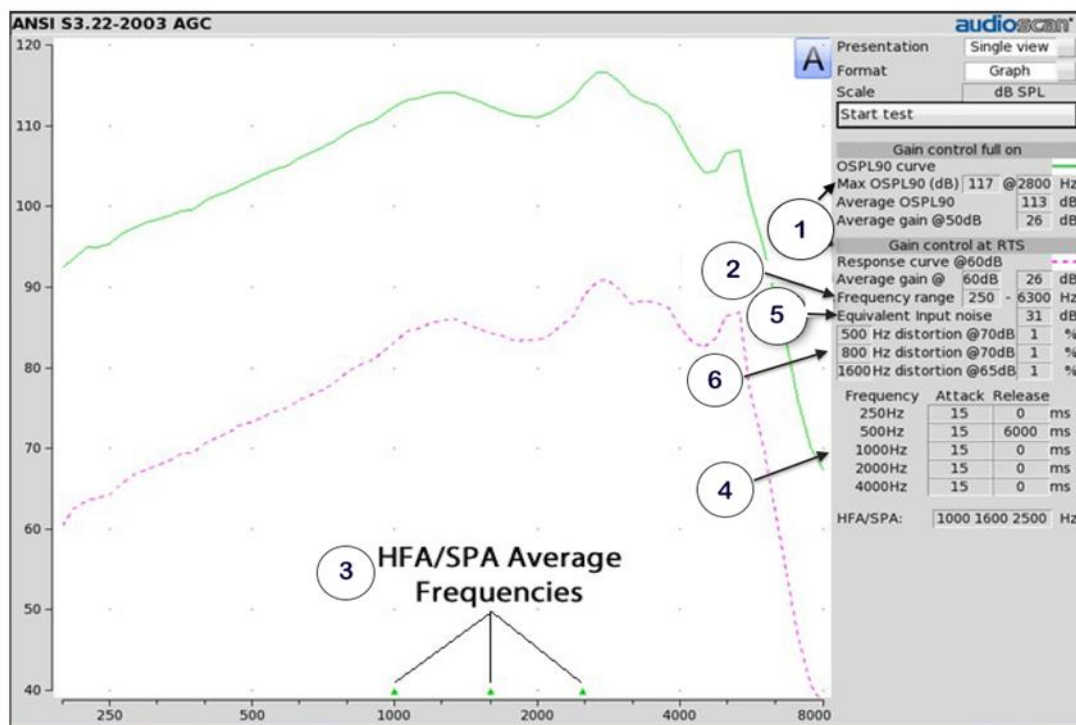
Figure 6. Example of electroacoustic analysis. 1. OSPL90; 2. Frequency range; 3. High-frequency average; 4. Attack and release times; 5. Equivalent input noise; 6. Distortion. Adapted from "Test box measures – setup." by Audioscan, 2015, *Verifit User's Guide Version 4.4*.

Real-ear Measurements. Another way to measure hearing aid or PSAP function

is REMs. This type of measurement assesses the hearing aid output recorded in the

patient's ear. Further, REMs make sure the hearing aid is meeting prescribed targets

across all amplified frequencies at different input levels (Dillon, 2012). The prescribed

targets are generated by a formula based on the patient's pure tone thresholds. The

generated targets represent the amount of gain needed at each frequency and input level.

REMs are performed by inserting a probe tube into the ear canal, close to the

tympanic membrane. To account for the patient's natural ear canal resonance, an unaided

response is generally measured first. Then, the hearing aid is put in place and a speech,

noise, or pure tone signal is delivered. The signal is delivered at soft, moderate and loud

input levels to ensure that the hearing aid output is meeting prescriptive targets in the ear

canal at each level. An example of REMs can be seen in Figure 7 below. The yellow line

represents the patient's hearing loss. The green icons are the prescriptive targets that the

hearing aid should be meeting for a 65 dB SPL input. The surrounding green striped

region is the Long Term Average Speech Spectrum (LTASS), with the average

represented by the blue line. The red crosses represent the estimated uncomfortable

loudness levels (UCLs) based on the patient's pure tone thresholds. Maximum Power

Outputs (MPOs) are measured to ensure the hearing aid output will not exceed the

estimated UCLs.
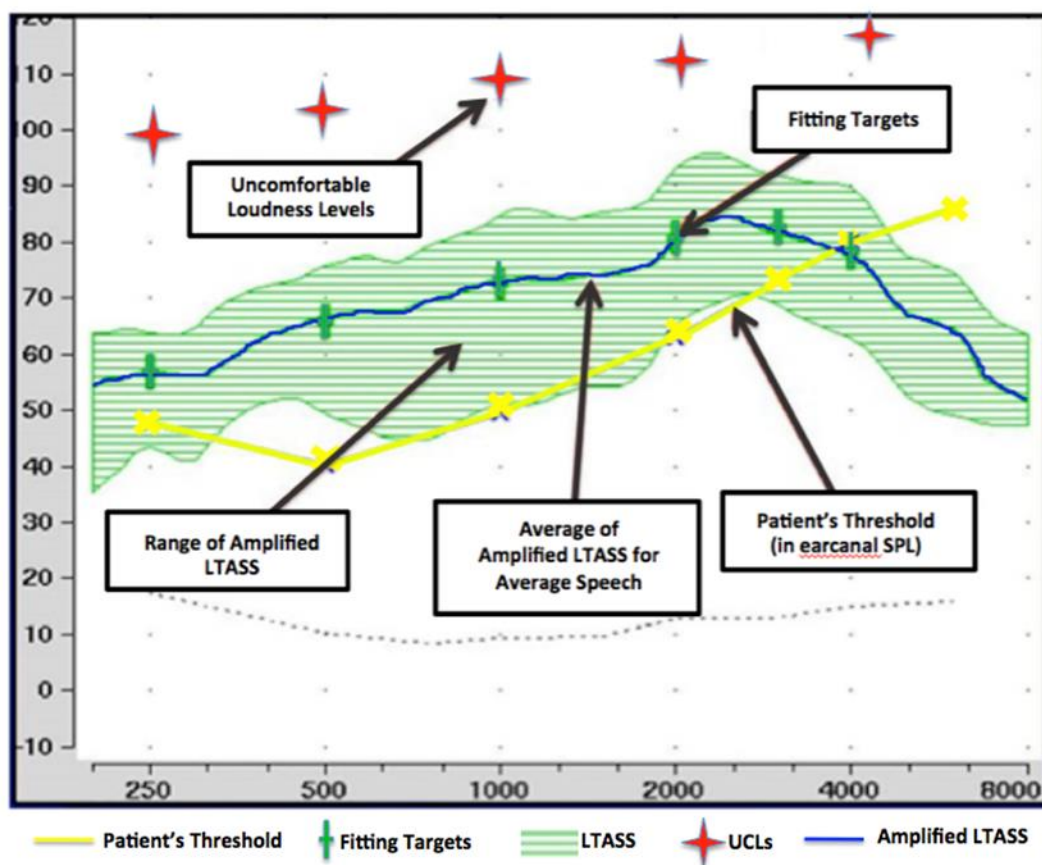
Figure 7. Example of real-ear measurements of a hearing aid with a 65 dB SPL speech input and NAL prescriptive targets. Adapted from "20Q: Real-ear probe-microphone measures – 30 years of progress?" by H.G. Mueller, 2014, *Audiology Online*.

Speech in Noise Tests. Another way to test hearing aid benefit is with speech measures. Hearing in background noise is one of the most common complaints of hearing aid users. Therefore, these speech-in-noise measures are useful, because they evaluate the listener's ability to understand speech in the presence of background noise, which cannot be predicted based on an individual's audiogram (Killion & Niquette, 2000). Speech-in-noise measures have also recently been reported as being useful for hearing aid validation (Beck & Nilsson, 2013). The following sections will include a brief description and supporting literature for the AzBio test and the Coordinate Response Measure (CRM), the speech-in-noise measures that were utilized in this study.

31

Discussion of the AzBio Test. The AzBio, a speech-in-noise sentence test, is intended to evaluate speech understanding in background noise. Developed in 2004 by Sphar and Dorman at the Arizona Biomedical Institute at Arizona State University, the test initially consisted of 33 lists of sentence materials and a total of 1000 sentences. Spahr et al. (2012) evaluated the validity of these sentence materials by presenting all 33 lists to 15 cochlear implant users in random order. These investigators reported that there were significant differences in the results among the various sentence lists. Therefore, Spahr and colleagues produced the current version of the AzBio test, which is a set of 8 lists consisting of equally difficult sentences, with the intention of it to be used clinically with hearing impaired patients and cochlear implant users.

The AzBio has been successfully administered to cochlear implant users to evaluate their performance pre and post implantation. For example, Gifford, Dorman, McKarns, and Spahr (2007) administered AzBio sentences to eleven participants pre and post implantation in quiet and at a +10 and +5 dB SNR. They also administered AzBio sentences in an electric-only and in an electric plus contralateral acoustic condition after implantation. Results suggested participants performed better on the AzBio sentences after implantation in the electric plus contralateral acoustic condition than they did pre implantation (Gifford et al., 2007).

In 2013, Hansen and colleagues also conducted a study using the AzBio sentences pre and post implantation. Their study was conducted on 29 participants receiving cochlear implants due to semicircular canal dehiscence resulting from Meneire's disease. AzBio sentences were administered in quiet before implantation and at three, six, and twelve month intervals post implantation. Overall, results revealed improved AzBio

32

scores after cochlear implantation, with significant improvement at three and six months post implantation compared to pre implantation (Hansen, Gantz, & Dunn 2013). Therefore, the AzBio test has been successfully used to evaluate word recognition pre and post cochlear implantation. The AzBio test can also be utilized to evaluate speech understanding with hearing aids.

Reliability of the AzBio Test. Schafer, Pogue, and Milrany (2012) evaluated the reliability of the AzBio test. They administered 15 lists of AzBio sentences in ten-talker babble to 14 adults with normal hearing and 12 adolescents or adults with cochlear implants. The AzBio sentences were presented at a fixed intensity of 73 dB SPL and both a 0 and a -3 dB SNR was used for normal hearing participants and a +10 dB SNR was used for participants with cochlear implants. Schafer et al. (2012) reported no significant differences in listener's performance across ten of the fifteen lists. These investigators also observed the reliability of participant's scores across lists by calculating the standard deviation of the within-subject differences. In the normal hearing group, the average standard deviations for the 0 and -3 dB SNR conditions were 5.4% and 5.9% respectively. In the cochlear implant group, the average standard deviation for the +10 dB SNR condition was 2.7%. Therefore, the variability in the listener's performance on the AzBio test was low across lists and across participants. Based on these findings, Schafer and colleagues concluded the AzBio test is valid and can be reliably used for individuals with normal hearing and cochlear implants (Schafer et al., 2012).

Discussion of the Coordinate Response Measure. The CRM, first developed by researchers at the Air Force Research Laboratory (Moore, 1981), is a speech intelligibility measure, which consists of 2048 possible phrases (Brungart, Ericson, Scott,

33

& Simpson, 2001). The phrases are of the form "ready (call sign) go to (color) (number) now". There are eight possible call signs (Charlie, Arrow, Baron, Eagle, Chopper, Laker, Ringo, and Tiger), four color options (red, blue, white and green), and eight numbers (1-8) (Brungart, 2001). These phrases are presented by four female talkers and four male talkers, each voicing 256 possible phrases. This yields a total of 2048 available phrases.

The listener is asked to listen for the sentence containing a selected call sign. This is called the target phrase. Meanwhile, masker phrases which contain random call signs other than the selected call sign are presented simultaneously. See Figure 9 for an example of the response screen where the listener selects the color and number they heard in the target phrase.
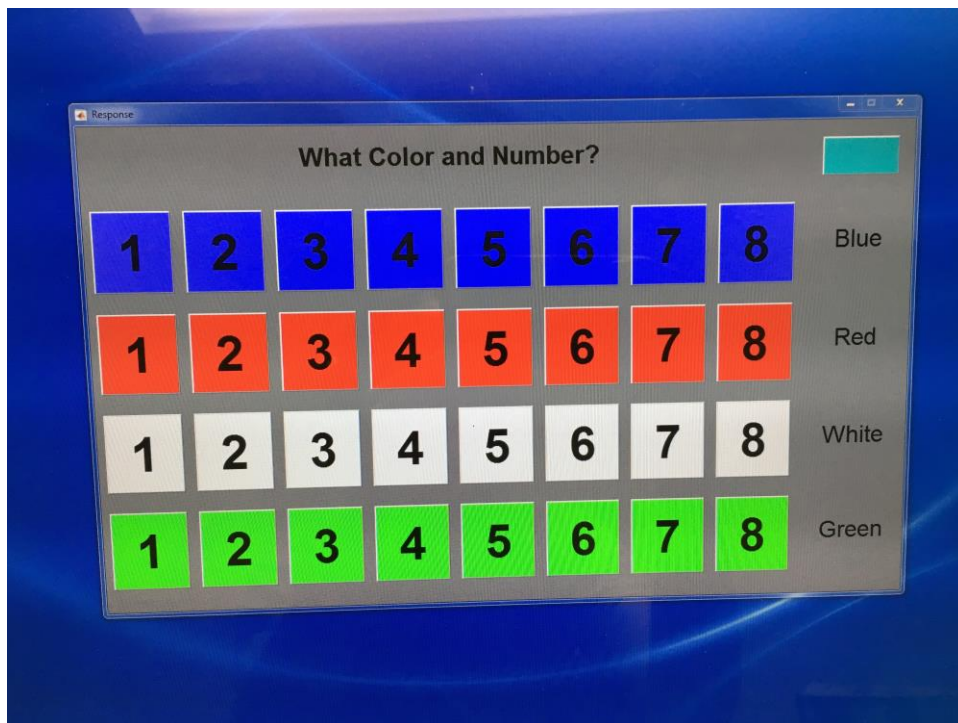
Figure 8. CRM response screen where the listener selects the color and number they heard as part of the target phrase.

Spatial Separation of Target and Maskers. The target and masker phrases of the CRM can be presented at a co-located condition or they can be spatially separated.

Best, Gallun, Ihlefeld, and Shinn-Cunningham (2006) investigated the impact of spatially separating target and masker sentences on speech intelligibility. These researchers used the CRM to administer speech materials to eight normal-hearing participants. Results revealed that participant's ability to comprehend the desired "target" speech signal in the presence of a masker signal improved when the target and maskers were spatially separated compared to when the target and masker were at a co-located location. This pattern was also seen in hearing impaired listeners, as demonstrated in a study by Srinivasan, Jakien, and Gallun in 2016. These researchers investigated the impact of spatially separating target from maskers on speech intelligibility in normal hearing and hearing impaired listeners. They also used the CRM to administer target and masker sentences to their participants. However, they presented the target and maskers at various spatial separations to investigate the smallest separation at which participants were able to comprehend speech. Results revealed that hearing impaired listeners required a greater spatial separation of the target and masker in order to comprehend speech when compared to their normal hearing peers.

Reliability of the CRM. In 2001, Brungart reported that the CRM test has numerous advantages over other speech intelligibility measures (Brungart, 2001). First, results of Brungart (2001) suggested that the CRM is sensitive to small intelligibility changes in difficult listening environments, such as those employed in this study. Secondly, the CRM can be used across languages, as all languages have words for colors and numbers. Therefore, phonetically balanced word lists do not need to be derived in other languages to use the CRM. Third, the CRM is a useful speech intelligibility tool with multiple simultaneous talkers. The call signs allow for a designated target phrase

without relying on a difference in location, onset time, or talker characteristics to separate it from the simultaneous phrases. Finally, the CRM is relatively easy to set-up and run and the corpus is publicly available. Every trial can use the same response list, as the listener will have the same 32 possible responses each time. This makes data collection and processing easier for CRM compared to sentence-based or phonetically balanced tests, such as the MRT (Brungart, 2001).

Validity of the CRM. The structure of the CRM sentences lend to its effectiveness for measuring speech intelligibility in multi-talker environments, as has been demonstrated by studies such as McKinley et al. (1994), Ericson and McKinley (1997), and Kidd, Mason and Gallun (2005). Because the sentences are relatively context-free, it can be assumed that changes in speech intelligibility are a result of the experimental manipulations (Bolia, Nelson, Ericson, & Simpson, 2000). A recent study by Semeraro, Rowan, van Besouw, and Allsopp in 2017 investigated the validity of the British-English CRM test as a speech-in-noise test for occupational auditory fitness for duty (AFFD) assessment. Semeraro and colleagues conducted two studies on normal hearing individuals and one study on hearing impaired military personnel. The researchers presented CRM sentences using an adaptive procedure and measured the participant's speech reception thresholds. Results revealed the CRM is influenced by hearing impairment and researchers concluded that the CRM was a valid, reliable test that can be used as an AFFD assessment tool with military personnel. This study affirmed the validity of the CRM as a tool that corresponds to speech perception abilities needed to carry out 'job specific hearing critical tasks'. Therefore, rather than simply assessing a

participant's ability to identify beeps, the CRM assesses an individuals ability to carry out a task with non-contextual auditory instructions.

In conclusion, functional outcome measures, such as EAA and REM, as well as the two speech-in-noise measures described above can be reliably used to verify hearing aid benefit. As such, these measures can also be useful to verify PSAP function. Therefore, EAA, REMs, the AzBio, and the CRM were used in this study to evaluate the benefit of a traditional hearing aid and a PSAP for the hearing impaired participants.

Previous PSAP Studies

A few preliminary studies have been conducted to investigate the acoustic function and the effectiveness of PSAPs for individuals with hearing loss. Callaway and Punch (2008) investigated objective benefit of 11 low-end and mid-level PSAPs using electroacoustic measures. Electroacoustic analysis was performed on the low-end devices at two different times which were two months apart to ensure validity and reliability. Results revealed that the mid-level PSAP devices met gain and output targets better than the low-end devices. Also, although total harmonic distortion was generally low for the devices, all of the low-end PSAPs had high equivalent input noise levels. Lastly, two of the three mid-level devices met the recommended frequency range. Callaway and Punch (2008) concluded that the low-end PSAPs were limited primarily because they provided too much gain in the low frequencies and too little gain in the 1000-2000 Hz frequency range. However, the researchers concluded that mid-level PSAPs may be a suitable option for hearing impaired individuals.

More recently, Chan and McPherson (2015) conducted electroacoustic analysis on ten PSAPs priced under $115 each to investigate the acoustic properties of the devices.

Results revealed that while nine out of the ten devices had acceptable total harmonic distortion, seven had high equivalent input noise levels. Similar to the results of Callaway and Punch (2008), results of Chan and McPherson (2015) revealed that all ten devices had a peak response in the mid or low frequencies, suggesting that PSAPs may not be appropriate for individuals with high frequency hearing loss. Both of these studies conclusions were based solely on objective measures.

Using both objective and subjective measures, McPherson & Wong (2005) investigated the effectiveness of a PSAP device in 19 older adults with mild to moderate mixed or sensorineural hearing loss. The objective measures included real-ear insertion gain and aided hearing thresholds. The subjective measures included three questionnaires and open-ended interviews. Results from the objective measures revealed that while the device met insertion gain targets at 2000 and 4000 Hz, it did not meet insertion gain targets at 1000 Hz. These results suggest that appropriate gain is achieved at the higher frequencies, but not enough gain is achieved at the lower frequencies. The subjective results from the questionnaires revealed three things: 1) Answers of individuals using the PSAP device were comparable to those of hearing impaired individuals who have worn traditional hearing aids, 2) The majority of participants reported that their hearing was better when they were wearing the PSAP device, and 3) In everyday listening environments, most participants experienced difficulties infrequently. Open-ended interviews with the participants resulted in both positive and negative comments related to the perceived benefit from the PSAP device. Most of the negative complaints were related to feedback or background noise (McPherson & Wong, 2005).

Overall, these preliminary studies revealed that PSAPs meet some electroacoustic specifications, such as THD and frequency range. However, they may over-amplify low frequencies which would not be ideal for an individual with high-frequency hearing loss. Subjectively, participants have reported similar perceived benefit with PSAPs compared to perceived benefit of individuals using traditional hearing aids, but complaints of feedback and background noise among PSAP users have been reported. These preliminary studies were limited, because they lacked the use of objective speech measures. The studies described in the following sections utilized electroacoustic analysis as well as speech-in-noise measures to evaluate the benefit of PSAPs for individuals with mild to moderate sensorineural hearing loss.

Polyak (2016) compared the objective benefit of five PSAPs to a traditional hearing aid. Thirteen individuals, ages 61-80 years old, with mild to moderate hearing loss, participated in the study. The traditional hearing aid was programmed for the participant's hearing loss using NAL-NL2 prescriptive targets, while PSAPs were adjusted based on the participant's degree of hearing loss per manufacturer instructions. The audiologist conducted the programming for both the traditional hearing aid and the PSAP devices. The performance of each device was evaluated using EAA, REMs, and the AzBio speech-in-noise task.

Results of EAA revealed the low-end PSAP devices had higher THD and EIN values, as well as a narrower frequency range, compared to high-end PSAPs. Results of REMs revealed the traditional hearing aid met targets better than any of the five PSAP devices and the high-end PSAPs met NAL targets better than the low-end devices. REM results showed that the low-end PSAP provided too much low-frequency gain, but not

enough high-frequency gain. Lastly, results of the AzBio test revealed the participant's

mean aided AzBio scores improved with the traditional hearing aid, the high-end PSAPs

and the mid-level PSAP in comparison to their mean unaided score. The mean aided

AzBio score for the low-end PSAP, however, was worse than their mean unaided score.

The mean AzBio scores revealed that the high-end and mid-level PSAPs performed very

comparably to the traditional hearing aid.

Reed and colleagues (2017) conducted a follow-up study using the same methods

as Polyak (2016) and was able to increase the subject pool to 42 hearing impaired

participants. Reed et al. (2017) reported mean aided percentage scores on the AzBio

speech-in-noise test for each device. Additionally, Reed et al. (2017) reported on the

improvement in performance from the unaided to aided scores and the difference in

performance between PSAP and the traditional hearing aid. Table 3 provides an overview

of the data from Reed et al. (2017).

Table 3

Unaided and Aided Performance (in percentage) on the AzBio

Device	Mean Accuracy	Change from unaided scores	Difference between PSAP and HA change
Unaided	76.5	NA	NA
Traditional HA	88.4	11.9	NA
CS-50+	87.4	11.0	-1.0
Soundhawk	86.7	10.2	-1.8
Bean	84.1	7.7	-4.3
Tweak	81.4	4.9	-7.0
MSA	65.3	-11.2	-23.1

Note. Abbreviations: NA, not applicable; PSAP, personal sound amplification product; HA, hearing aid. Adapted from "Personal Sound Amplification Products vs a conventional hearing aid for speech understanding in noise" by Reed, N. S., Betz, J., Kendig, N., Korczak, M., and Lin, F. R., 2017.

Based on this data, Reed et al. (2017) concluded that: 1) improved speech understanding occurred with use of select PSAPs; 2) the improved speech understanding individuals received with a select group of PSAPs (Cs 50+, Soundhawk and the Bean) was comparable to the aided improvement that individuals obtained with th traditional hearing aid; 3) the use of one mid-level PSAP (Tweak) resulted in very little improvement of speech understanding re the unaided score; and (4) the use of a low-end PSAP (MSA) actually degraded speech understanding. As previously mentioned, the PSAP devices employed in both Polyak (2016) and Reed et al. (2017) were fit by an audiologist in a quiet test booth environment. PSAPs, however, are typically purchased by the consumer online or in a retail store. As a result, consumers often follow the instructions provided by the manufacturers and/or use the manufacturer's cell phone

applications that accompany some of the high-end PSAPs to make additional adjustments to the devices.

Recently, Oliver (2017) conducted a study to investigate the influence, if any, of the type of fitting protocol on participant's performance with PSAPs. Oliver (207) utilized the two top performing PSAPs from the Polyak (2016) and Reed et al. (2017) studies, which were the SoundHawk and CS-50+ devices. Oliver (2017) utilized three fitting strategies: "out-of-the-box" self-fit, "advanced-user" self-fit, and the "gold standard" audiologist fit. The "out-of-the-box" self-fit consisted of each participant fitting the PSAP by following the manufacturer's instructions. For the "advanced-user" self-fit, participants further adjusted the PSAP using the manufacturer's cell-phone app. Lastly, audiologist fit, also known as the "gold-standard" fitting protocol, consisted of an audiologist fitting the device to NAL-NL2 prescriptive targets.

Nine individuals, ages 51 to 82 years, with slight to moderate sensorineural hearing loss participated in the study. Similar to the methods of Polyak (2016), EAA, REMs, and the AzBio test were the objective measures used to evaluate the PSAPs. EAA was performed before each test session to ensure proper functioning of the devices. REMs were performed on each PSAP for each fitting strategy. Measurements were taken using an average speech level (65 dB SPL) and NAL-NL2 prescriptive targets. Results of REMs revealed that both PSAPs met NAL targets best at 500 Hz (~83%) and worst at 4000 Hz (~28%). Results revealed that the ability of the devices to meet NAL targets did not vary substantially across the three fitting strategies. The gold-standard fitting strategy yielded the best results, with 69% and 64% of targets met for the CS-50+ and the Soundhawk devices, respectively. The poorest results with the CS-50+ device were seen

for the out-of-the-box self-fit strategy, with ~53% of targets met. However, the poorest results with the Soundhawk were seen for the advances-user self-fit strategy, with ~58% of targets met.

Lastly, aided versus unaided AzBio difference scores were examined for each fitting strategy. Results revealed the greatest improvement in aided versus unaided AzBio scores occurred with the gold-standard fitting strategy, followed by the advanced-user self-fit strategy, for both PSAP devices. The poorest improvement scores for both PSAP devices occurred with the out-of-the-box self-fit strategy.

Overall, the results of these studies suggest that high-end PSAPs, such as the CS-50+ and Soundhawk, can perform similarly to traditional hearing aids, with the best performance resulting from a gold-standard (audiologist-fit) fitting strategy. One possible limitation of these current studies is that they have been conducted in a quiet, test booth environment. It may be that any substantial difference between traditional hearing aids and PSAPs may come to light in more adverse listening environments. Therefore, the goal of this study was to evaluate high-end PSAP devices in a common adverse listening environment, which often degrades speech intelligibility. This adverse listening environment is reverberation.

Reverberation

Audiometric testing typically takes place in a sound-proof booth, which is an ideal listening environment. However, typical listening environments involve all sorts of background noise, as well as other adverse listening conditions, making it difficult for the listener to hear the original speech signal. The current study focused on the effects of reverberation on speech intelligibility as assessed by the AzBio test and the CRM test.

Definition. Reverberation occurs when sound reflects off of walls and other surfaces, causing the listener to hear delayed versions of the original signal (Dillon, 2012). Reverberation consists of both early and late reflections. Early reflections generally enhance the audibility and intelligibility of the original signal, as they arrive at the listener's ear not long after the original signal (Boothroyd, 2004). Late reflections, however, are considered to be equivalent to noise, because they arrive too late after the original signal and reduce intelligibility (Boothroyd, 2004).

Reverberation Time. Reverberant sound will decrease after the sound source ceases until it becomes inaudible. The reverberation time (RT) is the point at which it reduces by 60 dB (Boothroyd, 2004). Reverberation time has a proportional relationship to effective signal-to-noise ratio (Boothroyd, 2004). This relationship is shown graphically in Figure 10, where it is assumed that a 15 dB SNR is needed for complete audibility of the speech signal. As can be seen, this 15 dB SNR criterion is only met for RTs less than 0.2 seconds.
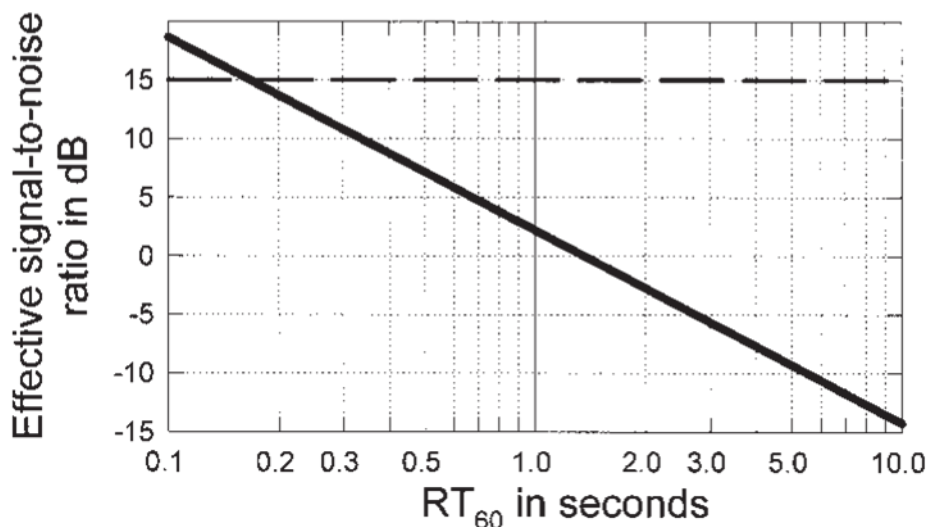
Figure 9. Estimated effective signal-to-noise ratio as a function of reverberation time. Adapted from "Room acoustics and speech perception" by Boothrooyd, A., 2004, *Seminars in Hearing*, *25*(2), 155-166.

Reverberation time in a large, reflective room, such as a gymnasium, can reach 2 to 3 seconds. In contrast, small classrooms contain absorbent surfaces and can have RTs as low as 0.3 or 0.4 seconds (Boothroyd, 2004). A typical room RT would be 0.75 seconds. Therefore, this reverberation time was employed in the current study.

Distance. Listeners close to the original sound source will receive a direct signal that is louder than the reverberant sound. However, listeners further from the sound source will receive reverberant signals at a louder level than the direct signal. The distance at which the direct sound and reverberant sound are equal in level is called the critical distance (Boothroyd, 2004). An example of an average speech level as a function of distance can be seen in Figure 11. This example displays a small room with a relatively short reverberation time and a critical distance of 6 ft. Most of the listeners in this example receive a combination of direct and reverberant signals, however, the listeners in the last three rows are only hearing the reverberant speech. While this figure shows that many listeners receive an increased speech level from the addition of reverberation, this does not equate to an increase in intelligibility (Boothroyd, 2004).
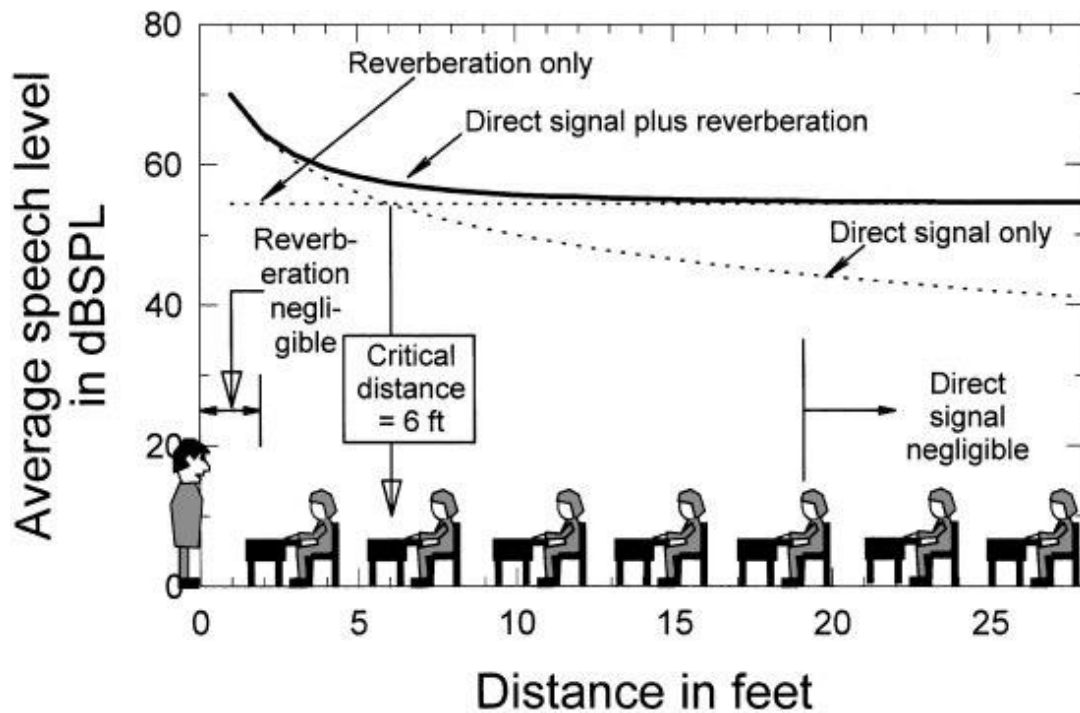
Figure 10. Estimated speech level as a function of distance in a 30 x 20 x 9 ft room with a 0.5 reverberation time. Adapted from "Room acoustics and speech perception" by Boothrooyd, A., 2004, *Seminars in Hearing*, *25*(2), 155-166.

Speech Intelligibility. It is well known that long reverberation times result in poor speech intelligibility. Helfer and Wilber (1990) conducted a study to investigate the effect of reverberation on speech perception. The researchers studied the perception of nonsense syllables in four groups of subjects: younger (≤35 years of age) and older (>60 years of age) listeners with mild-to-moderate sensorineural hearing loss, normal hearing individuals and adults with minimal hearing loss. They used four reverberation times (0.0, 0.6, 0.9, 1.3 seconds) and cafeteria noise at a +10 dB SNR. Results suggested that both age and degree of hearing loss negatively affect the ability to understand noisy, reverberant speech.

Additionally, speech intelligibility will typically decrease as the reverberation time increases. Reinhart and Souza (2016) evaluated speech intelligibility and working

memory in 30 individuals with mild to moderate sensorineural hearing loss. They split

the participants in to two groups based on their working memory (high working memory

and low working memory). Both groups repeated back low-context sentences in the

presence of various reverberation times and their intelligibility (% correct) was calculated

for each reverberant condition. Researchers then calculated the percent reduction in

intelligibility by comparing the participants' intelligibility with reverberation to their

intelligibility without reverberation. They found that as reverberation time increased,

reduction in intelligibility increased as well. Further, participants were performing poorer

in reverberation compared to no reverberation and their intelligibility declined further

when more reverberation was added. Figure 11 displays the percent reduction in speech

intelligibility as reverberation time increases relative to performance without
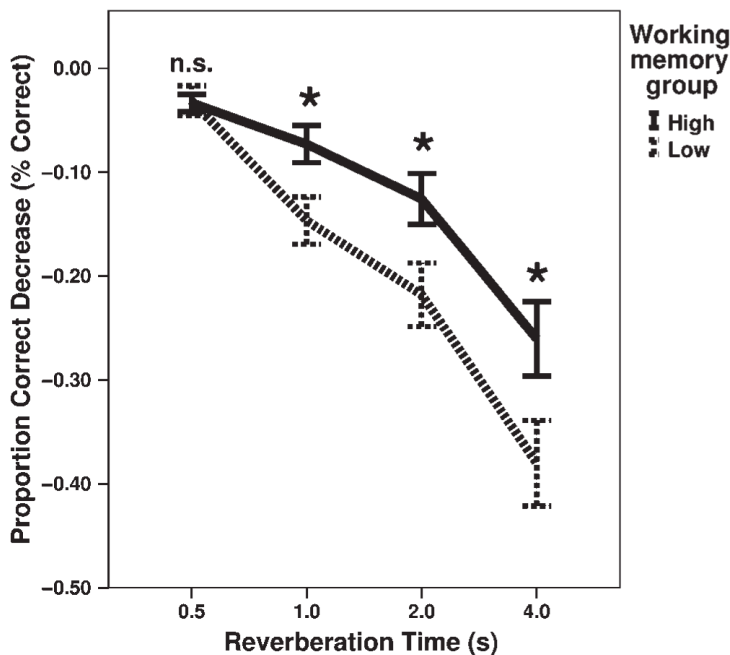
reverberation.

Figure 11. Decline in speech intelligibility as a function of reverberation time relative to
performance without reverberation. Adapted from "Intelligibility and clarity of
reverberant speech: Effects of wide dynamic range compression release time and working

memory" by Reinhart, P., & Souza, P., 2016, *Journal of Speech, Language & Hearing Research*, *59*(6), 1543-1554.

Reverberation and Hearing Loss. Even though reverberation will make it difficult for anyone to hear, it makes it especially difficult for individuals with hearing loss. In order for an individuals to achieve 50% correct speech recognition, normal hearing individuals need speech to be about 2 dB louder than background noise (IOM, 2014). In contrast, individuals with hearing loss need speech to be about 12 dB or more above background noise to meet the same criterion of 50% correct speech recognition (IOM, 2014). The intervention approach for these difficult listening environments is usually assistive listening technology, such as loop systems or FM systems, which can be combined with hearing aid technology (IOM, 2014). As previously discussed, investigating the effectiveness of amplification devices in adverse listening environments is important, as many complaints of hearing aid users are related to background noise.

Aims of the Current Study

The current study aims to investigate the effect of a typical reverberation time (0.75 seconds) on speech intelligibility in a group of hearing impaired listeners using a traditional hearing aid versus a high-end PSAP. The two speech-in-noise measures that will be evaluated in this study are the AzBio and the CRM test. The use of the AzBio will permit comparison of the hearing impaired subjects' performance in this adverse listening condition to the performance of a similar group of hearing impaired subjects in quiet test conditions in the earlier Polyak and Reed (2016) studies.

CHAPTER 3

METHODS

Participants

Thirteen individuals were recruited to participate in the current study. However, ten of those individuals did not meet the criteria to participate (PTAs < 20 dB). Therefore, only three individuals (two males and one female) met our criteria to participate in the testing. These participants were recruited from the Institute for Well-Being Audiology Clinic and the local community via flyers and word-of-mouth. Specific criteria for participation included 1) bilateral symmetrical hearing loss (500, 1000, and 2000 Hz pure tone averages of ≥20 dB and ≤55 dB), 2) hearing loss of a sensorineural nature (air-bone gaps <10 dB), 3) no evidence of hearing loss secondary to a medical condition, 4) normal immittance results (0.9 – 2.0 ml ear canal volume, 0.2 – 1.5 static admittance, and -103.5 – 4.2 daPa (Roup et al., 1998; Wiley et al., 1996)) 5) no evidence of noise-induced hearing loss, 6) no evidence of significant cognitive decline (a score of ≥25 on the Department of Veterans Affairs St. Louis University Mental Status (VA-SLUMS) examination), and 7) no experience with hearing aids > 1 month. Participants received a gift card as reimbursement for their time.

Procedures

Testing was conducted in a sound-treated booth at the Towson University Audiology Clinic. Each subject's performance with a pair of traditional hearing aids and a pair of high-end PSAPs was evaluated using EAA, REMs, and two speech-in-noise measures. The pair of traditional hearing aids and high-end PSAPs that were used in this study were the Oticon Nera2Pro Mini RITEs and the Soundworld Solutions Sidekicks,

respectively. These devices were chosen for comparability to the methods and results of Polyak (2016). Polyak (2016) compared the Oticon Nera traditional hearing aid to various PSAPs and found that participant's performance with the CS-50+ PSAP was similar to their performance with the Oticon Nera traditional hearing aid in an ideal listening environment. Although Polyak (2016) used the CS-50+ device, Soundworld Solutions has since developed a "companion hearing aid" device called the 'Sidekick'. These sidekick devices resemble hearing aids more than the CS50+ devices. Therefore, the aim of the current study was to compare performance of the Soundworld Solutions Sidekick devices to the Oticon Nera2Pro miniRITEs in the presence of reverberation.

Each participant completed one test session which lasted approximately two hours. To ensure proper functioning and fitting of these amplification devices, EAA and REMs were performed on each device using the Audioscan Verifit. Before each participant arrived to begin their test session, the following EAA measurements were conducted on each device: average OSPL90, frequency range, equivalent input noise, and total harmonic distortion Once the participant arrived, aided real-ear measurements were performed at an average speech level (65 dB SPL) to measure the output of the device in the participant's ear canal. Measurements obtained from the participant's ear canal were then compared to NAL-NL2 prescribed targets. A gold standard audiologist led fitting protocol was employed with both sets of devices in the current study. Specifically, the clinician made adjustments to the devices to meet the NAL-NL2 targets within ± 5 dB at 500, 1000, 2000, and 4000 Hz. This type of fitting protocol was employed in the current study because Oliver (2017) reported that her hearing impaired participants performed

best when the PSAPs were fit using a gold-standard audiologist led fitting protocol in comparison to two self -fitting protocols (i.e., out-of-the-box and advanced-user).

At the beginning of the test session, the following demographic data was measured for each participant: a VA-SLUMs score which was used to evaluate the participant's cognitive functioning, otoscopy, acoustic immittance testing, pure tone air conduction testing at 250 to 8000 Hz, and bone conduction testing at 500 to 4000 Hz. Next, the participants performed two speech-in-noise tasks, the AzBio and the CRM.

AzBio. The AzBio speech-in-noise sentences were administered in both unaided and aided conditions with a +5 dB SNR at 25 dB SL re: the patient's PTA at 500, 1000, and 2000 Hz. Each participant was administered the AzBio from a speaker located at 0 degrees azimuth under the following six test conditions. These conditions included:

1. Unaided condition.

2. Unaided condition with 0.75 reverberation time.

3. Aided (PSAP) condition.

4. Aided (PSAP) condition with 0.75 reverberation time.

5. Aided (HA) condition.

6. Aided (HA) condition with 0.75 reverberation time.

The sequence for testing the traditional hearing aid and the PSAP device was randomized across subjects to account for fatigue and practice effects.

Scoring the AzBio. Six lists of the AzBio test, containing 20 sentences each, were used in the current study. The AzBio test was scored by tallying the number of words in each sentence that were correctly identified by the participant. Next, a total score was calculated using the following formula: total number of words correctly

identified/total number of words present in the sentences x 100. This score was derived

for each participant with each device.

CRM. The CRM was administered at 20 dB SL re: the participant's PTA at 500,

1000, and 2000 Hz. Following EAA and REMs, the participant performed the CRM in a

sound-treated booth surrounded by an array of 16 speakers (See Figure 12).
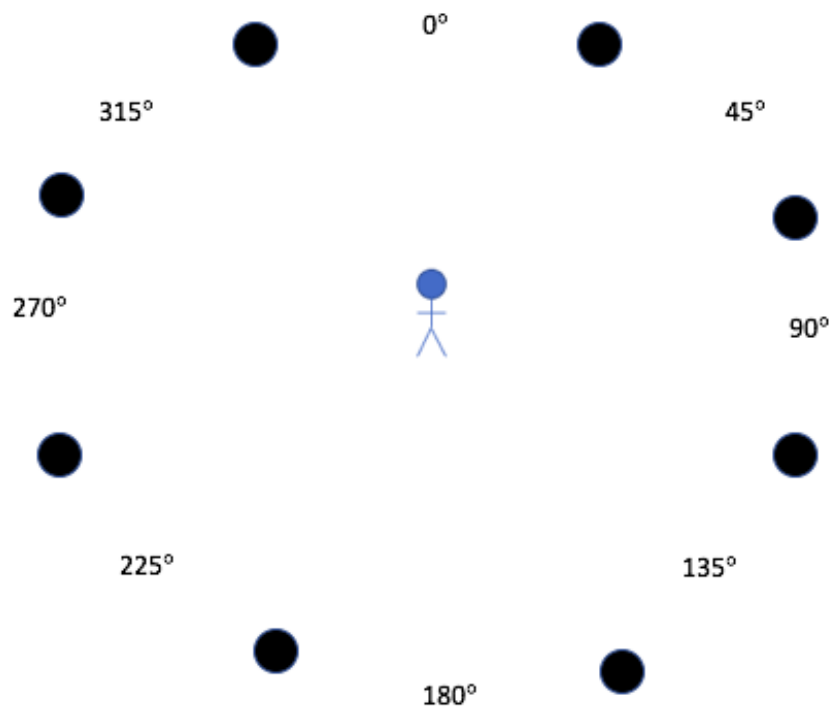
Figure 12. The 16 speaker array with each circle and number of degrees representing a speaker.

Each test condition (unaided, traditional hearing aid, and PSAP) was administered with

and without reverberation and with the target and maskers co-located and spatially

separated (SS). In the co-located condition, displayed in Figure 13, the target phrase and

masker phrases are at 0 degrees azimuth. In the spatially separated condition, displayed in

Figure 14, the target phrase is at 0 degrees azimuth and the masker phrases are at +/- 45

degrees azimuth. All 12 test conditions are summarized in Table 4. For example, in the

unaided condition, each participant performed the CRM in the spatially separated

condition with and without reverberation and then in the co-location condition with and

without reverberation. The sequence for testing the traditional hearing aid and the PSAP

device was randomized across subjects to account for fatigue and practice effects.
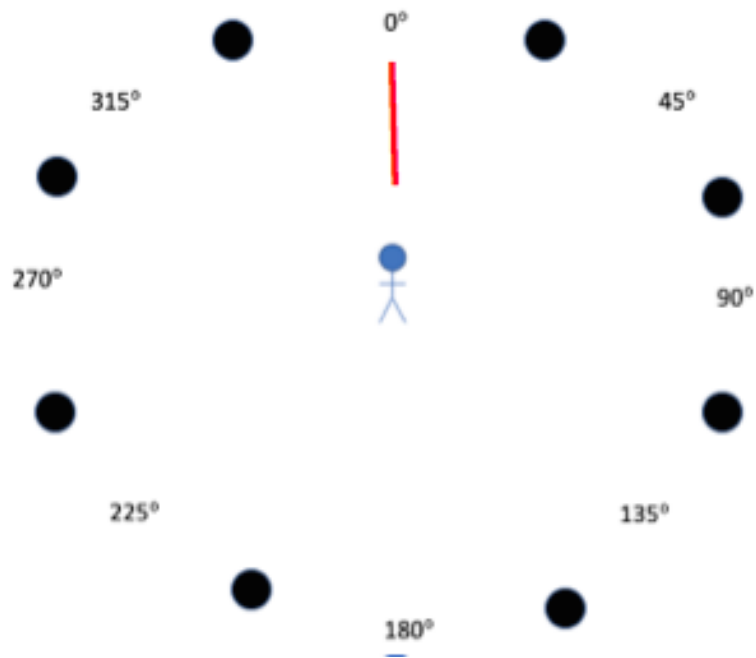
Figure 13. A diagram of the co-located condition, with target and masker phrases at 0 degrees azimuth.
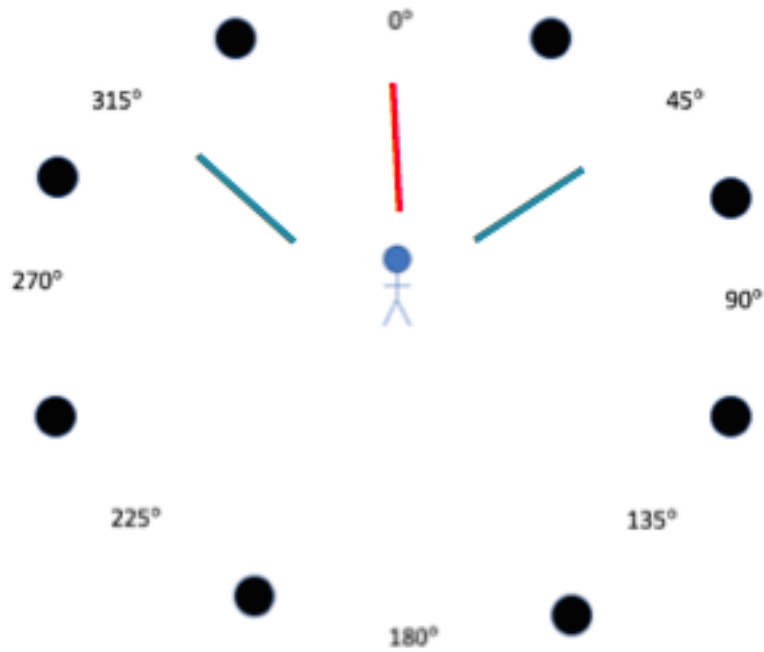
Figure 14. A diagram of the spatially separated condition, with the target phrase (red) at 0 degrees azimuth and masker phrases (blue) at 45 and 315 degrees azimuth.

Table 4

The 12 conditions under which each participant performed the CRM (SS stands for spatially separated).

Unaided				PSAP				Hearing Aid			
SS		Co-located		SS		Co-located		SS		Co-located	
Rev.	No rev.	Rev.	No rev.	Rev.	No rev.	Rev.	No rev.	Rev.	No rev.	Rev.	No rev.

The reverberant listening condition, with a reverberation time of 0.75 seconds, were

simulated using techniques described in Zahorik (2009), such that impulse responses

were calculated for each speaker, with delays and attenuations within +/- 11.25 degrees

computed using the image model.

Scoring the CRM test. For each test condition of the CRM, the participant's

target to masker ratio (TMR) identification threshold was established. This was done with

a one up, one down technique and a 5 dB step size, with the final threshold determined based on 1 dB steps. The identification threshold is an average of the last six reversals. These procedures are based on an adaptive psychometric procedure based on Levitt (1971) and this threshold procedure was automated in this study.

CHAPTER 4

RESULTS

In the results section, the behavioral pure tone findings of the three participants as well as their performance data with the Sidekick PSAPs and the Oticon Nera2 Pro HAs will be presented individually. Specifically, a behavioral profile of each participant will be reported, which will include their pure tone audiometric thresholds, tympanometric results, relevant case history information, and their VA-SLUMs score of cognitive function. Following this demographic information, the results of EAA, REMs and the speech-in-noise tasks will be reported for each participant. In the final section of the results, a comparison of these three participants' performance on REMs and the two speech-in-noise measures will be presented. Given the small number of participants, these results clearly represent a pilot study and should be interpreted with caution. These results may not be representative of the larger sample of the mild to moderate hearing impaired clinical population.

Participant 1

Participant 1, a 62 year old male, had a slight (250-1000 Hz) sloping to severe sensorineural hearing loss bilaterally, as seen in Table 5. His pure tone averages were 22 and 20 dB HL for the right and left ear, respectively. Participant 1 had type A tympanograms bilaterally and a VA-SLUMs score of 26, which is indicative of normal

cognitive function. His case history was relevant for bilateral tinnitus and a familial history of age-related hearing loss.

Table 5

Audiometric pure tone results of participant 1.

	250 Hz	500 Hz	1k Hz	2k Hz	4k Hz	8k Hz
AC- Right	20 dB HL	15 dB HL	25 dB HL	25 dB HL	40 dB HL	80 dB HL
AC- Left	15 dB HL	15 dB HL	20 dB HL	30 dB HL	60 dB HL	75 dB HL
BC	-	10 dB HL	20 dB HL	30 dB HL	55 dB HL	-

Note. AC = Air conduction, BC = Bone conduction.

EAA was conducted on each of the amplification devices prior to the test session to ensure proper functioning of the devices. As previously mentioned, the four acoustic measurements that were analyzed were average OSPL90, frequency range, EIN, and THD, as seen in Table 6. The results of the Oticon HAs can be seen in the top panel and the results of the Sidekick PSAPs are displayed in the bottom panel. This table also includes the manufacturer's specifications for each of these four acoustic features. The organization of the subsequent participants' EAA tables will follow the same pattern. As seen in Table 6, the Oticon devices, fit to both ears, were meeting specifications for average OSPL90, EIN, and THD. The frequency range for both Oticon devices, however, was not as broad as the manufacturer's specifications, especially in the low frequency region. Similarly, the Sidekick PSAPs met manufacturer's specifications for the frequency range, THD and EIN. The only exception was the EIN for the right ear, which was a little bit higher than the manufacturer's specifications.

Table 6

Electroacoustic Analysis measurements of the Oticon Nera2Pro and the Sidekick PSAP devices taken prior to the test session with participant 1 and the manufacturers' specifications for each device.

Device		Average OSPL90	Frequency Range	Equivalent Input Noise	Total Harmonic Distortion
Oticon Nera2Pro HA	*Right*	91 dB SPL	630-7100 Hz	33 dB SPL	1%
	Left	94 dB SPL	560-7100 Hz	31 dB SPL	2%
Manufacturer's Specifications		96 dB SPL	<200-8300 Hz	<34 dB SPL	<2%
Sidekick PSAP	*Right*	86 dB SPL	<200-8000 Hz	33 dB SPL	1%
	Left	91 dB SPL	<200-8000 Hz	27 dB SPL	0%
Manufacturer's Specifications		Not Available	200-8000 Hz	26 dB SPL	<2%

The audiologist programmed the Oticon HAs and the Sidekick PSAPs to meet NAL-NL2 targets at 500, 1000, 2000 and 4000 Hz as verified by REMs. The results of the REMs were analyzed to determine the accuracy with which these devices could meet the NAL targets. Meeting NAL-NL2 target was defined as being within ± 5 dB of target. The results were analyzed separately for each test frequency (500-4000 Hz). Table 7 displays the REM results for the Oticon HAs and Sidekick PSAPs for participant 1. The term 'Yes' means the NAL-NL2 target was met within ± 5 dB for that frequency. In contrast the term 'No' means the target was not met within ± 5 dB for that frequency. If a target was not met, this cell also contains an indication of how much the NAL-NL2 target was overshot or undershot. The up arrow (↑) indicates that the output from the device was above target (overshot). The down arrow (↓) indicates that the output from the device was below target (undershot). The number following the arrow indicates the actual amount in dB the device overshot or undershot the target. These results are broken down

by test frequency and also reported by total number of targets met. The same organization of the REM results will be used for all three participants.

As seen in Table 7, the Oticon HAs met NAL-NL2 targets at all test frequencies with the exception of 4000 Hz. At this frequency, the Oticon HAs undershot target by 15 and 25 dB in the right and left ear, respectively. Similarly, the Sidekick PSAPs also met targets at 500, 1000, and 2000 Hz for both ears, with the exception of 1000 Hz for the left ear where the target was overshot by 10 dB. Both Sidekick PSAPs also undershot the NAL target at 4000 Hz by 15-20 dB, which is in agreement with the performance of the Oticon devices. Lastly, the Oticon HAs did a slightly better job of meeting the total number of targets (6/8) versus the Sidekick PSAPs (5/8).

Table 7

NAL-NL2 targets met by frequency for the Oticon HAs and Sidekick PSAPs for participant 1. If NAL-NL2 targets were not met (>5 dB), then the value in dB that the target was overshot or undershot is indicated.

Device		500 Hz	1000 Hz	2000 Hz	4000 Hz	Total Targets Met
Oticon HA	Right	Yes	Yes	Yes	No ↓ 15 dB	3/4
	Left	Yes	Yes	Yes	No ↓ 25 dB	3/4
Sidekick PSAP	Right	Yes	Yes	Yes	No ↓ 15 dB	3/4
	Left	Yes	No ↑10 dB	Yes	No ↓ 20 dB	2/4
	Total Targets	4/4	3/4	4/4	0/4	11/16

Participant 1 also completed two speech-in-noise tasks, the AzBio and the CRM. The AzBio speech-in-noise task was administered in an unaided condition, an aided condition with the Sidekick PSAPs, and an aided condition with the Oticon HAs. Within

each of these three conditions, this speech in noise task was completed in a quiet (non-reverberant) environment and in a reverberant environment (0.75 reverberation time). The AzBio percent correct scores for participant 1 in each of these listening conditions are displayed in Table 8.

This participant had substantially poorer scores in the reverberant environment compared to the non-reverberant environment. This finding was true in both the unaided and aided test conditions. His reduction in performance ranged from a 66-74% decrease across test conditions. This participant scored extremely well in the unaided non-reverberant condition (95.5%), which created a ceiling effect. Therefore, there was no room for improvement in the aided condition with either amplification device.

Table 8

AzBio scores (% correct) for participant 1 in each listening condition.

Unaided		Sidekick PSAP		Oticon HA	
No Reverb	Reverb	No Reverb	Reverb	No Reverb	Reverb
95.5%	25.3%	94.9%	28.5%	92%	17.9%

The CRM speech-in-noise test was administered in 12 listening conditions. Similar to the AzBio test conditions, this participant was tested in the unaided and aided test conditions (Sidekick PSAPs and Oticon HAs). Within each of these three test conditions, the participant was tested in a spatially separated condition (SS) and a co-located (CL) condition. Lastly, the participant was tested in quiet and with a 0.75 reverberation time for each test condition. A TMR identification threshold was obtained for each test condition, with a lower identification threshold corresponding to better performance. The organization of the CRM results will be the same for the remaining participants.

59

The identification thresholds for participant 1 can be seen in Table 9. There are

three patterns, which are evident in the results of this participant's CRM test. First, this

participant consistently performed better in the spatially separated conditions compared

to the co-located conditions. This finding was true across unaided and aided conditions.

The second pattern involves the participant's performance in the reverberant and non-

reverberant conditions. This pattern was less consistent across test conditions compared

to pattern one. Participant 1 displayed better identification thresholds in the non-

reverberant environment for 50% of the test conditions (i.e. unaided spatially separated

condition and the aided Oticon test conditions) and had better identification thresholds in

the reverberant environment for the remaining 50% of the test conditions. The final

pattern of results for participant 1 was that his identification thresholds showed an overall

improvement in the aided Oticon HA conditions compared to the unaided conditions. The

identification thresholds for the aided PSAP conditions, however, did not show an overall

improvement when compared to the unaided identification thresholds.

Table 9

CRM identification thresholds (in dB) for participant 1 in each unaided and aided
listening condition (SS = spatially separated).

Unaided				Sidekick PSAP				Oticon HA			
Co-located		SS		Co-located		SS		Co-located		SS	
No rev.	Rev.	No rev.	Rev.	No rev.	Rev.	No rev.	Rev.	No Rev.	Rev.	No rev.	Rev.
7.67	4.77	-5	-2.89	7.63	5.27	-3	-3.87	1.77	3	-6.38	-4.89

Participant 2

Participant 2, a 61-year-old male, had a mild to moderate sensorineural hearing

loss bilaterally, as seen in Table 12. His pure tone averages were 27 and 32 dB HL for the

right and left ear, respectively. Participant 2 had type A tympanograms bilaterally and he received a score of 29 on the VA-SLUMS, which is indicative of normal cognitive functioning. Relevant case history includes some noise exposure (music, home lawn equipment) and a family history of hearing loss. The participant's brother was deaf in one ear from childhood.

Table 10

Audiometric results of participant 2.

	250 Hz	500 Hz	1k Hz	2k Hz	4k Hz	8k Hz
AC- Right	30 dB HL	25 dB HL	30 dB HL	30 dB HL	50 dB HL	45 dB HL
AC- Left	20 dB HL	20 dB HL	35 dB HL	40 dB HL	45 dB HL	55 dB HL
BC	-	30 dB HL	35 dB HL	40 dB HL	45 dB HL	-

Note. AC = Air conduction, BC = Bone conduction.

The results of EAA conducted prior to the test session with participant 2 are displayed in Table 11. Similar to the results with participant 1, the Oticon devices were meeting specifications for average OSPL90, EIN, and THD. However, the frequency range was not as broad in both the right and left devices. The Sidekick PSAPs met specifications for all measures with the exception of the EIN, which was slightly higher than the specifications in both the right and the left devices.

Table 11

Electroacoustic Analysis measurements of the Oticon Nera2Pro and Sidekick devices taken prior to the test session with participant 2 and the manufacturers' specification for each device.

Device		Average OSPL90	Frequency Range	Equivalent Input Noise	Total Harmonic Distortion
Oticon Nera2Pro HA	*Right*	92 dB SPL	560-7100 Hz	33 dB SPL	1%
	Left	93 dB SPL	500-6725 Hz	32 dB SPL	2%
Manufacturer's Specifications		96 dB SPL	<200-8300 Hz	<34 dB SPL	<2%
Sidekick PSAP	*Right*	83 dB SPL	<200-8000 Hz	34 dB SPL	1%
	Left	87 dB SPL	<200-8000 Hz	32 dB SPL	1%
Manufacturer's Specifications		Not Available	200-8000 Hz	26 dB SPL	<2%

Results of REMs on participant 2 can be seen in Table 12. The Oticon HAs met NAL-NL2 targets except at 1000 Hz and 4000 Hz in the left ear. At these test frequencies, the HAs undershot target by 10 and 20 dB, respectively. The Sidekick PSAPs undershot target at 4000 Hz and overshot target at 2000 Hz by 10-15 dB in both ears. The Oticon hearing aids met more total targets (6/8) compared to the Sidekick PSAPs (4/8), which is in agreement with the results of participant 1.

Table 12

NAL-NL2 targets met and overshoot and undershoot values for participant 2 with the Oticon HAs and Sidekick PSAPs.

Device		500 Hz	1000 Hz	2000 Hz	4000 Hz	Total Targets Met
Oticon HA	Right	Yes	Yes	Yes	Yes	4/4
	Left	Yes	No ↓ 10 dB	Yes	No ↓ 20 dB	2/4
Sidekick PSAP	Right	Yes	Yes	No ↑10 dB	No ↓ 10 dB	2/4
	Left	Yes	Yes	No ↑15 dB	No ↓ 15 dB	2/4
	Total Targets	4/4	3/4	2/4	1/4	10/16

Table 13 displays the percent correct scores that participant 2 scored in each listening condition on the AzBio. This participant consistently preformed substantially worse in the reverberant conditions compared to the non-reverberant condition, which is consistent with the performance of participant 1. The decrease in his performance ranged from ~56-71% across test conditions. Participant 2 also showed a ceiling effect, scoring 97% in the unaided condition without reverberation. Thus limiting any comparison between the unaided and aided test conditions.

Table 13

AzBio scores (% correct) for participant 2 in each listening condition.

Unaided		Sidekick PSAP		Oticon HA	
No Reverb	Reverb	No Reverb	Reverb	No Reverb	Reverb
97%	26%	99.3%	36.9%	100%	44.1%

The identification thresholds for participant 2 can be seen in Table 14. Three similar patterns that were seen in participant 1's results were evident with participant 2 as well. Frist, participant 2 consistently performed better in the spatially separated

conditions compared to the co-located conditions. This was true for both unaided and aided conditions. Secondly, this participant's performance in reverberant and non-reverberant conditions was less consistent, with some better identification thresholds in the reverberant condition and some in the non-reverberant condition. Specifically, he performed better in the non-reverberant conditions for 50% of the test conditions (both the spatially separated condition and the co-located condition for the Sidekick PSAPs and the spatially separated condition for the Oticon HAs). In the remaining 50% of test conditions, he performed better in the reverberant condition. Thirdly, in general, his identification thresholds improved in the aided Oticon HA conditions when compared to the unaided conditions. The only exception to this pattern was the reverberant co-located condition. In contrast, his aided performance with the PSAP device was less consistent. Specifically, he performed poorer in the unaided conditions versus the Sidekick PSAP conditions in the reverberant environment, with just the opposite pattern occurring in the reverberant conditions.

Table 14

CRM identification ratio thresholds (in dB) for participant 2 in each listening condition (SS = spatially separated).

Unaided				Sidekick PSAP				Oticon HA			
Co-located		SS		Co-located		SS		Co-located		SS	
No rev.	Rev.	No rev.	Rev.	No rev.	Rev.	No rev.	Rev.	No Rev.	Rev.	No rev.	Rev.
5.54	1.63	4.6	0	3.85	5.64	2.2	2.45	3.86	3.09	-3.44	-1.43

Participant 3

Participant 3, a 67-year-old female, had a moderately-severe rising to mild sensorineural hearing loss, as seen in Table 15. Her pure tone averages were 45 and 42

dB HL for the right and left ear respectively. Her case history was relevant for family

history of hearing loss, including her mother and sister. Participant 3 had type A

tympanograms bilaterally and achieved a VA-SLUMs score of 29, which is indicative of

normal cognitive functioning.

Table 15

Audiometric results of participant 3.

	250 Hz	500 Hz	1k Hz	2k Hz	4k Hz	8k Hz
AC- Right	45 dB HL	50 dB HL	45 dB HL	40 dB HL	45 dB HL	20 dB HL
AC- Left	55 dB HL	60 dB HL	40 dB HL	25 dB HL	35 dB HL	20 dB HL
BC	-	55 dB HL	40 dB HL	40 dB HL	35 dB HL	-

Note. AC = Air conduction, BC = Bone conduction.

Results of EAA prior to the test session with participant 3 can be seen in Table

16. The devices met manufacturer's specifications for each of the acoustic parameters.

The exceptions to this were the frequency range of both Oticon HAs, which was not as

broad as manufacturer's specifications, and the EIN of the both PSAPs, which was

slightly higher than specifications. These results are consistent with the EAA results of

the previous two participants. Additionally, the distortion of the left Oticon HA was 1%

higher than manufacturer's specification.

Table 16

Electroacoustic Analysis measurements of the Oticon and Sidekick devices taken prior to the test session with participant 3 and the manufacturers' specification for each device.

Device		Average OSPL90	Frequency Range	Equivalent Input Noise	Total Harmonic Distortion
Oticon Nera2Pro HA	*Right*	97 dB SPL	420-5600 Hz	27 dB SPL	1%
	Left	93 dB SPL	300-5600 Hz	31 dB SPL	3%
Manufacturer's Specifications		96 dB SPL	<200-8300 Hz	<34 dB SPL	<2%
Sidekick PSAP	*Right*	90 dB SPL	<200-8000 Hz	35 dB SPL	1%
	Left	89 dB SPL	<200-8000 Hz	36 dB SPL	1%
Manufacturer's Specifications		Not Available	200-8000 Hz	26 dB SPL	<2%

Results of REMs on participant 3 can be seen in Table 17. Both the Oticon HAs and Sidekick PSAPs had trouble meeting NAL-NL2 targets, undershooting at every frequency except 2000 Hz. These undershots ranged from 10-15 dB across frequencies. During the fitting, the audiologist attempted to turn up the volume on both sets of devices in order to better meet NAL-NL2 targets, however, the participant reported the signal was getting uncomfortably loud. As a result, only 25% (4/16) of the total NAL-NL2 targets were met for participant 3.

Table 17

NAL-NL2 targets met and overshoot and undershoot values for participant 3 with the Oticon HAs and Sidekick PSAPs.

Device		500 Hz	1000 Hz	2000 Hz	4000 Hz	Total Targets Met
Oticon HA	Right	No ↓ 10 dB	No ↓ 15 dB	Yes	No ↓ 10 dB	1/4
Oticon HA	Left	No ↓ 15 dB	No ↓ 10 dB	Yes	No ↓ 15 dB	1/4
Sidekick PSAP	Right	No ↓ 10 dB	No ↓ 10 dB	Yes	No ↓ 15 dB	1/4
Sidekick PSAP	Left	No ↓ 15 dB	No ↓ 10 dB	Yes	No ↓ 15 dB	1/4
	Total Targets	0/4	0/4	4/4	0/4	4/16

Results of participant 3's AzBio scores can be seen in Table 18. She performed substantially better without reverberation compared to with reverberation. This was true in both unaided and aided conditions and is consistent with the performance of the previous two participants. Her performance reduction ranged from ~59-77% across test conditions. Similar to participant 1 and 2, a ceiling effect occurred. Participant 3's performance was so good in the unaided condition (96.9%) that it prevented an opportunity to see any improvement in the aided conditions.

Table 18

AzBio scores (% correct) for participant 3 in each listening condition.

Unaided		Sidekick PSAP		Oticon HA	
No Reverb	Reverb	No Reverb	Reverb	No Reverb	Reverb
96.9%	37.7%	90.5%	22.8%	96.3%	19.3%

Participant 3's identification thresholds on the CRM test can be seen in Table 19. The same three patterns from participant 1 and 2 were analyzed. Participant 3 performed better in the spatially separated conditions in comparison to the co-located conditions. This finding was true for the unaided and test conditions and is consistent with the performance of participant 1 and 2. The only exception to this was participant 3 performed better in the co-located condition while wearing the Oticon HAs in the non-reverberant condition. Secondly, participant 3 performed better in the unaided non-reverberant condition when compared to the unaided reverberant condition. However, the opposite was true for the aided conditions, that is, she performed better in the reverberant versus non-reverberant conditions with the Oticon HAs and Sidekick PSAPs. Thirdly, participant 3 had a better unaided TMR threshold (0.71) compared to her aided identification thresholds (1.0 and 4.36 for the PSAP and Oticon HA conditions, respectively) in the non-reverberant environment. In contrast, the opposite pattern was true for the reverberant environment, in which her identification thresholds were better with the PSAPs and Oticon HAs versus her thresholds in the unaided conditions.

The three patterns in participant 3's CRM data were not as consistent with the performance of participant 1 and 2. This may be due to the inability of the audiologist to turn up the devices to meet NAL-NL2 targets. As such, the CRM results for this participant should be interpreted with caution.

Table 19

CRM identification thresholds (in dB) for participant 3 in each listening condition (SS = spatially separated).

Unaided				Sidekick PSAP				Oticon HA			
Co-located		SS		Co-located		SS		Co-located		SS	
No rev.	Rev.	No rev.	Rev.	No rev.	Rev.	No rev.	Rev.	No Rev.	Rev.	No rev.	Rev.
2.31	5.75	0.71	3.25	6.29	4.08	1.0	-0.56	3.63	2.33	4.36	0.82

Comparison of REM and Speech-in-Noise Data Across the Three Participants.

REM Results

The REM results of the three participants were compared in Table 20. As can be seen, the greatest number of NAL-NL2 targets were met at 2000 Hz (10/12) followed by 500 Hz (8/12) and 1000 Hz (6/12). The least number of targets were met at 4000 Hz (1/12). Overall, the Oticon HAs did a better job of meeting NAL-NL2 targets, as they met 58.3% (14/24) of targets, compared to the Sidekick PSAPs, which met 45.8% (11/24) of the targets.

Table 20

Number of NAL-NL2 targets met as a function of frequency across the three participants. The total number of NAL targets met by each device is also indicated.

Device		500 Hz	1000 Hz	2000 Hz	4000 Hz	Total Targets Met
Oticon HA	**Right**	2/3	2/3	3/3	1/3	8/12
	Left	2/3	1/3	3/3	0/3	6/12
Sidekick PSAP	**Right**	2/3	2/3	2/3	0/3	6/12
	Left	2/3	1/3	2/3	0/3	5/12
	Total Targets	8/12	6/12	10/12	1/12	25/48

AzBio Scores

It was evident that each of the participants performed substantially worse on the AzBio test when a 0.75 second reverberation time was introduced compared to their performance in the non-reverberant conditions. Therefore, a percentage of reduction in AzBio performance from the non-reverberant environment to the reverberant environment was calculated for each participant. This calculation was performed by subtracting the reverberant score from the non-reverberant score. The percent reduction was calculated separately for the unaided condition as well as the two aided conditions. The percent reduction in AzBio performance from the non-reverberant environment to the reverberant environment for each participant can be seen in Table 21. These three participants had similar reductions in performance across the unaided and aided conditions. The mean percent reduction scores ranged from ~65%-69% across test conditions.

Table 21

AzBio % decrease in performance from the non-reverberant condition to the reverberant condition.

	Unaided	Sidekick PSAP	Oticon HA
Participant 1	70.2%	66.4%	74.1%
Participant 2	71%	62.4%	55.9%
Participant 3	59.2%	67.7%	77%
Average	66.8%	65.5%	69%

CRM Identification Thresholds

There were three patterns evident in the CRM data, which have previously been discussed for each participant individually. Those three patterns will now be summarized across participants. First, all three participant's performed better in the spatially separated condition versus the co-located condition as shown by the lower identification thresholds. In order to investigate this further, each participant's identification thresholds with and without reverberation were averaged. This calculation was made separately for the spatially separated condition and for the co-located condition. Then mean identification thresholds were calculated for the SS and CL test conditions in the unaided and two aided conditions. This information can be seen in Table 22. The mean identification thresholds for the three test conditions (unaided, Sidekick PSAPs and Oticon HAs) are also displayed graphically in Figure 15, with spatially separated mean identification thresholds in blue and co-located mean identification thresholds in green.

Table 22.

Average identification thresholds (in dB) for spatially separated and co-located conditions and the mean TMRs across participants.

	Unaided		Sidekick PSAP		Oticon HA	
	Co-located	**SS**	**Co-located**	**SS**	**Co-located**	**SS**
Participant 1	6.22	-3.95	6.45	-3.44	2.39	-5.64
Participant 2	3.59	2.30	4.75	2.33	3.48	-2.44
Participant 3	4.03	1.98	5.19	0.22	2.98	2.59
Mean	**4.61**	**0.11**	**5.46**	**-0.30**	**2.95**	**-1.83**
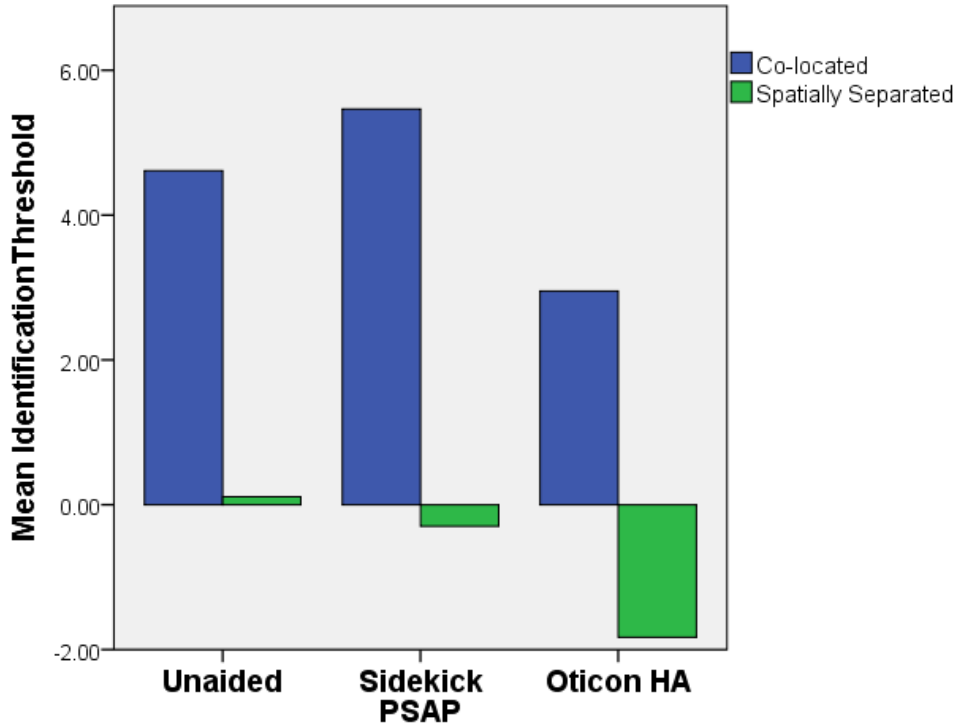
Figure 15. Mean identification thresholds (in dB) across unaided and aided conditions with spatially separated thresholds in blue and co-located thresholds in green.

In order to examine the participants' CRM data further, each participant's identification thresholds as well as the mean thresholds across participants are displayed in Table 23. The means are then displayed graphically in Figure 16. In this figure, the unaided condition thresholds are displayed first, followed by the Sidekick PSAPs and the Oticon HAs. The spatially separated condition is displayed in green. Specifically, the non-reverberant condition is in dark green and the reverberant condition is in light green. The co-located condition is displayed in blue. Specifically, the non-reverberant environment is in dark blue and the reverberant environment is in light blue. See Figure 17 for a color-coordinated key of this graph.

The first pattern to be explored in this table is non-reverberant versus reverberant scores. According to the means, participants performed better in the reverberant

72

environment compared to the non-reverberant environment. This was true for the unaided

and two aided conditions. However, when looking at the scores individually, participants

performed better in the reverberant condition about 50% of the time. Therefore, the other

50% of the time they performed better in the non-reverberant condition. Next, unaided

scores were compared to aided scores. When looking at the means, participants

performed better in the aided Sidekick PSAP condition versus the unaided condition in

2/4 scenarios (50%). On the other hand, participants performed better with the Oticon HA

versus unaided conditions in 4/4 of the scenarios (100%).

Table 23

Coordinate Response Measure identification thresholds for each participant. Mean TMR thresholds for the 12 conditions are also displayed.

	Unaided				Sidekick PSAP				Oticon HA			
	SS		Co-located		SS		Co-located		SS		Co-located	
	No rev.	Rev.	No rev.	Rev.	No rev.	Rev.	No rev.	Rev.	No Rev.	Rev.	No rev.	Rev.
Participant 1	-5	-2.89	7.67	4.77	-3	-3.87	7.63	5.27	-6.38	-4.89	1.77	3
Participant 2	4.6	0	5.54	1.63	2.2	2.45	3.85	5.64	-3.44	-1.43	3.86	3.09
Participant 3	0.71	3.25	2.31	5.75	1.0	-0.56	6.29	4.08	4.36	0.82	3.63	2.33
Mean	**0.10**	**-1.81**	**5.17**	**4.05**	**0.07**	**-1.98**	**5.92**	**4.99**	**-1.82**	**-1.83**	**3.09**	**2.81**
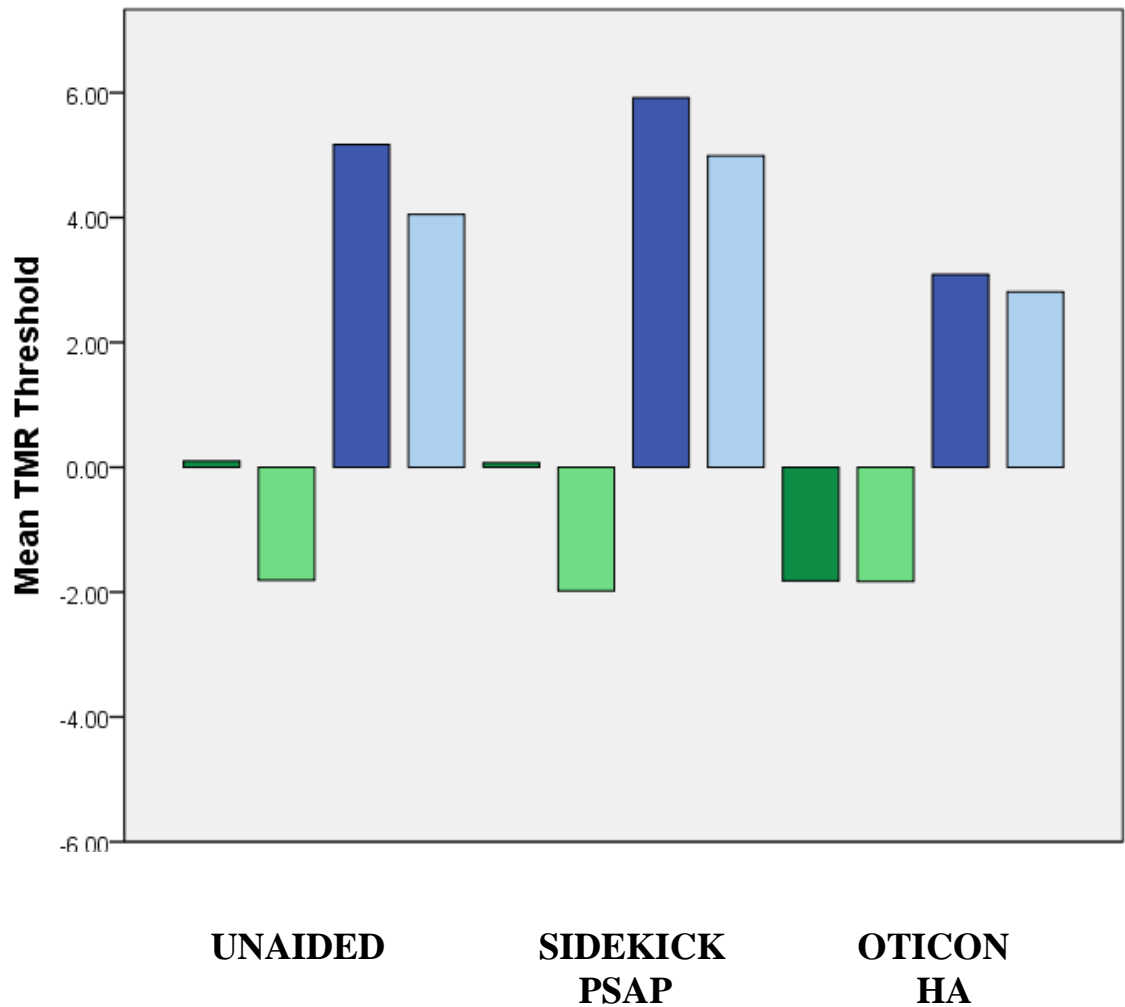
Figure 16. Mean TMR thresholds across the 12 listening conditions. Unaided conditions are displayed first, followed by the Sidekick PSAPs and the Oticon HAs (See Figure 17 for the color coordinated key).

Key

■ (dark green)	= Spatially separated: no reverberation
■ (light green)	= Spatially separated: 0.75 reverberation time
■ (dark blue)	= Co-located: no reverberation
■ (light blue)	= Co-located: 0.75 reverberation time

Figure 17. Key for the bar graph in Figure 15.

CHAPTER 5

DISCUSSION

In the discussion section, the results of this study will be compared to those of other relevant literature on the performance of PSAPs compared to traditional hearing aids. This comparison will follow the same organization used throughout the results section. As such, EAA and REMs will be discussed first, followed by the two speech-in-noise measures. These comparisons will be followed by a discussion of the limitations of the current study and directions for further research.
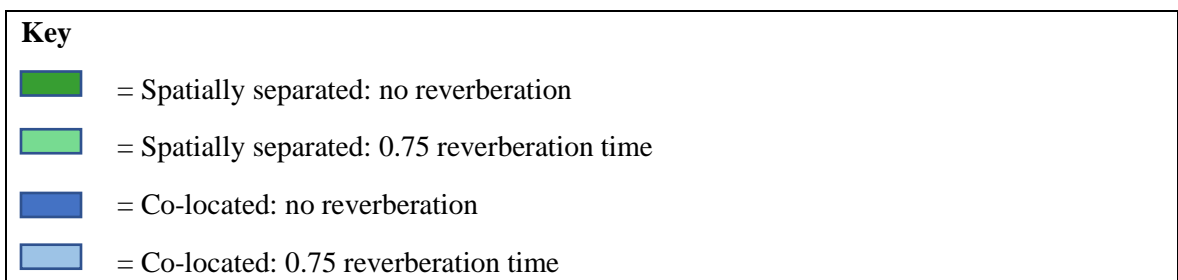
EAA

Overall, the EAA results in the current study revealed that both the Oticon HAs and the Sidekick PSAPs met manufacturer's specifications relatively well. The only exceptions to this were that the frequency range of the Oticon HAs was not quite as broad as the manufacturer's specification and the EIN of the Sidekick PSAPs was a little bit higher than manufacturer's specification. These findings are consistent with the EAA results of Polyak (2016) and Oliver (2017), who also reported slightly high EIN values for the CS-50 PSAP, which is manufactured by the same company as the Sidekick PSAP.

REMs

Results of REMs in the current study revealed that both the Oticon HAs and Sidekick PSAPs met NAL-NL2 targets the best at 2000 Hz. However, both sets of devices frequently undershot target at 4000 Hz. The results of the Polyak (2016) and Oliver (2017) studies also revealed that an Oticon HA and the CS-50 PSAP had the most difficulty meeting NAl-NL2 target at 4000 Hz compared to the other test frequencies. In the current study, the Oticon HAs did a better job of meeting NAL-NL2 targets (~58%)

compared to the Sidekick PSAPs (~45%). This finding is consistent with the results of Polyak (2016), who also found that the traditional Oticon HA met more total targets (~90%) compared to the CS-50 PSAP (~60%).

AzBio Speech-in-Noise Test

In the current study, the AzBio test was administered in a quiet environment as well as in a reverberant environment. Results revealed that participant's performance on the AzBio was substantially reduced when a 0.75 second reverberation time was introduced. This finding is consistent with research suggesting that reverberation negatively impacts speech intelligibility (Helfer & Wilber, 1990; Reinhart & Souza, 2016). However, when Reinhart and Souza (2016) presented low-context sentences to 30 individuals with mild to moderate hearing loss, they only found about a 10-15% overall reduction in speech intelligibility from the non-reverberant environment to the environment with a one second reverberation time. In the current study, the average reduction in performance was substantially higher, with the percent reduction in performance ranging from ~65-69%.

In the current study, the participants' unaided AzBio performance revealed a ceiling effect for all three participants. The participant's unaided scores ranged from 95.5% to 97%. The participants performed so well in the unaided condition that there was no room to see improvement in the aided conditions. Polyak (2016) also reported that a ceiling effect occurred in her pilot data when she presented the AzBio test to her hearing impaired participants at 50 dB HL. In order to address this effect, Polyak (2016) chose to administer the AzBio test at 30 dB HL for participants with mild sensorineural hearing losses and at 50 dB HL for participants with moderate sensorineural losses. In the current

study, the AzBio speech stimuli were presented at a +5 dB SNR at 25 dB SL re the participants' PTA at 500, 1000 and 2000 Hz. This SL approach resulted in a possible limitation in this current study as two out of the three participants presented with normal or near normal air conduction thresholds at 500 and 1000 Hz. This good sensitivity at these frequencies likely contributed to their excellent performance in the unaided test condition. This issue is discussed in further detail in future directions section.

CRM Test

In the current study, there were three patterns of findings evident in the CRM results. The first pattern was that all the participants had lower TRM thresholds in the spatially separated condition compared to the co-located condition, indicating better performance in the former. This pattern of findings is consistent with the literature that suggests speech intelligibility on the CRM test improves when the target and masker sentences are spatially separated versus co-located (Best, Gallun, Ihlefeld, & Shinn-Cunningham, 2006; Srinivasan, Jakien, & Gallun, 2016). Best et al. (2006) suggested that speech intelligibility improved in eight normal hearing listeners when the CRM target was spatially separated from the masker versus co-located. Results of Srinivasan et al. (2016) also supported this finding with both normal and hearing impaired participants. Srinivasan et al. (2016) also suggested participants with hearing loss required a greater amount of spatial separation of the target and masker sentences in order to achieve similar speech intelligibility to their normal hearing peers.

The second pattern consisted of the participants' performance in the non-reverberant environment versus the reverberant environment. This pattern was not consistent, with participant's performing better in the non-reverberant condition about

half of the time and performing better in the reverberant condition the other half of the time. This was true across the unaided and aided test conditions. This is not consistent with the literature, as the Helfer & Wilber (1990) and Reinhart & Souza (2016) studies discussed previously demonstrated that speech intelligibility is consistently poorer in a reverberant environment compared to a non-reverberant environment. Our unexpected finding in the current study may partly be due to the third participant, who was not able to meet NAL-NL2 targets with either device, as the loudness was becoming uncomfortable for her. Part of the inconsistency may also be due to participant fatigue and lack of concentration, especially since the CRM test was administered toward the end of the two-hour session with each participant.

The last pattern indicated that as expected the participants had lower TMR thresholds or better performance in the vast majority (6/8) of the aided conditions versus the unaided conditions. The only exception to this was for the co-located condition with the Sidekick PSAPs, where the opposite pattern was true. The results of the CRM test cannot be directly compared to Polyak (2016) and Oliver (2017), because they did not use the CRM test in their studies. However, both studies reported improved performance on speech-in-noise tasks in aided versus unaided conditions. This is consistent with our findings with the CRM test, with the exception of the Sidekick PSAPs in the co-located condition. The performance with the Sidekick device may be inconsistent with past studies due to the small number of participants in the current study. As discussed previously, the third participant's inability to hit NAL targets or participant fatigue could also have contributed to the inconsistent findings.

Limitations

There were a few limitations to this study, including the small number of participants and the ceiling effect observed in the results of the speech-in-noise tests. The first limitation, small sample size, was due to difficulty in recruiting individuals with mild to moderate sensorineural hearing loss who had little to no experience with hearing aids. Recruitment relied heavily on word of mouth and although 13 participants were tested, only three qualified to participate. With only three participants, very little analysis could be done and few conclusions drawn from the data presented. Therefore, the results current pilot study may not be generalized to the larger mild to moderate hearing impaired population and must be interpreted with caution. The other limitation of this study was the ceiling effect that occurred in the unaided AzBio speech-in-noise test. This may have occurred because of the 20 dB SL re: participant's PTA (500, 1000, & 2000 Hz) presentation level approach. Different approaches will be discussed in the following section on future directions for research.

Future Directions

Due to the small number of participants in this pilot study, it is recommended that a follow up study be conducted with a larger number of hearing-impaired participants. This would allow for more analysis and interpretation of the results. However, future studies investigating the performance of high-end PSAPs versus traditional hearing aids may need to consider different recruitment techniques and presentation levels for speech-in-noise tests. These ideas are described further below.

Recruitment Techniques. Future studies in need of hearing impaired participants with little to no hearing aid experience could utilize better recruitment techniques than

79

those used in this study. The two suggestions for better recruitment that will be discussed in this section are to keep a database of hearing impaired participants who are willing to participate in future PSAP studies and to perform hearing screenings at local senior centers.

One suggestion for better recruitment is to keep a database of hearing impaired individuals who have participated in past studies. In order to keep a database, individuals who participate would need to give the researchers permission to be contacted about future studies. This would hopefully reduce some of the time and effort involved in recruitment and increase the number of participants for future studies. Since some of the faculty involved in these projects work across two sites, Towson University and Johns Hopkins University, it would be helpful to keep a combined database.

Additionally, it is recommended that future student researchers consider performing hearing screenings at a local senior center or assisted living facility and recruit those hearing impaired individuals who do not pass a hearing screening. If this recruitment technique is used, it may be necessary to apply for funding to transport the participants to Towson University for additional diagnostic testing. It may also be of interest to contact the PSAP company (Soundworld Solutions) to see if they would be willing to give participants a discount on the device. This would provide those individuals who do not pass the screening an incentive to participate in the study, because they not only would get to try out the device during testing, but they would be able to purchase the device at a discounted rate if they so desired.

Presentation Level of Speech-in-Noise Tasks. Due to the ceiling effect that was evident in the current study, future studies utilizing speech-in-noise tasks to evaluate the

performance of PSAPs and traditional hearing aids may consider using a different presentation level approach. Further, rather than administering speech-in-noise tasks at 20 dB SL re: PTA at 500, 1000, and 2000 Hz, it may be beneficial to use a sensation level approach at the frequencies that the individual has hearing loss. For example, the participants in this study had near normal hearing at 500 and 1000 Hz. However, they more commonly presented with a greater amount of hearing loss at 2000 and 4000 Hz. Therefore, a high-frequency PTA or a PTA at the frequencies that the participant has hearing loss may help to avoid a ceiling effect. Another approach would be to adjust the presentation level based on the participant's degree of hearing loss. For example, a lower presentation would be used for an individual with mild hearing loss, while a higher presentation level would be used for an individual with a moderate hearing loss, similar to the approach employed by Polyak (2016).

APPENDIX A:

Informed Consent Form

<u>Purpose of the Study:</u>

      The Towson University Audiology Department is conducting a research study to examine the potential benefits of personal sound amplification products (PSAPs) that can be purchased online or over-the-counter by individuals with mild to moderate sensorineural (inner ear) hearing loss. PSAPs are considerably less expensive than traditional hearing aids and may be beneficial for hearing impaired individuals with this degree of hearing loss. However, currently there is little empirical research regarding the benefit of the PSAPs in adverse listening environments, such as background noise and/or reverberation. The goal of this study is to compare participant's aided performance with pair of high end PSAP fit to each ear to their performance with a pair of traditional digital hearing aids. The aided benefit the participant's receive from amplification with each of these devices will be assessed using two speech-in-noise tests and real ear measurements.

<u>Criteria for Participation</u>: Participants must be 40-80 years old (males or female) with mild to moderate sensorineural (inner ear) hearing loss and no or minimal use of hearing aids (less than one month).

<u>Procedures:</u>

Participants in this study will attend two 2-hour test sessions at the Towson University Department of Audiology in Van Bokkelen Hall. The first session will begin with questions regarding your hearing and a traditional hearing test. During the remainder of the test session, we will ask you to wear a pair of PSAPs and a pair of traditional hearing aids as we obtain real-ear measures and perform speech-in-noise testing. Real-ear measurement is a standard audiologic procedure in which a small flexible probe tube is placed in your ear to measure sound. During the first speech-in-noise test you will be asked to repeat sentences that are played from an audio recording with background noise. During the second speech-in-noise test you will be asked to listen for a target phrase in the presence of masker phrases, all played from an audio recording. You will then be asked to select the color and number corresponding to the target phrase on a computer screen.

<u>Risks/Discomfort:</u>

There are no known risks associated with participation in this study. Should any discomfort occur, your participation will be terminated immediately.

Benefits:
It is hoped the results of this study will provide insight into how these PSAP devices perform in adverse listening environments and secondly how their performance compares to traditional digital hearing aids.

Alternatives to Participation:
Participation in this study is voluntary. Any questions that you may have may be asked freely at any time and will be answered to the best of my ability. You are free to withdraw from this study at any time and this decision will in no way affect any future services you may receive from the Towson University Hearing and Balance Clinic nor will there be any other consequences.

Compensation: You will be given $30 for your participation and completion of this study. If your hearing loss does not meet our inclusion criteria you will be compensated $5.00 for coming in to have your hearing evaluated.

Confidentiality:
All data collected in the study will be kept confidential. If any data collected in this study is presented at a future conference or is published, your identity will remain confidential.

If you have any questions at any time feel free to contact myself, Christina Downs, at cdowns4@students.towson.edu or 301-712-7822; Dr. Korczak (faculty sponsor) at pkorczak@towson.edu or 410-704-5903; or Dr. Elizabeth Katz, Chairperson of the Institutional Review Board for the Protection of Human Participants at Towson University at irb@towson.edu or 410-704-2236.

I, _____, affirm that I have read and

understood the above statement and have had all of my questions answered.

Signature: _____Date: _____

Witness: _____ Date: _____

APPENDIX B:

IRB APPROVAL

Office of Sponsored
Programs and Research

Towson University
8000 York Road
Towson, MD 21252-0001

t. 410 704-2236
f. 410 704-4494

APPROVAL NUMBER 1712026808

MEMORANDUM

TO: Christina Downs

FROM: Institutional Review Board for the Protection of Human
Participants, Elizabeth Katz, Chair

DATE: December 14th, 2017

RE: Approval of Research Involving the Use of Human Participants

Thank you for submitting an Application for Approval of Research Involving
the Use of Human Participants to the Institutional Review Board for the
Protection of Human Participants (IRB) at Towson University. The IRB hereby
approves your proposal titled:

***Objective Comparative Analysis of Personal Sound Amplification Products
(PSAPs) in the Presence of Reverberation***

Please note that this approval is granted on the condition that you provide the
IRB with the following information and/or documentation:

N/A

If you should encounter any new risks, reactions, or injuries while conducting
your research, please notify the IRB. Should your research extend beyond one
year in duration, or should there be substantive changes in your research
protocol, you will need to submit another application for approval at that time.

We wish you every success in your research project. If you have any questions,
please call me at (410) 704-2236.

cc: Peggy Korczak

Date: December 14th, 2017

NOTICE OF APPROVAL

TO: Christina Downs   ***DEPT:*** Audiology

PROJECT TITLE: Objective Comparative Analysis of Personal Sound Amplification Products (PSAPs) in the Presence of Reverberation

SPONSORING AGENCY: N/A

APPROVAL NUMBER: 1712026808

The Institutional Review Board for the Protection of Human Participants has approved the project described above. Approval was based on the descriptive material and procedures you submitted for review. Should any changes be made in your procedures, or if you should encounter any new risks, reactions, injuries, or deaths of persons as participants, you should notify the Board.

A consent form   ☑ is required of each participant
                        ☐ is not

Assent   ☐ is required of each participant
                        ☑ is not

This protocol was first approved on __12/14/2017__.
This research will be reviewed ***every year*** from the date of first approval.

Elizabeth Katz, Chair
Towson University Institutional Review Board, IRB

85

References

Abrams, H. (2017). Audiologists: Respond to disruption with best practices. American Speech-Language-Hearing-Association. Retrieved from http://www.asha.org/Articles/Audiologists-Respond-to-Disruption-With-Best-Practices/

Abrams, H. B. & Kihm, J. (2015). An introduction to MarkeTrak IX: A new baseline for the hearing aid market. *The Hearing Review, 22*(6).

Agrawal, Y., Platz, E. A., & Niparko, J. K. (2008) Prevalence of hearing loss and differences by demographic characteristics among US adults. *Archives of Internal Medicine, 168*(14). 1522-1530. doi:10.1001/archinte.168.14.1522

Alzheimer's Association (2017). Retrieved from: http://www.alz.org/what-is-dementia.asp

American Speech-Language-Hearing Association (n.d.). Overview of hearing aids. Retrieved from http://www.asha.org/public/hearing/Hearing-Aids-Overview/

Audioscan (2015). Test box measures – setup. *Verifit User's Guide Version 4.4*. Retrieved from https://www.manualslib.com/manual/1234038/Audioscan-Verifit.html?page=104#manual

Bean. (n.d.). *Technical Specs*. Retrieved from http://www.etymotic.com/consumer/personal-sound-amplifiers/bean-qsa.html

Beck, D. L., & Nilsson, M. (2013). Speech-in-noise testing: A pragmatic addendum to hearing aid fittings. *Hearing Review*, *20*(5), 24-26.

Best, V., Gallun, F. J., Ihlefeld, A., & Shinn-Cunningham, B. G. (2006). The influence of spatial separation on divided listening. *Journal of the Acoustical Society of America*, *120*(3), 1506-1516. doi:10.1121/1.2234849

Bolia, R., Nelson, W., Ericson, M., & Simpson, B. (2000). A speech corpus for multitalker communications research. *Journal of the Acoustical Society of America*, *107*(2), 1065-1066. doi:10.1121/1.428288

Boothroyd, A. (2004). Room acoustics and speech perception. *Seminars in Hearing*, *25*(2), 155-166.

Brungart, D. S. (2001). Evaluation of speech intelligibility with the coordinate response measure. *Journal of the Acoustical Society of America*, *109*, 2276-2279. doi:10.1121/1.1357812

Brungart, D., Ericson, M., Scott, K., & Simpson, B. (2001). Informational and energetic masking effects in the perception of multiple simultaneous talkers. *Journal of the Acoustical Society of America*, *110*(5), 2527-2538. doi:10.1121/1.1408946—

Callaway, S., & Punch, J. (2008). An electroacoustic analysis of over-the-counter hearing aids. *American Journal of Audiology*, *17*(1), 14-24.

Cassel, C., & Penhoet, E. (2015). PCAST recommends changes to promote innovation in hearing technologies. Retrieved from https://obamawhitehouse.archives.gov/blog/2015/10/26/%E2%80%8Bpcast-recommends-changes-promote-innovation-hearing-technologies

Chan, Z. Y. T., & McPherson, B. (2015). Over-the-counter hearing aids: A lost decade for change. *BioMed Research International*.

Cheng, C. M., & McPherson, B. (2000). Over-the-counter hearing aids: Electroacoustic

　　characteristics and possible target client groups. *Audiology: Journal of Auditory*

　　Communication, *39*(2), 110.

Chia, E., Wang, J., Rochtchina, E., Cumming, R., Newall, P., & Mitchell, P. (2007).

　　Hearing impairment and health-related quality of life: the Blue Mountains

　　Hearing Study. *Ear & Hearing*, *28*(2), 187-195.

Chien, W., & Lin, F. (2012). Prevalence of hearing aid use among older adults in the

　　United States. *Archives of Internal Medicine*, *172*(3), 292-293.

　　doi:10.1001/archinternmed.2011.1408

Dillon, H. (2012). *Hearing aids*. New York, NY: Thieme Publishers.

Donahue, A., Dubno, J. R., & Beck, L. (2010). Accessible and affordable hearing health

　　care for adults with mild to moderate hearing loss. *Ear and hearing*, *31*(1), 2-6.

　　doi: 10.1097/AUD.0b013e3181cbc783

Fagan, J. J., & Jacobs, M. (2009). Survey of ENT services in Africa: Need for a

　　comprehensive intervention. *Global Health Action*, *2*(1), 1932-1939.

　　doi:10.3402/gha.v2i0.1932

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-mental state": A practical

　　method for grading the cognitive state of patients for the clinician. *Journal of*

　　Psychiatric Research, *12*(3), 189-198.

Food and Drug Administration (2016). Hearing aids. Retrieved from

　　http://www.fda.gov/MedicalDevices/ProductsandMedicalProcedures/HomeHealth

　　andConsumer/ConsumerProducts/HearingAids/default.htm

Gallacher, J., Ilubaera, V., Ben-Shlomo, Y., Bayer, A., Fish, M., Babisch, W., & Elwood,

P. (2012). Auditory threshold, phonologic demand, and incident dementia. *Neurology*, *79*(15), 1583-1590.

Gifford, R. H., Dorman, M. F., McKarns, S. A., & Spahr, A. J. (2007). Combined electric and contralateral acoustic hearing: Word and sentence recognition with bimodal hearing. *Journal of Speech, Language, and Hearing Research, 50*(4), 835-843.

Gopinath, G., Gourinchas, P., Hsieh, C., & Li, N. (2011). International prices, costs, and markup differences. *The American Economic Review*, *101*(6). 2450-2486.

Gopinath, B., L. Hickson, J. Schneider, C. M. McMahon, G. Burlutsky, S. R. Leeder, and P.Mitchell. (2012). Hearing-impaired adults are at increased risk of experiencing emotional distress and social engagement restrictions five years later. *Age and Ageing, 41*(5), 618–623.

Gosselin, P. A., & Gagné, J. (2011). Older adults expend more listening effort than young adults recognizing speech in noise. *Journal of Speech, Language & Hearing Research*, *54*(3), 944-958. doi:10.1044/1092-4388(2010/10-0069)

Goulios, H., & Patuzzi, R. (2008). Audiology education and practice from an international perspective. *International Journal of Audiology*, *47*(10), 647-664. doi:10.1080/14992020802203322

Hansen, M. R., Gantz, B. J., & Dunn, C. (2013). Outcomes following cochlear implantation for patients with single-sided deafness, including those with recalcitrant Ménière's disease. *Otology & neurotology: official publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology*, *34*(9).

Hearing Health and Technology Matters (2017). US senate passes OTC hearing aid

legislation. Retrieved from

http://hearinghealthmatters.org/hearingnewswatch/2017/senate-passes-over-

counter-hearing-aid-act

2017/?utm_source=newsletter&utm_medium=email&utm_campaign=otc

Helfer, K. S., & Wilber, L. A. (1990). Hearing loss, aging, and speech perception in

reverberation and noise. *Journal of Speech, Language, and Hearing Research

(JSLHR)*, *33*(1), 149-158.

Institute of Medicine. (2014). Hearing loss and healthy aging; workshop summary.

Retrieved from http://iom.nationalacademies.org/Reports/2014/Hearing-Loss-and-

Healthy-Aging.aspx

Kamil, R. J., Betz, J., Powers, B. B., Pratt, S., Kritchevsky, S., Ayonayon, H. N., & ...

Lin, F. R. (2016). Association of hearing impairment with incident frailty and

falls in older adults. *Journal of Aging and Health*, *28*(4), 644-660.

doi:10.1177/0898264315608730

Kidd Jr., G., Mason, C. R., & Gallun, F. J. (2005). Combining energetic and

informational masking for speech identification. *Journal of the Acoustical Society

of America*, *118*(2), 982-992. doi:10.1121/1.1953167

Killion, M. C., & Niquette, P. A. (2000). What can the pure-tone audiogram tell us about

a patient's SNR loss?. *The Hearing Journal*, *53*(3), 46-48.

Kochkin, S. (2007). MarkeTrak VII: Obstacles to adult non-user adoption of hearing aids.

Hearing Journal, *60*(4), 24-51.

Kochkin, S. (2009). MarkeTrak VIII: 25-year trends in the hearing health market.

Hearing Review, 16(11), 12-31.

Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *The Journal of the Acoustical Society of America*, *49*(2), 467-477.

Lin, F. (2016). Hearing loss in older adults: A public health perspective [PowerPoint Slides].

Lin, F. R., Ferrucci, L., An, Y., Goh, J. O., Doshi, J., Metter, E. J., ... & Resnick, S. M. (2014). Association of hearing impairment with brain volume changes in older adults. *Neuroimage*, *90*, 84-92.

Lin, F. R., Metter, E. J., O'Brien, R. J., Resnick, S. M., Zonderman, A. B., & Ferrucci, L. (2011). Hearing loss and incident dementia. *Archives of Neurology*, *68*(2), 214-220. doi:10.1001/archneurol.2010.362.

Lin, F. R., Yaffe, K., Xia, J., Xue, Q. L., Harris, T. B., Purchase-Helzner, E., ... & Health ABC Study Group. (2013). Hearing loss and cognitive decline in older adults. *JAMA Internal Medicine*, *173*(4), 293-299.

Lopez, D., McCaul, K. A., Hankey, G. J., Norman, P. E., Almeida, O. P., Dobson, A. J., & ... Flicker, L. (2011). Falls, injuries from falls, health related quality of life and mortality in older adults with vision and hearing impairment—is there a gender difference?. *Maturitas*, *69*(4), 359-364. doi:10.1016/j.maturitas.2011.05.006

MacDonald, M. (2011). *The association between degree of hearing loss and depression in older adults* (Doctoral dissertation, University of British Columbia). Retrieved from

https://circle.ubc.ca/bitstream/id/123306/ubc_2011_fall_macdonald_mary.pdf

Margolis, R., & Morgan, D. (2008). Automated pure-tone audiometry: An analysis of capacity, need, and benefit. *American Journal of Audiology*, *17*(2), 109-113.

McPherson, B., & Wong, E. T. L. (2005). Effectiveness of an affordable hearing aid with elderly persons. *Disability & Rehabilitation*, *27*(11), 601-609.

Moore, T. (1981). Voice communication jamming research. *Advisory Group for Aerospace Research and Development Conference Proceedings*, 311, 1-7.

Mueller, H. G. (2014). *20Q: Real-ear probe-microphone measures - 30 years of progress?* Retrieved from http://www.audiologyonline.com/articles/20q-probe-mic-measures-12410

National Institute on Deafness and Other Communication Disorders (NIDCD) (2016). Hearing loss and older adults. Retrieved from https://www.nidcd.nih.gov/health/hearing-loss-older-adults

Office of Science and Technology Policy (2011). About PCAST. Retrieved from https://obamawhitehouse.archives.gov/administration/eop/ostp/pcast/about

Oliver, A. (2017). *Objective comparative analysis of self-fit personal sound amplification products (PSAPs) using three types of fitting protocols: out-of-the-box self-fit, advanced-user self-fit, and audiologist fit.* (Unpublished doctoral thesis). Towson University, Maryland.

Peelle, J. E., Troiani, V., Grossman, M., & Wingfield, A. (2011). Hearing loss in older adults affects neural systems supporting speech comprehension. *The Journal of Neuroscience*, *31*(35), 12638-12643.

Phonak (n.d.) Phonak Audeo Q: Product information. Retrieved from https://www.phonakpro.com/content/dam/phonak/gc_hq/b2b/en/products/hearing

  instruments/product_families/audeo_q/_documents/Product_Information_Audeo
_Q_027-0109.pdf

Polyak, N. (2016). *Objective and subjective comparative analysis of personal sound amplification products (PSAPs) and a hearing aid*. (Unpublished doctoral thesis). Towson University, Maryland.

Pronk, M., Deeg, D. H., & Kramer, S. E. (2013). Hearing status in older persons: A significant determinant of depression and loneliness? Results from the longitudinal aging study Amsterdam. *American Journal of Audiology*, *22*(2), 316-320. doi:1059-0889(2013/12-0069)

Reed, N. S., Betz, J., Kendig, N., Korczak, M., & Lin, F. R. (2017). Personal sound amplification products vs a conventional hearing aid for speech understanding in noise. *Journal of the American Medical Association, 318*(1), 89-90.

Reinhart, P. N., & Souza, P. E. (2016). Intelligibility and clarity of reverberant speech: Effects of wide dynamic range compression release time and working memory. *Journal of Speech, Language & Hearing Research*, *59*(6), 1543-1554. doi:10.1044/2016_JSLHR-H-15-0371

Ross, M. (2015). The "stigma" of hearing loss and hearing aids. *Hearing Loss Magazine*, *36*(4), 28-30.

Roup, C., Wiley, T., Safady, S., & Stoppenbach, D. (1998). Tympanometric screening norms for adults. *American Journal of Audiology*, *7*(2), 55-60.

Saito, H., Nishiwaki, Y., Michikawa, T., Kikuchi, Y., Mizutari, K., Takebayashi, T., & Ogawa, K. (2010). Hearing handicap predicts the development of depressive

symptoms after 3 years in older community-dwelling Japanese. *Journal of the American Geriatrics Society*, *58*(1), 93-97.

Semeraro, H. D., Rowan, D., van Besouw, R. M., & Allsopp, A. A. (2017). Development and evaluation of the British English coordinate response measure speech-in-noise test as an occupational hearing assessment tool. *International Journal of Audiology*, *56*(10), 749-758. doi:10.1080/14992027.2017.1317370

Schafer, E. C., Pogue, J., and Milrany, T. (2012). List equivalency of the AzBio sentence test in noise for listeners with normal-hearing sensitivity or cochlear implants. *Journal of the American Academy of Audiology, 23*(7), 501-509.

Soundworld solutions. (n.d.). *CS50+ Specifications.* Retrieved from http://www.soundworldsolutions.com/personal-sound-amplifiers-psa/cs50/specifications

Spahr, A. J., Dorman, M. F, Litvak, L. M., Van Wie, S., Gifford, R. H., Loizou, P. C., . . . Cook, S. (2012). Development and validation of the AzBio sentence lists. *Ear and Hearing, 33*(1), 112-117. doi: 10.1097/AUD.0b013e31822c2549.

Smith, C., Wilber, L., & Cavitt, K. (2016). PSAPs vs hearing aids: An electroacoustic analysis of performance and fitting capabilities. Retrieved from http://www.hearingreview.com/2016/06/psaps-vs-hearing-aids-electroacoustic-analysis-performance-fitting-capabilities/

Srinivasan, N. K., Jakien, K. M., & Gallun, F. J. (2016). Release from masking for small spatial separations: Effects of age and hearing loss. *Journal of the Acoustical Society of America*, *140*(1), EL73-EL77. doi:10.1121/1.4954386

Swanepoel, D., Hall Iii, J., Clark, J., Koekemoer, D., Krumm, M., Ferrari, D., & ...

94

Barajas, J. (2010). Telehealth in audiology: The need and potential to reach underserved communities. *International Journal of Audiology*, *49*(3), 195-202. doi:10.3109/14992020903470783

Viljanen, A., Kaprio, J., Pyykkö, I., Sorri, M., Pajala, S., Kauppinen, M., & ... Rantanen, T. (2009). Hearing as a predictor of falls and postural balance in older female twins. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, *64*(2), 312-317. doi:10.1093/gerona/gln015

Wechsler, D. (1997). WAIS-III: Wechsler adult intelligence scale. San Antonio: Psychological Corporation.

Wiley, T. L., Cruickshanks, K. J., Nondahl, D. M., Tweed, T. S., Klein, R., & Klein, B. E. (1996). Tympanometric measures in older adults. *Journal of the American Academy of Audiology*, *7*(4), 260-268.

World Health Organization. (2017). Deafness and hearing loss. Retrieved from http://www.who.int/mediacentre/factsheets/fs300/en/

World Wide Hearing. (n.d.). Hearing loss facts. Retrieved from http://www.wwhearing.org/

Zahorik, P. (2009). Perceptually relevant parameters for virtual listening simulation of small room acoustics. *The Journal of the Acoustical Society of America*, *126*(2), 776-791. doi:10.1121/1.3167842

CURRICULUM VITA

Christina Downs, B.S.

██████████████████████

████████████████████████████

Education:

Doctor of Audiology, Towson University	May 2019

Bachelor of Science, Towson University
Major: Speech Language Pathology/Audiology   May 2015

Clinical Experience:

Healthy Hearing and Balance	Spring 2018
Lincoln Intermediate Unit	Fall 2017
ENTAA Care	Summer 2017
Live Better Hearing	Spring 2017
Towson University Hearing and Balance Center	Spring 2016 – Fall 2016

Professional Affiliations:

Member, Student Academy of Audiology	2015-Present