EVALUATING ENHANCED AUDITORY PERCEPTION AUGMENTATION VIA STOCHASTIC RESONANCE

by

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The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

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Sherman, Sage (M.Sc., Aerospace Engineering Sciences)

Evaluating Enhanced Auditory Perception Augmentation via Stochastic Resonance

Thesis directed by Assistant Professor Allison P. Anderson

This research thesis explores improving auditory perception through the use of stochastic resonance (SR), a phenomenon in which the throughput of non-linear signals is enhanced using additive noise. While SR has been successfully explored in a variety of perceptual channels (visual, tactile, vestibular), past psychoacoustic experiments have yielded conflicting results. This study aims to understand how SR can be observed in the auditory system accounting for individual differences.

Two studies were carried out to investigate SR within the auditory system. Both studies observed how white noise magnitude influences perception of pure tone stimuli across the frequency spectrum. The Threshold Optimization Study aimed to correlate SR enhancement with a subject's audiometric threshold, predicting that noise levels equal to the subject's threshold at a specific frequency tone would yield the highest SR benefit. Ten subjects completed pure tone audiometry with and without noise. Observing auditory thresholds with subthreshold, at-threshold, and suprathreshold additive noise yielded insignificant results. The noise levels tested did not improve or worsen audiometric performance across the board, which led to changes in the experimental methodology, specifically the noise levels that were presented and signal administration. Using those changes a second Protocol Development Study was conducted to replicate the results found in past psychoacoustic studies.

The additional study also aimed to observe SR, but expanded the noise spectrum to also find the masking that was not discovered in the first study. Four lab members completed pure tone audiometry with and without the presence of noise over a broad range of noise levels. A qualitative analysis suggests masking existed for frequencies with low thresholds given the noise levels that were tested. For some subjects, SR benefits may have been observed, but for others they did not appear to be present. With these small subject numbers, this study did not yield conclusive results. A discussion of the results, as well as, further improvements into the experimental methods is given. Applying these lessons learned, more accurate perceptual threshold testing can be conducted within the lab, allowing greater reporting confidence for future studies.

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I would also like to thank the other members on this committee, Dr. Torin Clark and Dr. Kathryn Arehart. Dr. Clark first introduced me to Bioastronautics in my undergrad and I immediately knew that I wanted to pursue a career in this research field. Within this work, Dr. Clark was an excellent resource when it came to experimental and statistical test development. Dr. Arehart was immediately willing to participate in this committee with no prior knowledge of the experimental goals, providing insight and help even at our first meeting. I look forward to working with her and the Speech, Language, and Hearing Sciences department as we move forward with future SR testing.

I want to thank Dr. Albert Kim for allowing us to complete testing within the acoustic sound booth at the Cognitive Neuroscience of Language Lab.

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Chapter 1. INTRODUCTION

1.1 Motivation

Aging, disease, and exposure to loud noises decrease the cochlea's ability to hear low intensity sound. Hearing loss is permanent and often attributed to the damage of hair cells or their connections to the spiral ganglion cells (Chai et al., 2017). While auditory perception is worsened due to these factors, extensive research is being done within this field to mitigate their effects. Currently, it is theorized that perception may be improved using stochastic resonance. Understanding this phenomenon, as it pertains to the auditory system, will provide insight into cochlear abilities, potentially allowing for further research into strategies that restore hearing loss.

Stochastic resonance (SR) is a phenomenon in nonlinear systems where noise can increase the throughput of a signal, periodic or aperiodic. This suggests that SR can improve auditory perception in low signal-to-noise environments by having noise resonate with subthreshold signals, amplifying them to suprathreshold signals. This study aims to find whether this is found in normal hearing subjects.

As part of a larger in-channel SR observation research goal, positive and significant results will lead to further investigations of the mechanisms within the cochlea responsible for SR enhancement. The mechanism by which SR would improve neural encoding within the cochlea is not well understood; therefore, studies to follow will examine whether SR imparts additional energy on the outer hair cells or assists with neural encoding of the inner hair cells.

1.2 Research Aims

The first aim of this study is to evaluate whether auditory perception can be enhanced across the frequency spectrum by mixing noise with an auditory signal. Identifying SR and its effect size in normal hearing subjects would be the first step in identifying SR in individuals with abnormal hearing. We hypothesize that, relative to pure tone thresholds at certain frequencies, non-suprathreshold levels of white noise will lower auditory thresholds of periodic signals.

While past research suggests certain noise may enhance perception, it is self-evident that loud noise inhibits incoming signals, but too low of an intensity may have no effect. The optimal level of noise to apply for SR benefits has conflicting results in the literature. Since SR improvements have been identified as individualistic, the second aim is to correlate hearing thresholds with the optimal level of noise that will produce SR. Morse & Roper (2002) proposed that the optimal level of noise to present for cochlear implants is equal to the nerve threshold. We hypothesize that a sensation level of 0 (noise magnitude equal to the threshold at that frequency) will result in the lowest auditory thresholds.

1.4 Research Methodology Overview

To test these hypotheses, ten human subjects participated in audiometry with and without the addition of broadband white noise. These subjects met strict inclusion criteria to determine if they have normal hearing. A Békésy-style tracking approach to audiometry was conducted to determine thresholds. Subjects first completed threshold testing at frequencies equal to 0. 5, 1, 4, 8, and 14 kHz without noise. Subject thresholds were then evaluated with white noise mixed into the signal. To test if the optimal level of noise at a given frequency is equal to the subject's threshold at that frequency without noise, white noise levels were presented in increments of 5 dB SPL (Sound Pressure Level), ranging from -15 dB SPL below threshold to +10 dB SPL above threshold. Pure tone audiometry with and without the addition of the hypothesized optimal noise were compared. Thresholds taken with varying noise levels were also compared.

1.5 Thesis Outline

This thesis is outlined as follows:

Chapter 2 provides a literature review of SR, including the modeling and experimental work completed within this field. The focus is on auditory SR, but is inclusive of other studies to be representative.

Chapter 3 outlines the experimental protocol developed to identify SR within normal hearing subjects. It outlines the criteria subjects had to meet to be included in the study and the tasks completed by the subjects. This chapter describes how variables were isolated and the testing equipment used to do so. Finally, it discusses the statistical tests to analyze the data.

Chapter 4 presents the results from the study on ten subjects, outlining what was hypothesized compared to what was observed. A discussion of the results and procedural improvements is also provided.

Chapter 5 details a second exploratory experiment that was conducted as a result of the discussion from Chapter 4. It gives an overview on the experimental changes conducted, as well as, the observations found testing this protocol.

Chapter 6 provides a final discussion and conclusion for this study and thesis.

Chapter 2. BACKGROUND

This chapter summarizes some of the previous work related to modeling and identifying SR. Section 2.1 gives a broad overview into the mathematical basis of SR. Then Section 2.2 delves into SR modeling and experimental observance within neurons and the auditory channel. Section 2.3 explores whether SR has utility when it comes to improving perception. A brief discussion on how the cochlea processes sound and how SR could manipulate sound perception is given in section 2.4.

2.1 Stochastic Resonance

SR suggests that noise can improve a nonlinear system's signal quantization. Quantization refers to the discretization of analog data. Stochastic is defined as being "randomly determined" and unpredictable. However, it is still probabilistic (McDonnell et al., 2008). White noise is based off a Gaussian distribution centered around zero, where the intensity is the same across all frequencies (flat spectral density). This non-deterministic noise accounts for the stochastic term. This noise resonates with the nonlinear signal, increasing the signal's throughput. Figure 1 visually represents how this may improve signal processing. The noise elevates subthreshold stimuli into a suprathreshold signal.

Figure 1. Visual representation of the non-dynamical model of SR. The threshold barrier represents the magnitude where signal perception is achieved. A nonlinear signal with a magnitude lower than this barrier may never be recognized. Adding noise to the signal allows information to cross this barrier.

SR is a nonlinear phenomenon; therefore, the correct level of noise must be applied to the system in order to achieve throughput benefits. Noise levels less than optimal would do little to elevate the stimuli; alternatively, a noise level that is too large may mask the signal, making the noise more prevalent than the stimuli. An optimal level of input noise exists to produce the greatest output power. This can be seen from the results of Simonotto et al. (1997) who used SR to enhance still images for visual perception. A gray scale image, shown in Figure 2, was augmented with noise to each individual pixel. The noise in each pixel was random but based off the same standard deviation. Too little noise presents a subthreshold image (left), and too much noise begins to mask the image (right). The middle image is utilizing an optimal level of noise, thus revealing the underlying image of Big Ben.

Figure 2: Gray-scale images from Simonotto et al. (1997) on visual perception SR. The noise intensity (σ) applied from left to right is 10, 90, and 300. Pixel gray values varied from 1 (black) to 256 (white). Permission granted from APSPhys, permission pending from author.

SR is understood to exist in two ways, non-dynamical SR and dynamical SR. Noise in both models add energy to the system, improving detection. The dynamic model of SR was proposed before its counterpart to explain periodic recurring ice ages. This model relates to bistable systems, where the system can rest in either one of two states. The most common way to represent this is a system within a double potential well, where a forcing function raises and lowers the potential wells, shifting the system's stability to favor one state. Figure 3 illustrates the behavior of this model. Inherent noise in the system can make it more sensitive to perturbations, shifting system it to the more stable state (Gammaitoni et al., 1998).

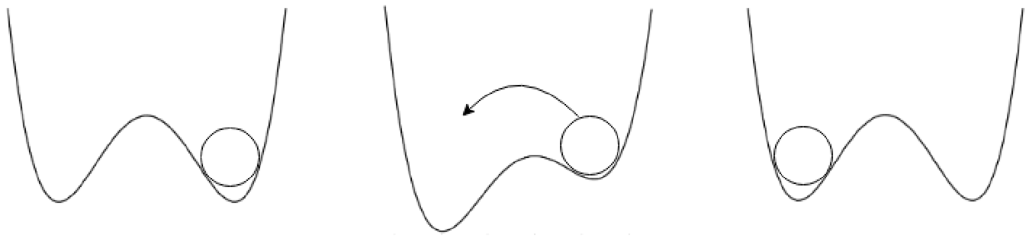

Figure 3: Visual representation of the SR dynamic model. The potential barrier between the two wells force the system to stay in one state. Weak periodic forcing lowers a potential well. This forcing is too weak to change the system's state, but internal noise allows the system to move into the new state.

This paper is concerned with the simplified non-dynamical model which discusses thresholds in the presence of noise and subthreshold stimuli (Gingl et al., 1995). This model is demonstrated in Figure 1 and shows SR can occur in systems that are not multistable dynamical systems. The non-dynamical model is the simplest way to model SR, detailing it as a threshold crossing detector. In this model, whenever the threshold is crossed a pulse train is created. The non-dynamical characteristic implies that the input frequency does not affect the periodic response of the system, suggesting that SR can be found across all frequencies. SR benefits could be applied to the entire frequency spectrum, benefiting all neural and electrical systems. It should be noted that with this study's current hypothesis, the optimal level of noise should be correlated with the input frequency since auditory thresholds are frequency dependent.

While the notion of SR came about in the 1980's, a similar technique of signal quantization, dithering, was developed in the 1960's. Dithering is another method in signal processing that involves adding noise to nonlinear systems. This technique adds a noise signal to the input signal before it becomes digitized. The phenomenon is used to help with analog-to-digital conversion, improving digital signals. This technique adds additional output power, and it reduces harmonic distortion effects caused by low amplitude signals (McDonnell et al., 2008). This method is often used for image processing and audio signals. Now dithering and SR appear to be mutually exclusive, but this debate seems to be ongoing and lost in the semantics. Both SR and dithering can enhance subthreshold and suprathreshold signals, both involving additive noise to a signal. Ando and Graziani (2001) detail that dithering is a manmade process done to manipulate signals, whereas, SR is a phenomenon observed in nature. Wannamaker et al. (2000) clarifies that SR can occur as a result of dithering, or observed in dithered systems. Most of the literature detailing the addition of noise to improve auditory performance refers to it as SR instead of dithering as will the rest of this paper.

The notion of improving non-linear signals with noise is enticing, but it holds little promise in benefitting perception unless analyzed within biological systems.

2.2 Extension to Biological Systems

Using numerical modeling, several groups investigated what SR could do for information transfer across individual neurons and neuron groups. It has been theorized that information within the human brain is represented as discrete data rather than analog data (Tee & Taylor, 2018). This could imply that neurological systems may be improved by using SR. In fact, neuron models suggest the phenomenon could play a role in brain function and the communication of neuronal assemblies (Moss et al., 2004). Neuronal assemblies are usually modeled by energy detector models, similar to the one used by Gingl et al. (1995), where pulse trains signify information transfer. Tougaard (2000) found that noise improves detection in energy detector models, but he remained skeptical in its significance for biological receptors. Being able to model this phenomenon is one thing, observing it is another.

Extensive time and effort have gone into modeling SR within the auditory system and its potential relevance in neural encoding. Sumner et al. (2002) developed a comprehensive model of the auditory nerve complex stating that action potential timing is determined by the quantal and stochastic release of neurotransmitters. This complete model ignores the stochastic behavior of the stereocilia though. Brownian motion of the inner hair cells produce neural noise that can also be represented as stochastic behavior, implying that stochastic behavior plays a larger role in information encoding than the complete model suggests.

An assumption in most of the literature is that the external signal is periodic, but in reality signals are not as ideal. The stimuli found in these models are sinusoidal (periodic); therefore, have a Gaussian distribution. However, aperiodic stimuli (found in music and speech) are better represented as Laplacian signals with slow decaying tails. McDonnell et al. (2008) discusses this issue, implying that the information gain due to SR is small for aperiodic signals. This may call into question the usefulness of SR for improving day to day life, but McDonnell goes on to explain that the compressive effects of the ear remove the long tails in the signal distribution, making signals that are not periodic, such as components of speech, also susceptible to SR improvement. Therefore, it can be expected that SR can improve performance for periodic tones as well as aperiodic tones.

Since SR is a method of improving quantization, work had gone into analyzing how this method could be applied to cochlear implants, which connect to the cochlear nerve and apply discretely encoded signals. Morse and Evans (1996) sparked this research when they found that gaussian noise enhances vowel encoding for the cochlear nerve of toads, using cochlear implants as the nerve stimulation device. While SR perturbations are usually represented as continuous noise, stochastically generated pulse trains help detect weak signals in the Hodgkin Huxley model (Danziger & Warren, 2014). Artificial neural stimulation is done through the use of voltage pulses, usually not broadband noise. Direct stimulation using pulses could be applied to cochlear implants to assist with neural encoding. Another model developed by Morse and Roper (2000) explains that SR enhances temporal representation of speech for implants. This model describes the optimal noise level for information transfer is equal to the threshold level of the nerve. This is the only SR model, to date, that predicts the optimal level of noise in any system. Logically it would follow that a noise magnitude with the highest power output, while not masking the signal, would produce the highest energy for detection. This notion is the main reasoning behind the current hypothesis of this thesis.

While models allow for quantitative reasoning and development behind a phenomenon, experimental analysis must be conducted to confirm the validity of any model. One of the first experiments that observed external input SR in biological systems was done by Douglass et al. (1993) with crayfish mechanoreceptor cells. Using an electromagnetic motion transducer to apply sinusoidal stimuli and white noise to the cells, they found that information transfer can be enhanced along individual neurons using noise. Similar results were found in cricket and rat neurons three years later (Levin & Miller, 1996);(Collins et al. 1996). Finding that SR exists in neuron receptors implies that the energy detector models were correct and applicable to biological systems, suggesting noise enhances information transfer, improving detection.

Confirming SR along individual neurons is enlightening, but noticing it within a neural system, specifically the cochlea would provide confidence in its applicability to psychoacoustics. The role of SR in the auditory system is Jaramillo's & Wiesenfeld's (1998) study on Brownian noise in hair cell bundles. They observed displacement of leopard frog hair cells as they provided mechanical stimulations (electrical stimulus and noise signals) to the bundle's bulb. Their findings concluded for maximum SNR the displacement given from mechanical transduction is comparable to the levels of Brownian motion in the hair cell. This implies Brownian motion plays a direct role in neural encoding. External mechanical noise could also assist with neural encoding though. Henry (1999) evaluated SR in Gerbil cochleae by presenting two phase locked tone burst stimuli with Gaussian noise and measuring the response with a microphone. He found that responses can be improved by optimal noise levels; however, this ideal noise level varied for each Gerbil.

Numerical modeling and animal testing confirmed the utility of using SR for information transfer along neuron systems; however, it is unclear if this improvement is carried through an entire sensory pathway.

2.3 SR within Psychophysical Systems

While observing information transfer across neurons is important, SR ideally carries through higher order cognition to see performance benefits. Psychophysics is the branch of psychology that observes the relationship between physical sensations and the mental perceptions they produce. Psychophysical SR experiments are conducted by applying noise to humans and recording their perceptual thresholds. The noise can be applied to an external stimulus, as represented in Figure 2, or through neural stimulation. This section also details SR as in-channel or cross-modal. In-channel refers to the use of SR within the same sensory pathway, cross-modal is the use of SR across different sensory pathways. This section observes noteworthy psychophysical experiments that found perception improvements utilizing SR phenomena.

Visual enhancement has been noted in various white noise delivery methods. Beyond the visual experiments explained in section 2.1 where external noise was administered to still images (Simonotto et al., 1997);(Piana et al., 2000), noise can also be introduced into a system by applying alternating current to information processing organs. Transcranial random noise stimulation (tRNS) of the visual cortex is shown improve the detection of subthreshold stimuli (Groen and Wenderoth, 2016). It has been proposed that tRNS prevents homeostasis in neural systems, increasing neuron sensitivity rather than just adding noise to the system (Miniussi et al. 2013). This theory suggests SR benefits cognition through a separate mechanism beyond imparting additional energy to the system.

SR has also been observed in other senses, such as balance and touch. Using actuators, Collins et al. (1996) observed SR behavior for tactile thresholds by applying two rounds of vibratory noise (or rounds without noise for the baseline) to subjects' fingertips, where only one of the rounds had the stimulus. Nine out of the ten subjects were able to identify the stimulus round with higher accuracy for the noise treatment than the baseline. They also found subjects had separate optimal levels of noise to achieve correctness. Galvan-Garza et al. (2018) used Galvanic Vestibular Stimulation to apply electrical noise to the vestibular system. Improved tilt thresholds were found to occur in 78% of subjects. Both of these studies point toward the benefits of using in-channel noise.

Another interesting notion is "Cross-modal" SR or improving perception across one sensory channel by stimulating a separate channel with noise. The theory behind the mechanism is that SR can cause neural synchronization across different sensing modalities. It has been demonstrated that high levels of auditory white noise (~70 dB SPL) can improve visual (Lugo et al., 2008);(Manjarrez et al., 2007), tactile, and proprioceptive thresholds in humans (Lugo et al., 2008). The utility of using additive noise to help lower perceptual thresholds has been proven across many senses (visual, balance, tactility), but the evidence for helping with hearing is conflicting.

The current study discussed in this paper builds off of in-channel SR psychoacoustic studies performed on normal hearing subjects. The first to observe this was Zeng et al. (2000) where white noise, with a 13,080 Hz bandwidth, was administered alongside pure tones at 1 and 4 kHz. Their results showed enhanced threshold perception by about 2 dB SPL at a noise level equal to -15 dB/Hz spectrum level (spectrum level is a sound wave's intensity level within a 1 Hz band). Ries (2007) ran a similar experiment where he found improved thresholds between -35 to -30 dB/Hz range. Ries tested 2 kHz sine pure tones with a 12 kHz bandwidth. Contrary to Zeng, Ries found masking behavior as low as -20 dB/Hz. Since thresholds at 2 kHz are usually lower than 4 kHz in humans, this data suggests the optimal noise level is frequency dependent. Long et al. (2004) investigated the standard deviation of the additive noise applied to the signal in a forced choice auditory task. The standard deviation is a measure how far the noise deviates from the mean, where the mean is centered at the magnitude of the noise level. In order for there to be noise, there must be some variation from the mean; however, their results showed that too large of a variance provides little SR benefit. A standard deviation of 0.1 yielded the highest number of correct responses in all three of their testing conditions (suprathreshold, at threshold, and subthreshold). They clarify that stimuli substantially above or below threshold do not benefit from additive noise. While these experiments claim to have found SR, they give rather conflicting results. Ries found the ideal noise level to be lower than Zeng defined, and Ries masking at lower noise levels. Further evaluation into characterizing normal hearing SR via external noise presentation is needed.

SR could have promising benefits for individuals that have to use cochlear implants. The absence of hair cell Brownian motion makes the implant a relatively non-noisy environment, so neural firing is reduced. This has led to a plethora of research using additive noise to enhance implants. A wide range of researchers studied SR for cochlear implants, one of which was Zeng in his study previously cited in this paper. Zeng observed thresholds of different sinusoidal frequencies with and without the addition of electrical noise. Zeng states that "the signal and noise were delivered to the apical electrode using a voltage to current source". Electrical noise lowered auditory thresholds for low frequency stimuli (<300 Hz) and elevated auditory thresholds for high frequency stimuli (>300 Hz). They hypothesize this may be due to low-pass filtering in the auditory brainstem. Chatterjee & Robert (2001) also explored SR for subjects with cochlear implants. Using an implant research interphase, they applied stimuli directly to the implant's radio frequency transmitter. They then delivered "prosthetic noise" via arbitrary pulse combinations. Their results showed enhancement in modulation sensitivity for implant users. These results point toward the necessity of noise within the sensing organ when it comes to information processing, previously detailed in Section 2.2.

Many psychophysics experiments (auditory or otherwise) have reported having subjects that did not exhibit SR, while subjects who do benefit from noise see varied improvement from one another at different noise levels (Galvan-Garza et al., 2018);(Ries, 2007). This suggests that individual differences cannot be overlooked when trying to find the "optimal" level of noise. Therefore, there is a need to characterize individualized noise presentation to find SR.

2.4 Cochlear Mechanisms

When a sound is made pressure waves are collected by the Auricle and sent into the ear canal to displace the tympanic membrane (eardrum). This mechanically drives motion through the bones of the middle ear (the malleus, incus, and stapes), displacing the oval window of the cochlea. This causes pressure waves within the fluid filled scala, causing displacement of the basilar membrane. Inner hair cells are activated in response to the displacement of this membrane, neutrally encoding the information to be transmitted along the auditory nerve for processing in the brainstem and ultimately the auditory cortex of the brain. The cochlea is tonotopically organized and the sound frequencies dictate the location of the basilar membrane's maximum displacement. High frequency information is processed closer to the oval window, while low frequency information is processed towards the cochlea's apex. (Kandel et al., 2000). Thus analog sound waves are processed into meaningful information through neural encoding.

The cochlea is organized as a series of bandpass auditory filters, that enable noisy information with frequencies outside of the signal of interest to be ignored. Therefore, noise at one octave bandwidth centered at 1 kHz, has little impact on 8 kHz stimuli. This is detailed in Figure 4, where noisy frequencies significantly below or above the critical band of an auditory filter do not affect energy in the filter (Moore, 2012). SR benefits caused by colored noise have the potential to be lost as a result of these filters. Colored noise intensity is frequency dependent (e.g. pink noise has higher intensities at low frequencies), meaning that noise would have a hard time entering high frequency auditory filters. Broadband white noise ensures uniform noise transfer, and thus energy, into the auditory filters across the frequency spectrum. But there is reason to believe noise benefits in the auditory system are seen as an organ stimulation process as well, instead of being directly attributed to the signal.

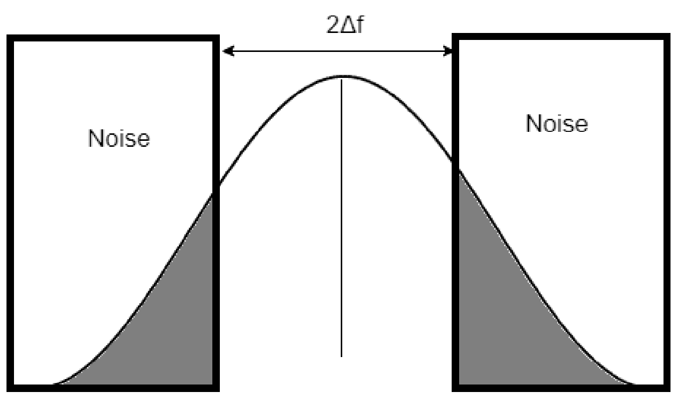

Figure 4. Visual Representation of the Auditory Filter Model. The vertical axis is power and the horizontal axis is frequency. Noise under the curve is included in the auditory filter, while noise outside of it is ignored by the filter. Broadband white noise ensures information transfer into most auditory filters. The filter's critical band is the middle, vertical line.

Hong et al. (2006) developed an auditory model to explain a potential mechanism for SR enhancement that went beyond adding energy to subthreshold signals. Previous models relied on information modulation to produce this effect; however, they propose the system itself adds energy to the signal by processing presented noise. The use of broadband white noise stimulates the entire cochlea, providing more energy to the auditory nerve and subsequently the signal. It can be seen that stimulation of the cochlear nerve complex provides increased energy through the auditory system and is a more promising mechanism for observing SR within the entire sensory pathway.

Similar to the example in Figure 2, it is expected that there is an optimal level of noise presentation to produce auditory SR, anything above that level will mask the incoming signal, and noise levels below that will not provide any benefit. Figure 5 is an arbitrarily developed SR curve to demonstrate how this is expected to be seen for thresholds in the auditory system.

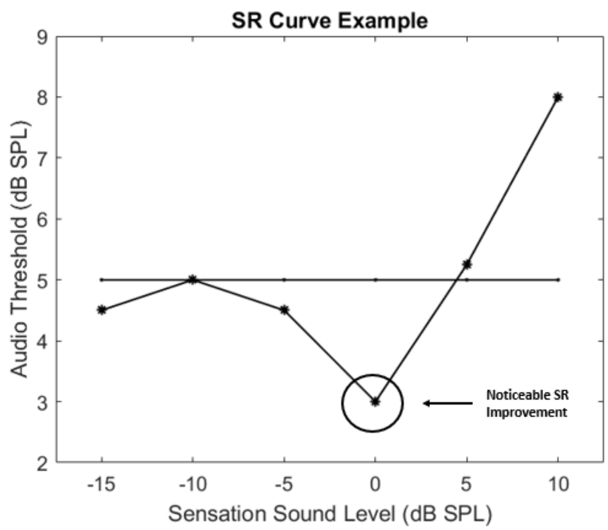

Figure 5: Arbitrarily developed SR curve example. The horizontal line marks the audiometric threshold without noise.

2.5 Summary

SR has been characterized as a signal quantization method, where noise is a catalyst to elevate nonlinear signals. Studies conducted on neurons and animals have found that SR can increase information transfer, while psychophysics experiments observed total sensory improvement utilizing SR. As detailed, there is an optimal level of noise to improve signal throughput and it appears to be individualistic. The study proposed will evaluate if a priori knowledge of an individual's threshold can be taken advantage of when finding the optimal level of noise to produce noticeable SR.

Chapter 3. EXPERIMENTAL METHODOLOGY

The utility of using white noise to improve auditory perception via SR was evaluated using the methodology defined within this chapter. Subjects were exposed to pure tone audiometry. Békésy-style tracking procedures were completed to evaluate audiometric thresholds. These thresholds were found with and without the addition of administered noise. These procedures were approved by the University of Colorado's Institutional Review Board, and all subjects signed a written informed consent form. The following sections detail the first optimization experiment performed.

3.1 Apparatus and Materials

Tests were completed in the Cognitive Neuroscience of Language Lab at the University of Colorado Boulder. Testing was completed inside an acoustic sound booth. Pure tone audiometry and white noise were presented through Sennheiser HDA 200 Audiometric Headphones using the Creare Hearing Assessment (CHA) system. Tests were operated and data was saved using the CHA's MATLAB Interface (CHAMI). Pure tones were presented for 250 ms with 25 ms duration ramps at the start and end of each tone. White noise was generated using the CHA's "white noise" setting, which presents uniform noise up to 20 kHz. Tones and noise were digitally mixed within the hardware and played in units of dB SPL for this study. The CHA and headphones are shown in Figure 6.

Figure 6: Visual image of testing equipment. The red cuff is placed on the right ear, blue on the left. Subjects hold the CHA during the exam and press down the blue button when they hear tones.

The desired noise level was inputted in units of dB SPL via the CHAMI interface (i.e. a setting the researcher can choose), this noise is defined as total power and not spectral power.

3.2 Subjects

10 (6M/4F) healthy subjects successfully participated in the study with a median age of 22 years old, ranging from 20-24. Subjects were invited to participate in the study if they were native English speakers and had healthy hearing. Healthy hearing was determined using the following procedures. All subjects completed two questionnaires related to their health and hearing history. These questionnaires examined history with loud noises, ototoxins, and disorders that have been linked to auditory processing. Participants were not allowed to participate if they had a history with ototoxins or participated in activities that caused noticeable hearing damage. It was up to the discretion of the experimenter to include subjects based on their hearing questionnaires. An otoscopic exam of the right ear canal was completed to evaluate external ear health. This was done to assess scarring, eardrum damage, or excessive earwax blockage. A tympanometry exam was performed in the right ear to evaluate external ear health and signs of middle ear pathology. Normal tympanometry results are defined as peak pressure between -100 daPa and +50 daPa, canal volume between 0.6 ml and 1.9 ml, and static admittance between 0.3 ml and 1.7 ml. Subjects also completed Békésy-style tracking procedures to confirm audiometric thresholds ≤25 dB HL up to 8 kHz. Failing to have healthy ear canals, normal tympanometry, or meet ANSI standards for normal hearing excluded subjects from participating, separate from researcher's discretion.

3.3 Independent Variables

There are two categories of independent variables in this study: The first is the presence of white noise mixed with the tones. The second is the dB level at which the noise is played. The magnitude of the white noise administered depended on the subject's audiometric threshold without noise for that frequency, relating to the hypothesis that the optimal level of noise to play is equal to the subject's auditory threshold for that frequency. The white noise levels tested ranged from -15 dB SPL below threshold to +10 dB SPL above threshold in 5 dB SPL increments.

3.4 Dependent Variables

Audiometric thresholds were the dependent variable for this experiment. Since hearing is a frequency dependent sensation with large differences in measured threshold by frequency, the thresholds were analyzed within the pure-tone frequency administered.

3.5 Tasks

Subjects completed a Békésy-style tracking procedure to determine audiometric thresholds with and without added noise. Figure 7 is an example of this procedure. Subjects are initially presented suprathreshold tones. The subject then holds down a button on the CHA, which decreases the intensity of subsequent tone presentations until the tone is no longer evident (subthreshold to the subject's auditory perception). The subject then releases the button and the tones increase in sound level intensity until the stimulus is detectable again. At this point the subject holds down the button again. One reversal is known as an excursion. The subject repeats this for 10 excursions to converge on their audiometric threshold. The step size of the tone presentation increased and decreased by 2 dB SPL.

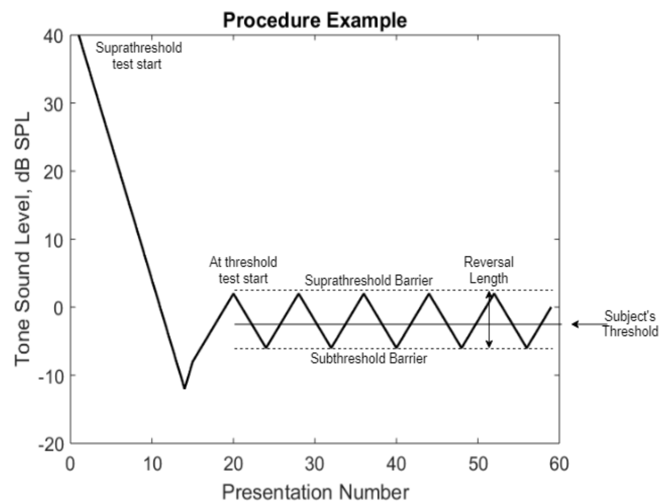

Figure 7: Békésy-style tracking procedure example

3.6 Experimental Procedure

This study was completed in one session over the course of 2.5 hours. All procedures were conducted in the right ear. Once it was determined that the subject met all of the inclusion criteria, thresholds without noise were measured at frequencies 0.5, 1, 4, 8, and 14 kHz. The thresholds were taken three times at each frequency and the average of the three exams was determined to be the subject's threshold at that frequency without noise. Table 1 displays the design of this procedure where the cells observe the number of trials (T) tested by the number of subjects (S). A total of 15 thresholds were taken from each subject in this procedure.

Table 1. Baseline Threshold Testing Matrix: Columns are ordered by frequency trial. The frequency trials were treated as independent tests. Three threshold runs (T) were completed by each subject (S) for each condition.

	500 Hz	1,000 Hz	4,000 Hz	8,000 Hz	14,000 Hz
No Noise	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$

Once baseline thresholds were established, new thresholds conducted with noise levels, ranging from -15 dB SPL subthreshold to +10 dB SPL suprathreshold, were measured. Subjects then completed the audiometry procedure with white noise added. Although the non-dynamical SR theory extends to all types of colored noise (e.g. pink, brown, etc.), broadband white noise was used in the present study, ensuring noise entered each of the auditory filter represented within the cochlea.

Noise intensity for each frequency depended on the subject's specific threshold (λ) without noise for each frequency. The noise ranged from -15 dB SPL below the threshold to +10 dB SPL above the threshold in increments of 5 dB SPL, ensuring the noise levels presented are below, at, and above the hypothesized optimal noise level. The frequencies were tested in a random order across subjects, and all conditions for any frequency were performed in a group. Subjects were given a one to five-minute break between frequencies to keep them alert and focused. This resulted in a total of 5 trials (one trial for each frequency). The six noise levels were presented in a random order. All conditions were tested three times to receive an average, totaling 18 threshold measurements for each frequency. These 18 runs were presented to the subject in a randomized order. Table 2 displays the design of this procedure where each row represents a different noise level presented with the tones. A total of 90 thresholds are taken from each subject in this procedure.

Table 2. Noise Threshold Testing Matrix: Rows are ordered by noise level, where λ is the subject's individual threshold and the columns are the frequency trial. The frequency trials were treated as independent tests. Three threshold runs (T) were completed by each subject (S) for each condition.

	500 Hz	1,000 Hz	4,000 Hz	8,000 Hz	14,000 Hz
λ-15 dB SPL	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$
λ-10 dB SPL	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$
λ-5 dB SPL	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$
λ dB SPL	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$
λ+5 dB SPL	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$
λ+10 dB SPL	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$	$3\ (T) * 10\ (S)$

3.7 Data Analysis

The metric of interest was the difference between subject baseline thresholds (T_B) and the thresholds with noise (T_N) at each condition tested across each frequency observed. The differences are calculated using Equation 1. We hypothesize that subthreshold and at-threshold noise level differences will be predominantly negative, suggesting SR and suprathreshold noise level differences being positive, suggesting masking.

$$D = T_N - T_B \tag{1}$$

A repeated measures ANOVA test will confirm any statistical significance between the test treatments. The average of each replicate test condition will be used for analysis. If significance is found, a Tukey HSD post hoc test will confirm which of the treatments is most significant. A paired t-test will also be conducted to identify if there is a difference between 0 dB SPL and the differences created by hypothesized optimal noise level (i.e. if there is a statistical difference between the difference values and a null result of no change).

Chapter 4. THRESHOLD OPTIMIZATION STUDY

The hypothesis is that adding white noise to a stimulus will improve the listener's ability to hear that stimulus at subthreshold intensities. Figure 8 provides a refresher on the SR curve anticipated from subjects, where a Sensation Sound Level (SSL) of zero is equal to the subject's threshold without noise (at threshold); therefore, negative SSLs are subthreshold and positive SSLs are suprathreshold. SR is noticed when the addition of noise results in lower auditory thresholds than the thresholds without noise, suggesting increased signal throughput to the subject has been achieved. It is expected that a zero SSL noticeably improves auditory thresholds, negative SSLs to provide little threshold improvement, and positive SSLs to mask the stimuli.

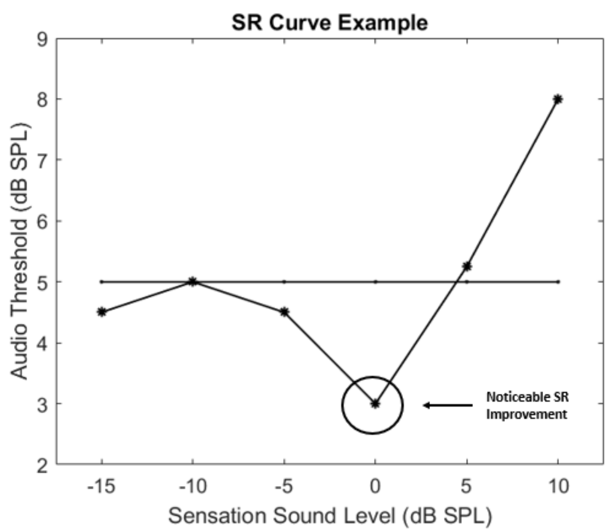

Figure 8: Expected SR Curve

A few subjects (the number should be no greater than 1 in 3) may not exhibit SR. This is noted because previous experiments have detailed finding SR in most subjects, but not all (Henry, 1999);(Ries, 2007);(Galvan-Garza et al., 2018).

4.1 Threshold Optimization Study Results

While the SR curve in Figure 8 was expected across subjects, individual differences were found across the test. Figure 9 is an example of one subject's response to the treatment (chosen at random). While conclusions cannot be determined from one subject's performance, high variability was found between the subjects, some exhibiting improved thresholds as a result of noise addition, others not. SR curves for all 10 subjects can be found in Appendix A.

An in-depth description of this plot collection is as follows:

The first five plots correspond to the subject's SR curve at each frequency. The solid horizontal dash represents the subject's mean threshold without noise at that frequency. The dotted horizontal line provides a reference of that threshold for comparison simplicity. The solid curves are the mean thresholds at the white noise SSLs tested. Each asterisk is a single threshold found at that SSL. An SSL of 0 is the white noise magnitude equal to the subject's threshold without noise at that frequency. The final plot explores the difference between the threshold without noise and the 0 SSL threshold at each frequency. Negative differences imply the noise improved auditory perception.

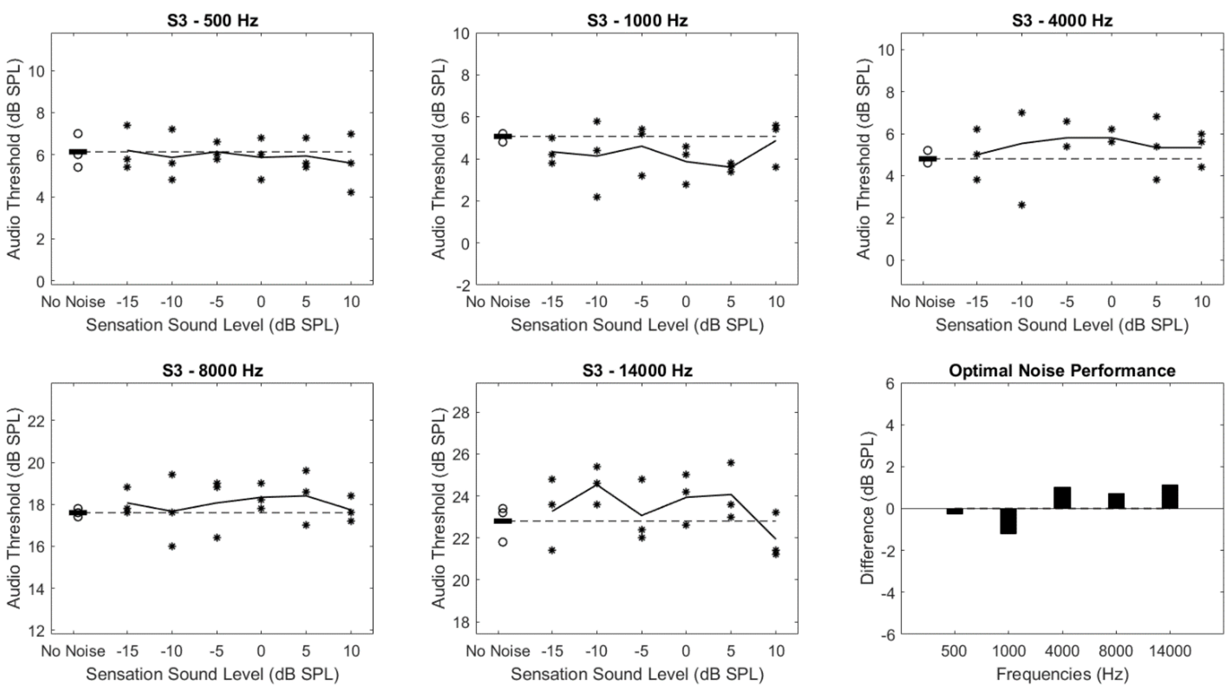

Figure 9: Example of one subject's SR performance. The first five plots are their SR curves for each frequency, the last being their performance using the hypothesized optimal level of noise.

The example for Figure 9 was chosen at random, but the following figures illustrate variability between subjects. Figure 10 displays results from the subject most likely to exhibit SR benefit, while Figure 11 displays results from the subject least likely to exhibit SR benefit.

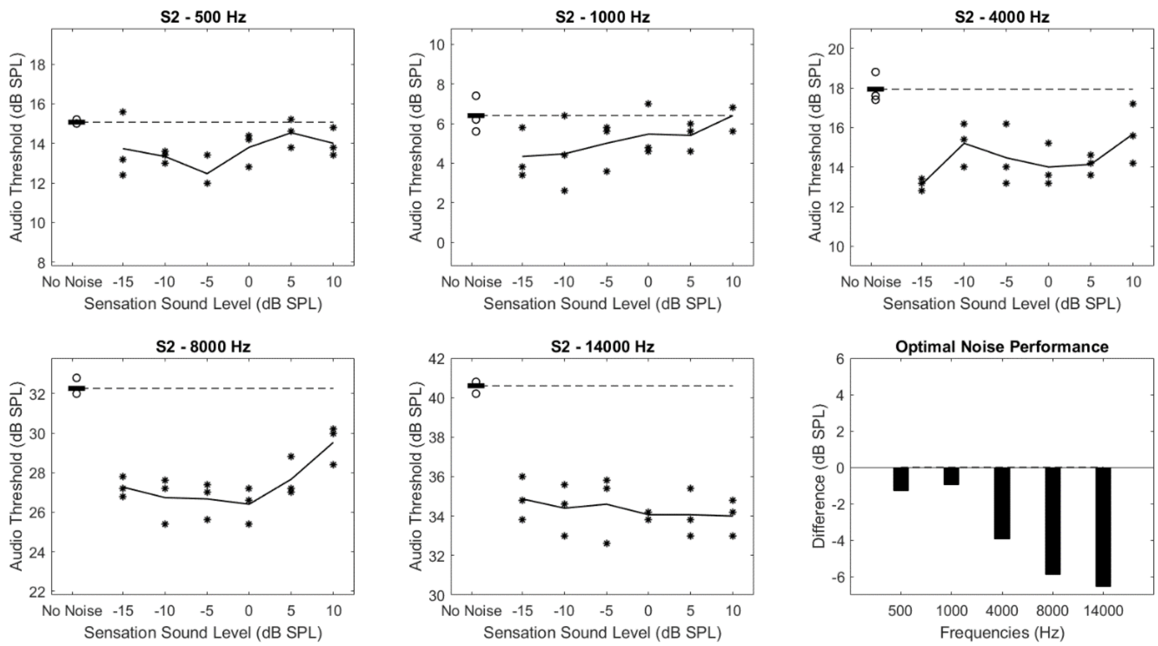

Figure 10. SR performance from the subject most likely exhibiting SR benefit.

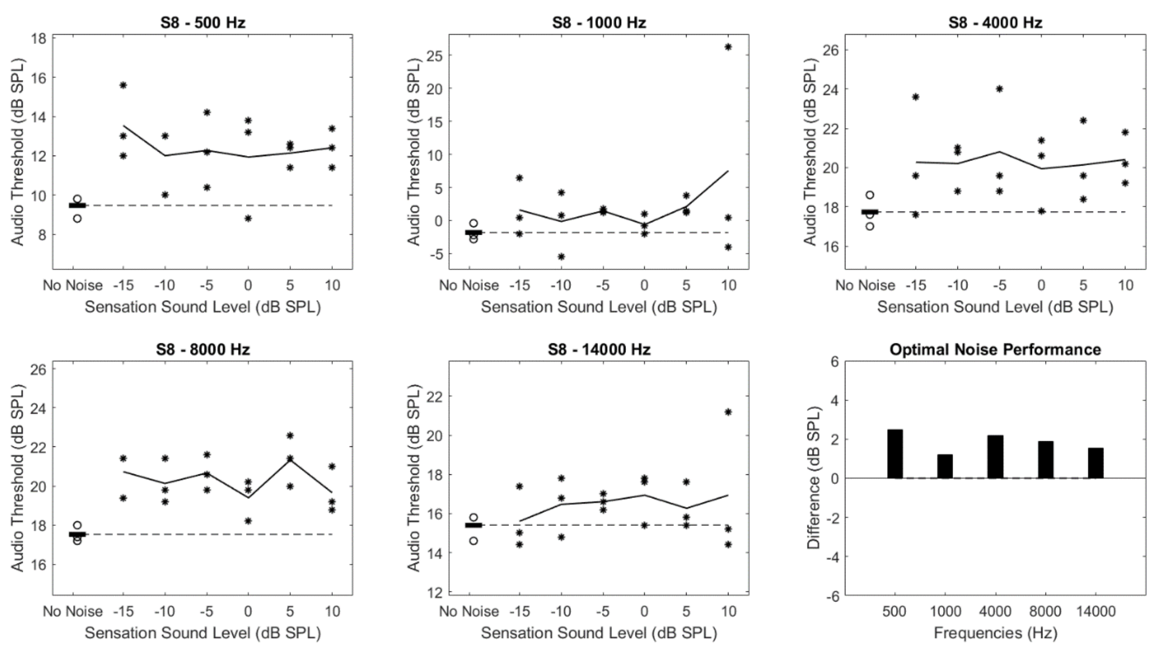

Figure 11. SR performance from the subject least likely exhibiting SR benefit.

While it is anticipated that a few subjects would not exhibit SR, it seems that a majority of the subjects did not. The results appear to be variable between subjects and their tested frequencies. Table 3 documents whether noise appeared to improve thresholds for individual subjects, listing the frequencies where those improvements were seen. It also details whether noise worsened thresholds or if it is too ambiguous to tell. This table is developed by qualitative observance, evaluating the frequency trials independent of one another. The researcher would deem that noise improved thresholds if the SR curves were sufficiently below the baseline threshold, and that thresholds were worsened if the SR curves were sufficiently above the baseline threshold. If the SR curves were localized around the baseline threshold, it was deemed uncertain.

Table 3. Individual Threshold Comparison: Rows are based on subject and columns are based on whether noise impacted thresholds compared to baseline. The phenomena this occurred is detailed by frequency trial. Subjects and frequency trials are treated as independent.

Subject	Improved Thresholds	Worsened Thresholds	Uncertain
1	-	1, 4, 8, 14 kHz	0.5 kHz
2	0.5, 1, 4, 8, 14 kHz	-	-
3	1 kHz	4, 8, 14 kHz	0.5 kHz
4	-	0.5, 1, 4, 8, 14 kHz	-
5	-	1, 14 kHz	0.5, 4, 8 kHz
6	-	1, 4 kHz	0.5, 8, 14 kHz
7	-	0.5, 1, 4, 8 kHz	14 kHz
8	-	0.5, 1, 4, 8, 14 kHz	-
9	0.5, 1 kHz	4, 8 kHz	14 kHz
10	0.5, 1, 4 kHz	14 kHz	8 kHz

The results defined in Table 3 imply that treatments had an insignificant effect, demonstrating high variability between subjects and frequencies. In a large amount of cases, noise worsened thresholds but in many it seemed to have no effect. While the results appear inconclusive qualitatively, a quantitative analysis was completed for the threshold differences. This was completed in the following manner: Across subjects, three thresholds were collected at each noise level for a given frequency. The mean of these noise thresholds was then compared to the subject's threshold mean without noise. The difference between the two measures was calculated and pooled across all subjects for each noise level. This aggregated data allows for the quick evaluation of global trends. Figure 12 illustrates the results of these pooled differences.

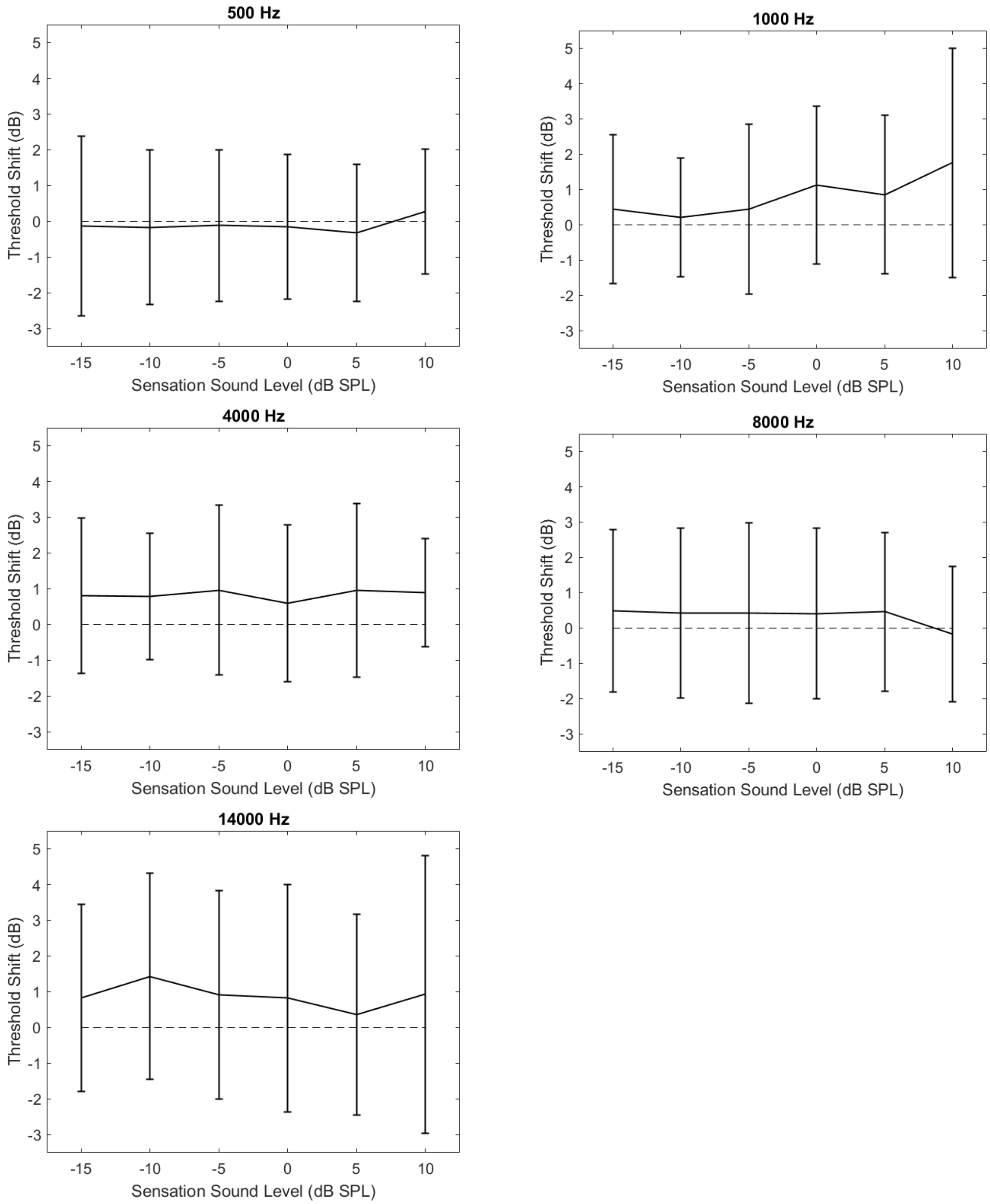

Figure 12: SR curves across pooled subjects. The line plot represents the average difference across the pooled subjects, the error bars are the standard deviations of the differences from the averages.

Negative differences imply the noise level may have improved thresholds, positive implies worsened thresholds.

Figure 12 and Table 3 demonstrates that the results appear insignificant and the treatment may have had no effect. The variability in differences is substantial and the differences are localized around zero, suggesting a small effect size. As Figure 8 previously showed, the expected SR curves would have negative differences for subthreshold and at threshold noise levels (the lowest being at threshold) with positive differences at suprathreshold levels, where masking is expected to occur. With the exception of 500 Hz, every frequency had positive differences across most noise levels presented. Positive differences could imply that the noise masked the tones instead of making them more prominent, suggesting that the tested noise levels were too loud or out of the range for SR enhancement.

As described in Section 3.6, a repeated measures ANOVA across the treatments was conducted, as well as, a paired t-test between the baseline and hypothesized optimal. Table 4 shows the results for each frequency. No statistical differences were found.

Table 4. Threshold Optimization Study Statistical Results: An RMANOVA was completed to identify whether the differences across the noise level treatments contrasted significantly. A paired t-test analyzed differences for the optimal level of noise. The frequency trials were tested independent from one another.

Frequency (Hz)	F(6,54) value	F test p-value		t(9) t-value	t test p-value
500	0.34	0.91		0.23	0.82
1000	2.27	0.05		-1.60	0.14
4000	0.97	0.45		-0.87	0.41
8000	0.55	0.76		-0.54	0.60
14000	0.77	0.59		-0.81	0.43

4.2 Discussion

To elucidate potential confounding factors contributing to the null findings, an investigation was completed on the noise levels tested, experimental design, and signal presentation.

4.2.1 Level at which noise was administered

One possible confounding factor could be the level of noise presented to the subjects. For discussion simplicity, the findings from Zeng and Ries are converted to dB SPL from spectrum level using Equation 2 and the white noise bandwidth used within these studies.

$$dB\ SPL = \frac{dB}{hz} + 10\log(BW) \tag{2}$$

Zeng found an ideal noise level across subjects to be approximately 26 dB SPL for a 4 kHz stimuli. However, they had also observed slightly improved thresholds at noise levels lower than 26 dB SPL, implying the Threshold Optimization Study should have seen some threshold improvement at noise levels lower than 26 dB SPL. Ries suggested between 6 and 11 dB SPL was optimal for a 2 kHz stimuli. The current results for the low frequency stimuli conditions (.5, 1, & 4 kHz) did not observe notable SR effects below an SSL of 0 or below the optimal noise levels detailed by Zeng and Ries. Even if optimal level of SR was not found using the Threshold Optimization Study's noise levels, some SR should have been identified. While it cannot be confidently stated that replicating the noise levels in past studies would yield SR given the current experimental setup. However, testing fixed noise levels (independent of subject threshold) presented in previous studies may shed light on the utility of using increasingly suprathreshold noise given that our study found no significant threshold increases for the positive SSLs tested.

4.2.2 Methodology by which auditory threshold was determined

Auditory thresholds are variable and subject to changing due to fatigue, frequency, and even previous sounds (Yoshida et al., 2007). These factors were evaluated to determine if they were issues in this study. Figure 13 shows the standard deviation, duration to complete the Békésy procedure, and the average reversal lengths of the procedure (refer to Figure 7 for a visual representation of reversals) across frequencies and trial number (1 being the first frequency trial tested, 5 being the last). This figure's standard deviation measurement is the mean of the standard deviations taken at each subject's threshold for a given sound level, across the trial.

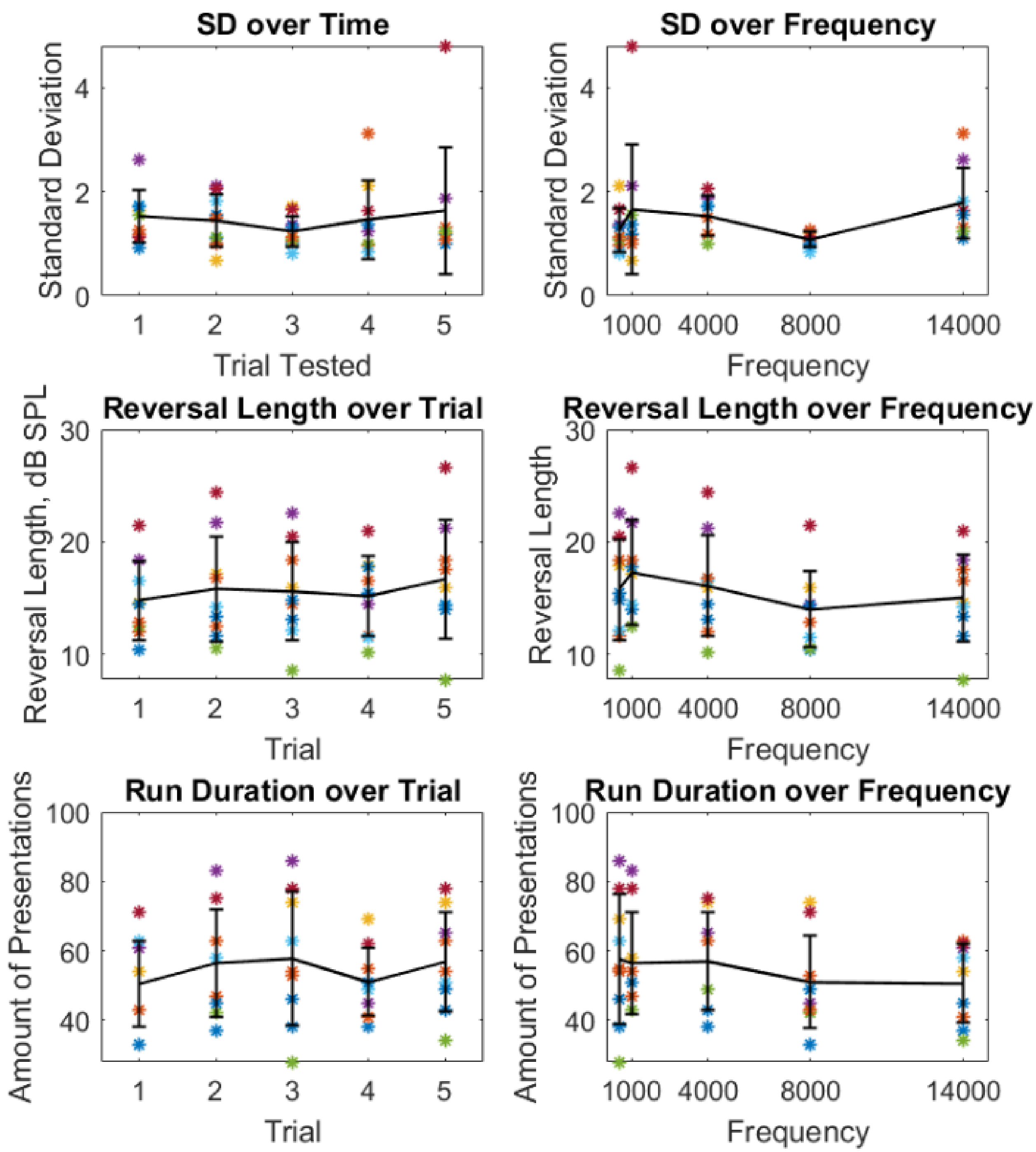

Figure 13: Observing the Békésy procedure performance across the trials and frequency tested. Top two: The average standard deviation of the subject's threshold at all noise levels for a given trial (variability in reported thresholds). Middle two: The average number of presentations it took

the subject to converge on their threshold (length of time to determine threshold) across all runs of a trial. Latter two: The average length of the Békésy reversals (how tight the response was centered around the threshold) across all runs of a trial. Error bars represent the standard deviation of the results away from the mean.

The collection of plots suggests there is no correlation between Békésy procedure performance and the time or frequency of the presented trials. An RMANOVA was performed across the trials and frequencies to identify if any levels were different from the others. The results of this RMANOVA are found in Table 5. It should be noted that Subject 1's reversal data was not complete and not included in the statistical analysis.

Table 5. Threshold Determination Statistical Results: An RMANOVA was completed for every Békésy performance parameter.

Békésy Parameter	F(4,32) Value	P Value
SD over Time	0.43	0.79
SD over Frequency	1.9	0.14
Reversal Length over Time	0.93	0.46
Reversal Length over Frequency	3.4	0.02
Run Duration over Time	1.5	0.23
Run Duration over Frequency	1.4	0.25

5 out of the 6 procedure parameters failed the Omnibus F test, confirming that no trial or frequency level is different than the others. There does appear to be a difference in reversal length for frequency though. A Bonferroni pairwise comparison evaluated the levels in this specific performance parameter. It was found that the frequency levels of 1 and 8 kHz were statistically different from one another ($p<0.05$), no other comparisons were significant. Even those these two frequencies are statistically different, it is difficult to state that there is an effect of frequency of reversal length performance as none of the other frequencies are different from one another. Considering most of the procedure parameters failed the Omnibus F test and the one that passed only differed between two frequencies, any effects due to fatigue or tested frequencies can be ruled out as possible causes for testing errors.

As a brief aside, psychometric curves were fit to some of the Békésy staircase results, in hopes of identifying more accurate thresholds. The variable of concern were the pure tones in the staircase. A score of 1 was given to tones that were heard (decreasing reversals) and 0 was given to tones that were not heard (increasing reversals). The tone level that resulted in a 0.5 score within the psychometric curve was determined to be the threshold. These thresholds were fairly close to the ones produced by the Békésy staircase, so the researcher chose to stick with the Békésy thresholds because of improved data filtering techniques (like consistent reversal identification) within the CHA for determining these Békésy thresholds.

4.2.3 Analyzing acoustic mixing

Previous psychoacoustic studies (Zeng et al., 2000);(Ries, 2007), including this Threshold Optimization Study, have digitally mixed the white noise signal with the stimuli within the software prior to presentation. At first, the research team theorized this may not be the appropriate delivery method for mixing the noise with the stimuli. SR is a method of improving signal quantization and understanding analog signals. Therefore, presenting separate analog signals may stimulate the information processing organ to a higher degree than one complex acoustic signal. Previous animal studies have stimulated their system with separate stimuli and noise signals (Henry, 1999);(Collins et al., 1996); however, some animal studies have also found SR while stimulating their system with one digitally mixed signal (Jaramillo & Wiesenfeld, 1998). Prior experience with Distortion Product Otoacoustic Emission (DPOAE) mapping led the team to believe acoustically separate signals may have improved resonance, creating a harmonic that improves comprehension of the mixed signal along the auditory pathway. DPOAEs are a measure of outer hair cell health and are created by presenting two separate tones (with different frequencies). The tones interact, creating harmonics at their distortion product (Kemp, 2002). Since in the DPOAE technique acoustic mixing is critical, it was conceived that sound pressure wave mixing may also be crucial for SR application where the interaction of the noise and underlying signal is what creates the improved thresholds.

This method of sound administration may improve aural harmonics and deviates from the experimental methodology of previous psychoacoustic SR studies. The two signals will be presented ipsilaterally by modifying the sound administration protocol using a DPOAE probe. One channel of the probe presents the tone and another presents the white noise at the desired level.

4.3 Conclusion

SR was not observed across the ten subjects in the current experimental design. While fatigue and frequency could have been factors in this null finding, threshold collection performance was not affected by these factors. The sound delivery methods and noise levels tested were discussed as well. The researcher chose to acoustically mix the noise and stimuli signals for the future Protocol Development Study. No strong evidence suggests this technique will improve energy delivery to the system, but this delivery method better represents the paradigm described in Figure 1. Overall, the results did not exhibit the desired shape, as shown in Figure 5, where low levels of noise do not change the threshold, SR levels of noise improve thresholds, and high levels of noise mask the signal. Moving forward the researcher decided to expand the noise envelope to discover the results that other researchers had found. This may result in finding noticeable SR or identify masking. Masking is important because it confirms anticipated results which provides confidence that the experimental protocol is correct. The current results find no significant masking at suprathreshold noise levels. Past research conducted by Zeng and Ries identified masking with suprathreshold noise (~30 dB SPL). While increasing the noise magnitude may not produce detection improvement, it should produce masking, creating a curve that resembles the one found in Figure 5, which the researcher was not able to observe. The preliminary results to investigate these protocol changes are presented in Chapter 5.

Chapter 5. PROTOCOL DEVELOPMENT STUDY

The researcher conducted a protocol development study on four team members to replicate SR behavior found in previous psychoacoustic studies. The following section details the experimental methodology and results behind these tests.

5.1 Experimental Methodology

Four lab members (2M/2F) were tested under the new procedure. One of the participants was the author of this thesis. The objective of this preliminary work was to investigate the protocol issues identified in Chapter 4. In this study, the procedure was revised in two ways. First, the procedure tests additional suprathreshold noise levels to achieve the curve demonstrated in Figure 5. Second, the stimulus and noise are acoustically mixed within the ear canal. Note that because this was a protocol development study, the first two subjects completed the testing with the noise levels defined in Chapter 3, as well as the noise levels used by Zeng (16 dB SPL to 41 dB SPL in increments of 5 dB SPL). The results from these subjects dictated the noise levels presented to the remaining two subjects. This was done to reduce testing time caused by overlapping noise levels which will be discussed in section 5.2. All inclusion and threshold testing were conducted in the right ear.

The screening process was similar to the one outlined in Chapter 3. All test subjects had normal hearing and healthy external ears. It should be noted that Subject 3 did not exhibit normal tympanometry, but since the subject had normal hearing and this study was for initial protocol development, this subject was still tested. Subjects were native English speakers with no reported hearing or brain damage.

Auditory thresholds were found using the Békésy-style tracking procedure with and without noise. Since acoustic sound mixing was done, the sound was administered with a DPOAE probe rather than the over ear headphones used in the first study. The probe has two speakers. One speaker of the probe presented the stimuli and the other presented the white noise. To ensure proper placement of the probe, prior to testing subjects were fit with a custom earmold that the researcher used to hold the DPOAE probe in place. Figure 14 is an image of this interface. The probe is placed in the earmold and the earmold is fixed into the subject's concha (just outside the ear canal). Passive noise attenuating headphones were placed over the ears and probe to ensure the stimulus and noise administered by the probe were isolated. A chirp test was then completed to determine proper placement of the probe within the ear. The chirp test provides a frequency sweep to the ear canal and records the feedback amplitude. Consistent probe placement was confirmed by completing a chirp test every time the probe was removed and inserted back into the canal. Comparing to the baseline, the test operator ensured a tight seal within the ear and minimal bending of the sound delivery tubes. Figure 15 shows a representative example of the chirp frequency response, comparing the baseline to a noise test.

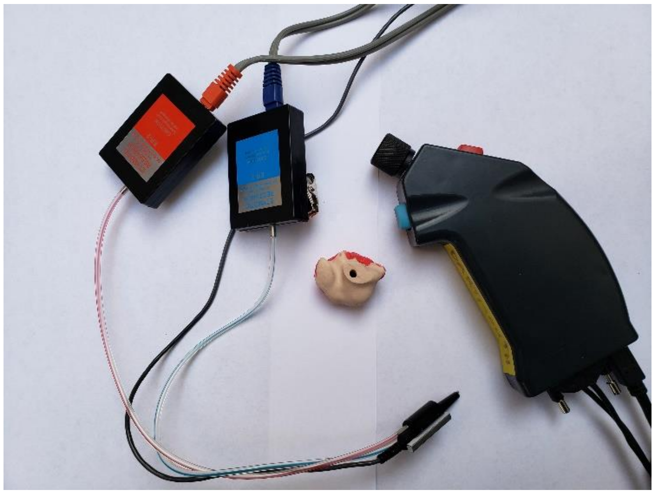

Figure 14: DPOAE probe and custom ear mold

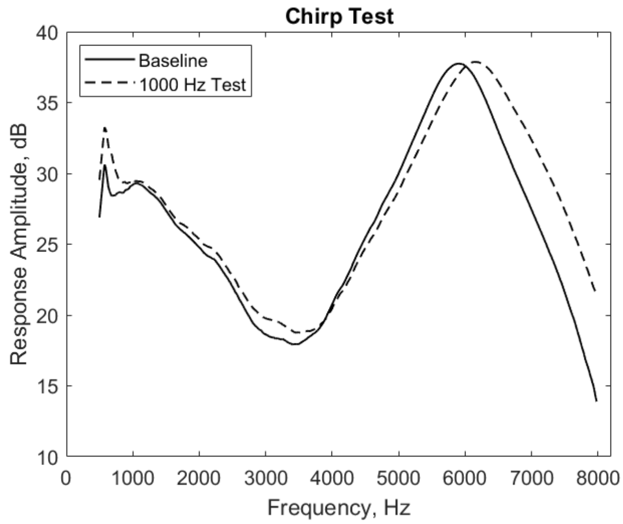

Figure 15: Chirp frequency response example

The frequencies tested were 1, 4, and 8 kHz. The other two frequencies from the first study were excluded for the sake of time. Baseline thresholds without noise were taken three times at each frequency to find an average baseline value. Subjects were then asked to complete audiometry with the addition of noise, completing three tracking procedures at each noise level. In general, the noise levels administered varied in 5 dB SPL increments from -5 dB SPL to 40 dB SPL. All tests for a given frequency were tested as a set of measures, but the frequency trial order was randomized. The specific noise levels and frequency trial order for each subject is detailed in Table 6. The noise levels presentation order was also randomized, and the subjects were blinded to which noise level was being played. Subjects were allowed to take breaks between the frequency trials; however, a chirp test was completed every time the probe was removed and inserted to ensure proper placement.

No statistical tests were completed on the following data set because of the small sample size and differences in protocol between the first two and last two subjects. Only qualitative evaluations were done into identifying the presence of the hypothesized SR curve for the four subjects (i.e. to investigate whether or not the threshold patterns matched that of Figure 5). It was predicted that testing suprathreshold noise runs with increased white noise magnitude would provide the stimulus masking, as expected in the SR curve. It was also predicted that low levels of noise would have no impact on threshold, while levels of noise near threshold would produce SR benefits. The following section details the results from this experiment.

Table 6: Noise and Frequency Information for Protocol Development Subjects. Subjects 1 and 2 completed testing at noise levels defined by the Threshold Optimization Study and by Zeng, hence the multiple noise level entries. Subjects 3 and 4 completed testing using the same noise levels.

Subject	Frequency Order, kHz	Noise Levels, dB SPL			
		Opt 1 kHz	Opt 4 kHz	Opt 8 kHz	Zeng
1	4, 8, 1 & 1, 4, 8	-5, 0, 5, 10, 15, 20	-0.5, 4.5, 9.5, 14.5, 19.5, 24.5	0.5, 5.5, 10.5, 15.5, 20.5, 25.5	16, 21, 26, 31, 36, 41
2	4, 1, 8 & 1, 4, 8	-8, -3, 2, 7, 12, 17	-7.5, -2.5, 2.5, 7.5, 12.5, 17.5	3, 8, 13, 18, 23, 28	16, 21, 26, 31, 36, 41
3	4, 8, 1	-5, 0, 5 10, 15, 20, 25, 30, 35, 40			
4	8, 4, 1	-5, 0, 5 10, 15, 20, 25, 30, 35, 40			

5.2 Results

The first two subjects completed testing in two sessions, using the noise magnitudes defined by the Threshold Optimization Study protocol (which provided more subthreshold noise levels) and the noise magnitudes defined by Zeng (which provided more suprathreshold noise levels). Both of these noise protocols were done using the acoustic mixing procedure. Figure 16 displays the SR curves found for these two subjects. Subject 1's results are the three left plots within the figure and Subject 2's results are on the right. These tests were completed on two separate days; therefore, baseline thresholds were taken on both days. The bolded dash is the average of these six individual baseline thresholds. The curves are split to show the threshold response to the noise levels defined by the Threshold Optimization Study (left) and by Zeng's study (right), these noise levels are previously detailed in Table 6. It should be noted that Subject 2 was the author.

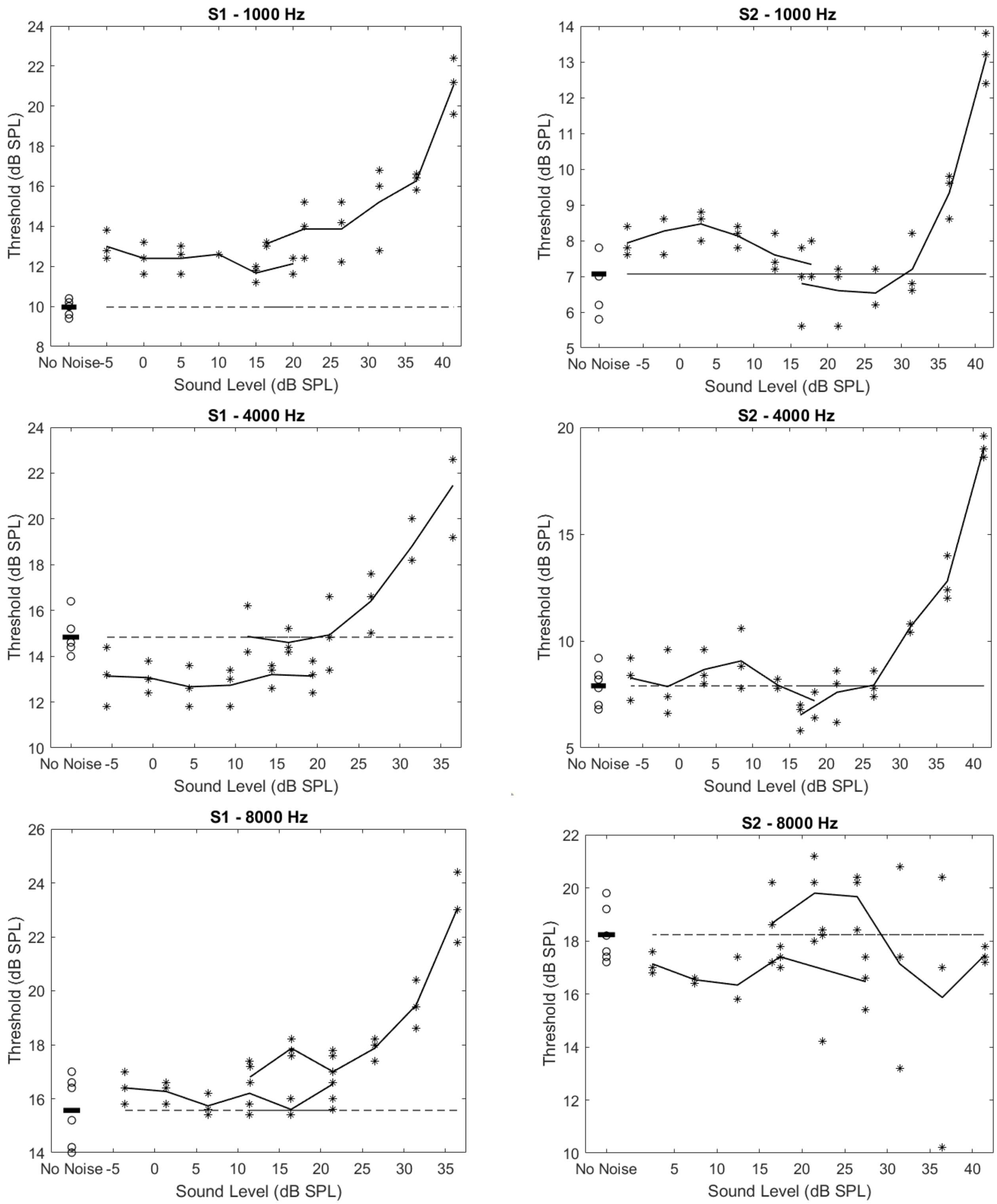

Figure 16: SR curves observed using Optimization's and Zeng's noise. The left curve in each plot is a result of using noise levels defined by the Threshold Optimization Study, the right curve in each plot is a result of using noise levels defined by Zeng's study.

While prominent SR is not identified in Figure 16 for these two subject's, the curves appear to be more indicative of the behavior expected for an SR curve. The case can also be made that slight SR is seen for Subject 2, as the curve dips below the average without noise. This lowered threshold is small in effect size relative to the baseline, and the uncertainty in threshold measurements may make this difference insignificant. However, it is still promising in the fact that the noise had not worsened thresholds as was seen in most subjects who participated in the Threshold Optimization Study. For both subjects, low level noise has a small impact on auditory thresholds, then at some suprathreshold noise level, auditory thresholds are noticeably worsened and continue to worsen with noise increases. This phenomenon is observed for both subjects across the frequency spectrum, except for Subject 2 for an 8 kHz stimuli. While improved thresholds via SR were not identified as found by Zeng, noticeable masking was found using these higher noise levels.

Two additional subjects were tested based on the results of the first two. It was determined that presenting noise as low as -5 dB SPL has little impact on thresholds and providing noise as high as 40 dB SPL provides definitive masking. Therefore, the noise levels presented ranged from -5 dB SPL to 40 dB SPL in 5 dB increments. Baseline measurements were taken twice to total six thresholds. Subject 4 only had three baseline measures recorded, so the Subject's accepted baseline is the average of three thresholds. Also, during with Subject 4's test, the CHA became disconnected during the 8 kHz trial. The subject took a brief

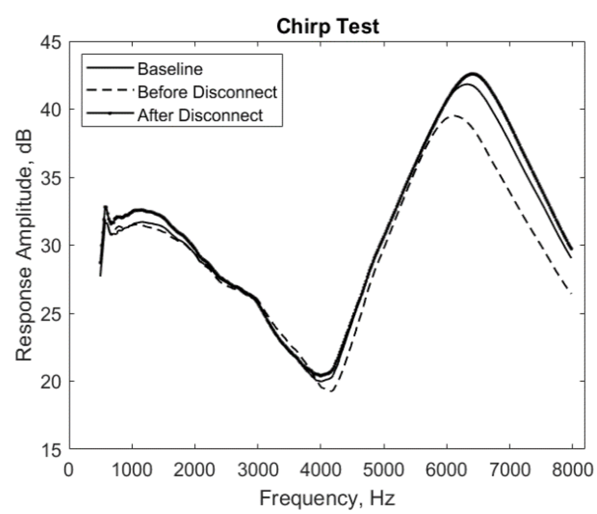

Figure 17: Subject 4's chirp results

break while the researcher reconnected the CHA. The remaining noise levels were tested but thresholds after this break were 3-5 dB lower on average. This is most likely the result of improper probe placement for the first test. Figure 17 compares the chirp results for the baseline, before disconnection, and after disconnection. The 3 dB response difference at 8 kHz imply inhibited sound delivery. Therefore, Subject 4's 8 kHz are excluded from the study. All SR curves and their associated chirp results are found in Appendix B.

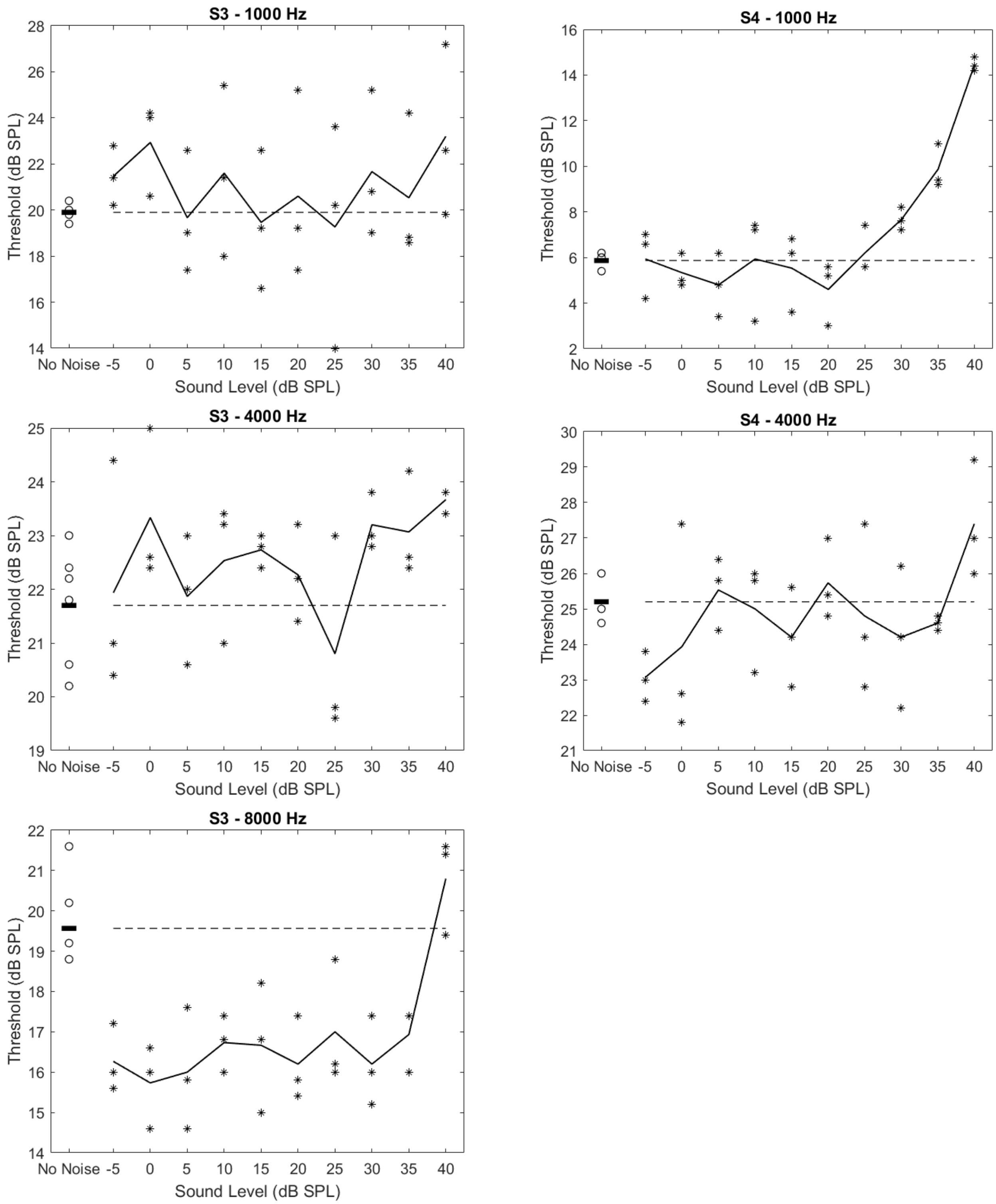

Figure 18: SR for Subjects 3 and 4. Subject 3's responses are found in the plots to the left, while Subject 4's data is to the right. These results were taken over a wide noise envelope. Subject 4's results at 8 kHz are excluded from this figure.

The results from Subjects 3 and 4 are relatively inconclusive. Subject 3 appears to have lowered and worsened thresholds at most noise levels tested for 1 and 4 kHz, producing curves that do not indicate SR improvements or resemble the steep increase in masking for higher noise levels. Subject 3 has improved auditory thresholds for most noise levels tested at 8 kHz with worsened thresholds at 40 dB SPL. This is not indicative of the predicted SR curve since low level noise thresholds are not near the subject's threshold without noise, even though it would appear noise does help Subject 3 at this frequency. The results for Subject 4 at 1 kHz resemble the expected SR curve where low level noise produces thresholds close to baseline, the threshold receives benefit with noise at 20 dB SPL, higher noise levels then begin to produce noticeable masking. This behavior was not present for the 4 kHz trial. While SR may be observed in two of the curves, threshold variability seems relatively high compared to the variability seen in Subjects 1 and 2. The traditional curve is only present for Subject 4 at 1 kHz for the five curves shown in Figure 18. Further protocol development is necessary before advising SR testing on additional subjects.

5.3 Discussion

Four subjects found their auditory thresholds with and without the presence of noise. Noise benefits could be present in some of the curves, but the uncertainty (considering the spread of the three individual thresholds for the treatments) between baseline and the improved threshold measurements of these curves overlap, so it cannot be definitively concluded that SR was found. There is a stronger case for the successful identification of masking though.

Masking only occurred in some of the trials, indicating that the noise may not have been administered at sufficiently elevated levels at all frequencies and for all subjects. This is important because by demonstrating masking, interactions between noise and thresholds are confirmed, since

SR benefits are anticipated just before masking begins. Lower baseline thresholds (<20 dB SPL) seem to allow for the identification of masking with the noise levels that were administered for this test. This loosely ties in with the second research aim and hypothesis. The SR curve is hypothesized to be a frequency dependent phenomenon. Strong masking may not be observed for Subjects 3 and 4 since their baseline thresholds are relatively high; however, if higher noise magnitudes were tested, noticeable masking might be observed. Testing with additional subjects and varying suprathreshold noise levels, dependent on their baseline, would have to be conducted before any conclusions are made.

The new experimental protocol induced masking of the traditional SR curve for some frequency trials across three of the subjects tested but was unable to find noise levels that enhanced auditory perception to a noticeable degree. The use of acoustic mixing also seemed to have little effect in inducing strong SR, but the results in this study are closer to resembling the results found in past psychoacoustic SR studies. The Threshold Optimization Study had, on average, worsened thresholds at every noise level tested, even subthreshold noise levels. But a few of the results for this protocol development study, thresholds at low noise levels are closer to the baseline and stay close to the baseline until some substantially suprathreshold noise level. This could suggest the utility for using acoustic mixing. Although SR was not strongly identified in either study, the Protocol Development Study had more promising results compared to the Threshold Optimization Study. The following chapter discusses the limitations of the current protocol and the path forward in auditory threshold testing.

Chapter 6. CONCLUSION

The following conclusions are a discussion on the studies conducted. New hypotheses and future work are identified based on the conclusions from the Threshold Optimization Study and the protocol development study presented in this work. The challenges in observing in-channel auditory SR are also identified.

6.1 Threshold Optimization Study

This study aimed to find in-channel SR by varying noise centered on subject specific threshold into the subthreshold and suprathreshold noise levels, to identify the optimal level to present noise. This study hypothesized that the optimal level of noise to produce noticeable auditory SR would be equal to the subject's threshold for that frequency (Morse & Roper, 2000). Ten subjects completed the Threshold Optimization Study under the testing protocol described in Chapter 3. The results of this study were inconclusive and the noise failed to have an effect as determined by an RMANOVA and a paired t-test.

Differences between individuals could be an issue in identifying SR. The research team attempted to control for this with strict inclusion criteria; however, there was a wide response range to the treatments tested where some subjects saw improvement and others did not. Previous psychophysical studies document that the optimal level of noise depends on the individual (Galvan-Garza 2018);(Groen & Wenderoth, 2017). Therefore, it would be expected that a small percentage, approximately 1/3 of subjects tested may not see improvement due to noise. Even with this caveat, most subjects had worsened thresholds as a result of additive noise at all levels. Therefore, this study only further highlights the challenges and variability across methodologies in the auditory SR research field for normal hearing subjects. The results of other researchers were not replicated.

An analysis of the Threshold Optimization Study was completed to elucidate potential confounding factors the resulted in the null finding. A discussion of previous psychoacoustic SR studies was given and additional noise levels were added to the testing envelope as a result. An RMANOVA determined that fatigue and frequency did not influence subject's performance in collection thresholds. Finally, the sound delivery method was called into question and the use of acoustic sound mixing was incorporated into the experimental methodology. These design changes were implemented and a following protocol development study was conducted.

6.2 Protocol Development Study

A second study to iterate on the experimental protocol was completed with members of the research team. In this study, the emphasis was on achieving the full SR curve, including masking, to ensure a broad range of noise levels were tested, and therefore would assist in ensuring the optimal SR level of white noise was tested. An acoustic mixing delivery method was also utilized in hopes that it would improve aural harmonics, assisting with auditory perception. Four subjects completed testing with the modified protocol. Upon qualitative examination, SR may have only been exhibited in one subject at two frequencies. A total of four trials did not exhibit masking. This was particularly true at 8 kHz where only Subject 1 had strong masking. Likely, this is because the thresholds at that frequency are higher. Therefore, the envelope at which noise was administered should have been expanded. Of those trials that exhibited masking three did not exhibit SR. In these subjects, noise did not elevate thresholds across all noise levels administered, unlike the Threshold Optimization Study. This is potentially important in that the only difference this could be derived from is the use of acoustic mixing, as opposed to digital mixing used in the first study. This would imply further experimental protocol changes must be implemented to find SR.

6.3 Limitations and Recommendations

Previous literature and results in this study point out that SR benefits have a small effect size. Zeng et al. (2000) and Ries (2007) both identified SR improvements of approximately 2 dB SPL in normal hearing subjects, but with conflicting optimal levels of noise to produce this effect. Long et al. (2004) observed SR in normal hearing subjects but paid more attention to the standard deviation of the noise with the signal, rather than the magnitude itself. There is currently no set method into identifying the optimal level of noise for maximum SR benefits in normal hearing subjects. While this work was focused on developing this method, the results were inconclusive, even when trying to replicate past research work, no SR was identified. Therefore, future auditory perceptual testing must account for small effect sizes.

One potential issue with this study is the data collection technique. The Békésy-style tracking procedure can be flawed when it comes to precise threshold testing. Subjects can unknowingly (or knowingly) decide their threshold, meaning the subject cognitively places the barrier for what they believe to be their threshold. One subject could release the button a couple seconds after not hearing the tone, while another releases immediately. This can go the other way, where a subject makes the signal significantly suprathreshold before pushing down the button again, affecting the means of their excursions. Since the tones are equally spaced, it is also easier for subjects to "trick" themselves into hearing the tone when they actually would not perceive that on their own. The hope was that subjects would remain consistent with how they responded in every tracking procedure they completed.

Zeng used Békésy-style tracking to find thresholds for cochlear implant subjects, but for normal hearing subjects Zeng both utilized a forced choice two-interval procedure, while Ries used a three-interval forced choice procedure. In this threshold determination task, subjects are given two presentations, one of the presentations contain a stimuli and the other does not. The subject then chooses which one had the stimuli. Should the subject get it correct a certain number of times (say three or four times) the stimuli magnitude is lowered and they complete the task again. If the subject answers incorrectly, the stimuli magnitude is increased. This is done until the subject converges on his or her threshold. This technique reduces the ability for the subject to decide his or her own threshold; however, this protocol methodology can be time consuming. The study duration would be prohibitive to implement a two-interval task. Previous studies explored SR for one or two frequencies but this work sought to investigate SR across a broader range of frequencies. The two-interval procedure is unrealistic when it comes to subject testing every noise level treatment three times for five frequencies; therefore, the researcher chose to use Békésy-style tracking. It should be noted that precise threshold collection may negate the need to collect three thresholds, but Zeng et al. (2000) details that they collected three threshold measurements and then reported the mean. Future threshold testing should collect data at one frequency and employ a forced choice two-interval procedure to reduce threshold variability.

Another change recommendation based on the study results may be a return to using headphones again. The reason being that probe placement plays a critical role in acoustic mixing presentation and leads to increased subject discomfort and setup time, as well as, increases the chances for hindered sound delivery. That being said, auditory thresholds were not elevated by the presence of noise, as was found for all noise levels for many subjects in the Threshold Optimization Study. Strict probe placement criteria, along with, the two-interval procedure may identify auditory SR. A further trade study is required to identify the hardware that should be used for future sound delivery.

While experimental changes must be implemented in the current setup, it may be worth noting that SR could be hard to find or is non-existent in the paradigm presented (in-channel, externally applied noise). Previous psychoacoustic studies for normal hearing subjects had small effect sizes for a small subject pool, leaving room for potentially false positive results in their conclusions. The results in this thesis also imply that if auditory SR exists for a population, the effect size would be small and hard to detect.

6.4 Final Remarks

SR has been observed in multiple sensory systems by adding noise to a non-linear signal. This study aimed to evaluate the phenomenon within the auditory system for normal hearing subjects across a wide range of frequencies. This thesis outlines two studies that aimed to find SR by adding external white noise to a periodic pure tone. Psychoacoustic auditory thresholds were used as the metric by which the presence of SR was evaluated. When compared to the baseline, the addition of noise did not produce statistically significant results and SR was not found. Alterations to the experimental protocol were performed and provided useful insight into experimental procedures that can be implemented in future studies. This work informs experimental design changes for future perceptual threshold testing, but does not resolve inconsistencies or replicate findings from prior work in auditory stochastic resonance investigations.

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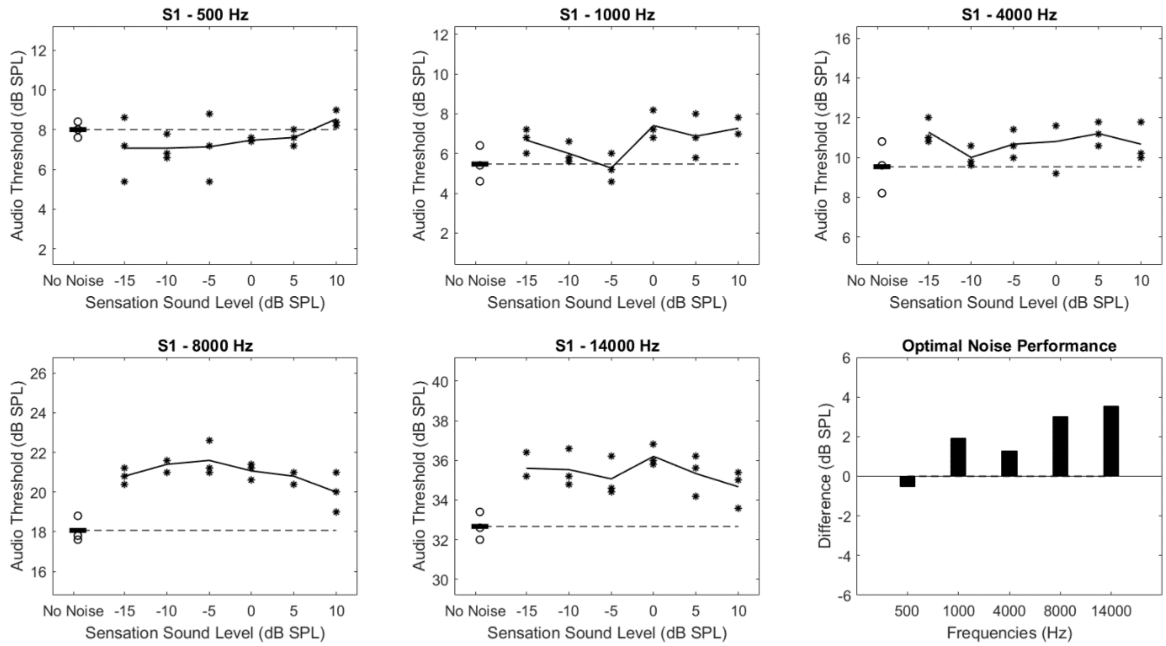
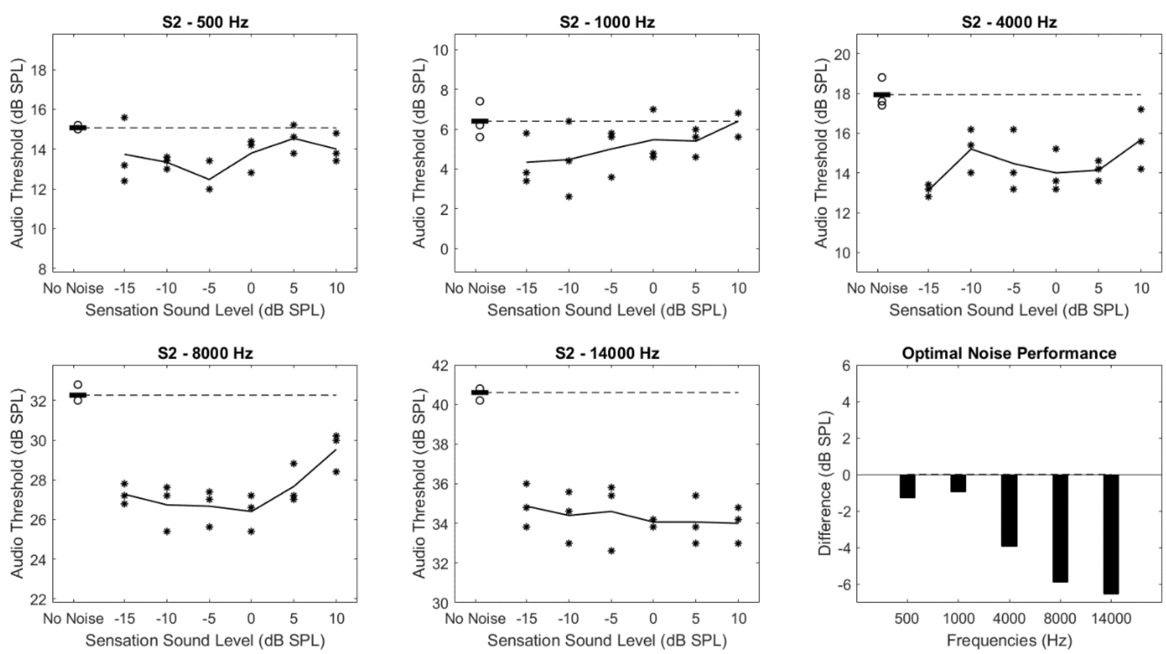
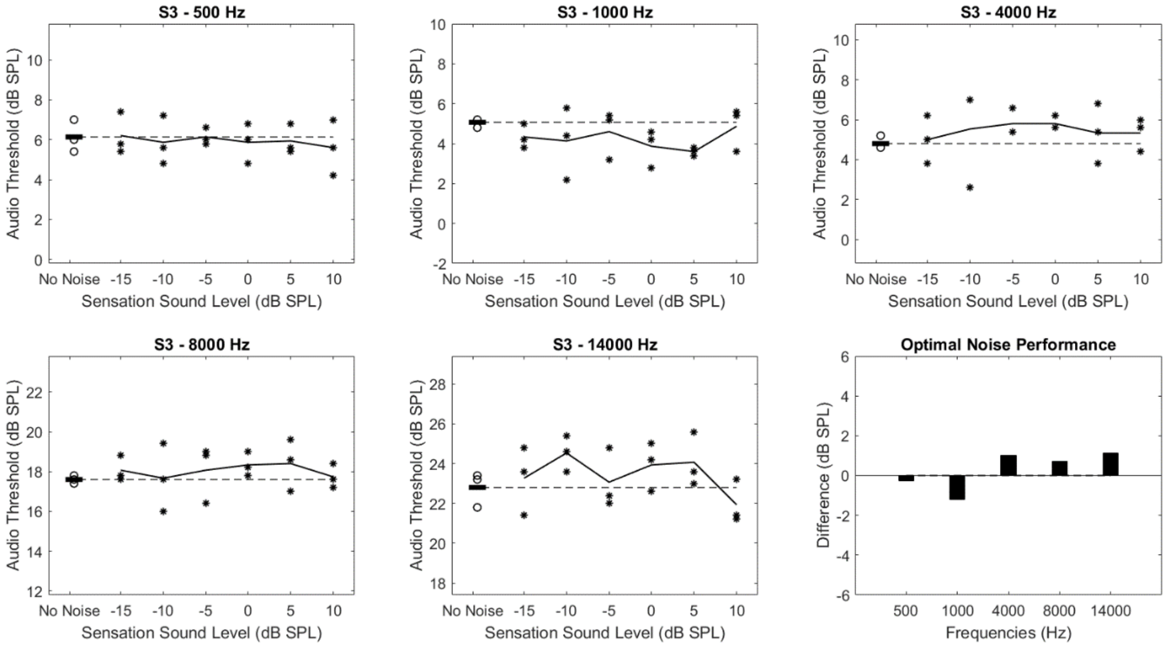
Appendix

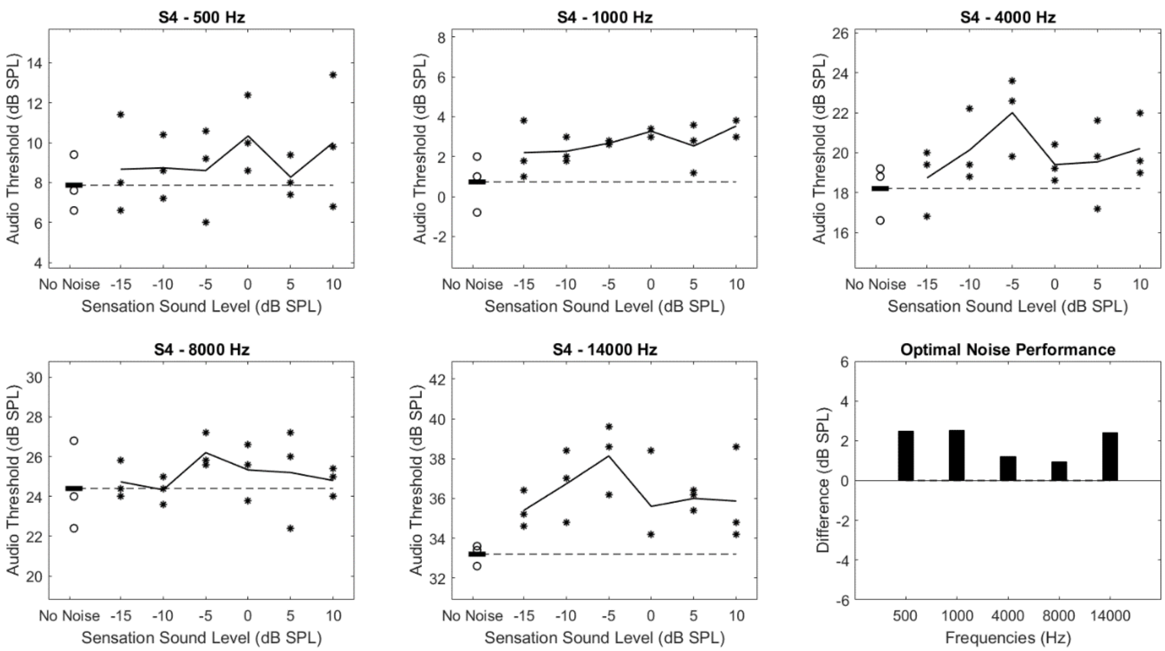
Appendix A.

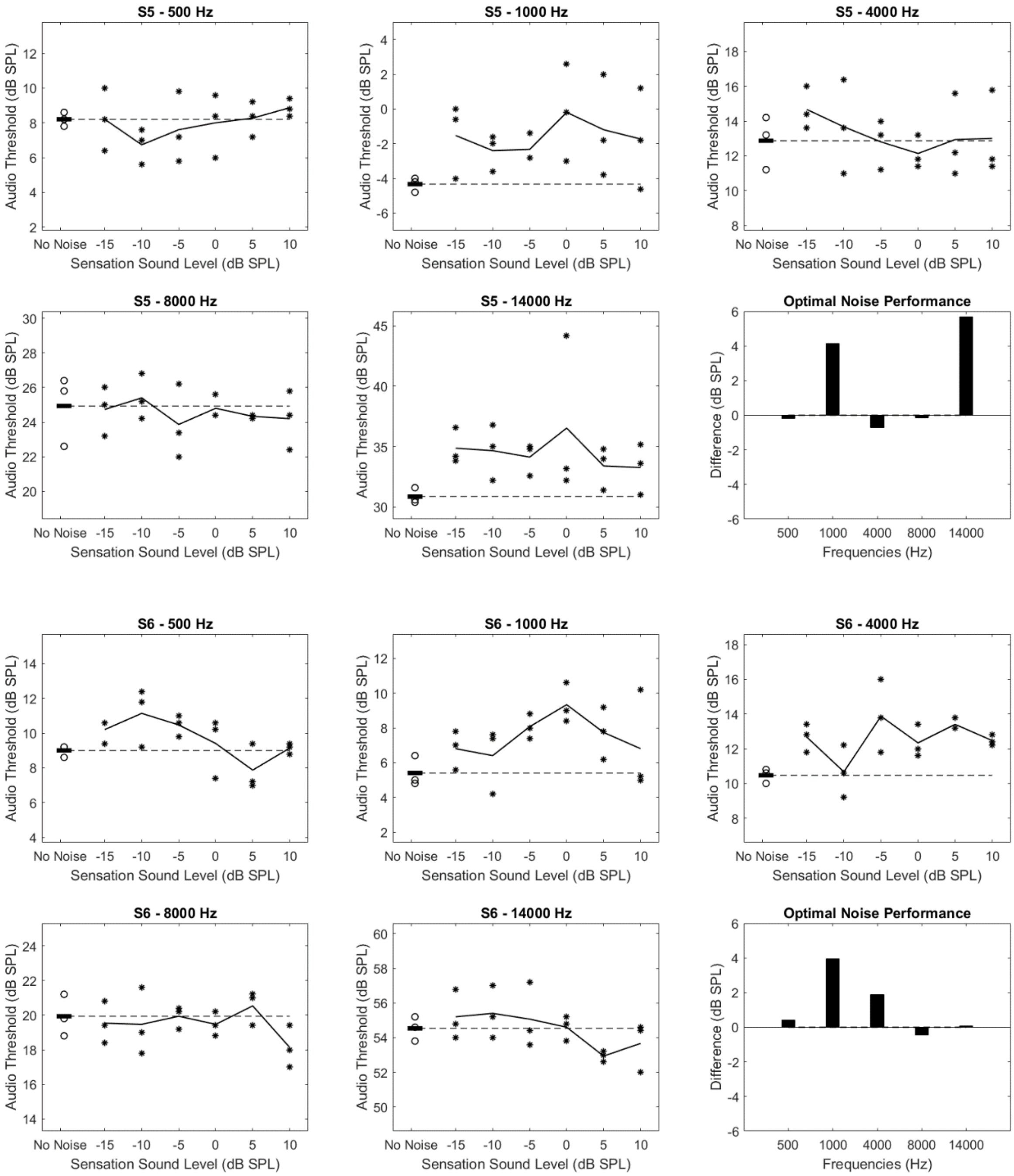
This collection of figures are SR curves for individual subjects during the Threshold Optimization Study.

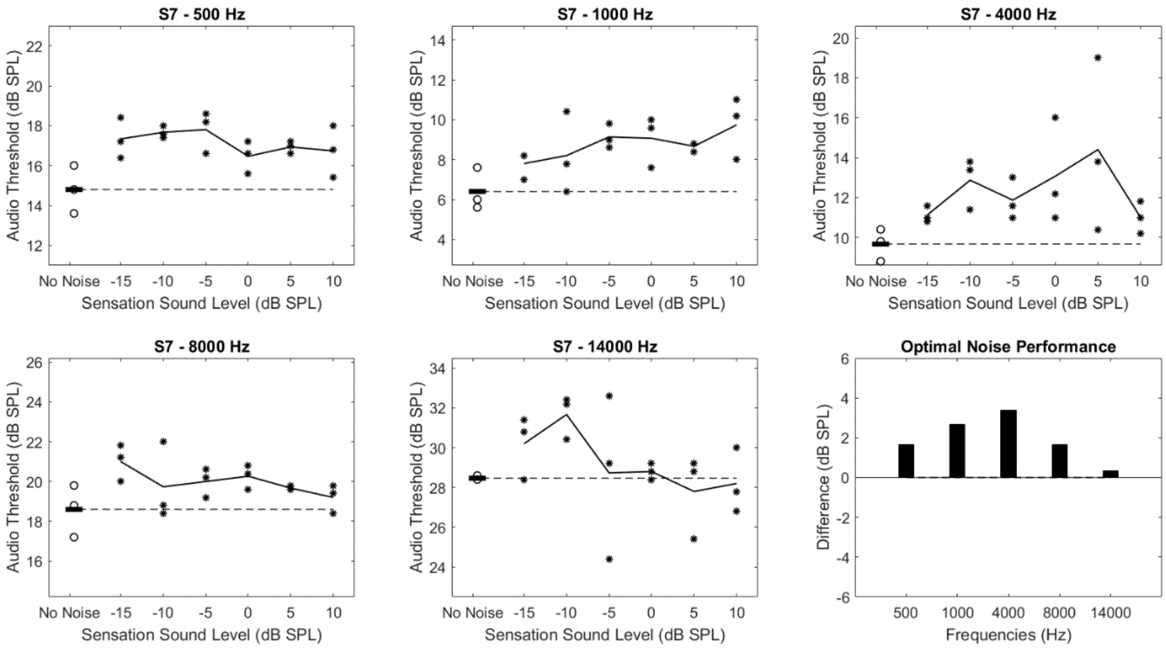


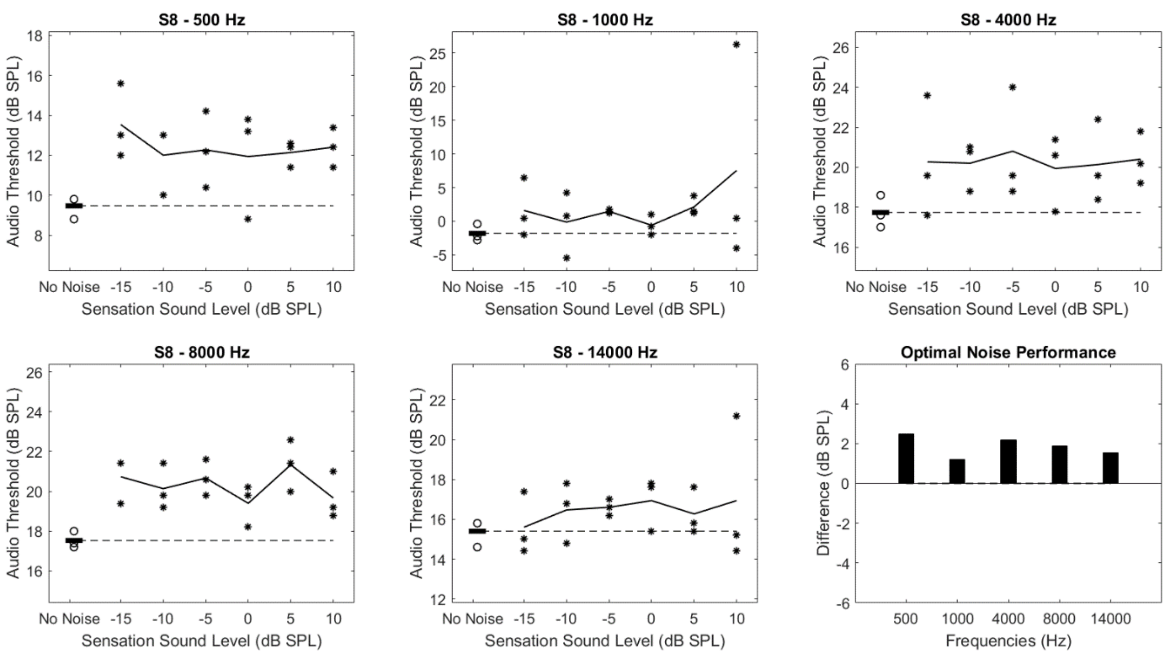


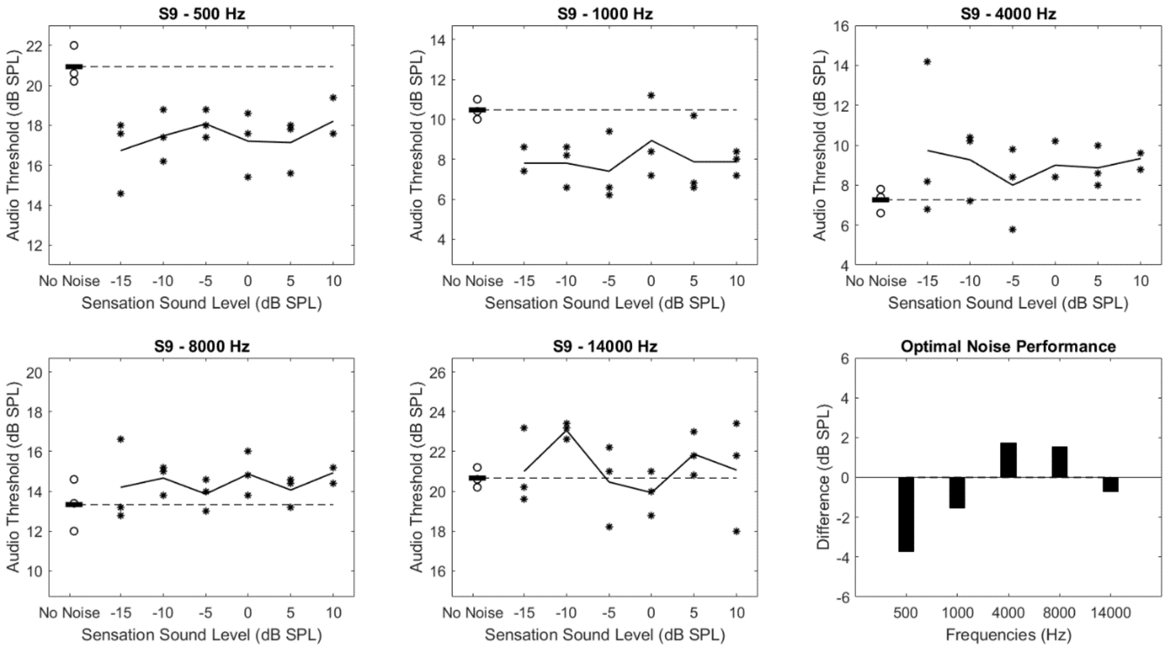

S3 - 500 Hz
S3 - 1000 Hz
S3 - 4000 Hz
S3 - 8000 Hz
S3 - 14000 Hz
Optimal Noise Performance
Audio Threshold (dB SPL)
Sensation Sound Level (dB SPL)
No Noise -15 -10 -5 0 5 10
Difference (dB SPL)
Frequencies (Hz)
500 1000 4000 8000 14000

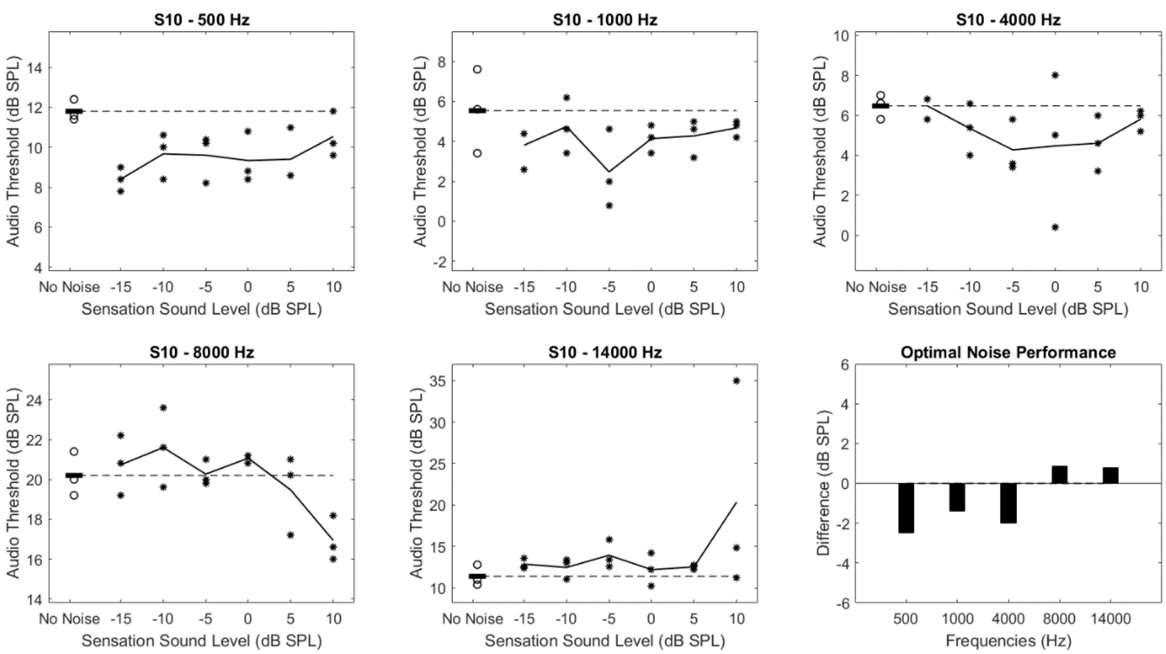

S4 - 500 Hz
S4 - 1000 Hz
S4 - 4000 Hz
S4 - 8000 Hz
S4 - 14000 Hz
Optimal Noise Performance
Audio Threshold (dB SPL)
Sensation Sound Level (dB SPL)
No Noise -15 -10 -5 0 5 10
Difference (dB SPL)
Frequencies (Hz)
500 1000 4000 8000 14000


S5 - 500 Hz
S5 - 1000 Hz
S5 - 4000 Hz
S5 - 8000 Hz
S5 - 14000 Hz
Optimal Noise Performance
S6 - 500 Hz
S6 - 1000 Hz
S6 - 4000 Hz
S6 - 8000 Hz
S6 - 14000 Hz
Optimal Noise Performance
Audio Threshold (dB SPL)
Sensation Sound Level (dB SPL)
No Noise -15 -10 -5 0 5 10
Difference (dB SPL)
Frequencies (Hz)
500 1000 4000 8000 14000


S7 - 500 Hz
S7 - 1000 Hz
S7 - 4000 Hz
S7 - 8000 Hz
S7 - 14000 Hz
Optimal Noise Performance
Audio Threshold (dB SPL)
Sensation Sound Level (dB SPL)
No Noise
-15
-10
-5
0
5
10
Difference (dB SPL)
Frequencies (Hz)
500
1000
4000
8000
14000


S8 - 500 Hz
S8 - 1000 Hz
S8 - 4000 Hz
S8 - 8000 Hz
S8 - 14000 Hz
Optimal Noise Performance
Audio Threshold (dB SPL)
Sensation Sound Level (dB SPL)
No Noise
-15
-10
-5
0
5
10
Difference (dB SPL)
Frequencies (Hz)
500
1000
4000
8000
14000

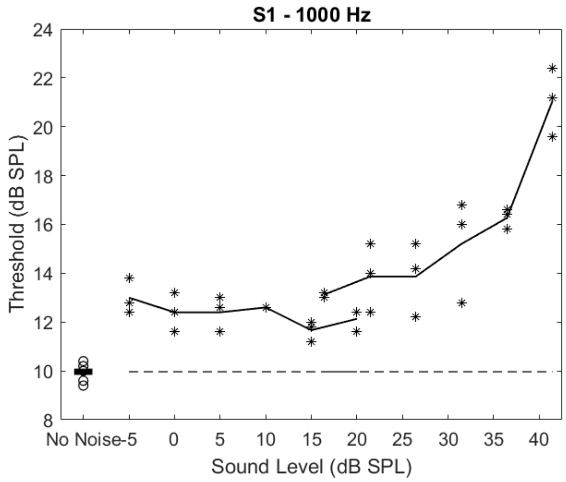

S9 - 500 Hz
S9 - 1000 Hz
S9 - 4000 Hz
S9 - 8000 Hz
S9 - 14000 Hz
Optimal Noise Performance
Audio Threshold (dB SPL)
Sensation Sound Level (dB SPL)
No Noise -15 -10 -5 0 5 10
Difference (dB SPL)
Frequencies (Hz)
500 1000 4000 8000 14000

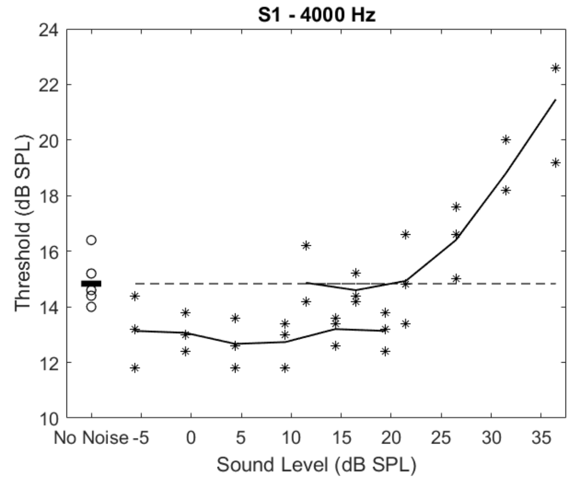

S10 - 500 Hz
S10 - 1000 Hz
S10 - 4000 Hz
S10 - 8000 Hz
S10 - 14000 Hz
Optimal Noise Performance
Audio Threshold (dB SPL)
Sensation Sound Level (dB SPL)
No Noise -15 -10 -5 0 5 10
Difference (dB SPL)
Frequencies (Hz)
500 1000 4000 8000 14000

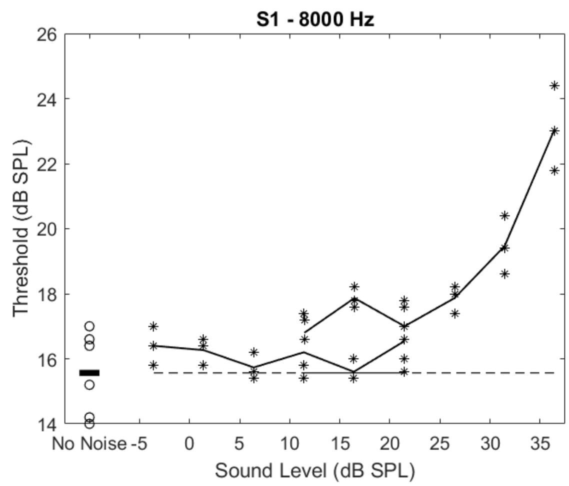
Appendix B.

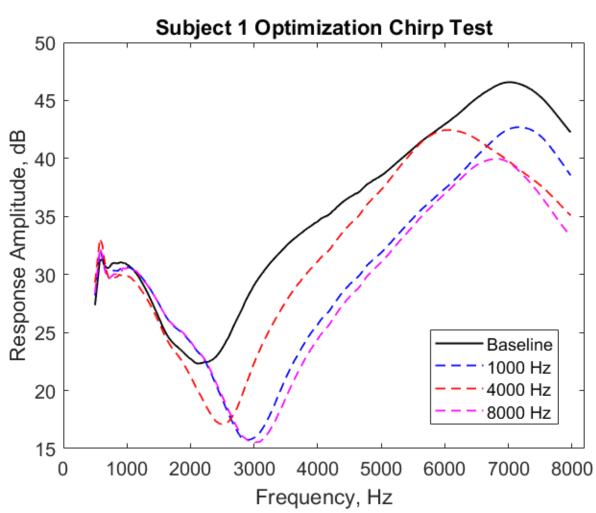
This collection of figures are SR curves and their chirp results for individual subjects during the Protocol Development study.

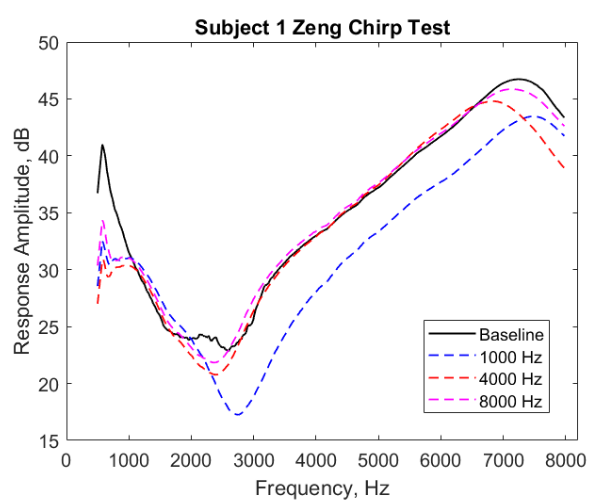
SUBJECT 1:



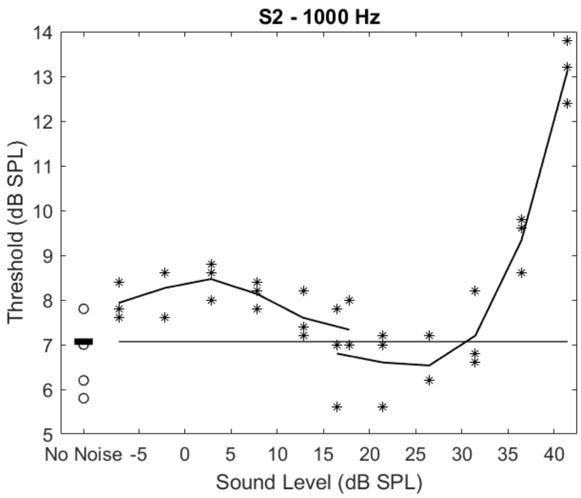


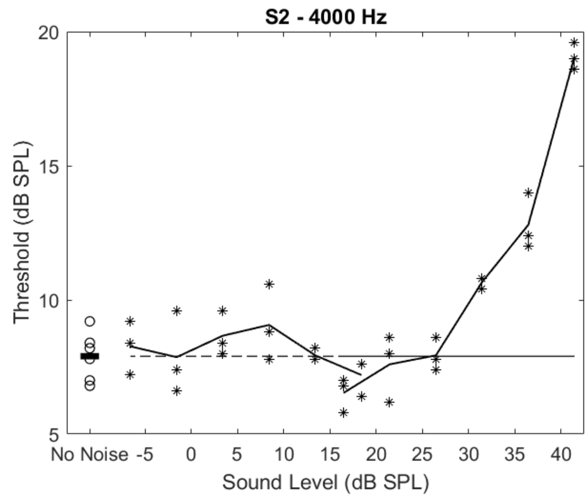


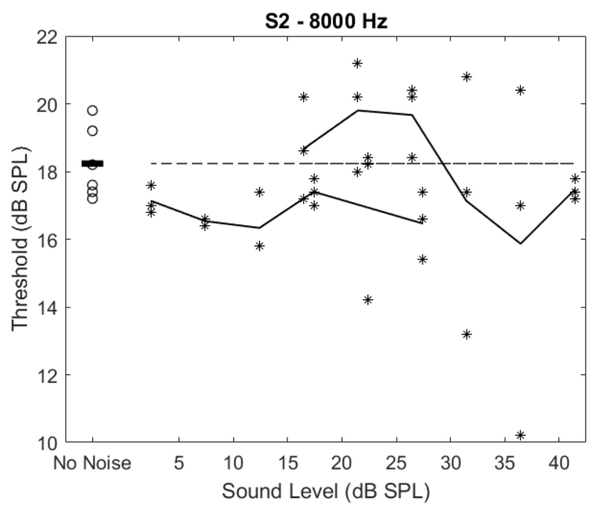


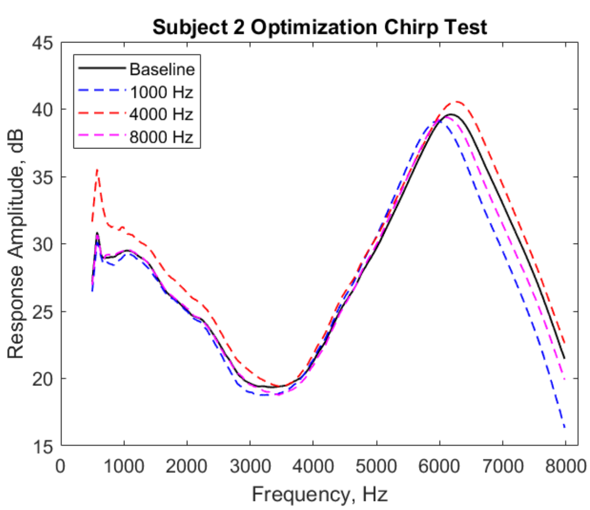


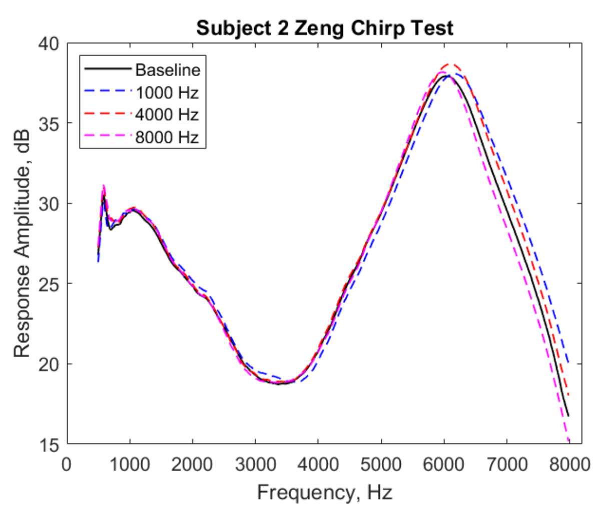
SUBJECT 2:


S2 - 1000 Hz
Threshold (dB SPL)
Sound Level (dB SPL)
No Noise

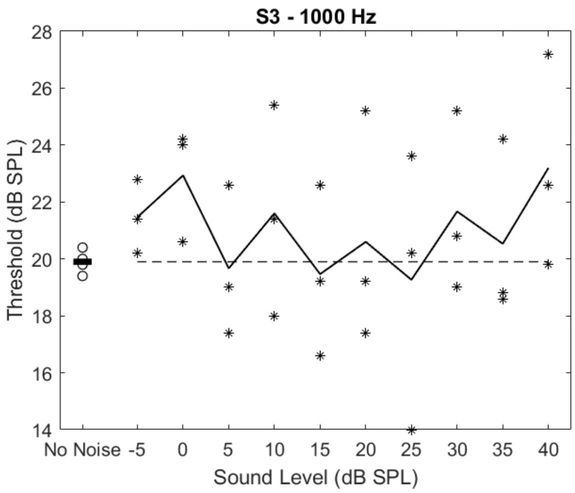

S2 - 4000 Hz
Threshold (dB SPL)
Sound Level (dB SPL)
No Noise

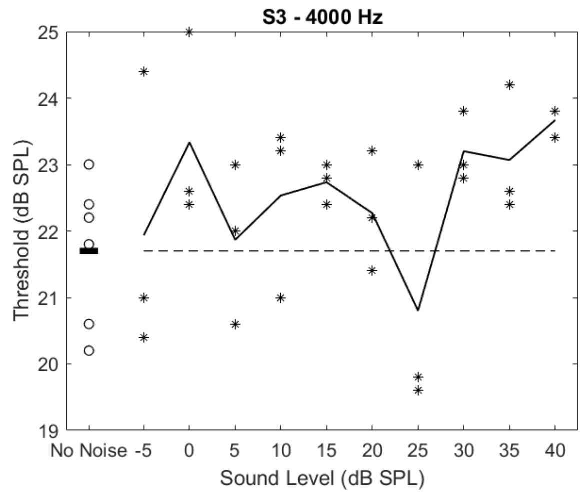

S2 - 8000 Hz
Threshold (dB SPL)
Sound Level (dB SPL)
No Noise

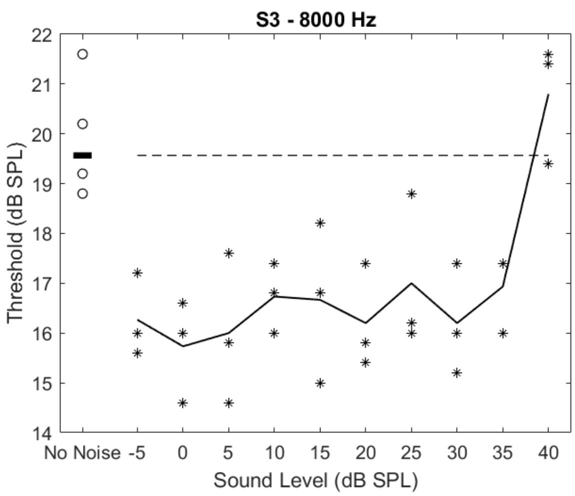

Subject 2 Optimization Chirp Test
Baseline
1000 Hz
4000 Hz
8000 Hz
Response Amplitude, dB
Frequency, Hz

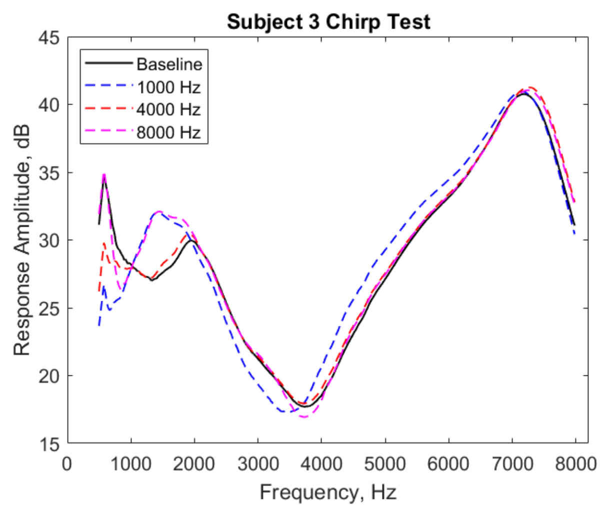

Subject 2 Zeng Chirp Test
Baseline
1000 Hz
4000 Hz
8000 Hz
Response Amplitude, dB
Frequency, Hz

SUBJECT 3:

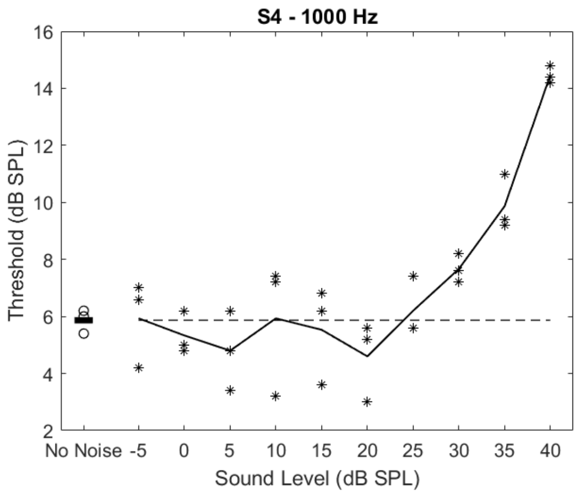

S3 - 1000 Hz
Threshold (dB SPL)
Sound Level (dB SPL)
No Noise

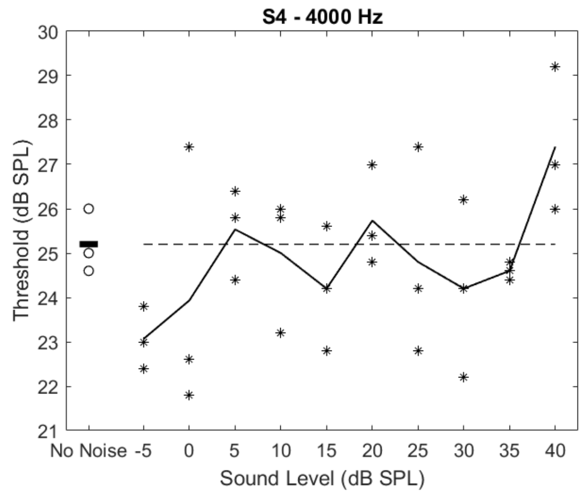

S3 - 4000 Hz
Threshold (dB SPL)
Sound Level (dB SPL)
No Noise

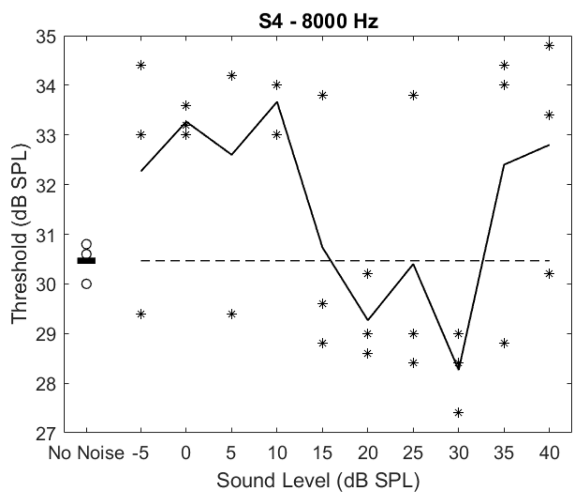

S3 - 8000 Hz
Threshold (dB SPL)
Sound Level (dB SPL)
No Noise

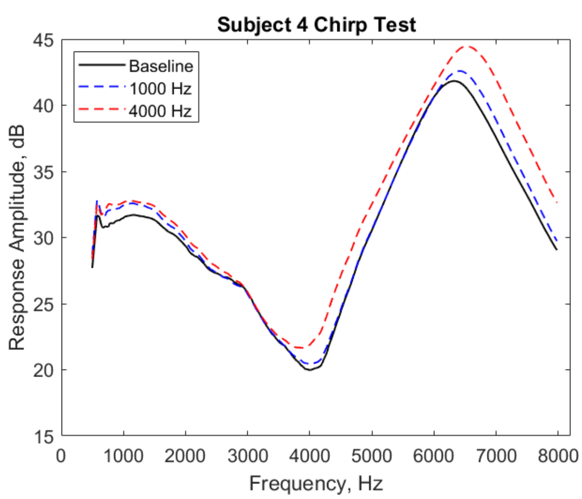

Subject 3 Chirp Test
Baseline
1000 Hz
4000 Hz
8000 Hz
Response Amplitude, dB
Frequency, Hz

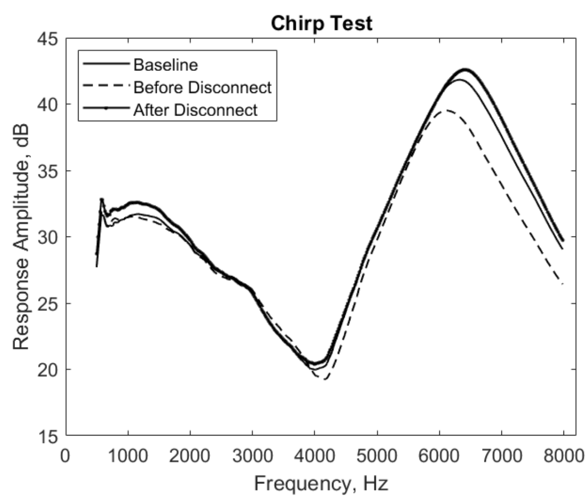
SUBJECT 4:


S4 - 1000 Hz
Threshold (dB SPL)
16
14
12
10
8
6
4
2
No Noise -5 0 5 10 15 20 25 30 35 40
Sound Level (dB SPL)


S4 - 4000 Hz
Threshold (dB SPL)
30
29
28
27
26
25
24
23
22
21
No Noise -5 0 5 10 15 20 25 30 35 40
Sound Level (dB SPL)


S4 - 8000 Hz
Threshold (dB SPL)
35
34
33
32
31
30
29
28
27
No Noise -5 0 5 10 15 20 25 30 35 40
Sound Level (dB SPL)


Subject 4 Chirp Test
Baseline
1000 Hz
4000 Hz
Response Amplitude, dB
45
40
35
30
25
20
15
0 1000 2000 3000 4000 5000 6000 7000 8000
Frequency, Hz


Chirp Test
Baseline
Before Disconnect
After Disconnect
Response Amplitude, dB
45
40
35
30
25
20
15
0 1000 2000 3000 4000 5000 6000 7000 8000
Frequency, Hz