8-6-2021

Stereo hearing with unilateral bone conduction amplification

Megan Crouse

Recommended Citation

Crouse, Megan, "Stereo hearing with unilateral bone conduction amplification" (2021). *Dissertations, 2020-current*. 45.
https://commons.lib.jmu.edu/diss202029/45

Stereo Hearing with Unilateral Bone Conduction Amplification

Megan Crouse

A dissertation submitted to the Graduate Faculty of
JAMES MADISON UNIVERSITY
In
Partial Fulfillment of the Requirements
For the degree of
Doctor of Audiology

Department of Communication Sciences and Disorders

August 2021

FACULTY COMMITTEE

Committee Chair: Lincoln Gray, Ph.D

Committee Members/ Readers:

Bradley Kesser, M.D.

Jaime Lee, Ph.D.

Yingjiu Nie, Ph.D.

Acknowledgements

Thank you to my research committee, Dr. Lincoln Gray, Dr. Bradley Kesser, Dr. Jaimie Lee, and Dr. Yingjiu Nie. I know that this has been a very unconventional process- trying to complete a dissertation amidst a global pandemic. You each handled the constant rescheduling and project adaptations with grace and patience. I am immensely grateful for the time, knowledge, and understanding that you have shared with me. Special thanks to Dr. Casazza, who finished our multi-subject data collection after I had to move away for my fourth-year placement. Without your help, half of this dissertation would not exist. Working with such a diverse group of incredibly intelligent professionals has been an absolute honor.

To the wonderful research participants and their families, thank you so much for offering your time to help us progress our fields. It is my hope that the information we have learned from these studies will serve as a benefit for not only the professionals in our fields, but for the patients who trust us to do our utmost for them. When it comes down to it, the most important part of this research is always the patients.

Dr. Gray, the mentorship and support you have shown throughout my graduate career has had a profound impact on me. Despite all the curveballs thrown our way, you always found another pathway through, and I could not have possibly asked for a greater advisor. The way you stay true to your passions and always have kindness for those around you (including the trees at the National Park!) is something I will aspire to every day.

To my friends, family, and loved ones- you already know that I could not have made it this far without the overwhelming love and support you’ve given. These past

years have been unparalleled in sheer number of tragic events. Even through my worst days and constant stress venting, you have stood by me with nothing but your full confidence in my abilities. Allie, words could not do justice to how much you have helped me this past year. You gave me the strength to keep writing even when I was worried my health was failing me. You loved me through it all and I will love you through whatever may come in your own new graduate journey. Always.

None are more deserving of praise than my parents, Marc and Cheryl. Thank you for reminding me not to sweat the little stuff (“and everything is little stuff”) and to go watch The Last Lecture when I need to put life back into perspective. I am immeasurably blessed to have this true and loving support system. Love is always the most important.

Finally, to Pap Pap, whose greatest wish for me was that I achieve my academic dreams. We did it, Pap. I hope to make you proud- not from the piece of paper that I earn, but though utilizing my education to help others. You and Grandma taught me the importance of following your dreams, without any excuses. I am forever grateful.

Thank you all.

Table of Contents

List of Figures

Abstract

Conductive hearing loss results when the neural integrity of the auditory system is healthy, but sound is prevented from reaching the cochlea in its entirety. Unilateral Congenital Aural Atresia (UCAA) is a birth defect in which there is no external ear canal, resulting in the reduction of sound able to reach the middle ear. Two primary options for correcting this conductive hearing loss are canalplasty or a bone anchored hearing device (BAHD). We want to compare the benefit level from these options, specifically in two conditions: sound localization and the ability to detect speech from one ear while there is competing background noise presented to the other ear. While canalplasty has been well studied, there is little research available on whether a unilateral bone conduction implant will provide any benefit in these binaural tasks. The purpose of this study is to determine the effect BAHD use has on localization and speech in noise understanding, so that audiologists and ENTs can advise patients of their treatment options. A stereo computer and semi-circular speaker setup was used to determine sound-localization accuracy of the participants by having them select which speaker they thought the signal noise was being presented from. Performance was quantified through percent correct and root mean squared of error in degrees azimuth. Speech in noise understanding was assessed through four different test conditions in which the participant chose the color and number spoken by a randomized recording, while competing noise played from the opposite hemifield. Data were analyzed in terms of signal-to-noise ratio. Two separate studies were designed for this dissertation. In the single-subject design, one participant had asymmetrical conductive hearing loss and took both tests twice a day, alternating BAHD use daily, for a total of six days. In the multi-subject design, six patients with UCAA each took both tests while unaided, and then again with their BAHD activated. Results showed that while BAHD use does not produce significant benefits in localization or speech in noise comprehension for all users, the unaided thresholds for asymmetry of hearing and air-bone gaps (ABGs) are predictive of whether an individual will benefit from implantation or not in these tasks. More specifically, if pre-implantation thresholds are poor (~>44dB), then activation of the BAHD improves these two aspects of binaural processing; conversely, with relatively minor asymmetry BAHD activation makes binaural processing worse.

I. Introduction

There are several benefits to binaural listening, with two main advantages being the ability to localize sound and the increased ability to detect speech amidst competing background noise. Binaural sound cues are of utmost importance for localizing or determining the location of a sound source in space. With the head shadow effect, the body acts as a physical barrier that creates two different spectral signals at each ear. Interaural time differences (ITDs) are the minimum detectable difference between time(s) of sound arrival to two ears. These are mainly produced when the longer wavelengths of low frequency sounds take longer to reach the ear more distal to the sound source. High frequencies have shorter wavelengths that bounce across the folds of the ear more easily, and so they are less likely to produce ITDs. However, the head shadow effect does create significant interaural level differences (ILDs) as the skull is a physical barrier that attenuates the intensity of high frequency sounds across the head. Low frequencies bend around the head more easily and are not as subject to head shadow. Utilizing both ITDs and ILDs, the auditory neurons of the brainstem can assimilate data from both ears, analyze it centrally, and depict an approximation of where the signal is coming from on the horizontal plane.

While it is true that a completely unilateral listener may detect and understand speech amidst background noise to some degree, this ability is greatly improved with the joint auditory processing of binaural hearing. Binaural squelch is a neural process in which the signal to noise ratio (SNR) is increased when the signal and noise arrive to the two ears with different ITDs. By comparing the differences between the competing signals, two separate auditory objects are formed, and the brain can focus on the desired object (speech) while directing attention away from the noise (Avant et al., 2015). With monaural or diotic listening, speech and noise are simultaneously analyzed as only one auditory object, and there aren’t two separate signals to create any ITDs, ILDs, or other spectral differences. Losing this binaural effect results in either a significant directional advantage or handicap, depending on which ear is closer to the signal. If the speech is closer to the better hearing ear and the noise is presented to the opposite side, then there will be a decrease (improvement) in SNR. Conversely, if the noise is closest to the listening ear and the speech is coming from the opposite side, then there will be an increase in SNR as the noise will mask the speech. Thus, when a listener has asymmetric binaural hearing, the SNR is lowest when the speech is presented toward the better ear.

Unilateral Congenital Aural Atresia (UCAA) is a birth defect in which there is no external ear canal, resulting in a reduction of sound reaching the cochlea. Those with UCAA may have up to a maximum conductive hearing loss as a result. It has been long established that children with sensorineural hearing loss are more likely to repeat a grade and have academic difficulties (Culbertson & Gilbert, 1986). Research by Kesser et al. in 2013 found that children with unilateral conductive loss secondary to UCAA are also susceptible to academic struggles, though they are less likely to have to repeat a grade. Almost all of these children, however, did require some form of academic assistance, including hearing aids, frequency modulated systems, individual education plans, and speech therapy. No parent or health care professional wants to see a child struggle in school, and so it is important that we know the best treatment options for these children. Two prominent options for correcting this hearing loss are reconstructive canalplasty or a bone anchored hearing device (BAHD).

Surgical repair is commonly considered the gold standard for UCAA treatment. In opening a new ear canal, this procedure generally restores conductive hearing lost secondary to the UCAA. Over time, the benefits are maintained as research shows "atresiaplasty surgery in individuals with congenital aural atresia can yield reliable, lasting hearing results with a low incidence of complications" (Cruz, 2003). Surgical repair of atretic ears has a statistically significant likelihood of improving each of interaural temporal difference limens, alternate and simultaneous loudness balances, sound localization, binaural detection thresholds, and speech perception in noise postoperatively (Wilmington et al., 1994). As a direct immediate result from this physical change in structure of the auditory pathway, canalplasty patients gain functional head shadow effect and improved speech-in-noise hearing. However, this is a purely physical change. Improvement from central neural processing is dependent on the plasticity of the brain, and therefore on the age of the patient. Specifically, "[an average] of 2dB of binaural gain is lost for each decade that surgery is delayed, and zero (or poorer) binaural benefit is predicted after 38 years of age. Older adults do more poorly, possibly secondary to their long period of auditory deprivation" (Gray et al., 2009). Research by Breier et al. in 1997 likewise suggest the presence of this critical period for surgical correction of atresia before puberty for maximum benefit. Overall, canalplasty is a reliable and effective treatment for UCAA, but it is imperative to consider patient age as well as invasiveness of the surgical procedure when evaluating whether surgical reconstruction or implantation of a BAHD would be most beneficial for an individual patient. However, data on BAHD performance with restoring binaural processing is limited and controversial.

Implanting a BAHD (surgically attaching a magnet, oscillator, or both to the temporal bone, depending on the BAHD type) does still share the common risks of any surgical procedure involving anesthesia, though in general a BAHD surgery is less invasive than canalplasty. While reconstructive surgery allows the patient to maintain two separate and functional ears, BAHDs transduce sound to not only the atretic ear, but to both cochleas by mechanism of bone conduction. Thus, the ITDs and ILDs between ears are theoretically reduced upon BAHD activation, and this may interfere with the abilities to localize sound and understand speech amidst background noise. Some studies show that BAHD use may still provide the wearer with improved sound localization (Asp & Reinfeldt, 2018). However, the advantage was mostly seen in those with bilateral implantation, a result found in other studies as well (Bosman, 2001; Gawliczek, 2018). Other studies have researched individuals who use BAHDs as a contralateral rerouting system (CRoS) for unilateral deafness. Wazen 2005 and Hol 2005 found that this population had poor sound localization, no better than chance, that did not improve with use of a BAHD. Within pediatrics, the most common indicator for need of a BAHD is having UCAA, and BAHDs have the highest satisfaction rate with this specific population (Lustig et al., 2001). While this data may be highly variable in resulting statistics, Hagr’s research in 2007 also revealed that the unaided baseline pure tone average (PTA) of bone conduction thresholds may be a predictor of improvement with BAHDs. However, not much research is available on the specifics of how BAHD use may impact localization and speech understanding in noise accuracy for those with unilateral or asymmetric conductive hearing loss, such as those with UCAA.

This dissertation consists of two separate studies designed to assess the benefit of BAHDs for those with asymmetric or unilateral conductive hearing loss. The purpose of these studies is the same- to determine the effect that a bone anchored hearing device has on both sound localization ability and speech reception amidst competing noise. This information is paramount when an atretic patient is choosing between a BAHD or canaloplasty as medical treatments for hearing loss. ENTs and Audiologists need to know what option would be most beneficial for their patients so they can advise them to the best of their ability. We suspect that, for atretic patients, a BAHD will be inferior to unaided listening in sound localization and speech in noise tasks and thus inferior to a successful canalplasty surgery.

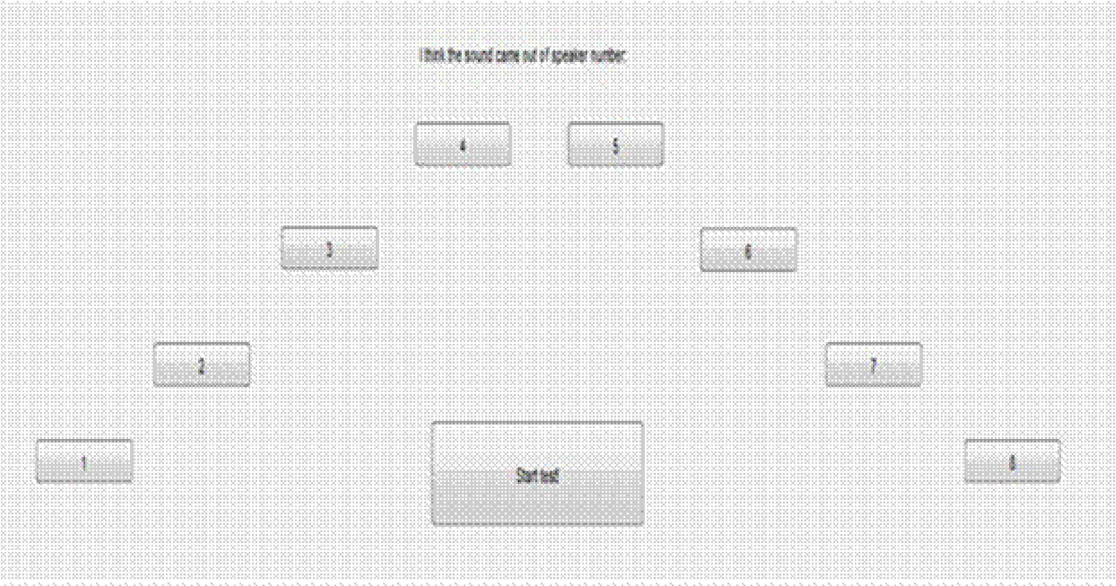
II. Methods

This dissertation is a combination of a single-subject design and a multiple subject-design that each measure the effect bone-conduction hearing devices may have on both sound localization accuracy and speech understanding in noise. A laboratory-made computer and speaker array system provided controlled testing in both studies. This testing array consists of a laptop computer and eight identical speakers arranged at 0, 20, 40, 60, 120, 140, 160, and 180 degrees azimuth around the laptop, and labeled on the speaker base from 1 (at 0 degrees) through 8 (at 180 degrees) respectively (Ganev, 2017). This machine and its programming allowed for testing of the sound location accuracy and speech understanding in noise tasks that are described in detail below.

Figure 1: Photo of the computer and speaker system used by the subject to complete the Sound Localization Accuracy and Speech Understanding in Noise tasks.

Sound Localization Accuracy Task

The subject sat in a chair in front of the laptop device and was instructed to keep their head located approximately in the center between the first speaker (1) and the last speaker (8), (see Figure 1) for the duration of testing. There were 48 sequential trials in which the program randomly activated one speaker with a 250ms broadband noise at a level ranging at or between 65 and 75 dB SPL. After each sound stimulus was presented, the subject clicked on the corresponding image of the speaker on the laptop screen (see Figure 2 below) that they perceived the sound to come from. There was no time limit for making each selection, and no feedback was given indicating the subject’s accuracy in the speaker they chose. Outcome measures were then derived and analyzed in the form of RMS error in degrees and the percentage of correct (PC) speaker identifications out of the 48 total trials.



I think the sound came out of speaker number:

Figure 2: Screenshot of the computer screen where the participant chooses the speaker number that matches the speaker they perceive the stimulus noise to have come from.

Speech Understanding in Noise Task

The speech-in-noise tasks used only speakers 1, 4, 5, and 8 in four combinations. In two tests the speech was to the left of the listener (speakers 1 or 4) and in two tests the speech was to the right (speakers 5 or 8). Sentences from the Coordinate Response Measure (CRM) corpus (Bolia, Nelson, Ericson, Simpson, 2000) were used to measure the subject's speech understanding in noise. Recorded dialogue was presented from a speaker in one designated hemi-field, while broadband noise was simultaneously presented from a speaker in the opposite hemi-field. These different conditions were designed so that the difference in presentation side of the speech and noise, as well as the difference in proximity of the speech and noise to the listener and each other, could be analyzed. In the first condition, CRM1, the speech was presented from speaker 1 (left side, most distal) and the noise was presented from speaker 8 (right side, most distal). In

CRM2, the speech was presented from speaker 5 (right side, most medial) and the noise was presented from speaker 4 (left side, most medial). CRM3 presented speech from speaker 4 (left side, most medial) and the noise from speaker 5 (right side, most medial). Finally, CRM4 was programmed so that the speech was presented from speaker 8 (right side, most distal) and the noise was presented from speaker 1 (left side, most distal). A brief training exercise was completed by the subject, in which they must correctly respond to 5 consecutive trials before they could proceed to CRM1-4 testing.

The presented speech was formatted to say “Ready Charlie, go to (color)(number) now” and participants were instructed to match the color and number they heard with the corresponding combination on the computer screen grid (see figure 3). For example, if the dialogue said “Ready Charlie go to blue 2 now” then the correct response would be to click on the blue box with the number 2 in it. For each presentation, the speech remained stable at 60 dB SPL. In contrast, the intensity of the presented noise was altered with an adaptive one up, one down track. Noise was increased (correct response given) or decreased (incorrect response given) in 6 dB SPL steps until the 4th change in direction. Then, the noise would respectively increase or decrease by 4 dB SPL. Noise levels were limited to a maximum presentation level of 80 dB SPL. Testing for each CRM ended after eight changes in direction, or 25 total trials, and then the threshold was calculated as the mean dB(A) of the noise level at the resulting 5th to 8th directional change.

If the listener has equal hearing in each ear, then the results from each test condition should be comparable to one another. With asymmetric hearing, the SNR will be lowest when speech is presented toward the better ear, and noise toward the poor ear. Additionally, when the speakers for both speech and noise are located closer together (more medially), then the signals are theoretically harder to separate into individual auditory objects. Conversely, if the speakers are located more distally, there is less overlap and the signals may be more easily distinguished. For a listener with a right-ear deficit the “best” or most favorable condition is CRM 1, and the least favorable or “worst” condition is CRM 4, which will be elaborated on in the multi-subject design segment of the methods section. The thresholds of the different CRMs were compared and analyzed. For a listener with a left-ear deficit the best and worst conditions would be reversed, but for the purposes of the analyses below, the conditions of listeners with left-ear deficits are mathematically reversed so they are analyzed as if they had right-ear deficits.

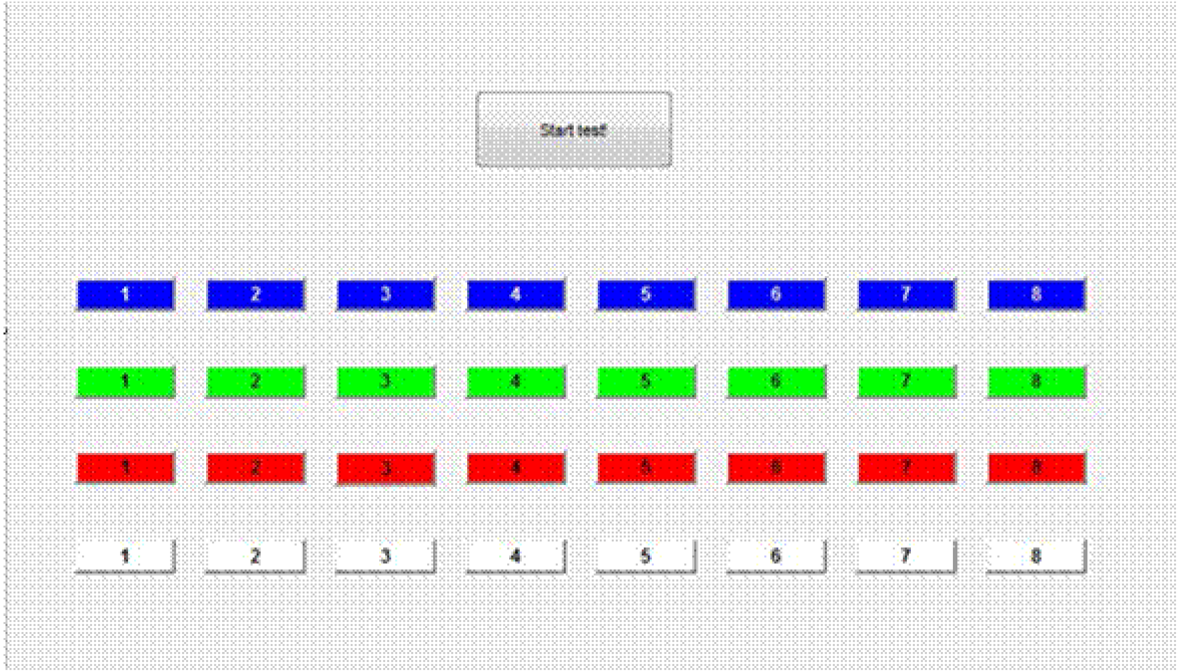


Figure 3: Screenshot of the speech in noise CRM testing screen in which the subject selects the number and color that they perceive to match the given stimulus.

Single Subject Design

Within the single-subject design, the participant was a 26-year-old female with an asymmetric, entirely conductive hearing loss (CHL) as a result of multiple middle ear infections and tympanoplasties of the left ear, as well as multiple surgeries of the right ear to remove a cholesteatoma tumor which resulted in a mastoid cavity and placement of a Total Ossicular Replacement Prosthesis. The better (left) ear has a mild to moderately-severe CHL, and the poorer (right) ear has a moderate to severe CHL (see figure 4 below). There was hearing loss present in both ears, however it was more severe in the right ear. The participant was implanted with an Osia2 BAHD on the right side, and this device was used for testing in the aided conditions. This participant had their BAHD implanted 6 months prior to participation in this study. For the unaided conditions no amplification was used. The subject tested themself twice a day, at 6:30am and 6:30pm, for 6 consecutive days resulting in a total of 12 tests. Aided and unaided testing was performed for each test session. An ABAB alternating experimental design was used, alternating which condition was performed initially for each day for all testing (unaided first, followed by aided testing the next day and so on).

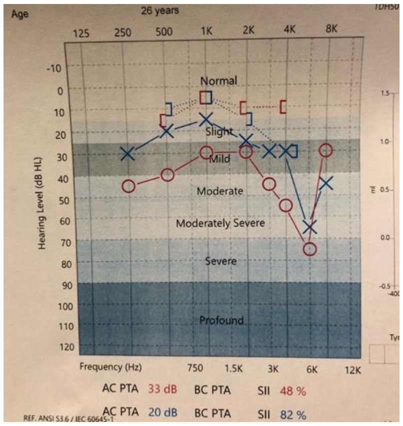


Figure 4: The personal audiogram of the participant in the single-subject experimental design.

Multiple-Subjects Design

In the multiple subject design, six subjects were tested, ranging from 7 to 16 years of age. There were 2 females and 4 males tested. Each subject had an asymmetric or unilateral conductive hearing loss due to congenital aural atresia, and a surgically implanted bone-anchored hearing device (BAHD). The interval of time between BAHD implantation and participation in this study ranged from 2 months to 2 years. The pure tone average (PTA) level of air conduction thresholds ranged from a 5-15 dB in the "better" ear, and from 30-73 dB for the "poor" ear. Air-bone gaps (ABGs) ranged from 0-10 dB in the good ear, and from 31-65 dB in the poor ear.

For five of these subjects, the "better" hearing ear was the left and the "poor" ear was the right. As the final subject conversely had better hearing on the right side, their resulting data was flipped in order to match the other participants and assimilate all subject data onto the same scale. These participants were recruited from and tested at the ENT clinic of the University of Virginia (UVA) Hospital. The participants' BAHDs were all professionally programmed by audiologists at the UVA audiology clinic. Each subject performed the sound localization accuracy and speech understanding in noise tests once unaided, and then another sequential time while aided with their BAHD. IRB approval was obtained for both studies in this dissertation. Both consent and ascent forms were read, reviewed, and signed by participants or their legal guardians.

III. Results

Single-Subject Design

Localization Accuracy

The first test measure recorded and analyzed from the single-subject localization task was the root mean squared (RMS) error in degrees of horizontal localization.

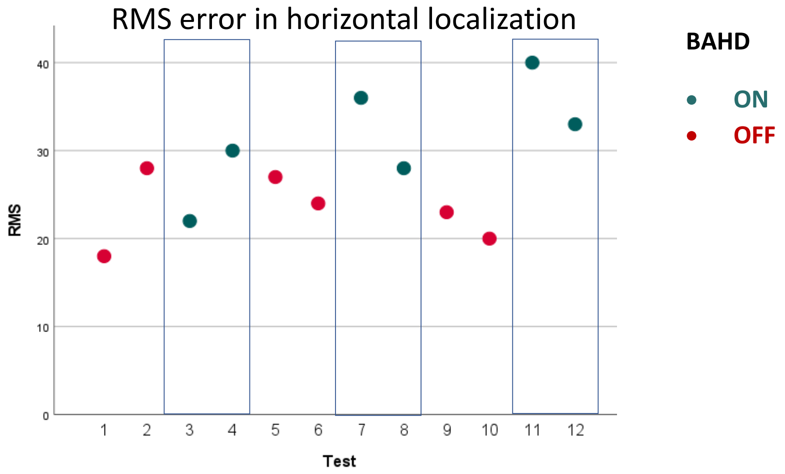


Figure 5: The amount of RMS error in horizontal localization recorded from each trial. Two trials were performed each day. The aided and unaided conditions were alternated daily, starting with unaided testing (red circles, unshaded) on day one, followed by aided testing (green circles, shaded bar) on day two, and so on, for a total of 6 days and 12 tests.

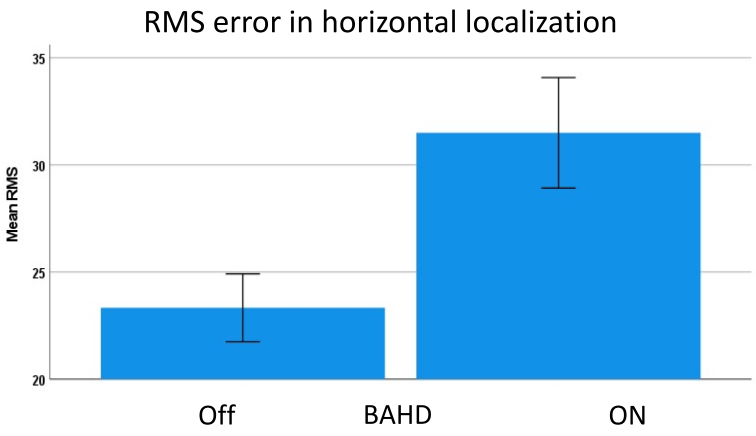


Figure 6: The mean RMS error in horizontal localization recorded from each trial in the unaided condition (0) compared to the aided condition (1).

With RMS error of sound localization, this study revealed an average RMS of 23.3 degrees in the unaided condition and 31.5 degrees in the aided condition. Technically correct statistical evaluation of these multiply repeated measures in a single subject is not possible. However, treating the 12 measures (6 days, half on half off, tests am and pm) as independent measures, which they are not, yields a two-tailed student's t-test with p= 0.04. Therefore, the main effect of BAHD activation might be statistically significant. There is no statistical significance in the comparison of morning trials and evening trials (p=0.88), meaning that the time of day in which testing took place had no significant effect on the subject's ability to accurately tell which speaker was producing noise. In summary sound localization appears to be worse with BAHD activation in the repeated testing of the single subject.

Next, localization ability was analyzed with the percentage of correctly chosen speakers on the horizontal plane.

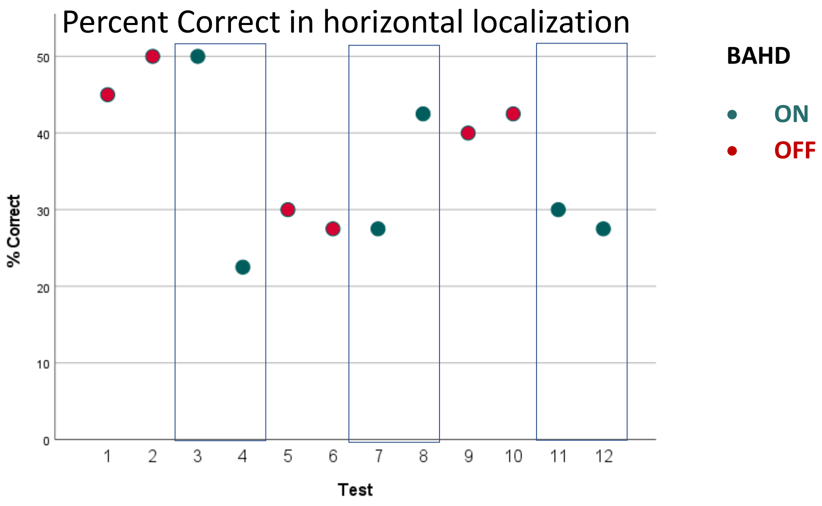


Figure 7: The percent correct in horizontal localization recorded from each trial. Two trials were performed each day. The aided and unaided conditions were alternated daily, starting with unaided testing (red circles,

unshaded) on day one, followed by aided testing (green circles, shaded bar) on day two, and so on, for a total of 6 days and 12 trials.

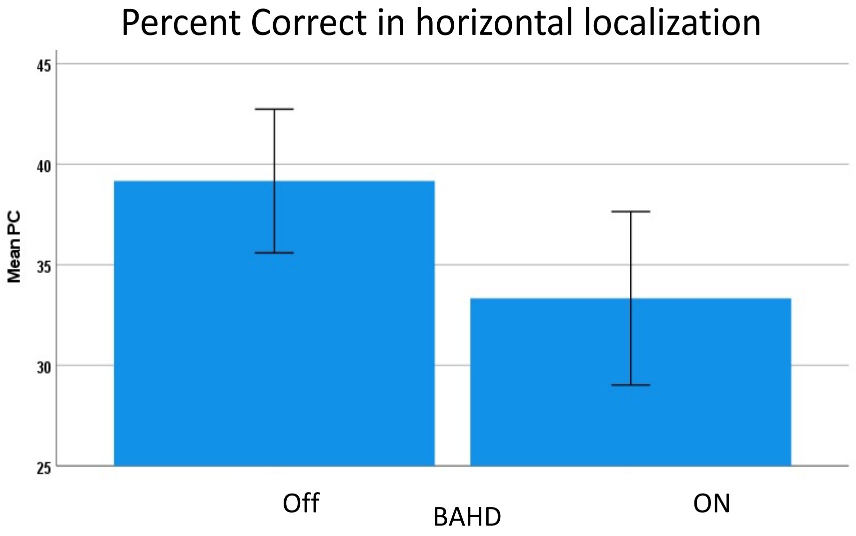


Figure 8: The mean percent correct in horizontal localization recorded from each trial in the unaided condition (0) compared to the aided condition (1).

On average, the subject was able to correctly identify the speaker 42% of the time unaided, and 35% of the time with their BAHD activated. When the data was analyzed for percent correct of sound localization, the P-value is 0.32 and thus not statistically significant. Therefore, BAHD activation did not make a significant difference in the subject's ability to accurately localize sound in terms of PC.

Speech Understanding in Noise

Following the localization tasks, the subject's ability to correctly understand speech amidst noise was evaluated in terms of the signal-to-noise ratio (SNR). In order to determine the impact that BAHD use may have on this task, the SNR from the best condition was subtracted from that of the worst condition. A large difference between conditions would suggest that a subject hears differently in each condition (asymmetric hearing). Conversely, a small difference in conditions would suggest that the subject is hearing similarly in each condition (more symmetric hearing).

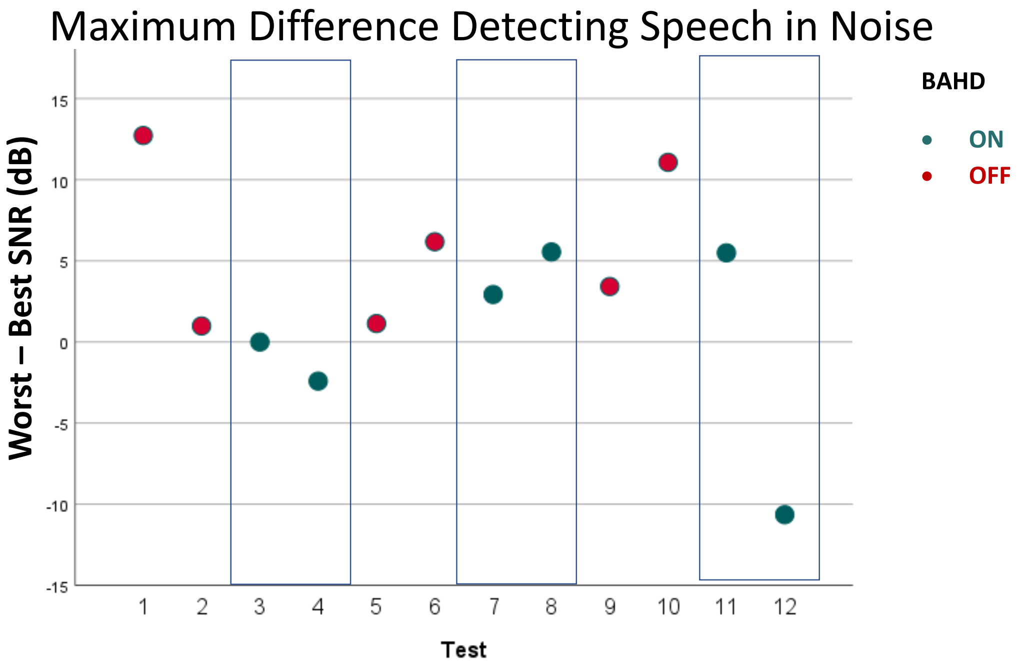


Figure 9: The difference between the most favorable and least favorable conditions in speech understanding in noise recorded from each trial and measured by subtracting the mean SNR at CRM threshold in the ‘worst’ condition from the ‘best’ condition.

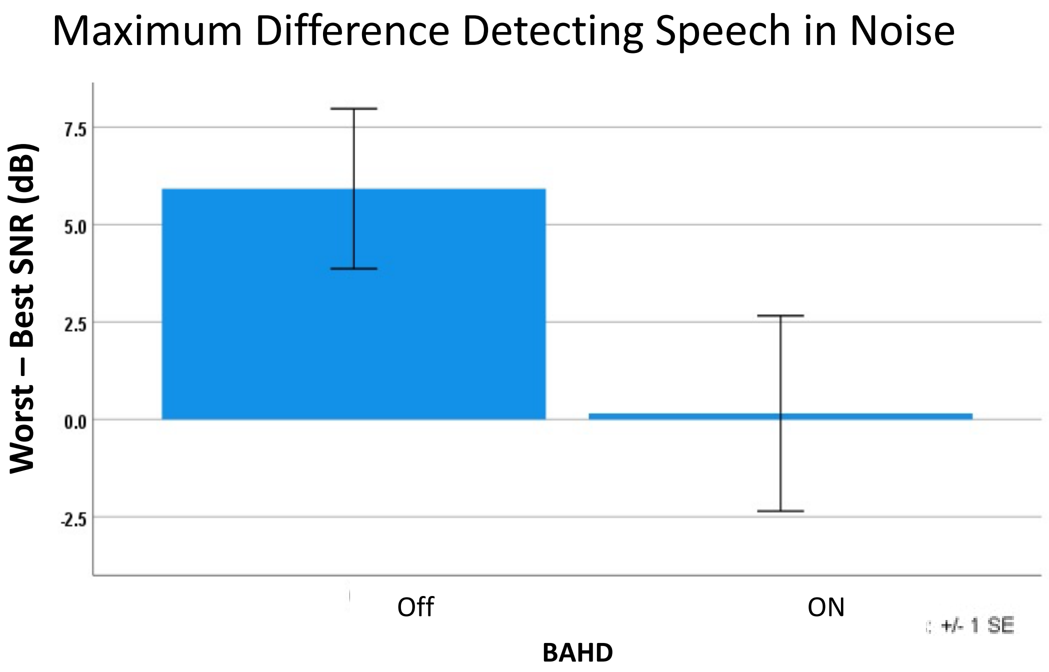


Figure 10: The averaged difference between the most favorable and least favorable conditions in speech understanding in noise, measured by subtracting the mean SNR at CRM threshold in the 'worst' condition from the 'best' condition. Recorded from each trial in the unaided condition compared to the aided condition.

The average SNR in the best listening condition (CRM1) was 3.2 dB unaided, and 7.1 dB aided. In the worst listening condition (CRM4), the average SNR was 9.1 dB unaided, and 7.2 dB aided. Unaided conditions show a directional preponderance, where there is a better (lower) SNR when speech is directed toward the better ear. However, the resulting P-value of 0.1 is greater than 0.05, and thus there is no statistically significant improvement of speech in noise understanding as a direct result of BAHD use.

Multiple-Subject Design

Localization Accuracy

With the multiple-subject design, the first test measure analyzed was likewise localization accuracy in terms of RMS error, and then in PC.

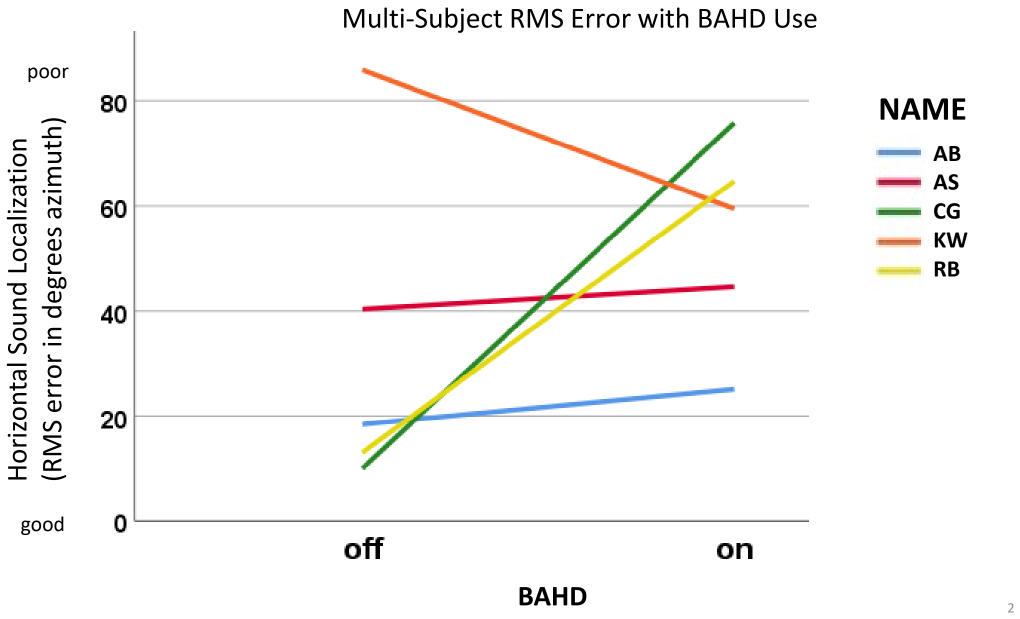


Figure 11: The RMS error in horizontal localization recorded from each subject in the unaided condition (off) compared to the aided condition (on).

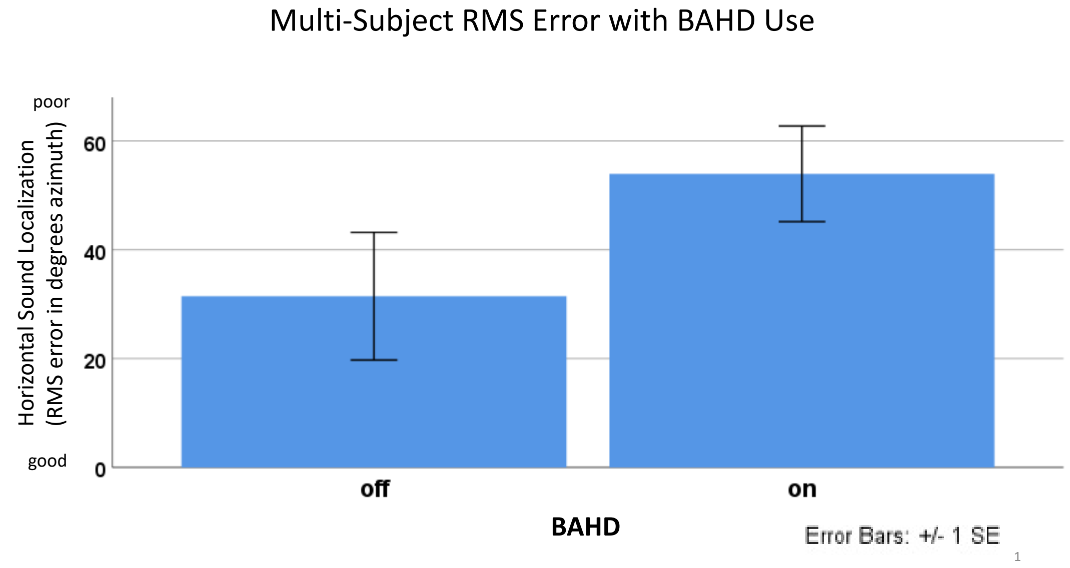


Figure 12: The mean RMS error in horizontal localization recorded from each subject in the unaided condition (off) compared to the aided condition (on).

This study showed an average RMS error of 33.6 degrees in the unaided condition, and 54 degrees in the aided condition. A paired samples t-test revealed $t_4=-1.2$, and $p=.3$; thus, there is no statistically significant effect of the BAHD in localization accuracy.

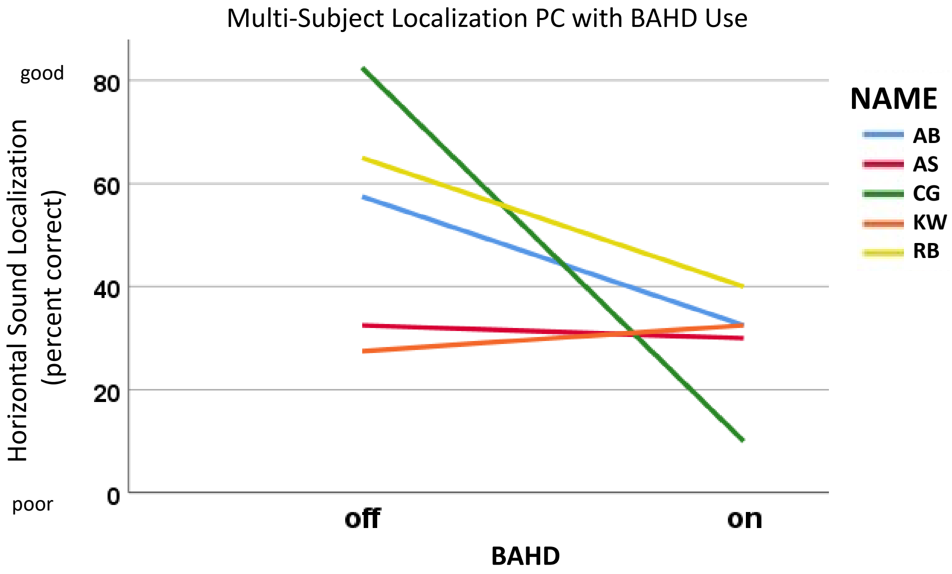


Figure 13: The percent correct in horizontal localization recorded from each subject in the unaided condition (off) compared to the aided condition (on).

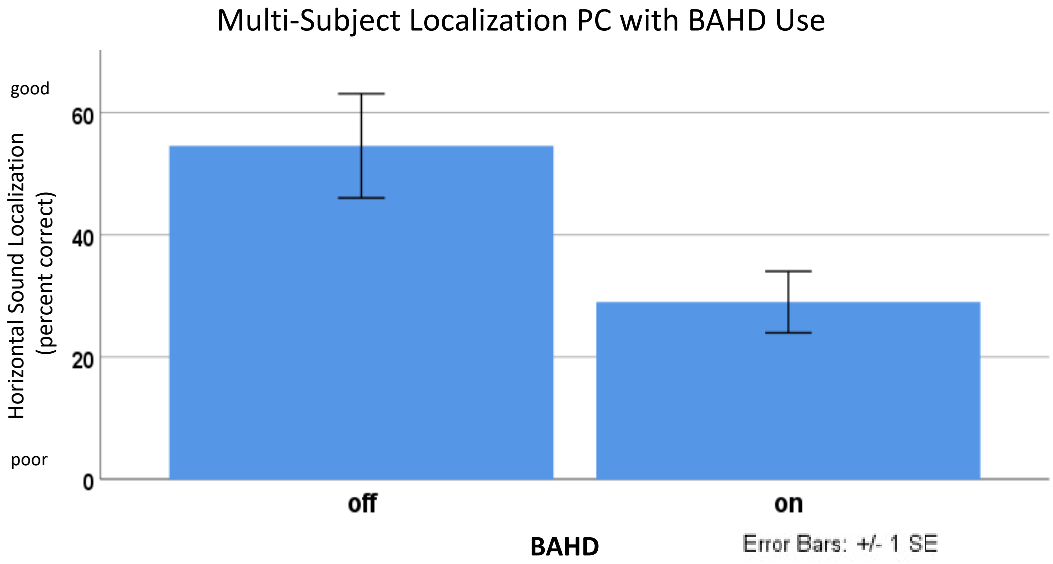


Figure 14: The mean percent correct in horizontal localization recorded from each subject in the unaided condition (off) compared to the aided condition (on).

On average, these subjects chose the correct speaker 53% of the time unaided, and 30% of the time when using their BAHD. The paired samples t-tests likewise showed no significant effects of the BAHD on sound localization accuracy in percentage correct (t_4=1.7, p=.15).

When looking at the effect sizes, however, they were between 'medium' (Cohen's d =.5; for RMS) and 'large' (Cohen's d=.8 for percent correct). There was no significant correlation between the paired measures (p=.96 for RMS aided versus unaided; and p=.4 for percent correct). Power analysis (SPSS V27) estimates that testing 12 participants (7 more than the current sample of 5) would have an 80% chance of finding significantly lower PC of localization with the BAHD (given the observed effect size of 0.8).

Linear regression shows the potential predictive value of the unaided PC on aided sound localization success in figure 15 below. When comparing how much the PC changed upon BAHD activation to the baseline (unaided) PC, a clear and statistically significant (P= 0.015) trend is delineated. A negative correlation shows that as unaided localization improves, aided localization gets comparatively worse. That is, for the 'good' listeners, BAHD activation makes their localization worse.

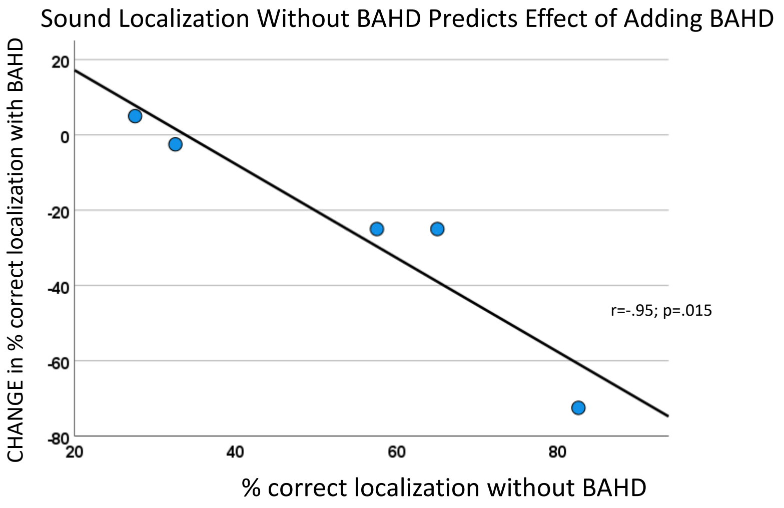


Figure 15: This graph of linear regression displays the change in percent correct of horizontal sound localization when the BAHD is activated (Unaided percent correct minus aided percent correct) and its relationship to the percent correct without the BAHD.

Speech Understanding in Noise

Data was next analyzed for the multiple subjects' abilities to understand speech in noise secondary to BAHD use in each test condition.

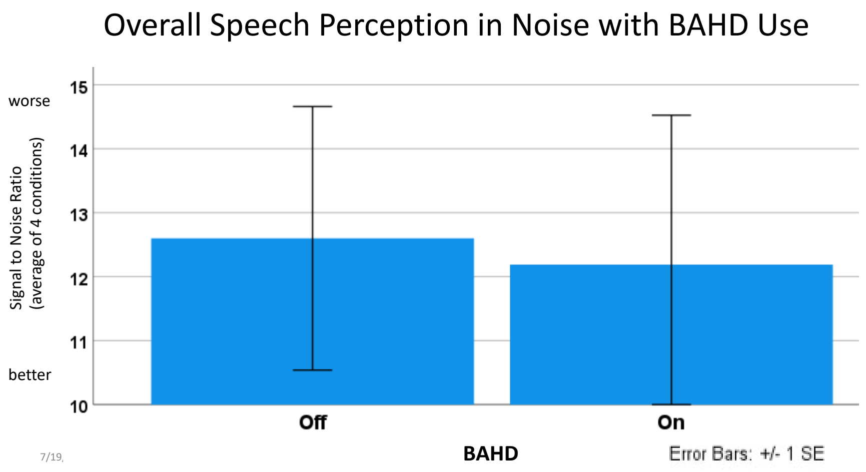


Figure 16: The mean SNR of speech understanding in noise, recorded from each subject in the unaided condition (off) compared to the aided condition (on).

When looking at the difference in SNR thresholds between the unaided and aided groups, across all four conditions, there is not a significant difference (P=0.38) in ability to understand speech amidst competing noise.

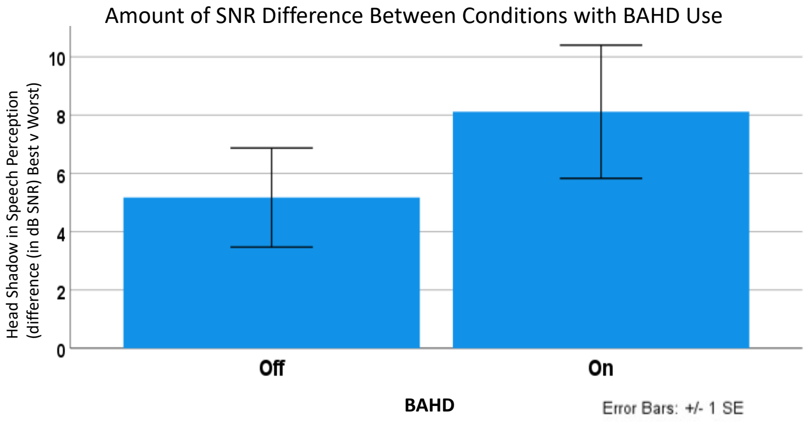


Figure 17: The amount of difference in mean SNR of speech understanding in noise from the best (CRM1) to worst (CRM4) conditions, recorded from each subject in the unaided condition (off) compared to the aided condition (on).

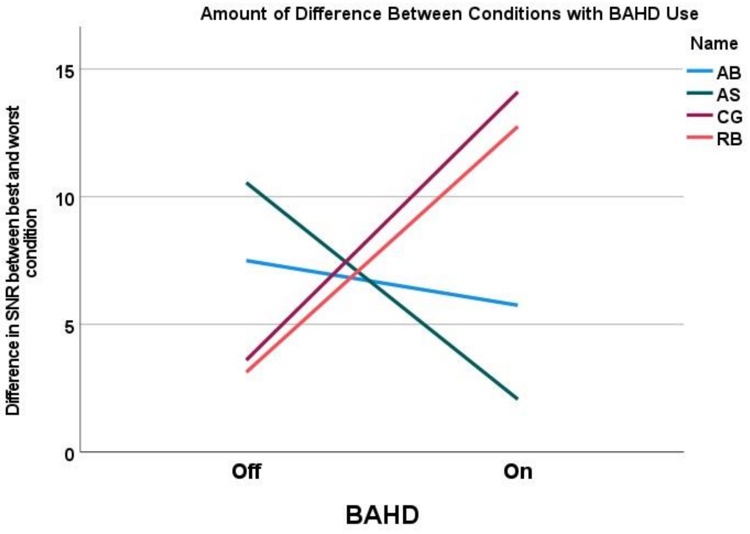


Figure 18: The difference between mean SNR of speech understanding in noise from the best (CRM1) to worst (CRM4) conditions, recorded from each subject in the unaided condition (off) compared to the aided condition (on).

Data was also analyzed looking at SNR scores from the best to worst conditions specifically. BAHD usage in itself yielded high variability in these resulting SNRs (t3=-0.5, p=.63). This variability will be discussed in the discussion section of this dissertation and is related to multiple discovered predictive correlates.

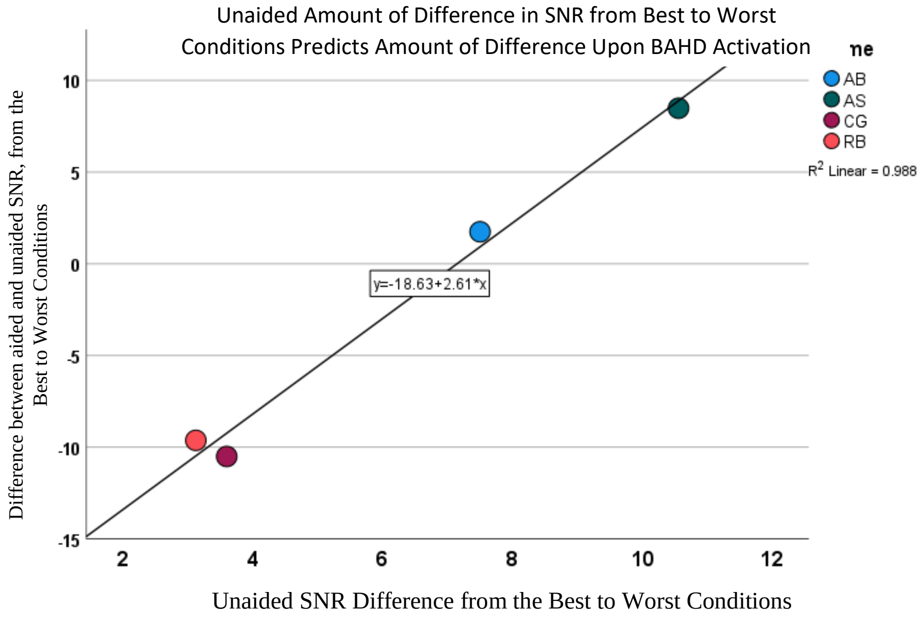


Figure 19: The difference between mean SNR of speech understanding in noise from the best (CRM1) to worst (CRM4) conditions, recorded from each subject in the baseline unaided condition (off) predicts the resulting difference in mean SNR between the unaided to the aided condition (on).

Figure 19 displays the predictive value of baseline (unaided) difference in SNR (CRM1-CRM4), on how much difference there will be in CRM difference upon BAHD activation. These results were significant (P=0.006).

Four other correlate predictors of outcome SNR upon BAHD activation were found and analyzed in this study. These factors- subject pure tone average (PTA) of the worse ear, asymmetry in PTA, baseline ABG of the worse ear, and asymmetry of ABG- are all correlated and statistically significant predictors of mean SNR and the difference between SNR from the best to worst conditions, when the BAHD is activated. The strongest predictor correlate we discovered was asymmetry of ABG in the subject's hearing as a predictor of mean SNR when the BAHD is turned on (r= -0.995, p=0.000). ABG asymmetry was also correlated and a statistically significant predictor of best to worst CRM difference (r= -0.95 and p= 0.013). Additionally, subject baseline ABG of the poor ear, PTA of the poor ear, and asymmetry in PTA were all correlated and statistically significant predictors of both difference in SNR from the best to worst CRM conditions, and mean SNR (r= -0.9 and p= 0.04, r= -0.98 and p= 0.002, r= -0.89 and p= 0.044, r= -0.99 and p= 0.002, r= -.0.92 and p= 0.027, r=-0.99 and p= 0.001, respectively). Subject age at testing, age at implantation, as well as ABG and PTA of the better ear were all tested and revealed to not have any correlation or significant effect on mean RMS or difference in SNR from the best to worst conditions.

IV. Discussion

Single-Subject Design

Localization Accuracy

When a BAHD is used, it sends the incoming sound signal to both cochleas at nearly the same time by mechanism of bone conduction. If both cochleas are receiving a nearly identical signal, the listener cannot use the comparison between ears as a means of determining signal location. There is little difference in time delay or signal attenuation, two measurements that help to localize where a sound source is coming from.

Our data shows that when a BAHD is activated, the subjects' ability to determine where the noise came from worsened. This supports the theory that BAHD activation may worsen an individual's ability to accurately localize sound.

It is imperative to note that when looking at localization accuracy, the absolute accuracy (percent correct) may not best show true localization accuracy. For example, if the subject had incorrectly guessed speaker 1 when the correct answer was speaker 2, the subject would only be off by 20 degrees azimuth, which is still quite good localization (much better than a guess for speaker 8). Measuring solely in percent correct would only count those trials in which the answer was absolutely correct and would not take into consideration the closeness in proximity of the chosen speaker to the actual speaker. While the percent correct scores were not statistically significant, this explains why RMS error was indeed significant, and why both measurements should be looked at when determining localization ability.

Speech Understanding in Noise

As this subject hears best from the left ear and worst from the right ear, it stands to reason that the most favorable condition for hearing speech above the noise would be when the speech is presented from the far-left speaker (1), and noise is presented from the far-right speaker (8). Thus, the best condition for this subject is CRM1. The least favorable condition for this patient would be the opposite speech presented from the right speaker and noise presented from the left speaker which would be CRM4.

In agreement with the prediction, averaged SNR was lower when unaided than aided with a BAHD, across all CRM conditions. Unaided conditions do show a directional preponderance, where there is a better SNR when speech is directed toward the better ear. Not as much of a difference in sides is shown within the BAHD activated conditions. This makes sense as the BAHD essentially brings both ears to the same listening level, and thus there is theoretically no ‘best’ or ‘worst’ CRM condition, and so no directional preponderance. In order to best analyze the effect that wearing a BAHD device has on speech understanding in noise, the difference between the best and worst conditions were evaluated for both unaided and aided testing, and then compared. However, it was found that the BAHD activation did not have a statistically significant effect on the difference in SNR from the best to worst conditions. This may be in part due to the small number of days tested, as well as the built-in noise reduction capabilities of the BAHD.

Multi-Subject Design

Localization Accuracy

It was revealed that BAHD use did not have any statistically significant effects on sound localization accuracy, neither as measured by RMS error or percent correct. While the single-subject design might have had a significant effect on RMS, it is likely that the multi-subject design did not due to a greater level of variability. Covariates also greatly affect the outcomes, which will be discussed in more detail later on in the dissertation. The lack of correlation between the paired measures shows that some listeners get better sound localization accuracy, and some get worse when using the BAHD, all with great variability.

An interesting trend is the relationship between baseline localization ability (unaided percent correct) and its predictive value on the degree of change in percent correct there is when a BAHD is activated. Figure 1 delineates the relationship, showing that the better the baseline localization ability of the subject, the greater the reduction in PC (difference unaided vs aided) will be in the aided condition (BAHD activated). For example, if a subject has a very high PC baseline in the unaided condition, this predicts that their PC in the aided condition will be significantly worse. Nonetheless, if the subject has a poor PC baseline, there will not be as great of a difference in aided PC. If the baseline is poor enough, the PC may even improve slightly when activating their BAHD. When an individual is already struggling to determine where a sound is coming from, then losing the natural localization benefits of having two ears doesn’t make that much of a difference. Conversely, if an individual is used to relying on the differences between the signal as it reaches each ear in order to localize sound, then adding a BAHD that sends a nearly identical signal to both ears simultaneously would greatly confuse them and disrupt their ability to accurately localize sounds. Therefore, while the use of a BAHD itself is not a predictive factor on PC of localization accuracy, the baseline unaided BC is in fact a predictor of how well that individual would do when aided with a BAHD.

Speech in Noise

Two ears can act together as a differential amplifier allowing the brain to conceptually subtract common noise heard in both ears to strengthen the perception of the unique speech signal which is much more dynamic in nature than wide band noise. As

BAHDs reduce this ability when sending an identical signal to both ears, it stands to reason that SNR would not improve in the aided condition from unaided. The multi-subject data supports this theory as there was no statistically significant improvement of SNR as a sole direct result of BAHD activation. This stood true for both the average change in SNR across all four conditions and change in SNR from the best to worst conditions specifically. Resulting data showed both increased and decreased SNRs upon BAHD activation, with great variability, though other factors (elaborated on further down) apart from BAHD use itself were found to influence this. It also stands to reason that since these patients have atretic ears and a resulting unilateral or asymmetric hearing loss, their baseline ability to understand speech in noise would be poor compared to a "normal" hearing individual. Thus, the single act of turning on a BAHD may not dramatically worsen SNR thresholds in these subjects with unilateral atresia if their SNR was poor to start with.

A unilateral listener (hearing in one ear and deaf in the other) would theoretically have the maximum difference between conditions. When comparing the SNRs from just the best and worst conditions, data shows that the BAHD may cause the user to respond more like a unilateral listener. If there is not much difference in SNR between the best and worst conditions when unaided, then activating the BAHD will cause a greater difference in SNR between conditions, with the reverse being likewise true.

It is also important to consider the effect that the baseline (unaided) hearing and amount of asymmetry in hearing of each subject when analyzing this data. It is likely that the effect of BAHD use on change in SNR between conditions was statistically insignificant due to the participants' high variability of baseline hearing thresholds and bilateral asymmetry affecting the resulting SNRs. These covariates were found to be a better predictor of outcome than simple generalized BAHD use.

Figure 18 shows the difference in SNR from the best to worst conditions, when the BAHD is both on and off, for each subject. If the unaided difference in conditions was low to start (RB and CG), then the difference is more extreme when the BAHD is activated in those conditions. An explanation of this discovery is that both RB and CG had the best unaided thresholds and the least asymmetry between ears. Therefore, their ears were already functioning with bilateral listening much more than the subjects with more extreme asymmetries (AB and AS). When the BAHD was turned on for RB and CG, there became a greater difference between conditions because the SNR actually got worse. AB and AS have the most asymmetric hearing and also the greatest unaided best to worst difference. When aided, this difference was greatly reduced because the poorer ear was then brought to the level of the better ear, and both ears were brought to essentially the same level. Those with better unaided thresholds have less of a difference between conditions when aided, but those with worse unaided thresholds have a greater difference in conditions when aided, as they become more like a bilateral listener when aided.

While the effect of BAHD activation on speech in noise reception was not statistically significant, we found four predictors of outcome RMS with BAHD activation. These factors, subject pure tone average (PTA), asymmetry in PTA, baseline ABG, and asymmetry of ABG, all are statistically significant predictors of mean SNR and the difference between SNR from in the best to worst conditions, when the BAHD is activated. The strongest predictor correlate we discovered was asymmetry of air-bone gap in the subjects’ hearing as a predictor of mean SNR when the BAHD is turned on. The greater the asymmetry in hearing between ears, the greater likelihood that their mean SNR will improve upon BAHD activation. Conversely, the smaller the ABG asymmetry, then the greater the likelihood that the mean SNR will worsen with the BAHD turned on. This idea that ‘good’ or ‘poor’ initial hearing and asymmetry of hearing predicts the SNR outcome of the opposite nature is perpetuated through each of these correlate predictors. The dividing line is approximately 44dB, with an asymmetry at or less than 32dB constituting ‘good’ hearing, and ‘poor’ hearing constituting as any asymmetry greater than 57dB. There is a ‘grey’ area from 33-56dB in which it is not certain whether BAHD use will increase or decrease SNR scores. This predicted improvement of SNR upon activation for those with ‘poor’ hearing and worsening of SNR for those with ‘good’ hearing is especially evident in the ‘worst’ condition (CRM4). To show this effect, the subjects were separated into two different groups, “bad hearing” (59dB averaged) and “better hearing” (30dB averaged) based off the subject’s unaided ABG asymmetry.

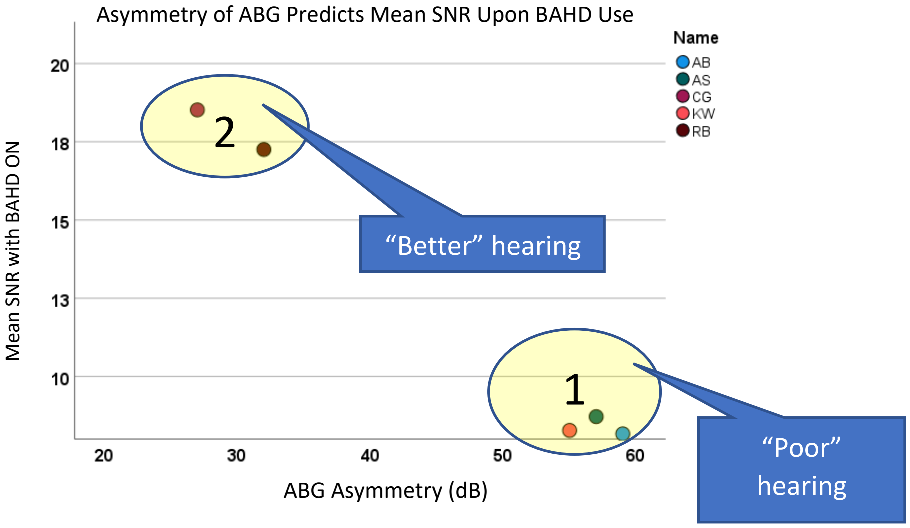


Figure 20: A scatterplot showing mean SNR as a function of asymmetry amount in decibels of air-bone gap each subject has between their ears.

Out of the subjects tested in this study, CG and RB had the best hearing (least asymmetry in ABG) while KW, AS, and AB had the worst hearing. Figure 20 shows the difference that baseline asymmetry in ABG makes on ability to understand speech amidst competing background noise (mean SNR) when the BAHD is turned on and used.

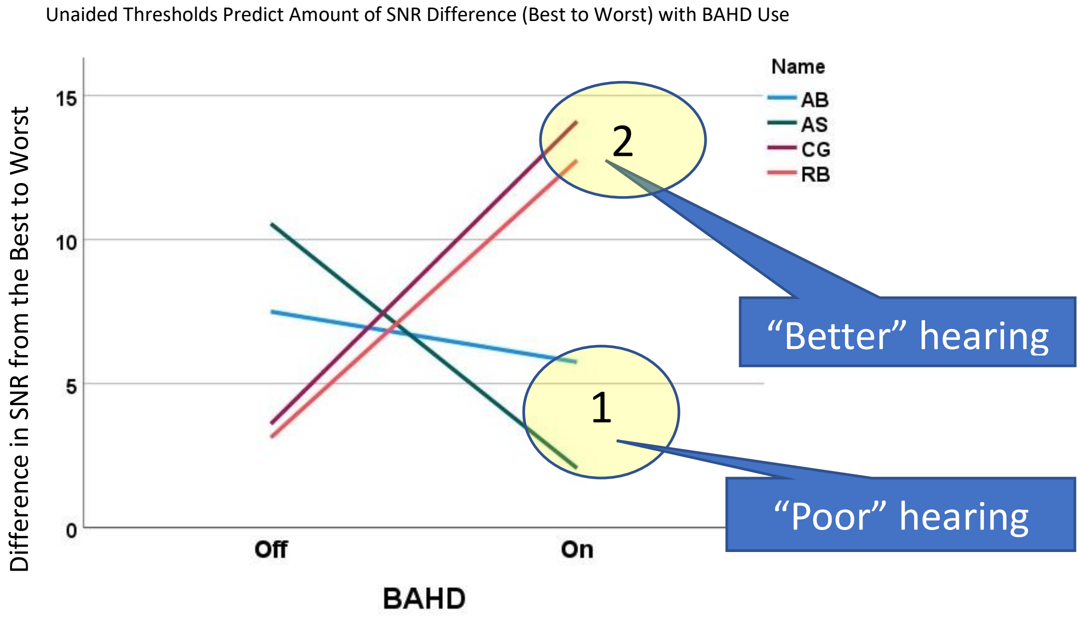


Figure 21: A scatterplot showing the SNR difference from best to worst CRM conditions as a function of BAHD activation.

Figure 21 likewise displays the difference between the SNR from the best to worst CRM conditions when the subject is unaided or aided with a BAHD. Those with better unaided hearing had a greater change in difference between conditions when the BAHD was activated, as their ability to hear speech amidst noise worsened. Those with worse baseline hearing had a smaller change in SNR from the best to worst conditions, as the level of hearing was essentially equalized upon BAHD activation.

Limitations of this Research

Future studies with a greater number of participants are necessary to confirm this discovery, as well as to test the difference in benefit level between the different styles (abutment, magnetic, or combination) of BAHDs. While it would be of additional benefit to know the BAHD aided thresholds of these participants, aided thresholds are not always recorded clinically. Follow up research would also help determine if aided localization and speech understanding in noise abilities might improve over time.

V. Conclusions

Unaided PTA, asymmetry in PTA, ABG, and asymmetry of ABG predict the likelihood that an individual patient will benefit from BAHD implantation in both localization and understanding speech in noise. When determining if a patient with UCAA will benefit more from canalplasty or BAHD implantation, it is extremely beneficial to check the individual's unaided thresholds so they may be informed of potential benefit levels in both treatment options. BAHD implantation is a less invasive option for UCAA patients who may not be good candidates for surgical reconstruction. Present data suggest that if their hearing loss has an asymmetry at or greater than 57dB, it is likely that sound localization and speech understanding in noise will improve postoperatively.

References

Asp, F., & Reinfeldt, S. (2018). Horizontal sound localisation accuracy in individuals with conductive hearing loss: effect of the bone conduction implant. *International Journal of Audiology*, *57*(9), 657–664. https://doi.org/10.1080/14992027.2018.1470337

Avan, P., Giraudet, F., & Büki, B. (2015). Importance of Binaural Hearing. *Audiology and Neurotology*, *20*(Suppl. 1), 3–6. https://doi.org/10.1159/000380741

Bosman, S. (2001). Audiometric Evaluation of Bilaterally Fitted Bone-anchored Hearing Aids: Evaluatión audíométrica de auxiliares auditivos tipo vibrador óseo bilateral. *International Journal of Audiology*, *40*(3), 158–167. https://doi.org/10.3109/00206090109073111

Breier, Joshua I., et al. (1997). Ear Advantage in dichotic listening after correction for early congenital hearing loss. *Neuropsychologia*: 209-216.

Culbertson, J. L., & Gilbert, L. E. (1986). Children with Unilateral Sensorineural Hearing Loss. *Ear and Hearing*, *7*(1), 38–42. https://doi.org/10.1097/00003446-198602000-00007

Cruz, Antonio De La. (2003). Congenital Aural Atresia Surgery: Long-term results. *Otolaryngology Head Neck Surgery*: 121-127.

Ganev, Sofia Antonov. (2017). Development and Deployment of a Small Stereo-Hearing Testing System. *Dissertations*. 154. https://commons.lib.jmu.edu/diss201019/154

Gawliczek, W. (2018). Speech Understanding and Sound Localization with a New Nonimplantable Wearing Option for Baha. *BioMed Research International*. 5264124–5264128. https://doi.org/10.1155/2018/5264124.

Gray, Lincoln, Bradley Kesser and Erika Cole. (2009). Understanding speech in noise after correction of congenital unilateral aural atresia: Effects of age in the emergence of binaural squelch but not in use of head-shadow. *International Journal of Pediatric Otorhinolaryngology*: 1281-1287.

Hagr, A. (2007). BAHA: Bone-Anchored Hearing Aid. *International Journal of Health Sciences*, *1*(2), 265–276.

Hol, B. (2005). Bone-anchored hearing aids in unilateral inner ear deafness: an evaluation of audiometric and patient outcome measurements. *Otology & Neurotology*, *26*(5), 999–1006. https://doi.org/10.1097/01.mao.0000185065.04834.95

Kesser, Bradley W., Kaelyn Krook and Lincoln C. Gray. (2013). Impact of Unilateral Conductive Hearing Loss Due to Aural Atresia on Academic Performance in Children. *Laryngoscope*: 1-6.

Lustig, L. R., Arts, H. A., Brackmann, D. E., Francis, H. F., Molony, T., Megerian, C. A., Moore, G. F., Moore, K. M., Morrow, T., Potsic, W., Rubenstein, J. T., Srireddy, S., Syms, C. A., Takahashi, G., Vernick, D., Wackym, P. A., & Niparko, J. K. (2001). Hearing Rehabilitation Using the BAHA Bone-Anchored Hearing Aid: Results in 40

Patients. *Otology & Neurotology*, *22*(3), 328–334. https://doi.org/10.1097/00129492-200105000-00010

Wazen, G. (2005). Localization by unilateral BAHA users. *Otolaryngology--Head and Neck Surgery*, *132*(6), 928–932. https://doi.org/10.1016/j.otohns.2005.03.014

Wilmington, Debra, Lincoln Gray and Robert Jahrsdoerfer. (1994). Binaural processing after corrected congenital unilateral conductive hearing loss. *Hearing Research*: 99-114.