# THE NOISY CHANNEL MODEL AND SENTENCE PROCESSING IN INDIVIDUALS WITH SIMULATED BROADENED AUDITORY FILTERS


by

**Kristen M. Nunn**

B.Phil, University of Pittsburgh, 2016


Submitted to the Graduate Faculty of

School of Health and Rehabilitation Sciences in partial fulfillment

of the requirements for the degree of

Master of Science

University of Pittsburgh

2018

UNIVERSITY OF PITTSBURGH

SCHOOL OF HEALTH AND REHABILITATION SCIENCE

This thesis was presented

by

Kristen M. Nunn

It was defended on

March 2, 2018

and approved by

Christopher Brown, Ph.D., Assistant Professor, Communication Science and Disorders & Psychology

Tessa Warren, Ph.D., Associate Professor, Psychology, Linguistics, & Communication Science and Disorders

Thesis Director: Michael Walsh Dickey, Ph.D., Associate Professor, Communication Science and Disorders, VA Pittsburgh Healthcare System

**THE NOISY CHANNEL MODEL AND SENTENCE PROCESSING IN INDIVIDUALS WITH BROADENED AUDITORY FILTERS**

Kristen M. Nunn, M.S.

University of Pittsburgh, 2018

Noise is abundant in every day communication. This high prevalence of noise means we need a language processing mechanism that can recover intended meanings when given noisy input. Research suggests that we do this by maintaining uncertainty about linguistic input and interpreting sentences in a way that is unfaithful to the literal syntax (Gibson, Bergen, & Piantadosi, 2013; Levy, 2011; Levy, Bicknell, Slattery, & Rayner, 2009). People with communication disorders like aphasia or hearing loss have an even higher prevalence of noise. Research has shown that both groups show higher degrees of uncertainty than controls (Gibson, Sandberg, Fedorenko, Bergen, & Kiran, 2015; Nunn, 2016, & Warren, Dickey, & Liburd, 2017). The present study aims to examine how different aspects of cochlear hearing loss influence certainty about linguistic information. While having their eyes tracked, 40 individuals were administered the Gibson Task with sound files simulating broadened auditory filters (BAF). The Gibson Task is a forced-choice picture task that requires participants to select which image best represents a sentence they heard. One illustration represents the literal syntax and one represents an alternate interpretation that may be obtained through edits to the literal syntax. Sentences of different structure (double object/prepositional object, active/passive) require different types and amounts of edits to switch between interpretations. Sentences of different plausibility are more or

less likely to be interpreted literally. Using data collected by Nunn (2016), comparisons were made between groups with simulated BAF, simulated reduced audibility of high frequency information (LPF), and no hearing loss (NoHL). The BAF and LPF groups were less accurate and showed higher degrees of uncertainty than the NoHL group. The BAF group was more faithful to the literal syntax than the LPF group for the double object/prepositional object condition. When comparing people with aphasia (PWA) to LPF and BAF, BAF outperformed PWA in all structures but the LPF group only outperformed PWA on actives/passives. Finally, groups with high accuracy scores sometimes showed covert signs of uncertainty in eye-tracking data. The variability between groups implies a complex relationship between noise, syntactic structure, and fidelity to a perceived linguistic signal.

TABLE OF CONTENTS

# LIST OF TABLES

## LIST OF FIGURES

## ACKNOWLDGEMENTS

This research would not have been possible without the support of my thesis committee, fellow Language and Brain Lab members, and family and friends. For their guidance and encouragement, I am truly grateful.

Dr. Dickey, thank you for encouraging me to pursue research and think deeply about language throughout my time at the University of Pittsburgh. Your knowledge and expertise has been invaluable. And your enthusiasm towards science has given me a passion for research and learning.

Dr. Warren, thank you for guiding me in thinking about the noisy channel model and how it influences language users. Your insight helped shape my thinking throughout the thesis.

Dr. Brown, thank you for taking the time to teach me about different aspects of cochlear hearing loss. Your patience gave me a deeper understanding of how hearing loss influences our ability to perceive linguistic information. Also, thank for your time spent simulating broadened auditory filters in the sentence stimuli.

Dr. Cohn, thank you for moderating my thesis defense and thank you for introducing me to research during my undergraduate career at the University of Pittsburgh.

To my fellow Language and Brain Lab members, thank you for making research fun and exciting. Becca Hayes, Yina Quique, and Haley Dresang, thank you for your willingness to help me throughout the thesis process and your encouragement. April Yoder, Gina D'Amore, and Kylie Dunne, thank you for your help running and scheduling participants.

Thank you to Phuong Nguyen for providing the drawings used in the practice trials of the Gibson task simulating broadened auditory filters.

To my family and friends, thank you for always being willing to listen to me and for your confidence in me over the past two years.

# 1.0 INTRODUCTION

There is a high incidence of noise in every-day communication. This noise can manifest itself as errors in production (e.g., misspeaking or dysarthria) or perception (e.g., low signal to noise ratio, hearing loss, or aphasia). For example, a speaker may omit a word producing the sentence, “The janitor lent the mop the teacher.” instead of “The janitor lent the mop *to* the teacher.” Similarly, a person with a high frequency hearing loss may experience constant noise in their language processing mechanism making it difficult to perceive high frequency information in speech. A successful communicative exchange can be thought of as an exchange in which the speaker’s intended meaning matches the listener’s perceived meaning. Given that noise is prevalent in everyday communication, we need a well-adapted language processing mechanism that can recover intended meaning when given noisy input.

Rational models of sentence comprehension (Levy, 2011; Levy et al., 2009) suggest that to do this, comprehenders take advantage of all available information in a linguistic signal including perceptual, semantic, and syntactic cues to make predictions about what is likely to occur next in a sentence and to revise already parsed information. Such models assume that language users use available information to increase the probability of a successful communicative exchange and have the consequence that language users may end up with an interpretation of a sentence that is unfaithful to the perceived linguistic input.

A noisy channel model put forth by Gibson et al. (2013) aims to examine how a rational sentence comprehender may act in the face of noise and suggests language users use Bayesian reasoning when determining whether to remain faithful to the perceived linguistic signal. Gibson et al. (2013) conducted experiments manipulating the types of sentences and amount of noise in a perceived linguistic signal. The task included alterations of sentence structures that varied in the amounts and types of edits necessary to switch between alternations. Furthermore, sentences were presented in varying amounts of noise: one experimental condition had 50% of the filler items containing syntactic errors while another condition increased the amount of implausible filler material. Results showed that sentence comprehenders are influenced by the amount of errors and the amount of improbable sentences in a linguistic signal and that comprehenders rely less on the perceived linguistic signal when the amount of noise is increased. They also found that the likelihood one would remain faithful to a linguistic signal depended on the type and amount of errors necessary to switch from one alteration to another.

Further research conducted by Gibson et al. (2015) and Warren et al. (2017) examining the noisy channel model in individuals with aphasia suggests that individuals with aphasia rely more heavily on semantic knowledge to increase the likelihood of a successful communicative exchange. Gibson et al. (2015) and Warren et al. (2017) found that while persons with aphasia (PWA) rely more on semantic information, they also adapt their reliance based on sentence structure and plausibility conditions. Nunn (2016) found that individuals given a simulated hearing loss perform like people with aphasia on an adapted version of the Gibson task used by

Gibson et al. (2013). Nunn (2016) used a version of the Gibson task identical to the one used by Warren et al. (2017), a forced-choice sentence-picture matching task. Accuracy scores for individuals with simulated hearing loss were as significantly reduced as accuracy scores for individuals with aphasia despite the different source of uncertainty (i.e., perceptual degradation of acoustic signal vs. central language impairment). This suggests that uncertainty, regardless of its source, may influence reliance on a perceived linguistic signal to a similar degree.

Given that individuals adjust their certainty about a perceived linguistic signal in the presence of noise but that individuals with significantly different types of noise act similarly (i.e., people with aphasia and people with simulated hearing loss), raises the question as to how different types of noise may influence reliance on semantic and syntactic information and to what degree. The current study aims to further understand how different types of perceptual degradation of the linguistic signal secondary to cochlear hearing loss influence one's reliance on a perceived linguistic signal.

## 1.1 BACKGROUND

### 1.1.1 Rational Sentence Processing

Non-noisy channel accounts suggest that we are able to communicate despite the high incidence of noise by taking advantage of the redundancy in linguistic signals and the vast range of linguistic information available (i.e., perceptual and lexical cues) (Tanenhaus, Spivey-

Knowlton, Eberhard, & Sedivy, 1995; Aylett & Turk, 2004). Such explanations suggest that once a word is parsed, language users are faithful in interpreting the intended meaning based on the perceived input. Levy (2008) claims this does not account for times in which a language user may hear a grammatically sound sentence and be unfaithful to this utterance in their interpretation of the intended meaning. In these cases, syntactic and semantic priors may override fidelity to a linguistic signal. Syntactic priors relate to information about the frequency of a particular grammatical construction while semantic priors relate to the likelihood of a particular utterance or intended meaning being conveyed. Levy (2008) suggests a rational approach to sentence comprehension that works under the assumption that language users take advantage of all available information when parsing perceived sentences. This includes levels of expected uncertainty and may result in the literal form of an utterance and the perceived meaning not matching.

Recent research indicates that language users are influenced by uncertainty about the linguistic signal they previously perceived, suggesting that they may assume it is inaccurate (Levy et al., 2009; Levy, 2011). Levy et al. (2009) proposed that comprehenders may be influenced by the probability of alternate interpretations involving orthographic near-neighbor substitutions or deletions. Levy et al. (2009) used sentences with the following structure in their study:

(1a) The coach smiled at the player tossed the frisbee.

(1b) The coach smiled at the player thrown the frisbee.

While the meaning of each sentence is equivalent, the (1a) alteration is much more difficult to parse than the (1b) alteration because, in (1a), the grammatical role of “tossed” is ambiguous and can be either a finite verb or a past participle. While the linguistic information prior to "tossed" may rule out any misinterpretations of (1a) the probability of a sentence that remains faithful to the previously parsed information is less likely than the probability of a sentence involving a near-neighbor substitution or deletion. For example, the orthographic neighbors of "at" ("as" and "and"), or a distortion involving the deletion of the word "who" following "player", would indicate the word following "player", "tossed", is a finite verb—a more likely grammatical construction. Levy et al. (2009) believe that Bayesian reasoning upon reading "tossed" causes a probability shift away from the actual content and towards the alternate interpretations involving near neighbor substitutions. This shift does not occur in alteration (1b) because "thrown" cannot be a finite verb. Levy et al. (2009) predicted that language comprehenders can remain uncertain about the identity of a word they have already read and claimed that if a newly encountered word challenges a comprehender's belief about the sentence, they may have behavioral responses such as longer fixation times or regressive eye-movements while reading.

In order to examine if comprehenders maintain uncertainty about previously read words, Levy et al. (2009) tested sentences (1a) and (1b) as well as sentences in which the word "at" was replaced with "toward," eliminating the possibility orthographic near-neighbor substitutions.

(2a) The coach smiled toward the player tossed the frisbee.

(2b) The coach smiled toward the player thrown the frisbee.

Levy et al. (2009) administered variations of these sentences to participants while they had their eyes tracked and found that comprehenders exhibited more regressive eye movements and longer fixation times when encountering sentence type (1a). These results suggest that readers maintain uncertainty about words they have previously read and that they consider alternatives of a previously read word.

Levy (2011) further explored rational sentence comprehension and the hypothesis that under certain circumstances, language comprehenders' interpretation of the sentence may be inconsistent with the linguistic input they received. Levy (2011) constructed sentences that may lead to a "hallucinated garden-path" in which a comma, which should in principle eliminate a garden path sentence, is ignored, creating a "hallucinated garden path." For example, take the garden path sentence "While Mary was mending the socks fell off her lap." The insertion of a comma after "mending" (i.e., "While Mary was mending**,** the socks fell off her lap") should eliminating the ambiguity and no longer creating a garden path sentence. The same should be true for the sentence below:

(3a) As the soldiers marched, towards the tank lurched an injured enemy combatant.

However, Levy (2011) suggests that because of the low frequency grammatical construction, language comprehenders will "hallucinate" a garden path. The structure leading to the hallucination is the locative inversion, in which the locative prepositional phrase ("towards the tank") is placed before the main verb ("lurched"). This is an extremely low frequency structure and as a result, sentence comprehenders may ignore the comma so that "toward the tank" would be a prepositional phrase of the subordinate clause "As the soldiers marched"—a more likely construction. Thus, by eliminating the comma, comprehenders "hallucinate" or create a garden path that should have been eliminated by the presence of the comma. This would support the notion that language users may maintain uncertainty about perceived linguistic input.

In order to examine this prediction, Levy (2011) administered a self-paced reading task to participants including a hallucinated garden path sentence (3a) as well as a version of (3a) in which a prepositional phrase is added, to eliminate the hallucinated garden path and to separate effects of the hallucinated garden path from effects of encountering the low frequency construction of a locative inversion.

(3b) As the soldiers marched *into the bunker*, toward the tank lurched an injured enemy combatant.

Furthermore, to eliminate possible effects of sentence length, Levy (2011) used two more sentences containing locative un-inverted versions of (3a) and (3b). Levy (2011) predicted that if a comprehender is considering this alternate interpretation it should be evident in longer reading times for the main verb, "lurched" in sentence (3a). Levy (2011) administered the task to 40 monolingual English speakers and followed each sentence with a comprehension question such as "Did the tank lurch toward an injured enemy combatant?" Results found that reading times were longest for the main verb in sentence construction (3a). This finding provides further support that language comprehenders entertain interpretations of sentences that are unfaithful to the linguistic input.

Levy et al. (2009) and Levy (2011) provide empirical evidence that language comprehenders are aware of possible alternatives to a perceived sentence and may seriously entertain these alternate grammatical constructions. Thus, language users are aware of the probability of an utterance or a particular grammatical construction and in cases where this probability is low, may assume that the linguistic input they received was incorrect and make edits to previously parsed input. Thus, language comprehension isn't only a forward process—

language users also go back and question the accuracy of previously parsed perceptual input. Furthermore, language users do not treat words as the most fundamental unit to language comprehension and may be unfaithful to a perceived word in their interpretations. This raises the question of what sources of uncertainty can push language comprehenders towards being unfaithful to linguistic input especially considering the high incidence of noise in everyday communication.

### 1.1.2 A Noisy Channel Model Approach

Gibson et al. (2013) sought to further understand how a rational sentence comprehender may act in the face of noise through the evaluation of four predications about a rational sentence comprehender. Gibson et al. (2013) put forth an equation intended to explain how comprehenders use Bayesian reasoning to recover intended meaning of a perceived sentence:

$$P(s_i|s_p) \propto \mathrm{P}(s_i)\, P(s_i \rightarrow s_p)$$

This model suggests that the probability of a language comprehender obtaining the sentence intended ($s_i$) from sentence the perceived ($s_p$) is proportional to the probability of $s_i$ occurring, $P(s_i)$, times the probability that one could derive $s_i$ from $s_p$, $P(s_i \rightarrow s_p)$. In other words, $P(s_i)$ is our semantic knowledge, which influences how likely a given sentence meaning or situation is. It also includes our knowledge of the kinds of sentences uttered and the likelihood of various grammatical constructions which, in turn, influence how likely a given sentence is. $P(s_i \rightarrow s_p)$ is our syntactic knowledge and represents the likelihood of $s_i$ being corrupted or changed to $s_p$; this relates to how likely it is that someone uttered $s_p$ but meant to utter $s_i$. Following this model, Gibson et al. (2013) predict how a comprehender would act under such conditions—the four predications are as follows:

(1) Comprehenders will be more faithful to the perceived sentence when more edits are necessary to switch to an alternate interpretation and vice-versa. For example, participants will be less likely to assume “The ball kicked the girl” was intended as “The ball *was* kicked *by* the girl.” (2 edits) than to assume “The mother gave the candle the daughter” was intended as “The mother gave the candle *to* the daughter.” (1 edit).

(2) Comprehenders will be more faithful to the literal interpretation when the distortion assumed is an insertion rather than a deletion and vice-versa. This is because it is more likely that a speaker could omit a single word or a comprehender could not hear a reduced word like “to” than it is for a language producer to accidently insert a particular word from their mental lexicon into a particular sentence position. For example, it is more likely the $s_p$ “The mother gave the candle the daughter” was intended as “The mother gave the candle *to* the daughter” (1 deletion) than “The mother gave the daughter to the candle” was intended as “The mother gave the daughter the candle.” (1 insertion).

(3) In the face of more noise, comprehenders will become less faithful to the literal interpretation relying more on their semantic knowledge. This is because in the face of more noise, the input becomes less reliable.

(4) In the face of more implausible sentences, comprehenders will be more likely to remain faithful to the literal interpretation relying less on their semantic knowledge.

This is because the P($s_i$) being an improbable sentence increases.

Gibson et al. (2013) presented sentences with varying plausibility and structure to participants on the experimental platform, Amazon Mechanical Turk. Sentences were either plausible or implausible. Sentences were either active/passive, transitive/intransitive, double object/prepositional object. The different sentence structures varied in terms of the kinds and number of edits necessary to switch from an implausible to plausible version and vice-versa and allowed Gibson et al. (2013) to look at the interaction between edit distance and plausibility.

**Table 1: Gibson et al. (2013) Sentence Types**

| **Structure** | **Edit Distance** |
| --- | --- |
| Active/Passive | Two edits |
| Subject-locative/Object-locative | One edit |
| Transitive/Intransitive | One edit |
| Double Object/Prepositional Object | One edit |
| Double Object/Prepositional Object Benefactive | One edit |

Gibson et al. (2013) presented subjects with variations of these sentence types followed by a comprehension question where an answer of either “yes” or “no” revealed whether the participant was relying on the literal or non-literal syntax. The results supported all four predictions. This suggests language comprehenders are not only aware of the plausibility of an uttered sentence, but also use Bayesian reasoning when deciding whether or not to remain faithful to the literal interpretation of the syntax. This again supports the idea that language users maintain uncertainty about an incoming linguistic signal. Furthermore, this paper suggests that in addition to language users using semantic and syntactic priors (knowledge related to the types of sentences likely to be uttered and the base-rate frequencies of various grammatical constructions), properties of the linguistic signal (frequency of errors and frequency of improbable sentences) can also influence one's reliance on the literal syntax. Furthermore, language comprehenders can adapt to changes in the amount and type of noise in a linguistic signal and make changes to their reliance on said linguistic input relatively quickly.

### 1.1.3 Noisy Channel Model and Aphasia

Gibson et al. (2015) further examined the noisy channel model in people with aphasia (PWA). Gibson et al. (2015) suggest the frequently noted trend that individuals with aphasia rely more on their semantic knowledge than controls may be explained by the noisy channel model. While heavier reliance on semantic information by PWA is often explained by impaired syntactic abilities causing PWA to rely more on their non-syntactic abilities, Gibson et al. (2015) argued that this explanation may be incomplete because it has been found that individuals with aphasia can judge grammaticality of a sentence. Gibson et al. (2015) propose that individuals with aphasia are instead aware there is a higher probability of the linguistic signal being corrupted by noise. This is comparable to the condition testing prediction 3 from Gibson et al. (2013), which found that in the face of more noise, individuals were less faithful to literal interpretations and more influenced by semantic information. Because PWA have more noise in their language processing mechanism, to increase the chances of recovering $s_i$

from $s_p$ they rely more on semantic information.

Gibson et al. (2015) used similar stimuli as the ones used in Gibson et al. (2013). They included active/passive and double object/prepositional object (DO/PO) sentences that were either plausible or implausible. Below are example sentences provided by Gibson et al. (2015).

**Table 2: Gibson et al. (2015) Sentence Stimuli**

| Sentence Type | Plausible | Distortion | Implausible | Distortion |
|---|---|---|---|---|
| DO | The brother gave the sister the bike. | 1 deletion | The brother gave the bike the sister. | 1 deletion |
| PO | The brother gave the bike to the sister. | 1 insertion | The brother gave the sister to the bike. | 1 insertion |
| Active | The man drove the truck. | 2 deletions | The ball kicked the nephew. | 2 deletions |
| Passive | The cake was eaten by the son. | 2 insertions | The daughter was folded by the blanket. | 2 insertions |

The task also included reversible active and passive sentences in which both alterations of the sentence were equally probable. The DO/PO and active/passive alternations differed in the types and amounts of edits necessary to switch between alternate interpretations. The "Distortion" column in the table above refers to the type of distortion produced by the speaker and how many edits must be made to the literal syntax to switch to the alternate interpretation. To test fidelity to the linguistic input, participants acted out their interpretation of a perceived sentence. Gibson et al. (2015) predicted individuals with aphasia would rely more on plausibility than controls. However, they also predicted that edit distance and sentence probability would affect both PWA and controls and that for both populations, they would be less faithful (1) to a sentence involving a deletion rather than an insertion and (2) to a sentence where more edits are necessary to switch from one interpretation to another.

Gibson et al. (2015) found that overall, compared to a group of younger and a group of older controls, PWA relied more on plausibility (semantic information). PWA relied on plausibility in both DO/PO and active/passive sentences. In terms of structure, persons with aphasia were more likely to remain faithful to the interpretation for implausible active and passive sentences (where the edit distance is larger) than for implausible DO and PO sentences. Furthermore, PO items (involving one insertion) were interpreted literally more than DO items (involving one deletion). This confirms that individuals with aphasia, while they do rely more on semantic information than controls, also partake in the same sorts of Bayesian reasoning as outlined in Gibson et al. (2013) suggesting that an individual with aphasia's reliance on semantic information may be attributed to a need to compensate for the excess noise present in their language processing mechanism.

In a comparable study, Warren et al. (2017) found similar results. Warren et al. (2017) also used DO/PO and active/passive sentence alterations. However, Warren et al. (2017) added additional plausibility conditions creating implausible/plausible active and passive sentences and adding more reversible items for which both the active and passive alteration were equally plausible. Below are example sentences provided by Warren et al. (2017).

**Table 3: Warren et al. (2017) Active Passive, Implausible Stimuli**

| Sentence Type | Plausible | Distortion | Implausible | Distortion |
|---|---|---|---|---|
| Active | The cat licked the girl. | 2 deletions | The girl licked the cat. | 2 deletions |
| Passive | The girl as licked by the cat. | 2 insertions | The cat was licked by the girl. | 2 insertions |

**Table 4: Warren et al. (2017) Active Passive, Reversible Stimuli**

| Sentence Type | Reversible |
|---|---|
| Active | The man held the woman. |
| Passive | The man was held by the woman. |

Rather than acting out the interpretation of the sentences, participants selected which of two illustrations (an illustration of the literal interpretation and an illustration of an interpretation that was not consistent with the literal syntax of the sentence) best represented what was heard in the sentence.

People with aphasia were less faithful to the literal interpretation than age-matched controls. And the same main effects of structure and plausibility were present. These results confirmed that while PWA rely more heavily on their semantic knowledge perhaps as a means of increasing the probability of a successful communicative exchange. Warren et al. (2017) also compared individual's performance on a semantic knowledge battery consisting of Kissing and Dancing test (Bak & Hodges, 2003), Pyramids and Palm Trees test (Howard & Patterson, 1992), and an event knowledge test. Interestingly, they did not find a correlation between syntactic or semantic impairment and semantic reliance. Perhaps, any increase in noise to an individual's language processing mechanism affects reliance on semantic information relatively equally. However, it is worth noting that Warren et al. (2017) did find a relationship between the number of literal-syntax interpretations that PWA accepted and their degree of sentence-comprehension impairment, as measured by the Comprehensive Aphasia Test (Swinburn, Porter & Howrad, 2004).

### 1.1.4 Noisy Channel Model and Hearing Loss

Gibson et al. (2015) and Warren et al. (2017) provided evidence that properties of a comprehender, like presence or absence of aphasia, influence fidelity to a linguistic signal. They suggested that PWA's reliance on semantic knowledge may be attributed to their higher uncertainty about the linguistic signal and an attempt to increase the likelihood of recovering the sentence intended from the sentence perceived. Nunn (2016) aimed to further examine how different properties of the comprehender may influence how individuals rely on semantic and syntactic information, in particular, absence or presence of simulated hearing loss to better understand how noise present due to difficulties processing the linguistic signal (i.e., aphasia) may influence certainty differently than noise present in the linguistic signal itself (i.e., hearing loss).

It is known that hearing loss affects speech comprehension (Desloge, et al., 2010; Duqesnoy, 1983; Gelfald, Ross, & Miller, 1987; Hornsby & Rickets, 2003). The sensory-processing impairments experienced by individuals with hearing loss can disrupt their ability to perceive different parts of the linguistic signal, including short and acoustically reduced function words like *to, was,* or *by*. It is these types of words that Levy et al. (2009) showed that language comprehenders were uncertain about in their study. These are also the words that distinguish the sentence structures that Gibson et al. (2015) and Warren et al. (2017) compared in their studies (active and passive, direct object, and prepositional object).

Recent research has found that individuals with hearing loss and without hearing loss have more difficulty understanding linguistically complex sentences in the face of noise

(Carroll & Ruigendijk, 2013; Wingfield, 2006). Carroll & Ruigendijk (2013) had participants listen to German canonical subject-verb-object (SVO) sentences, non-canonical object-verb-subject (OVS), and ambiguously case-marked OVS sentences in silence and in a signal to noise ratio (SNR) of -3dB. In the ambiguous OVS sentence condition, the noun phrase is ambiguously case-marked and thus, comprehenders have difficulty assigning a syntactic role (i.e., subject or object) to the noun. Carroll & Ruigendijk (2013) found that participants had more difficulty processing more complex, non-canonical OVS structures in the face of noise than canonical SVO structures as evident in longer reaction times for the target words. Carroll & Ruigendijk (2013) posit that this may be because of an increase in the demands of working memory when processing non-canonical sentences. Carroll & Ruigendijk (2013) also observed what they refer to as a "reanalysis effect" for the ambiguous OVS subject; after hearing the disambiguating part of the sentence (the case-marked adjective before the subject noun), participants exhibited longer reaction times for the subject noun. This affect was exacerbated in the noise condition. This finding is consistent with the findings by Levy et al. (2009) and Levy (2011) suggesting that participants may remain uncertain about previously parsed information and, as Carroll & Ruigendijk (2013) put it, face processing costs when they must "reanalyze" their previous interpretation. This cost appears to be more taxing in noise as evident through longer reaction times.

Wingfield et al. (2006) found that participants with hearing loss have more difficulty interpreting object relative clauses than subject relative clauses as evident in lower accuracy scores. Wingfield et al. (2006) also presented sentences to individuals at varying speech rates and found that for complex sentences, increasing speaking rate significantly decreased accuracy scores for individuals with hearing loss. Perhaps, this is because of an increase on processing demands during the processing of more complex sentences and faster speech. Given that individuals with hearing loss must exert additional effort to simply perceive a sentence, they may be more negatively impacted by increased speech rate and sentence complexity than individual without hearing loss.

Larsby et al. (2005) and McCoy et al. (2005) have found that individuals with hearing loss exert more effort when processing sentences than typical hearing controls. Larsby et al. (2005) administered speech understanding tasks to individuals with and without hearing loss in the presence and absence of noise. Larsby et al. (2005) measured the perceived effort necessary to complete the task—effort was measured by having participants self-report how much effort was necessary to complete the current task. They found that individuals with hearing loss reported more effort needed to complete the tasks than individuals without hearing loss, and all participants reported more effort necessary to complete the task in the face of noise. This study indicates that not only does hearing loss decrease accuracy and increase processing time, but also, individuals are aware of the increased effort necessary to process speech.

McCoy et al. (2005) also note the increased effort necessary for individuals with hearing loss to process a given sentence. McCoy et al. (2005) suggest an "effortful hypothesis," which claims that because individuals with hearing loss must exert additional effort in order to perceive a linguistic signal, they have less available resources for processing the sentence. McCoy et al. (2005) had participants with and without hearing loss listen to word lists and recall the last three words presented at randomly selected times. When word lists had lower levels of contextual constraint (meaning the words were less related to other words in the list), individuals with mild-to-moderate hearing loss had significantly lower levels of performance than individuals without hearing loss. Low levels of contextual constraint may cause lower levels of performance in individuals with hearing loss because of additional constraints on working memory—participants must exert more effort to remember unrelated words in a list than to remember related words. McCoy et al. (2005) suggest this decrease in performance is a result of a lack of available resources—because participants must exert additional effort to perceive the sentence, there are less processing resources available for processes like working memory. These resources are especially important for processing and understanding long or complex sentences.

Wendt, Kollmeier, & Brand (2015) used a similar design to Gibson et al. (2013), Gibson et al. (2015), and Warren et al. (2017) to examine how individuals with and without hearing loss comprehended sentences of varying syntactic complexity in the face of noise. Wendt et al. (2015) used eye-tracking as a measure to processing duration. Participants were presented with German canonical SVO, non-canonical OVS sentences, and non-canonical ambiguous sentences. These sentences, similar to the ambiguous OVS used by Carroll & Ruigendijk (2013), had ambiguously case-marked noun phrases making assigning the role of object or subject to the noun more difficult. Sentences were either presented in quiet or in noise. Across all auditory conditions, stimuli were presented at a speech recognition threshold (SRT) of 80, meaning that the sound level of stimuli presentation was adjusted so that each participant was able to understand 80% of the stimulus. This means that differences in groups may be attributed to characteristics of the group and not their ability to hear the sentence.

Results showed that participants with and without hearing loss had higher accuracy scores in quiet than noise. Individuals without hearing loss were more accurate at interpreting SVO and OVS structures in silence and noise than individuals with hearing loss. Participants in the hearing loss group showed longer reaction times than the normal hearing group for the OVS structure in noise and the ambiguous OVS structure in quiet. The lower accuracy scores and higher reaction times for ambiguous structures may reflect uncertainty in the hearing loss group. Because participants with hearing loss are more uncertain about the case-markings of determiners in these sentences as a result of degraded input, they take more time processing these sentences and are less accurate in their final interpretations.

Eye-tracking measures showed that a majority of participants took longer to process more complex and ambiguous structures as evident in longer durations to fixate on the target image. Participants also showed longer processing times in all conditions in noise, taking longer to fixate on the final image following the point of disambiguation (the time point after which the structure of the sentence and correct image can be deduced). Interestingly, Wendt et al. (2015) also found that performance amongst individuals with hearing loss was not equivalent. Individuals who did not use hearing aids took longer to fixate on their final image following the disambiguating part of the sentence than individuals who did use hearing aids. Because all stimuli were presented at an equal SRT across participants, this raises the question: what differences between hearing aid users and non-hearing aid users may affect processing times despite equal SRTs? Perhaps the groups differ in the way they adapt to uncertainty.

Given that previous research suggests individuals with real and simulated hearing loss have difficulties comprehending complex sentences and must exert more effort to comprehend a given sentence, Nunn (2016) aimed to explore how presence of a simulated hearing loss influences fidelity to a perceived linguistic signal. 80 college-aged participants were administered the same version of the Gibson task used by Warren et al. (2017). 40 participants were given an unmodified version of the task and 40 were given a version simulating high frequency hearing loss. In this version, sentence stimuli were altered so that frequencies above 2000 Hz were attenuated. This made speech sounds with frequency information above 2000 Hz more difficult to hear (Olsen, Hawkins, & Van Tasell, 1987) and was predicted to affect the audibility of easily reduced function words such as “was” “by” and “to.” These words are essential for sentence meaning and their audibility is particularly important when deciding between alternate sentence interpretations in the Gibson task. For example, prepositional object and double object sentences are differentiated by the presence or absence of “to” while active and passive sentences are differentiated by the presence or absence of “was” and “by”. The dependent variables included accuracy, reaction time, and the following eye-tracking measures: mean latency to fixate on the target image after the point of disambiguation (POD) and the sentence-offset, the mean number of fixations on after the POD and the sentence-offset, the proportion of gazes at the target image after the POD and the sentence offset, and the proportion of *first* fixations at the target image following disambiguation. The point of disambiguation was defined as the time point in which the structure of the sentence (and thus which image was faithful to the literal syntax) could be deduced given previously parsed information. Eye-tracking measures were used to gauge how much effort participants were exerting to choose between an interpretation that was faithful or unfaithful to the literal syntax.

Findings were consistent with predictions made by Gibson et al. (2013) and previous findings by Gibson et al. (2015) and Warren et al. (2017) suggesting participants partook in rational sentence inferencing. Participants were overall less accurate for implausible compared to plausible conditions. Comprehenders were more faithful to a perceived sentence when more edits were necessary to switch to an alternate interpretation. Accuracy for active/passives which require two edits to switch between alterations was higher compared to DO/POs which require one edit. Comprehenders were also more faithful to the literal interpretation when the distortion assumed was an insertion rather than a deletion. Participants with and without simulated hearing loss were less accurate for the DO construction which required the assumption that the word "to" was intended but omitted than the PO construction which assumed the word "to" was not intended but present. This deletion vs. insertion effect was not found for the active/passive alterations with both groups obtaining lower accuracy scores for passives than actives despite passives involving insertions and actives, deletions. This was consistent with findings by Gibson et al. (2013), Gibson et al. (2015), and Warren et al. (2017) which contradicts the noisy channel model set forth by Gibson et al. (2013). For individuals with simulated hearing loss, this may be because of a lack of available processing resources. Because a significant portion of processing resources are being expended to simply perceive the sentence, fewer resources are available to parse more linguistically complex sentences like passives. This is also consistent with findings by Ferreira (2003) that found individuals were more likely to rely on plausibility for noncanonical passive sentences compared to canonical active sentences. Because the passive sentence is more complex and requires more processing resources, individuals would be more likely to rely on a “go with what is most likely” heuristic. Individuals with increased noise in their language processing mechanism may be more likely to rely on this kind of strategy.

Findings also were consistent with the prediction that in the face of more noise, comprehenders will be less faithful to the literal syntax. Individuals with simulated hearing loss had lower accuracy scores in all conditions compared to individuals without simulated hearing loss. The manipulations in Nunn (2016) were used with participants with typical language processing mechanisms who were given noisy input for a brief period. The significant change in accuracy scores suggests that we can adapt our reliance on our language processing mechanism rapidly. Furthermore, it supports Levy’s (2009; 2011) suggestions that language users take advantage of all available information to revise already parsed information including the presence of temporary simulated hearing loss. Interestingly, performance of individuals with simulated hearing loss mirrored the performance of PWA in the DO/PO condition. While it was predicted that individuals with simulated hearing loss would outperform PWA in all conditions given that individuals with simulated hearing loss were experiencing noise in the acoustic signal as opposed to noise secondary to a central language processing deficit, the group’s similar performance suggests that for sentence constructions where edit distance is small, any type of noise, regardless of the source, may influence certainty equally.

Reaction time and eye-tracking measures tended to mirror accuracy scores, that is, when accuracy was low, reaction time and competition between alternate interpretations (measured via eye-tracking), was higher. This is predicted as one would expect that when one is more uncertain about a perceived sentence, one would be required to exert more effort to decide between alternate interpretations. Overall, individuals with simulated hearing loss had higher reaction times and more competition between competitor images than individuals without simulated hearing loss. Individuals with simulated hearing loss also appeared to reach ceiling in terms of available processing resources as measured with reaction time and eye-tracking data. When the NoHL group was more inaccurate, they had higher reaction times and when they were more accurate, they had lower reaction times. The LPF group had high reaction times regardless of their accuracy for a given sentence condition. This suggests that individuals with simulated hearing loss were putting in significantly more effort to simply perceive a sentence leaving less resources available to parse more complex structures. This is consistent with research by Larsby et al. (2005) and McCoy et al. (2005) which suggests hearing loss results in additional expenditure of processing resources which may be a contributing factor to difficultly individuals with hearing loss experience comprehending complex sentences. It is important to note that this assumes that measures of increased uncertainty (reaction time and eye-tracking) in Nunn (2016) correlate to expenditure of processing resources. Other measures, like pupillometry, may be a more accurate measure of this kind of cognitive effort (Johnsen, 2016).

Nunn (2016) found that individuals with simulated hearing loss partake in rational sentence inferencing. Despite participants being neurotypical adults with intact semantic and syntactic knowledge, they performed similarly to PWA in conditions where uncertainty was high. This may be a result of the decreased processing resources available given that individuals with simulated hearing loss must exert more effort to simply perceive a sentence leaving less resources available for higher linguistic processing. Similarly, people with aphasia also must exert more effort to recover an intended meaning given semantic and syntactic deficits. Despite the different sources of noise, it is likely that both groups rely on the same processing strategies to recover intended meaning given noisy input. This would be consistent with research by Amichetti, White, & Wingfield (2016) which suggest that given the demands of sentence processing, individuals may partake in shallow processing in which the meaning of a sentence is determined using word order and probability rather than by building a complete syntactic representation of the utterance. Perhaps, given that both individuals with simulated hearing loss and aphasia have increased uncertainty, they both relied on shallow processing. Amichetti et al. (2016) suggest that in most circumstances, both a shallow and more in-depth word-by-word processing strategy will result in the same meaning perceived unless the sentence intended is improbable (like the sentences used in the Gibson task). Thus, typically, relying on a probability heuristic is a successful processing strategy that even individuals without increased noise to their language processing mechanism rely on. Amichetti et al. (2016) aimed to examine the use of processing heuristics in older adults with hearing loss because individuals with hearing loss must exert more effort to simply perceive a sentence and older adults have decreased working memory abilities. Amichetti et al. (2016) predicted that these factors would increase the likelihood that older individuals with hearing loss would rely on a processing heuristic.

Amichetti et al. (2016) designed two experiments. In experiment one, plausible and implausible active and passive sentences were presented to younger and older adults with typical hearing. Participants were required to identify who was the agent or recipient of the action in the sentence. Results indicated that participants remained faithful to the literal syntax more for plausible as compared to implausible sentences. Younger adults were more faithful to the literal syntax than older adults. Finally, participants were more faithful to the literal syntax for actives than passives although this effect was marginal. In experiment two, plausible and implausible subject relative and more complex object relative sentences were presented to younger adults with normal hearing, older adults with normal hearing, and older adults with mild-moderate hearing loss. Researchers ensured the speech was audible by conducting audibility checks prior to administration of experimental stimuli. Again, participants were then required to identify who was the agent or recipient of the action in the sentence. Researchers also collected data on working memory capabilities using a letter number sequencing task. Amichetti et al. (2016) found individuals were more faithful to plausible than implausible sentences. They also found that older adults with hearing loss were less likely to remain faithful to the literal syntax than younger and older adults without hearing loss. There was also a significant effect of syntactic structure with individuals remaining more faithful for subject relative than object relative sentences. Researchers also found that working memory scores accounted for some of the variance in responses suggesting that decreased working memory increases the likelihood of relying on a processing heuristic. This suggests that decreased processing resources may contribute to why participants in Nunn (2016) interpret sentences in ways that is not faithful to the literal syntax.

Amichetti et al. (2016) note that the effect of structure was stronger for subject/object relative condition compared to the active/passive condition. For both conditions, one structure is more complex. However, the active/passive alteration has an additional variable that may contribute to the marginal effects of structure: edit distance. As outlined by Gibson et al. (2013), in order to assume that a passive was intended as an active, one must assume that you heard two words that were not intended by the speaker or not present. This deletion/insertion effect is not possible when considering whether an object relative was intended as a subject relative. Perhaps, the presence of the insertion/deletion effect in active/passives minimizes the complexity effect given these two effects encourage a comprehender to rely differently on the perceived linguistic signal. The complex structure of a passive encourages a comprehender to interpret an improbable passive as an active (unfaithful) via a processing heuristic. The deletion/insertion effect encourages a comprehender to interpret an improbable passive as a passive (faithful) as assuming a passive was actually an active requires us to assume we heard two words that were not intended/present in the signal, contradicting the noisy channel model set forth by Gibson et al. (2013). Thus, when thinking about the structural le of a given sentence, it may be important to consider how language users grapple with conflicting information about a perceived linguistic signal and the additive effect they may have on our certainty.

Amichetti et al. (2016) found that individuals rely on processing heuristics when comprehending improbable sentences, and that these effects are more profound for complex syntactic structures likely to increase processing demands. Individuals with already decreased processing resources (i.e., individuals with hearing loss or working memory deficits) were more likely to rely on processing heuristics. This research suggests that there may be multiple motivations to adapt a processing heuristic. It also suggested that participants with more decreased processing resources relied on these heuristics more: young adults relied on the strategies the least (no deficit), followed by older adults with good hearing (decreased working memory), followed by older adults with hearing loss (decreased working memory and more effort required to perceive the signal). Nunn (2016) found that individuals with simulated hearing loss performed nearly identically to individuals with aphasia on some structures despite individuals with simulated hearing loss having a more peripheral source of noise (i.e., linguistic signal versus linguistic processing). If individuals can rely on heuristics based on the degree of decreased processing resources, perhaps these individuals had equally degraded processing resources as a result of the noise to their language processing mechanism. Are there different perceptual consequences of hearing loss that may influence processing resources differently resulting in a more varied performance between people with aphasia and people with simulated hearing loss? The simulation by Nunn (2016) specifically targeted the audibility of easily reduced function words. Function words are also found to be particularly challenging for individuals with agrammatic aphasia. Perhaps, the similar degradation of this part of the linguistic signal resulted in similar performance. Research examining different aspects of cochlear hearing loss that may degrade different parts of the acoustic signal may be helpful in understanding how different sources of noise may influence our reliance on processing heuristics.

### 1.1.5 Perceptual Consequences of Hearing Loss and Uncertainty

Nunn (2016) simulated hearing loss by manipulating the audibility of high frequency perceptual input similar to the perceptual degradation of high frequency sounds present in individuals with high frequency hearing loss. Such a perturbation of the linguistic signal affected the audibility of short, easily reduced function words such as “to” “was” and “by.” These function words signal the structure of a sentence and their absence or presence play an important role in assigning grammatical roles to words. For example, the audibility of the word “to” in the sentence “The sister mailed the niece to the letter.” determines whether “the niece” is the theme or recipient of the sentence. Audibility of easily reduced function words can be thought of as especially important in improbable sentences in which one cannot simply rely on their semantic knowledge to deduce word order. However, the effects of cochlear hearing loss are not isolated to reduced audibility. Moore (1996) explains the following consequences of cochlear hearing loss:

(1) loudness recruitment: individuals with hearing loss have higher thresholds than individuals without hearing loss. For individuals with hearing loss, once a sound is above the threshold, the perception of loudness increases at a rate which is greater than that of typical hearing individuals.

(2) impaired intensity discrimination: individuals with hearing loss have more difficulty detecting differences in intensity between two sounds.

(3) impaired temporal resolution: individuals with hearing loss have more difficulty with some measures of temporal resolution, i.e., they may have more difficulty detecting gaps in noise.

(4) impaired temporal integration: for individuals with normal hearing, when a sound is played for a longer duration, the intensity of the sound is perceived as louder. This perceived increase in intensity with increased duration is reduced in individuals with hearing loss.

(5) impaired pitch perception: individuals with hearing loss have more difficulty determining if two tones are the same or different

(6) impaired frequency selectivity: individuals with hearing loss’s cochleae, have broader areas of excitation for a single tone resulting in a reduced ability to discriminate tones of different frequency, this is referred to as broadened auditory filters (BAF). The effects of broadened auditory filters are particularly evident in noise in which one sound masks the ability to hear a different sound.

The consequence of cochlear hearing loss, broadened auditory filters, is particularly interesting to study in the context of uncertainty. Our cochlea's ability to resolve frequency components of complex sounds is known as frequency selectivity (Moore, 1995). This aspect of hearing is extremely important for speech as it allows us to discriminate frequency information and identify phonemes. Frequency selectivity is achieved by the cochlea with the use of auditory filters (Moore, 1995). Auditory filters were first hypothesized by Harvey Fletcher in 1940. Fletcher experimented with a bandpass masker—a band of noise containing frequencies between a low and high cut off frequency. Fletcher used this bandpass masker to mask a target tone. He found that as the bandwidth of the bandpass masker increased, the threshold of the target tone (i.e., how loud it needed to be to be heard) increased up to a certain point. At this point and beyond, an increase in the bandwidth of the bandpass masker failed to further mask the target tone (Fletcher, 1940). Fletcher hypothesized that this must be the result of auditory filters. He proposed that along the length of the basilar membrane are bandpass filters that allow in frequencies between high and low cutoff frequencies and attenuate frequencies outside of this range. A bandpass masker with frequency information between the high and low cutoff frequencies would fall within the same auditory filter and mask the target tone. Frequency information outside of the cutoff frequencies would not fall within the auditory filter and not mask the target tone.

Like any other type of filter, if two frequencies fall within the same auditory filter, they will not be differentiated by the auditory system. If two sounds fall within different filters, they will be differentiated by the auditory system (Gelfand, 2010). Thus, when auditory filters are broadened, increasing the likelihood that two frequencies will fall within the same filter, the auditory system is less able to differentiate between these sounds. This reduces that auditory systems frequency selectivity and has a profound impact on our ability to understand speech, particularly in noise (Gelfand, 2010). In terms of uncertainty, the broadened auditory filters literally manipulate our certainty about frequency information making it difficult to differentiate between different frequency values.

Different aspects of cochlear hearing loss have different effects on the perception of speech. Broadened auditory filters, reduce the resolution of spectral information. Research has found that simulating broadened auditory filters can influence one's ability recognize phonemes and words. These effects of broadened auditory filters are particularly profound in noise (Baer & Moore, 1993a; Boothroyd et al., 1996; Leek et al., 1987; ter Keurs et al., 1992).

Boothroyd et al. (1996) for example, examined the effect of spectral smearing (an acoustic consequence of broadened auditory filters) on the recognition of phonemes, words, vowels, and consonants in quiet and noise. Boothroyd et al. (1996) presented participants with words that were smeared at bandwidths of 0 (unsmeared), 250, 500, 1000, 2000, 2828, 4000, 8000, and 20,000 (completely smeared). Although Boothroyd et al. (1996) was interested in examining the spectrum of smearing, it is important to note that smearing around 250 Hz is equivalent to the normal auditory filter width and thus should be the minimum amount necessary to influence speech recognition. In quiet, Boorthroyd et al. (1996) found that spectral smearing as little as 250 Hz influenced phoneme recognition, although the effects were minimal. For words in noise, a smearing of 250 Hz had a significant impact on word recognition. Ability to recognize phonemes and words decreased significantly as smearing bandwidth increased.

Results showed that smearing had a more profound effect on word recognition than phoneme recognition; however, this may because there is a higher probability of guessing the correct phoneme than the correct word given the total number of possible alternatives is higher for words than phonemes. Consonant perception was slightly less affected by smearing than vowel perception. Effects of smearing were more profound in noise than in quiet. It is also important to note that Boothroyd et al. (1996) found that when the stimuli were completely smeared (i.e., the speech was modulated by random noise), word and consonant recognition was not completely at 0. This suggests that other cues, such as amplitude envelopes, can also provide listeners with information needed for phoneme recognition.

Overall, Boothroyd et al. (1996) found that spectral smearing influences the intelligibility of phonemes and words. The effects were more profound in noise than in quiet. Thus, it is likely that the consequence of broadened auditory filters influences one’s certainty about the identity of phonemes and words. Given that we know individuals use all information available to make predictions about linguistic input and revise already parsed information (Levy, 2009; Levy, 2011) and that individuals can make rapid changes to their reliance on linguistic input when given degraded input (Nunn, 2016), it is likely that individuals with broadened auditory filters are more uncertain in noise than quiet.

Baer & Moore (1993a) also found that broadened auditory filters influenced intelligibility of speech and these effects were most profound in noise. Baer & Moore presented sentences simulating broadened auditory filters at 65 dB SPL to 9 participants in quiet and in noise. In the noisy condition, speech was presented at a signal to noise ratio of 0-dB S/N and -3-dB S/N, thus, in the first condition, the signal and noise were of equal loudness and in the second condition, the signal was 3 dB quieter than the noise. Filters were broadened by a factor of 3 and 6. Subjects repeated the sentences they heard to obtain accuracy scores. The authors used a “loose” scoring method in which singular and plural errors for nouns and tense errors for verbs were not counted as incorrect. In quiet, accuracy was almost 100% when broadened by a factor of 3 and 98.3% when broadened by a factor of 6. For the 0-dB S/N, accuracy was 95.7% when broadened by a factor of 3 and 69% when broadened by a factor of 6. Performance was markedly worse in the -3dB S/N condition with accuracy at 71.1% when broadened by a factor of 3 and 35.6% when broadened by a factor of 6. These results again suggest that broadened auditory filters have the most significant effect in noise. For this experiment, it would be interesting to know what the accuracy scores were without the “loose” scoring. Ability to accurately perceive singular/plural and tense markers may have a significant impact on one’s certainty about a perceived linguistic signal.

Both Leek, Dorman, & Summerfield (1987) and ter Keurs, Festen, & Plomp (1992) examined the effect of reduced spectral contrast on the ability to identify phonemes. Both found that the effect of broadened auditory filters on speech is minimal in quiet but more profound in noise. Leek et al. (1987) for example, examined individual’s ability to perceive vowels. Vowels can be identified through the differences in their high-amplitude peaks and low-amplitude troughs. Broadened auditory filters result in vowels with decreased contrast in the peaks and troughs. In order to determine how reduced contrast between peaks and troughs influence vowel identification, Leek et al. (1987) presented stimuli with varying peak-to-trough differences to individuals with normal hearing in quiet, normal hearing in noise, and hearing loss to determine the minimal peak-to-trough difference required to identify the vowel. After hearing stimuli, the participants had to indicate which vowel was heard by pressing a key on a response box. Researchers found that to obtain accuracy greater than 75%, normal hearing listeners in quiet required less than a 2 dB peak-to-trough difference while individuals with normal hearing in noise required a 4 dB difference and individuals with hearing loss required a 6 dB difference. The 1-2 dB peak-to-trough difference required by normal hearing listeners in quiet is close to the minimum difference in amplitude required to detect change in amplitude. Thus, Leek et al. (1987) suggest that the ability of individuals with normal hearing to identify vowels in quiet is minimally affected by broadened auditory filters. This research supports the notion that while broadened auditory filters may influence our certainty about spectral information, the impact on intelligibility of speech in quiet is minimal. Thus,

ter Keurs, Festen, & Plomp (1992) examined the effects of spectral smearing on vowel and consonant perception. Adults with normal hearing were presented with monosyllables and vowels in quiet and at a signal to noise ratio of +5, thus, the signal was 5 dBA louder than the noise. After being presented with the stimuli, participants wrote down the vowel or monosyllable they heard. ter Keurs et al. (1992) had four different smearing conditions: unsmeared, 1/8 octave, ½ octave, and 2 octave. ½ octave was the onset of reduced intelligibility as this is about the width of the auditory filters while the 2 octave condition represented smearing that would result in significantly decreased intelligibility. Identification of vowels in the unsmeared condition and minimally smeared condition resulted in 97% identification accuracy. The maximally smeared vowels had a 32% identification accuracy. For consonants, identification accuracy for unsmeared and minimally smeared consonants was 99%. For the maximally smeared condition, consonant identification accuracy was 72%. Overall, ter Keurs et al. (1992) found that identification of vowels and consonants was nearly unaffected by minimal smearing of ½ octave but negatively impacted by severe smearing of 2 octaves. Overall, vowels were more significantly influenced by broadened auditory filters than consonants as vowel identification depends on spectral contrasts. However, as Leek et al. (1987) found, individuals are still able to identify vowels with minimal spectral contrast. Both Leek et al. (1987) and ter Keurs et al. (1992) found that the effects of broadened auditory filters in quiet are minimal with the most profound effects on vowels and in noise. This suggests that while the broadening of auditory filters may reduce spectral contrast, individuals are still able to use other cues to recover the identity of phonemes. As a result, broadened auditory filters likely have a more significant impact on certainty than accuracy.

Overall, research has shown that broadened auditory filters reduce speech intelligibility in noise but have minimal effects on intelligibility in quiet. While the effects are particularly profound in noise, the nature of broadened auditory filters reduces the spectral contrast of sounds even in quiet. This noise in the linguistic signal likely influences certainty in both noise and quiet. While broadened auditory filters influences our ability to discriminate between spectral information, low-pass filtering (used by Nunn, 2016) influences our ability to perceive high frequency information. This is a perceptually different effect and may influence our certainty about linguistic information differently. Research has found that reduced audibility of high frequency information influences our ability to identify high frequency phonemes (Sher & Owens, 1974; Owens & Benedict, 1972).

Sher & Owens (1974) aimed to explore the phonemic errors of 35 individuals with high frequency hearing loss above 2000 Hz and 28 individuals with normal hearing given a simulated hearing loss above 2000 Hz. Participants heard a target word and had to indicate which word they heard given 4 possible options. Sher & Owens (1974) found that individuals with real and simulated hearing loss performed similarly with accuracy scores of 72.51% and 75.39% respectively. The groups had particular difficulty identifying the following phonemes: /p, b, t, k, s, θ, tʃ, ʃ, f, dʒ, z, v, d/. Both groups had phonemic substitutions, most commonly substituting phonemes of the same manner of the target phoneme.

Bhargava and Baskent (2012) examined the intelligibility of Dutch sentences that were low-pass filtered, interrupted by periods of silence, and both low-pass filtered and interrupted. Participants listened to sentences in an anechoic chamber and repeated the sentence to the experimenter. Bhargava and Baskent (2012) found that low-pass filtering had little to no effect on intelligibility except in the most severe (500 Hz) cut-off frequency. Bhargava and Baskent (2012) posit that the syntactic and semantic cues available from linguistic context were able to compensate for the lost high frequency information. This is an important differentiation because while Sher and Owen (1974) demonstrate that some phonemes become difficult to understand in low-pass filtered speech, when listening to semantically sound sentences, participants are able to recover intended meaning. Participants in Nunn (2016) experiencing low-pass filtered speech were more negatively influenced by low-pass filtered speech. This is likely because the stimuli contained improbable sentences and sentences with unreliable syntactic structures where probable alternate interpretations could be obtained through edits to the literal syntax. This increased participant uncertainty and decreased accuracy.

Leibod el at. (2014) demonstrated how the reduced audibility of these phonemes, particularly /s/ may influence our certainty about perceived linguistic information. Leibold et al.

(2014) looked at the effect of low-pass filtering on the identification of plural marking in adults and children. The two groups listened to singular and plural nouns that were low-pass filtered at the following cut-off frequencies: 8000, 5000, 4000, 3000, and 2000. This means that frequency information above the cut-off frequencies were attenuated. The participants were then presented with words via loudspeakers inside a soundproof booth and asked to choose which of two pictures (one representing the plural and one the singular) was the word they just heard. Leibold et al. (2014) found that both children and adults had more difficulty identifying plural /s/ markers when words were low-pass filtered below 5000 Hz. When the filter was below 3000 and 2000 Hz (the same filter characteristics of Nunn, 2016), accuracy dropped on average 16.4 percentage points in adults and 9.4 percentage points in children. While the listener's accuracy was influenced by low-pass filtering, it was not extremely detrimental and both groups performed above chance. Overall, Leibold et al. (2014) demonstrated that reduced audibility of high frequency information may influence our certainty about the presence of important grammatical morphemes.

The data also shed light on insertions vs. deletions in the context of the noisy channel model. Gibson et al. (2013) would predict that participants would be less faithful to a plural noun when they must assume "s" was intended but not perceived than when they must assume "s" was perceived but not intended. This would mean participants should be more likely to say "dog" was intended as "dogs" (assume that "s" was intended but not perceived) than to assumer "dogs" was intended as "dog" (assume "s" was perceived but not intended). The participants in Leibold (2014) showed the opposite pattern. The children had a total of 172 errors in the 2000 Hz cut-off condition. Of these errors, 35% were a result of a singular item being incorrectly identified as a plural (i.e., assuming you didn't hear a sound that was present) while 65% were assuming a plural was singular (i.e., assuming you heard something that wasn't intended/present). The adults had a total of 146 errors in the 2000 Hz cut-off condition. Of these errors, 20% were singular items being incorrectly identified as plurals and 80% were assuming a plural was singular. This brings to question what role the noisy channel model plays at different linguistic levels i.e., the word vs. the morpheme. Gibson et al. (2013) discusses the noisy channel model at the word level and makes predictions of how a listener would act in the face of noise; however, Leibold et al.'s (2014) findings raise the question as to how these predictions apply to different linguistic levels. Perhaps, at these smaller linguistic levels, the weight of the phoneme is so small, that the differentiation between insertion and deletion is less important. Similarly, perhaps, given the degraded input, participants were more likely to choose the most linguistically simple interpretation. Similarly to how participants tend to select images consistent with active sentences, perhaps participants were more likely to select images consistent with the less complex singular version. It is also possible that the insertion vs. deletion effect in the conception of edit distance is incorrect. This would also explain why participants are more faithful to passives than actives (Gibson et al., 2013; Gibson et al., 2015; Warren et al., 2017, Nunn et al., 2016) and Leibold's (2014) findings on plural markers. Regardless, more research continues to suggest that the insertion/deletion effect described by Gibson et al. (2013) doesn't apply in all contexts. It would be interesting to better understand in what contexts it does apply and what other linguistic calculations may be occurring that may account for the variance in the effect.

In terms of uncertainty, it is questionable as to whether different perceptual consequences may differ in how they influence one's uncertainty about a perceived linguistic signal. For example, is a comprehender more uncertain in the face of noise that degrades pivotal function words such as "to", "was" and "by" or more uncertain in the face of noise that reduces spectral contrast but has little effect on intelligibility in quiet. Alternatively, is it merely the presence and not the type of noise that influences our certainty about perceived linguistic input? Both people with aphasia and individuals with simulated hearing loss performed similarly on the Gibson task for the DO/PO construction (Warren et al., 2017; Nunn, 2016). Is this because both types of noise may have influences on the perception of function words which are important for assigning grammatical roles within the sentence? Or rather, does noise effect all comprehenders similarly? How would individuals with simulated broadened auditory filters perform on the Gibson task? Simulated broadened auditory filters manipulate our certainty about linguistic input while having minimal effects on overall intelligibility.

The present studied aims to examine how broadened auditory filters *in quiet* influence uncertainty of a perceived linguistic signal. Broadened auditory filters in quiet was chosen to better understand how a perceptual consequence of cochlear hearing loss influences uncertainty in the absence of influencing perceptual accuracy. In Nunn (2016), participants perceived sentences simulating an aspect of cochlear hearing loss that both degraded audibility of high frequency information and influenced uncertainty. Research supports that while broadened auditory filters smear spectral information, suggesting that they influence uncertainty, in quiet, they have minimal effects on perceptual accuracy (Baer and Moore, 1993a; Boothroyd et al., 1996; Leek et al., 1987; ter Keurs et al., 1992). It is important to remember that a high intelligibility does not necessarily correlate to high accuracy on the Gibson task. Once a sentence is perceived, the comprehender then uses linguistic knowledge to determine the meaning intended, within this transformation, participants may settle on interpretations that are unfaithful to the literal syntax. Thus, utilizing a manipulation that may leave intelligibility relatively intact but increase uncertainty about spectral information may provide insight into how different type of noise influence decisions about perceive linguistic input.

### 1.1.6 Practical Applications

By increasing our understanding about how different types of noise influence our certainty about linguistic input, we can develop strategies for communication partners of individuals with communication disorders to increase the likelihood of a successful communicative exchange. For example, Carter et al. (1996) explore the manipulation of semantic and syntactic context on the intelligibility of dysarthric speech. Six dysarthric speakers (3 moderate and 3 severe) recorded stimuli sentences and 36 listeners were instructed to transcribe as much of the sentences as possible. For example, for the following sentence "The police said the collision was not my fault" listeners were given semantic context ("accident") or syntactic context ("The _______ the _________ was not my _________") (Carter et al., 1996). While the manner in which the context is provided in this experiment is unnatural (i.e., listeners do not receive printed material with the context of a sentence definitively stated) listeners can use their semantic and syntactic knowledge to estimate the likelihood of certain grammatical constructions or utterances. The researchers found that intelligibility of severe dysarthric speakers was higher in both the semantic and syntactic context conditions. There was not a significant effect of semantic or syntactic context for moderate dysarthric speakers.

Thus, when there is a high amount of noise in a linguistic signal (i.e., severe dysarthric speech), altering the amount of semantic or syntactic context may aid in intelligibility. Similarly, when there is a high degree of uncertainty about the perceived linguistic input (because the comprehender has a communication disorder like aphasia or hearing loss), altering the semantic and syntactic context may aid in intelligibility. In what other ways could speakers alter their utterances to aid in comprehension? One more readily available manipulation of context is our semantic knowledge—the knowledge about the frequency of certain grammatical structures and the likelihood of a speaker will produce a given utterance. Levy's (2009; 2011) work suggests we are sensitive to these kinds of manipulations and take advantage of it to revise previously parsed information and make predictions about upcoming linguistic input. Nunn (2016) found that individuals with simulated hearing loss are less accurate for passive compared to active sentences, perhaps as a result of the lack of available processing resources to parse more linguistically complex sentences. Relying on more canonical sentence structures may be a way for communication partners of individuals with hearing loss to reduce mismatch between intended meaning and perceived meaning.

# 2.0 CURRENT STUDY: GOALS AND QUESTIONS

The current study aims to further explore how different perceptual consequences of cochlear hearing loss, in particular, broadened auditory filters, influence certainty about perceived linguistic input in relation to the noisy channel model set forth by Gibson et al. (2013). The specific research questions to be addressed are as follows:

1. How will sentence structure and plausibility influence fidelity to a perceived linguistic signal?
2. How does the absence or presence of broadened auditory filters affect one's fidelity to a perceived linguistic signal?
3. How does absence or presence of broadened auditory filters affect one's consideration of target and non-target interpretations of the sentence, as measured through eye-tracking and reaction time data?
4. How does individuals with broadened auditory filter's (BAF) performance on the Gibson task compare to people with simulated reduced audibility of high frequency information (LPF) and individuals without simulated hearing loss (NoHL)?
5. How does individuals with simulated hearing loss' performance on the Gibson task compare to individuals with aphasia's performance?

In order to answer these questions, participants completed a modified version of the Gibson task used by Nunn (2016) and Warren et al. (2017). This version of the task contains the same linguistic stimuli: double object/prepositional object and active/passive sentence alterations, varying in plausibility. Participants were given a version that simulates broadened auditory filters by a factor of 3. Previous studies have shown that simulated broadened auditory filters by a factor of 3 is similar to the broadening of auditory filters in individuals with mild-moderate cochlear hearing loss (Baer & Moore, 1993a; Baer & Moore, 1993b). Accuracy data was used as a measure of percent of sentences in which participants were faithful to the literal syntax. Reaction time and eye-tracking data were used to measure how uncertain an individual is when deciding between sentence alterations. Increased reaction times indicated the participant required more time to decide whether to remain faithful to the literal syntax. Eye-tracking measures showing more fixations between the competitor and target images or increased duration to fixate on the target image suggest more uncertainty about which interpretation is faithful to the literal syntax.

If participants with BAF perform differently than individuals with LPF, then this would suggest the perceptual consequences of different aspects of cochlear hearing loss influence our certainty about perceived linguistic input differently. Broadened auditory filters largely affect one’s ability to discriminate frequency information reducing our ability to take advantage of spectral contrasts in speech. While this likely influences one’s uncertainty about perceived linguistic input, in quiet, it has minimal effects on sentence intelligibility. Low-pass filtering speech, on the other hand, influences one’s ability to perceive phonemes containing high frequency information. This has the most profound effect at the phoneme level and may impair the ability to perceive important grammatical morphemes (Leibold et al., 2012). While both effects are secondary to cochlear hearing loss, their perceptual consequences on speech may influence certainty differently. This may inform our understanding of how information about the linguistic signal (i.e., what is degraded and to what degree) influences a rational sentence comprehender. This may help us understand how we can manipulate semantic and syntactic context to increase the likelihood of a successful communicative exchange in people with communication disorders.

## 2.1 HYPOTHESES

Below are the hypotheses for the above research questions 1-5:

(1 & 2) It is predicted that individuals with simulated broadened auditory filters will rely less on the literal syntax than individuals without simulated hearing loss. This is supported given Gibson et al.'s (2013) prediction that individuals are less faithful to the literal syntax in the face of more noise and further supported by previous studies conducted showing that individuals with increased noise in their language processing mechanism secondary to aphasia or simulated hearing loss are less faithful to the literal syntax (Gibson et al., 2015; Nunn, 2016; Warren et al., 2017). This will be evident in lower accuracy scores for individuals with simulated broadened auditory filters. However, like typical individuals, people with aphasia (PWA) and people listening to LPF speech, individuals with simulated broadened auditory

filters will partake in rational sentence inferencing in which they will be more faithful to the literal syntax when (1) a sentence is probable as opposed to improbable (2) there are more edits necessary to go from one alteration to the other and (3) a distortion involves an insertion rather than a deletion. This will be evident in lower accuracy scores for DO/POs than actives/passives as active/passives require two edits to switch between alterations (e.g., addition/deletion of “was” and “by”) and DO/POs require one (e.g., addition/deletion of “to”). It will also be evident in lower accuracy scores for DO’s compared to PO’s as distortions in DO sentences involve deletions (assuming an intended word was omitted) rather than insertions (assuming a word you heard was not intended). It is not predicted that individuals with be more faithful to passives than actives although a distortion involving passives requires two insertions while actives require two deletions. Rather, it is predicted that individuals will be more faithful to the active structure as evident in higher accuracy scores. This is consistent with findings by Gibson et al. (2013), Gibson et al. (2015), Warren et al. (2017), and Nunn (2016) that individuals with and without aphasia and with simulated hearing loss are more faithful to actives than passives. Gibson et al. (2015) suggests that these findings may be because passive sentences have longer dependencies and a lower structural frequency. This contributes to their complexity and increases the frequency of errors. Warren et al. (2017) suggest that the high complexity and low frequency of the passive structure results in lower quality representations of passive sentences for PWA and posits that PWA are less faithful to structures for which they have lower quality representations. While high complexity and low structural frequency may explain why participants in Nunn (2016) had reduced accuracy scores for passives compared to actives, given that the participants in Nunn (2016) were neurotypical adults with no history of speech, language, or hearing disorders, it is unlikely that lower quality representations contributed to their lower accuracy scores. It is possible, however, that the increased complexity and reduced frequency of the passive structure means that passives required more processing effort to be parsed compared to the less complex and more common active structure. Given that individuals with simulated hearing loss have been found to require more time to parse a complex or lower frequency sentence than typical individuals (Carroll & Ruigendijk, 2013; Larsby et al., 2005; McCoy et al., 2005; and Wendt, Kollmeir, & Brand, 2015), individuals with simulated hearing loss may simply lack the available processing resources to parse the more complex sentence making them more likely to rely on a processing heuristic. While both PWA and individuals with simulated hearing loss may have different reasons for being unfaithful to the literal syntax (i.e., lower quality representations vs. reduced processing resources) both groups ultimately rely on the same heuristic resulting in reduced accuracy.

(3) The presence of broadened auditory filters is predicted to result in behavioral indicators suggesting individuals are more uncertain about the perceived linguistic input and having more difficulty deciding between alternate interpretations. This would be evident in increased reaction times and increased consideration of competitor images as compared to individuals without simulated hearing loss. This is because reaction time and eye-tracking measures are a measure of how much time is required to parse a given sentence and how much consideration is given to alternate interpretations. Measures of effort, reaction time and eye-tracking data, are expected to mirror accuracy data. If participants are having more difficulty parsing a given sentence, it may take them longer to decide the intended meaning, increasing

the likelihood of them relying on a heuristic, and decreasing accuracy. Thus, reaction times should be higher for implausible compared to plausible sentences, DO/POs compared to actives/passives, DOs compared to POs, and passives compared to actives. Similarly, eye-tracking data should reveal that participants take longer to fixate on the target image and increased gazes between images for implausible compared to plausible sentences, DO/POs compared to actives/passives, DOs compared to POs, and passives compared to actives.

(4 & 5) The fourth and fifth research questions address the possible varied effects that different types of noise i.e., aphasia or different perceptual consequences of cochlear hearing loss may have on uncertainty and performance on the Gibson task. In order to predict how different perturbations of a linguistic signal might influence one's certainty, one must think about Levy's assertion that comprehenders take advantage of all available information in a linguistic signal when making predictions about upcoming information and revising already parsed information (2009; 2011). Low-pass filtering used by Nunn (2016) effects the perception of high frequency speech information reducing audibility of /p, b, t, k, s, θ, tʃ, ʃ, f, dʒ, z, v, d/ (Sher & Owens, 1974). On the other hand, broadened auditory filters have a more general effect on frequency information reducing the ability to discriminate spectral information and take advantage of spectral contrast in speech. In quiet, broadened auditory filters have minimal effects on intelligibility (Baer and Moore, 1993a; Boothroyd et al., 1996; Leek et al., 1987; ter Keurs et al., 1992). Rather, broadened auditory filters specifically target certainty about spectral components of the signal, not audibility. While comprehenders listening to low-pass filtered and speech simulating broadened auditory filters would be aware that the input to their

language processing mechanism was noisy, the perceptual consequences of the noise differ.

Nunn (2016) found that individuals with aphasia and individuals with LPF performed similarly on DO/PO sentences. Nunn (2016) suggested that for sentences with small edit distances, any type of noise, regardless of the type or degree may influence our fidelity to a linguistic signal equally. For active/passive alterations where edit distance was larger, PWA were more influenced by noise than people hearing LPF speech. Thus, while PWA and people with simulated LPF speech are both highly uncertain about DOs and POs, PWA are more uncertain about actives and passives than people listening to LPF speech. Either the differences in noise between the groups or the difference in structures must account for this variability. Research by Amichetti et al. (2016) explains how differences in available resources may influence fidelity to a linguistic signal. Amichetti et al. (2016) compared how individuals with decreased working memory (i.e., older individuals) and individuals with decreased working memory and more perceptual effort needed to perceive a linguistic signal (i.e., older individuals with hearing loss) performed on sentence comprehension tasks. Researchers found that older individuals without hearing loss performed better on sentence comprehension tasks than older individuals with hearing loss; these effects were amplified when using more complex sentence structures. Thus, Amichetti et al.'s (2016) findings suggest that fidelity to a linguistic signal is not always "all or nothing"—individuals with less available processing resources may be less faithful to a linguistic signal than individuals with more available processing resources.

These two studies suggest that while different types of noise may have similar effects on our fidelity to a linguistic signal, comprehenders may be able to adjust fidelity to a linguistic signal depending on their available processing resources. This suggests that in some experimental conditions, the BAF group may perform similarly to the LPF group and PWA while they may perform differently in other conditions. This is because the groups may differ in their available processing resources given how they are expending resources to compensate for noise to the linguistic signal. Given what we know from Nunn (2016) it is expected that individuals with BAF will perform similarly to individuals with LPF and PWA when listening to sentences that have smaller edit distances that are particularly susceptible to noise (i.e., DO/PO). This is because Nunn (2016) found LPF and PWA performed similarly for DO/PO's, despite the differences in the type and degree of noise for each group.

In the above prediction, it is suggested that groups with different types and degrees of noise will perform similarly because the DO/PO structure has a small edit distance and is highly susceptible to noise regardless of type and degree. However, the active/passive structure has a larger edit distance meaning that participants may need to be more uncertain or have fewer available processing resources to interpret it in a way that is unfaithful to the literal syntax. Nunn (2016) showed this in her study. While the LPF group and PWA performed similarly on DOs and POs, the LPF group outperformed PWA on actives and passives. This makes sense as PWA likely experience more uncertainty than the LPF group given that the noise experienced by PWA is a central language impairment as opposed to peripheral noise to the linguistic signal. Given this varied performance on actives and passives, it is predicted the BAF group will perform differently from the LPF group and PWA. It is expected that the BAF, like the LPF group, will outperform PWA. This is because the noise experienced by BAF is peripheral and only present in the linguistic signal itself. However, it is expected that the BAF group will outperform the LPF group. This is because the noise experience by the BAF group influences uncertainty about spectral information but it does not influence audibility of linguistic information as it does in LPF speech. Thus, the BAF group experiences uncertainty and not reduced audibility. The LPF group on the other hand experiences uncertainty as a result of the noise to their language processing mechanism and reduced audibility in which they have difficulty perceiving high frequency consonants.

It is expected the PWA will have the lowest accuracy scores on actives and passives. This is because of the central language impairment experienced by PWA is a higher degree of noise. The LPF group will outperform PWA. This is what was found in Nunn (2016) and is likely because the noise experienced by the LPF group is less than the noise experience by PWA because if is peripheral and only present in the linguistic signal itself. The BAF group will outperform the LPF group. Furthermore, we know from Amichetti et al. (2016) that participants with fewer processing resources are more likely to rely on a processing heuristic resulting in lower accuracy scores. Similar to the above predictions, PWA will likely have the least amount of processing resources available followed by LPF and then BAF. The LPF group is expected to have less available processing resources because the noise to their language processing mechanism results in more effort to perceive the linguistic signal, increased uncertainty, and reduced audibility of high frequency information. The BAF group, on the other hand, requires more effort to perceive the linguistic signal and has increased uncertainty but does not have effects of reduced audibility. Thus, on structures that are less susceptible to uncertainty, BAF will outperform the LPF group and PWA. This will be evident in equally low accuracy scores for DO/POs across the BAF, LPF, and PWA groups and higher accuracy scores for actives/passives for the BAF group compared to LPF and PWA. Again, reaction time and eye-tracking measures are expected to mirror accuracy time data: BAF will have similar reaction times for DO/PO alterations but lower reaction times for active/passive alterations than LPF. BAF will take equally as long to fixate on the target image and show a similar amount of gazes between images compared to LPF on DO/PO alteration but take less time to fixate on the target image and show fewer gazes between images compared to LPF for active/passive alterations. Individuals with BAF will also be less influenced by plausibility and edit distance compared to individuals with LPF given that the noise to the language processing mechanism specifically targets uncertainty and not audibility.

# 3.0 METHOD

## 3.1 PARTICIPANTS

40 individuals with normal hearing were given a version of the Gibson task simulating broadened auditory filters. 40 participants in each experimental group was decided on based on a previous study conducted by Carminati, van Gompel, Scheepers, & Arai (2008) that found significant results with a similar study design and with a similar-sized group of young adult participants. Furthermore, this group size matches the characteristics in Nunn (2016) facilitating comparisons between studies. Participants were required to be between the ages of 18-70, native English speakers, to have normal or corrected to normal vision and no history of speech, language, cognitive, or hearing disorders.

### 3.1.1 Recruitment

Participants were recruited through graduate and undergraduate Communication Science and Disorders classes at the University of Pittsburgh. Some students received extracredit for participating at the course instructor’s discretion. In addition, interested volunteers who heard about the study were recruited.

For the broadened auditory filter version of the task, 44 participants underwent screening procedures and 40 were successfully run on the Gibson task. The four participants were disqualified on the basis of history of speech/language disorder (1), failure of hearing screening (1), failure of Raven's Coloured Progressive Matrices (1), and difficulty eye-tracking (1).

### 3.1.2 Demographics

The mean age of participants in the BAF group was 23.7 years and ranged from 19 to 42 years. This group was compared to the data collected by Nunn (2016). In Nunn (2016), the mean age of the participants in the no hearing loss group was 19.7 years and ranged from 18 to 21 years. The mean age of participants in the simulated hearing loss group was 19.3 years and ranged from 18 to 24 years. All participants were University of Pittsburgh students.

## 3.2 MATERIALS

### 3.2.1 Screening Tasks

As a part of the screening procedure, all participants completed a pencil and paper based questionnaire on demographic and medical history. Participants were disqualified if they had a history of speech, language, or hearing disorders, a neurological disorder, or significant vision deficits. Participants also participated in a pure-tone bilateral hearing screening at 40dB using and audiometer and over the ear headphones. Participants completed the Mini-Mental Status Exam (MMSE), a measurement of cognitive impairment, and scored a 28 or above (Folstein et al., 1975). Participants also completed Ravens Coloured Progressive Matrices (RCPM), a measure of non-verbal reasoning, and scored a 30 or above (Raven, 1965). Results for MMSE and RCPM were recorded on paper and pencil response sheets. Participants also completed an Acuity and Mouse task to ensure they were comfortable using a computer

### 3.2.2 Experimental Task

Participants completed the Gibson task as a measure of reliance on semantic and syntactic information and fidelity to a perceived linguistic signal. The version of the Gibson task used sentence stimuli that simulated broadened auditory filters.

#### 3.2.2.1 Simulated Broadened Auditory Filters

The items from the Gibson task had previously been used in Warren et al. (2017), Gibson et al. (2013), and Nunn (2016) but sound files were altered to simulate broadened auditory filters. In order to simulated broadened auditory filters, the original sound files from Warren et al. (2017) were modified using a vocoder. Vocoders take advantage of bandpass filters. Bandpass filters allow frequencies between a low and high cut-off frequency through and attenuate frequencies outside of the cutoff frequencies. The range of frequencies between the low and high cut-off point is known as the analysis band. The output of the filter allows one to analyze how much energy is present in a given signal within the analysis band. This output is known as the envelope. Once the envelope is extracted from the signal, one can modulate a noise band with the same bandwidth as the analysis band to the envelope.

The width of the analysis band can be analogous to the width of our auditory filters. When the analysis bands are narrow and don't overlap, the output of the filter contains only energy from within that band. When the analysis bands are broadened, however, they begin to overlap, thus, the output of this filter contains energy that is also present in other outputs. This overlap in information reduces the distinction between spectral information and reduced spectral clarity. Thus, by putting speech through a vocoder, and then broadening the analysis bands by a factor of 3, the difference between the vocoded and broadened vocoded signal simulates the typical broadening of auditory filters in individuals with mild-moderate cochlear hearing loss (Baer & Moore, 1993a; Baer & Moore, 1993b). Below is an example of two speech spectrograms. The first spectrogram is of the modified stimuli put through a vocoder and the second is the modified stimuli put through the vocoder simulating broadened auditory filters by a factor of 3. Frequency is represented on the y axis, time on the x axis, and amplitude in grayscale.

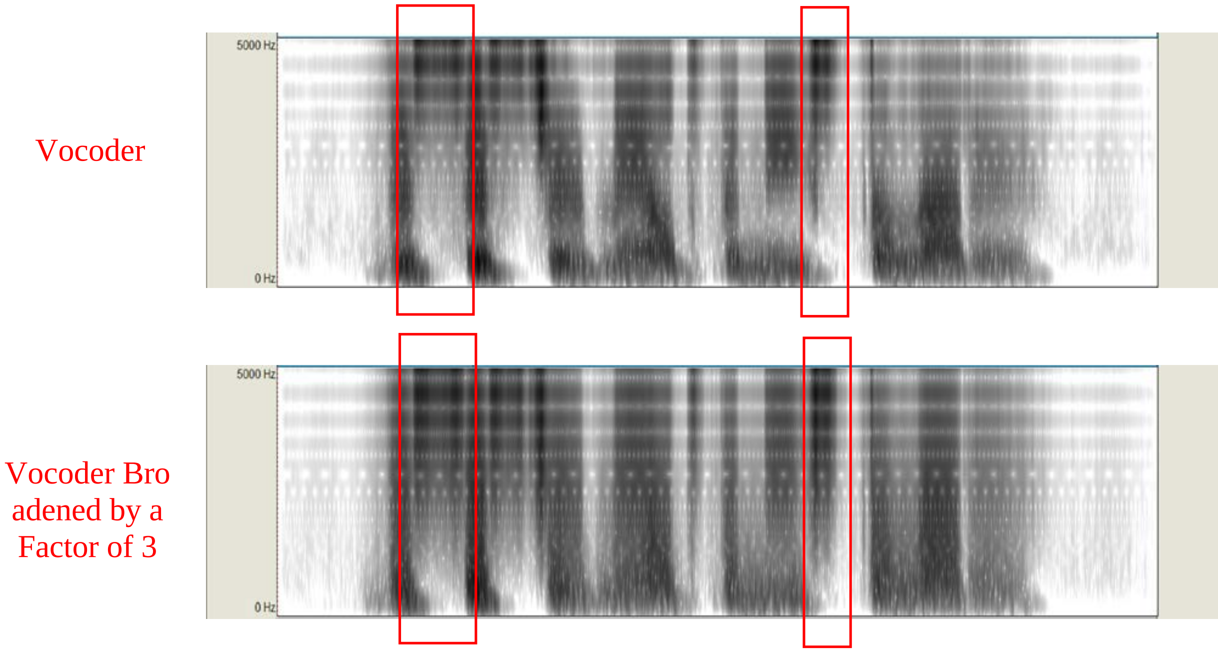


**Figure 1: Simulated Broadened Auditory Filters**

The second spectrogram is visibly darker than the first. Red boxes have been used to highlight spectral smearing as a result of broadened auditory filters. The darker lines on the second spectrogram means that more energy is present in the speech signal because of the overlapping filters resulting in reduced spectral contrast. In order to determine the degree of broadening, a pilot study was conducted.

#### 3.2.2.2 Pilot Study Results

Four versions on the broadened stimuli were created with slopes of 1, 2, 3, and 6. Using the pairs 1 & 3 or 2 & 6 would simulate the broadening of filters by a factor of 3. Because of the steeper slope, the 2 & 6 pair is more intelligible than the 1 & 3 pair. Previous studies have shown that simulating broadened auditory filters by a factor of 3 is similar to the broadening of auditory filters experienced by individuals with mild-moderate cochlear hearing loss (Baer & Moore, 1993a; Baer & Moore, 1993b)

In order to determine the optimal pair for the purpose of this study, 8 participants were run in a pilot study. Two participants were run on each list. The goal was to find the pair that simulated broadened auditory filters while minimally reducing intelligibility. Intelligibility was measured by presenting individuals with sentences from the Gibson task and instructing them to repeat the sentences to the experimenter. The experimenter recorded their responses for each word as correct or incorrect. Accuracy was also calculated for structures where participants were expected to be faithful to the literal syntax.

**Table 5: Pilot Data, Filter Accuracy**

| Filter | DO Poss Acc. | PO Imposs Acc. | Passive Poss Acc. |
|---|---|---|---|
| 1 (most severe) | 0.65 | 0.65 | 0.83 |
| 2 | 0.9 | 0.85 | 0.92 |
| 3 | 0.9 | 0.90 | 0.98 |
| 6 (least severe) | 0.9 | 0.85 | 0.98 |

The pilot data showed that the pair of 2 and 6 best simulated broadened auditory filters while minimally reducing intelligibility.

Percent repetition accuracy data was also used to determine whether or not practice trials should be added to the experiment to allow the participant to become accustomed to the hearing loss simulation prior to the experimental trials. Practice trials would reduce any effects of learning that may be accompanied by prolonged exposure to noisy speech. Below is the repetition accuracy data for the first through fourth quarter of the experiment for filters 2 and 6.

**Table 6: Pilot Data, Repetition Accuracy Over Time**

| | AP/Imposs Acc. | DOPO/Implaus Acc. |
|---|---|---|
| First Quarter | 75.2% | 70.1% |
| Second Quarter | 100% | 96.1% |
| Third Quarter | 98.5% | 90.2% |
| Fourth Quarter | 99.0% | 95.5% |

Based on the repetition accuracy, intelligibility improved significantly between the first and second quarter (about 16 trials) and plateaus over the last three quarters. As a result, it was decided to add practice trials containing 10 sentences. Sentences for the practice trials were probable and of different syntactic structures than those used in the experimental trials. All images in the practice trials were of probable events.

### 3.2.2.3 Sentence Structure and Plausibility

For the experimental portion, items 1 a-d and 2 a-d were originally included in Gibson et al. (2013) study while items 3 a-d and 4 a-b were added to the task by Warren et al. (2017). Four lists were created using a Latin Square Design. Each list contained 86 trials: 20 DO/PO Implausible/Plausible sentences, 20 Active/Passive Impossible/Possible sentences, 20 Active/Passive Implausible/Plausible sentences, 10 Active/Passive Reversible sentences, and 16 filler sentences. Thus, participants are exposed to 5 trials with each sentence construction (i.e., 5 DO plausible trials, 5 DO implausible trials, 5 active possible trials, etc.). Half of the sentence stimuli was processed through a vocoder while the other half was simulated through a vocoder using analysis bands that broadened by a factor of 3. Presentation of BAF and vocoded stimuli was randomized.

This first set of items crosses double object and prepositional object (DO/PO) syntactic alterations with plausible and implausible semantic coherence. The structures vary in the type of edits needed to get from one construction to the other. To get from a DO to a PO sentence, one must assume the speaker deleted the word “to.” In order to get from a PO to a DO, one must assume the speaker accidently inserted the word “to”. As consistent with the model presented by Gibson et al. (2013), comprehenders are more likely to be faithful to the syntax when the error involves an insertion rather than a deletion.

**Table 7: Double Object Prepositional Object Sentences**

| **Item** | **Structure** | **Probability** | **Sentence** | **Error if Distortion** |
|---|---|---|---|---|
| 1a | DO | Plausible | The sister mailed the niece the letter. | None |
| 1b | DO | Implausible | The sister mailed the letter the niece. | (1) Deletion of “to” |
| 1c | PO | Plausible | The sister mailed the letter to the niece. | None |
| 1d | PO | Implausible | The sister mailed the niece to the letter. | (1) Insertion of “to” |

The second set of 20 items crosses active and passive syntactic alterations with possible and impossible semantic coherence. The structures vary in the types of edits needed to get from one construction to the other. To get from an active to a passive sentence, one must assume the speaker deleted the words “was” and “by”. In order to get from a passive to an active, one must assume the speaker accidently inserted the words “was” and “by”.

**Table 8: Active Passive, Impossible Sentences**

| **Item** | **Structure** | **Probability** | **Sentence** | **Error if Distortion** |
|---|---|---|---|---|
| 2a | Active | Possible | The mother set the table. | None |
| 2b | Active | Impossible | The table set the mother. | (2) Deletion of “was” & “by” |
| 2c | Passive | Impossible | The mother was set by the table. | None |
| 2d | Passive | Possible | The table was set by the mother. | (2) Insertion of “was” & “by” |

The active/passive alterations differ from the DO/PO alteration in that DO/PO alterations are one edit away from an alternate interpretation while active/passive alterations are two edits away from an alternate interpretation. Recall that Gibson et al. (2013) found that language comprehenders are more likely to remain faithful to the literal syntax of a sentence when more edits are needed to go from one alteration to another.

The task is a forced choice-task in which participants selected which of two images best illustrates what they heard in the sentence. One illustration represented the literal syntax while the other represented an alternate interpretation that may be obtained through edits or distortions of the literal syntax. Images are selected by pressing a key on a standard keyboard corresponding to the image. Accuracy and reaction time data are collected based on these measures. Below is an example of what participants heard upon hearing the sentence: “The janitor lent the teacher the mop.” The same images were used for an alternate version of this sentence, “The janitor lent the teacher to the mop.” Left and right image placement was randomized during the creation of the task and fixed for each trial. The picture corresponding to the literal syntax was on the left and right side of the screen an equal number of times.

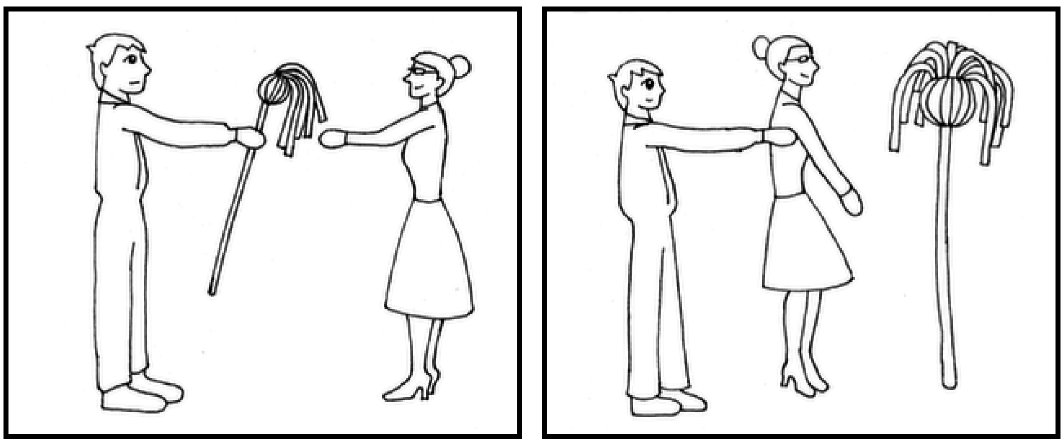

**Figure 2: Gibson Task Illustration**

The task used in Warren et al. (2017) was modified and rebuilt in Experiment Builder to allow eye-tracking for Nunn’s (2016) experiment; these modifications for eye-tracking were kept for the present study. While listening to the sentence and making their choice, participants’ eye-gaze was tracked using an Eyelink 1000 Tower Mount. Eye-tracking data was collected on: (1) the mean latency to fixate on the target image after the point of disambiguation (POD) and the sentence-offset; (2) the mean number of after the POD and the sentence-offset; (3) the proportion of gazes at the target image after the POD and the sentence offset; and (4) the proportion of first fixations that were at the target image following disambiguation. Measurements were obtained from the POD or sentence-offset until participants responded. As a result, for the active and DO sentences, the POD and the sentence offset were the same measurement as the POD for actives and DOs was the sentence offset. Both proportion of gazes at the target and overall number of gazes were used to measure competition between the two images. This is important because the proportion of gazes at the target may present a misleading picture of how much competition a participant is experiencing. For example, one participant might look at the target image two times and the competitor image two times, which would result in 50% of gazes at the target image. Another participant might look at the target image 10 times and the competitor image 10 times, also resulting in a score of 50%. However, the second participant would be exhibiting more competition between the target and competitor image.

The point of disambiguation (POD) is defined as the word in the sentence that after hearing participants would be able to determine which image was faithful to the literal syntax. The POD differed for the different sentence constructions and is illustrated in the table below. The red asterisk marks the POD.

**Table 9: Points of Disambiguation**

| **Items** | **Structure/Plausibility** | **Structure** | **Example** | **POD** |
|---|---|---|---|---|
| 1a & 1b | DO/Plaus-Implaus | NP V NP NP * | The sister mailed the niece the letter *. | Sentence offset |
| 1c & 1d | PO/Plaus-Implaus | NP V NP *to* * NP | The sister mailed the niece to * the letter. | “to” offset |
| 2a & 2b | Active/Poss-Imposs | NP V NP * | The mother set the table *. | Sentence offset |
| 2c & 2d | Passive/Poss-Imposs | NP *was* V *by* * NP | The mother was set by * the table. | “by” offset |

## 3.3 PROCEDURE

### 3.3.1 Screening

Upon arrival, participants underwent consent procedures and sign a consent form approved by the University of Pittsburgh Institutional Review Board. Participants filled out two paper and pencil based questionnaires regarding their demographic history (i.e., date of birth, native language, handedness, etc.) and medical history (i.e., history of vision deficit, speech or language disorders, etc.). Participants also had a pure tone hearing screening of frequencies 500, 1000, 2000, and 4000 Hz at 40dB. Participants completed the Mini- Mental Status Exam (Folstein et al., 1975) and Raven's Coloured Progressive Matrices (Raven, 1965). Finally, participants completed the Acuity and Mouse task. The Acuity and Mouse task consists of four trials during which participants heard a word and were instructed to choose which image presented on the screen best represented what they heard. If participants incorrectly selected an image, they were corrected and instructed on how to prevent a similar error in future trials.

### 3.3.2 Experimental Task

Following screening procedures, participants began the Gibson task. Stimuli were presented through desktop speakers on the left and right sides of the computer monitor at 60dB SPL (conversational loudness level). Participants were instructed to sit in a comfortable position and adjust the chair so they could place their head comfortably into the Tower Mount of the eye-tracker. The experimenter then read the experimental instructions and asked if the participant had any questions. Next, the participant was instructed to look straight ahead while the experimenter calibrated the equipment to their pupil size and corneal reflection. Then participants were directed to look directly at dots in different locations on the screen to map their eye-gaze in relation to the screen. These points were then validated using the guideline that the average error was no more than .5 degrees and the maximum error was no more than 1 degree. The participant was then told the experiment was starting. First the participants participated in practice trials (10 trials as determined by the pilot study). Following practice trials, participants were asked if they had any questions, then, experimental trials commenced. At the end of the task, participants were debriefed.

# 4.0 RESULTS

## 4.1 ANALYSIS AND DESIGN

### 4.1.1 Behavioral Measures

Behavioral data was extracted from Eye-Link Data Viewer. For comparisons between the BAF and vocoded stimuli, three-way ANOVAs were completed in SPSS. Separate analyses were conducted for each sentence condition (i.e., DO/PO vs. active/passive). Within subject factors included filter (i.e., BAF or vocoded), structure (i.e., active or passive; double object or prepositional object), and plausibility (i.e., implausible or plausible; impossible or possible). For comparisons between groups (i.e., BAF vs. LPF vs. NoHL) three-way ANOVAs were completed. Within-subject factors were structure and plausibility. The between-subjects factor was group.

Overall, the following comparisons were made with the data: BAF vs. NoHL, LPF vs. NoHL, BAF vs. LPF, BAF vs. vocoded (within subject). Because of multiple comparisons with the same data, a Bonferroni correction was calculated by dividing the significance level of .05 by 4 making the new significance level $p<.0125$. Main effects and interaction effects were only considered significant if they met this significance level.

### 4.1.2 Eye-tracking Measures

A fixation and trial report were generated from Eye-Link Data Viewer. The message report was used to extract the "Sound Played Time" for each trial. From this, a "corrected" critical time point could be determined that considered when the sound file was played and when a point of interest in the sentence occurred like the POD or sentence offset. Each fixation was centered with respect to the critical time points by subtracting the corrected critical time point from the current fixation time. A positive number indicated the fixation occurred before the critical time point. A negative number indicated the fixation occurred after the critical time point. The centered time points were then used to analyze fixations that occurred after two critical time points: sentence offset and point of disambiguation. Data was analyzed in SPSS using the same method for behavioral data.

## 4.2 ACCURACY

### 4.2.1 Broadened Auditory Filters vs. No Hearing Loss

For the double object and prepositional object structure, there was a main effect of group. Participants in the BAF group (mean: .74) were less accurate than participants in the NoHL group (mean: .89, $F=29.3$, $p<.001$). There was also a main effect of structure. Participants were less accurate for the DO (mean: .71) compared to the PO structure (mean: .92, $F=70.3$, $p<.001$).

There was also a main effect of plausibility. Participants were less accurate for the implausible (mean: .70) compared to the plausible sentences (mean: .93, F=96.8, p<.001). There was a plausibility by group interaction (F=23.6, p<.001). The BAF group was more influenced by plausibility than the NoHL group. There was also a structure by plausibility interaction (F=23.99, p<.001). Plausibility had more of an influence on accuracy for the DO compared to PO structure.

For the active and passive structure, there was a main effect of group. Participants in the BAF group (mean: .94) were less accurate than participants in the NoHL group (mean: .99, F=12.3, p<.001). There was also a main effect of structure. Participants were less accurate for passive (mean: .94) than active structures (mean: .99, F= 17.0, p<.001). There was no significant main effect of plausibility and no significant interactions.

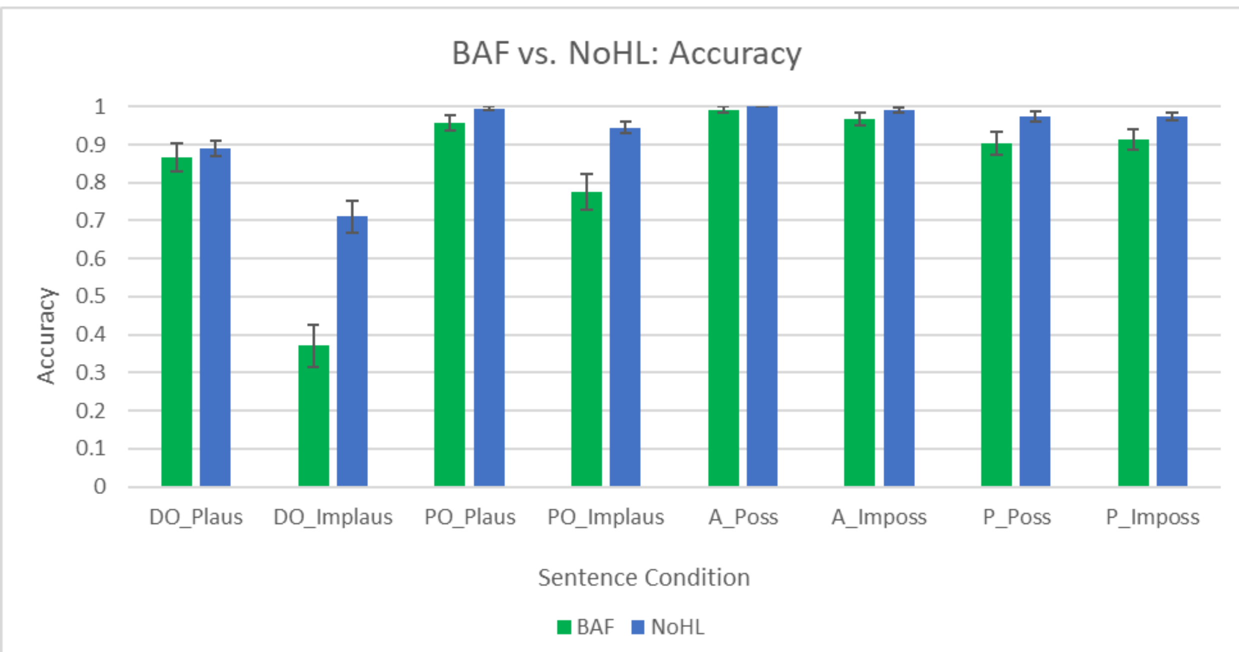


**Figure 3: BAF vs. NoHL, Accuracy**

### 4.2.2 Low Pass Filtered vs. No Hearing Loss

There was a main effect of group: participants in the group with low pass filtered stimuli were less accurate (mean: .63) than participants in the NoHL group (mean: .89, $F=186.5$, $p<.001$). There was also a main effect of structure. Participants in both groups were less accurate for the DO construction (mean: .66) than the PO construction (mean: .86, $F=106.9$ $p<.001$). There was also a main effect of plausibility. Participants were less accurate for implausible (mean: .60) than plausible items (mean: .92, $F=352.4$, $p<.001$). There was also an interaction between plausibility and group ($F=147.7$, $p<.001$). Participants in the LPF group were influenced more by plausibility than participants in the NoHL group. Furthermore, there was an interaction between structure and plausibility ($F=30.8$, $p<.001$). Participants were more influenced by plausibility for double object than prepositional object sentences.

For the active/passive sentences, there was a main effect of group: participants in the LPF group (mean: .93) were less accurate than participants in the NoHL group (mean: .99, $F=17.6$, $p<.001$). There were no significant interaction effects.

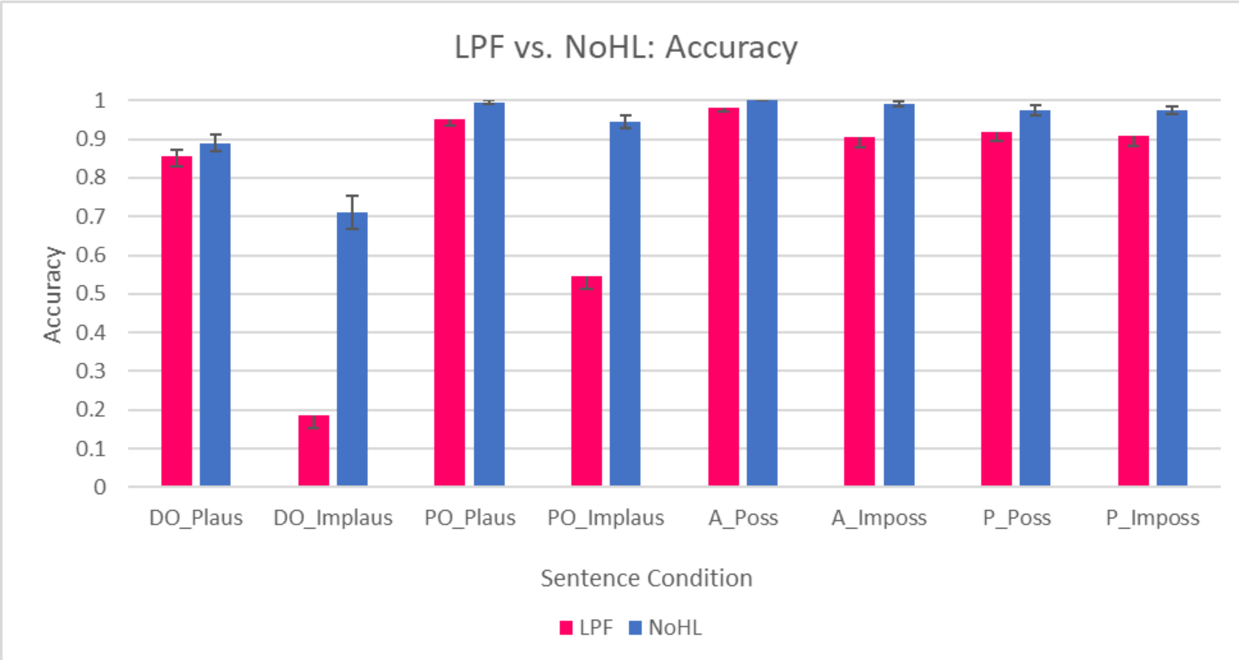


**Figure 4: LPF vs. NoHL, Accuracy**

### 4.2.3 Broadened Auditory Filters vs. Low Pass Filtered

For the double object and prepositional object structures there was a main effect of group. The BAF group had higher accuracy scores (mean: .74) than the LPF group (mean: .63, F=17.2, p<.001). There was also a main effect of structure. Participants were more accurate for the PO (mean: .81) compared to the DO structures (mean: .57, F=88.8, p<.001). There was also a main effect of plausibility. Participants were less accurate for implausible (mean: .91) compared to plausible structures (mean: .47, F=326.6, p<.001). There were no significant interactions.

For the active and passive structures there was no main effect of group or plausibility. There was a main effect of structure. Participants were more accurate for active (mean: .96) compared to passive sentences (mean: .91, F=11.5, p<.002). There were no significant interactions.

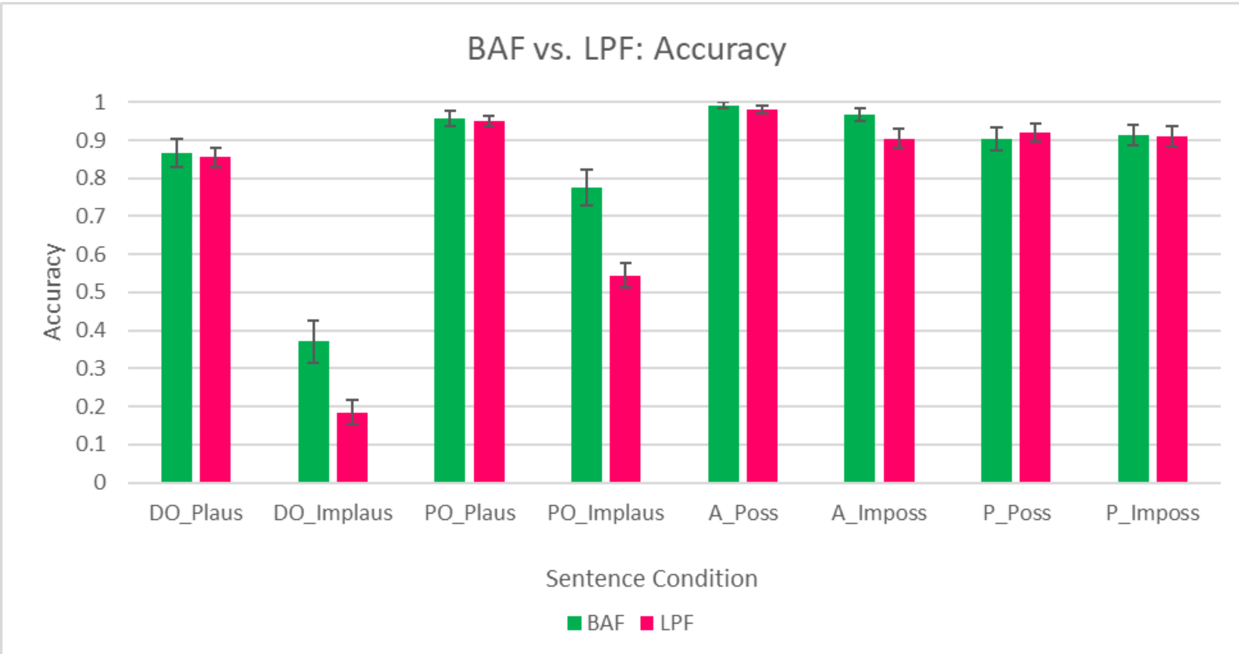


**Figure 5: BAF vs. LPF, Accuracy**

### 4.2.4 Broadened Auditory Filters vs. Vocoded

The following are within subject comparisons between filter conditions. A difference between performance in the BAF and vocoded condition demonstrates that performance in the BAF condition can be attributed to the simulation of broadened auditory filters and not simply listening to vocoded stimuli.

For the double object and prepositional object structures, there was a main effect of filter. People were more accurate in the vocoded condition (mean: .85) compared to the BAF condition (mean: .75, F= 16.6, p<.001). There was a main effect of structure. Participants were less accurate for DO (mean: .68) than PO sentences (mean: .92, $F=79.0$, $p<.001$). There was also a main effect of plausibility, participants were less accurate for implausible (mean: .67) than plausible sentences (mean: .92, $F=56.4$, $p<.001$). There was also a filter by plausibility interaction. Participants were more influenced by plausibility when listening to BAF stimuli than vocoded only stimuli ($F=22.0$, $p<.001$). There was also a plausibility by structure interaction. Participants were more influenced by plausibility for DO sentences than PO sentences ($F=30.0$, $p<.001$).

For the active and passive structures, there was a main effect of filter. Participants were more accurate in the vocoded condition (mean: .98) compared to the BAF condition (mean: .94, $F=14.7$, $p<.001$). There was also a main effect of structure. Participants were more accurate for the active (mean: .98) than passive structure (mean: .94, $F=11.8$, $p<.002$). There was no main effect of plausibility or significant interactions.

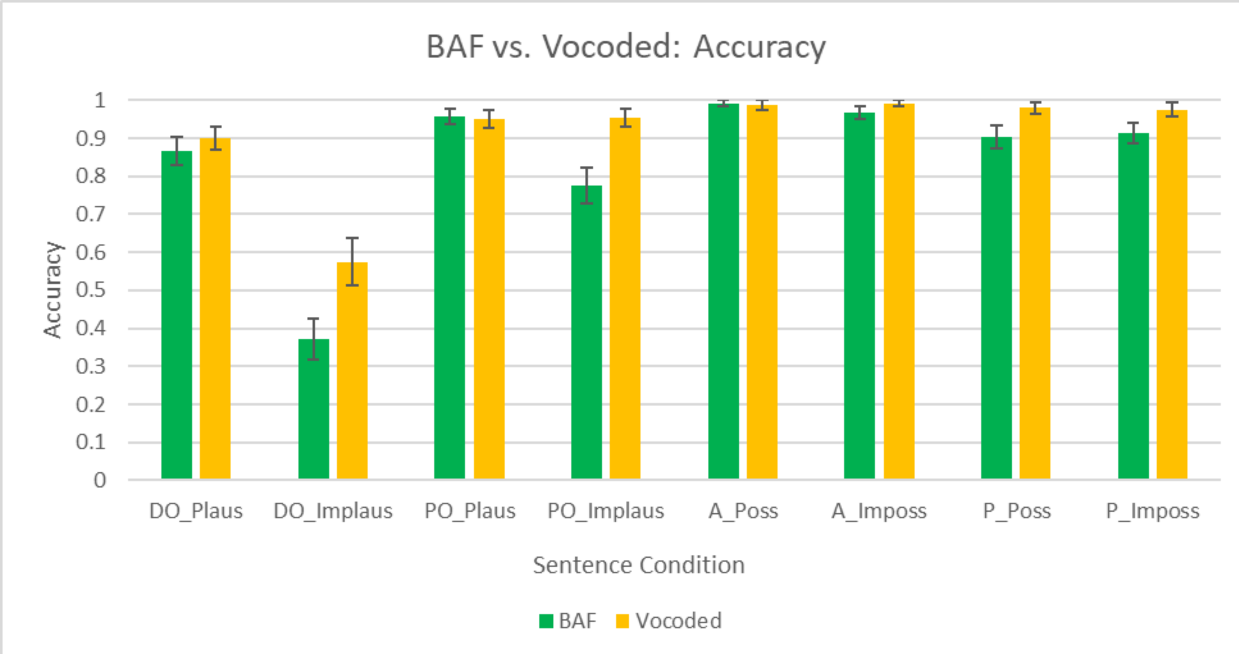


**Figure 6: BAF vs. Vocoded, Accuracy**

### 4.2.5 Summary of Accuracy Data

Overall, both the BAF and LPF groups were less accurate than the NoHL group. The LPF group was less accurate than the BAF group for the DO/PO structure only. Finally, participants were less accurate in the BAF condition than in the vocoded condition. Overall all groups acted in a way consistent with the hypotheses set forth in which they were less accurate for DOs compared to POs and passives compared to actives as well as improbable compared to probable sentences. Participants experiencing simulated hearing losses were more influenced by plausibility than the NoHL group. And participants were more influenced by plausibility in the DO compared to PO sentences.

## 4.3 REACTION TIME

### 4.3.1 Broadened Auditory Filters vs. No Hearing Loss

For the double object and prepositional object structures there was a main effect of group. The BAF group had higher reaction times (mean: 1564 ms) than the NoHL group (mean: 1027 ms, F=16.5, p<.001). There was a main effect of structure. There were longer reaction times for DO (mean:1477 ms) compared to the PO sentences (mean: 1114 ms, F=37.4, p<.001). There was also a main effect of plausibility. People had longer reaction times for implausible (mean: 1442 ms) compared to plausible sentences (mean: 1149 ms, F=26.4, p<.001). There were no significant interactions.

For active and passive structures, there was a main effect of group. The BAF group had longer reaction times (mean:1276 ms) than the NoHL group (mean:790ms, F=20.8, p<.001). There was also a main effect of structure. Participants had longer reaction times for passive (mean: 1120 ms) compared to active sentences (mean: 946 ms, F=12.5, p<.002). There was a main effect of plausibility. Participants had higher reaction times for impossible (mean: 1155 ms) compared to possible sentences (mean: 910 ms, F=20.0, p<.001). There were no significant interactions.

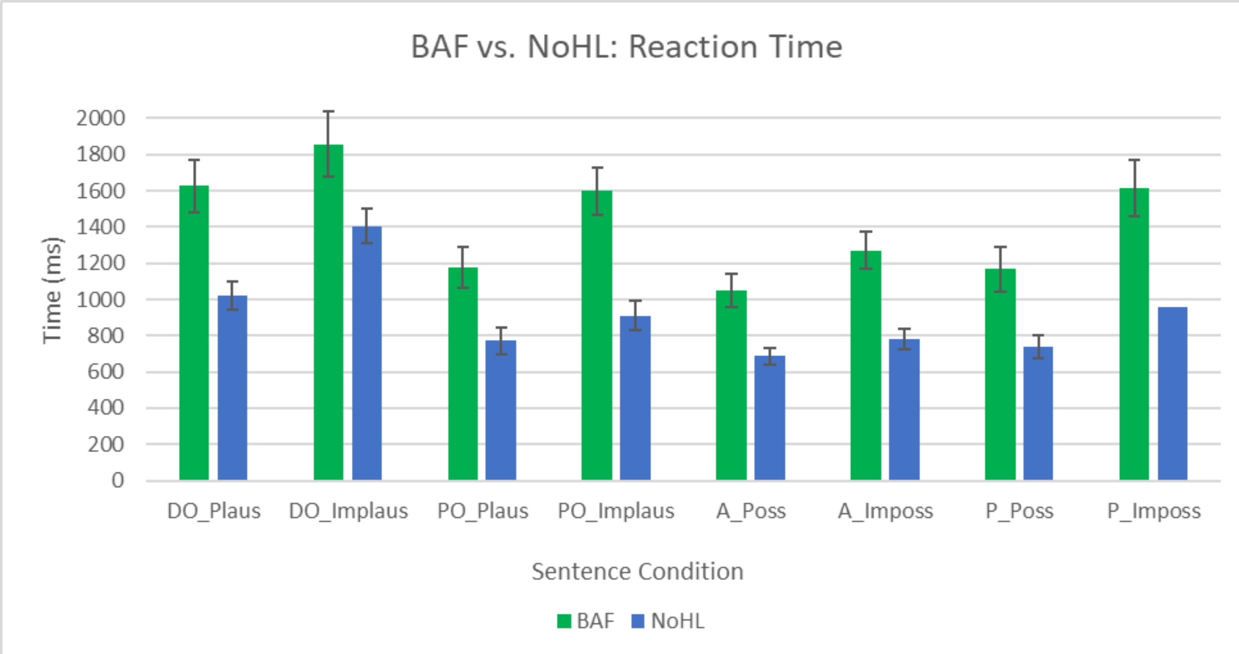


**Figure 7: BAF vs. NoHL, Reaction Time**

### 4.3.2 Low Pass Filtered vs. No Hearing Loss

For the DO/PO condition, there was a main effect of group: participants in the LPF group had longer reaction times (mean: 1472 ms) than the NoHL group (mean: 1027 ms, $F=18.3$, $p<.001$). There was also a main effect of structure. Participants in both groups were slower for the DO construction (mean: 1357 ms) than the PO construction (mean: 1142 ms, $F=28.9$, $p<.001$). There was also a main effect of plausibility. Participants took longer to respond to the implausible (mean: 1333 ms) than plausible items (mean: 1166 ms, $F=9.6$, $p<.003$). Furthermore, there was an interaction between structure and group ($F=15.0$, $p<.001$). Participants in the NoHL group were more influenced by structure than participants in the LPF group. There was also an interaction effect between structure, plausibility, and group ($F=14.9$, $p<.001$). Participants were more influenced by plausibility in the DO compared to PO condition and this effect was stronger for the NoHL group than the LPF group.

For the active/passive sentences, there was a main effect of group: participants in the LPF group had longer reaction times (mean: 1240 ms) than the NoHL group (mean: 790 ms, F=30.3, p<.001). There was also a main effect of plausibility: participants had faster reaction times for the possible (mean: 931 ms) than for the impossible sentences (mean: 1098 ms, F=12.5, p<.001). Overall, participants had longer reaction times for the DO/PO construction (mean: 1230 ms) than the active/passive sentence construction (mean: 1015 ms, F=47.4, p<.001).

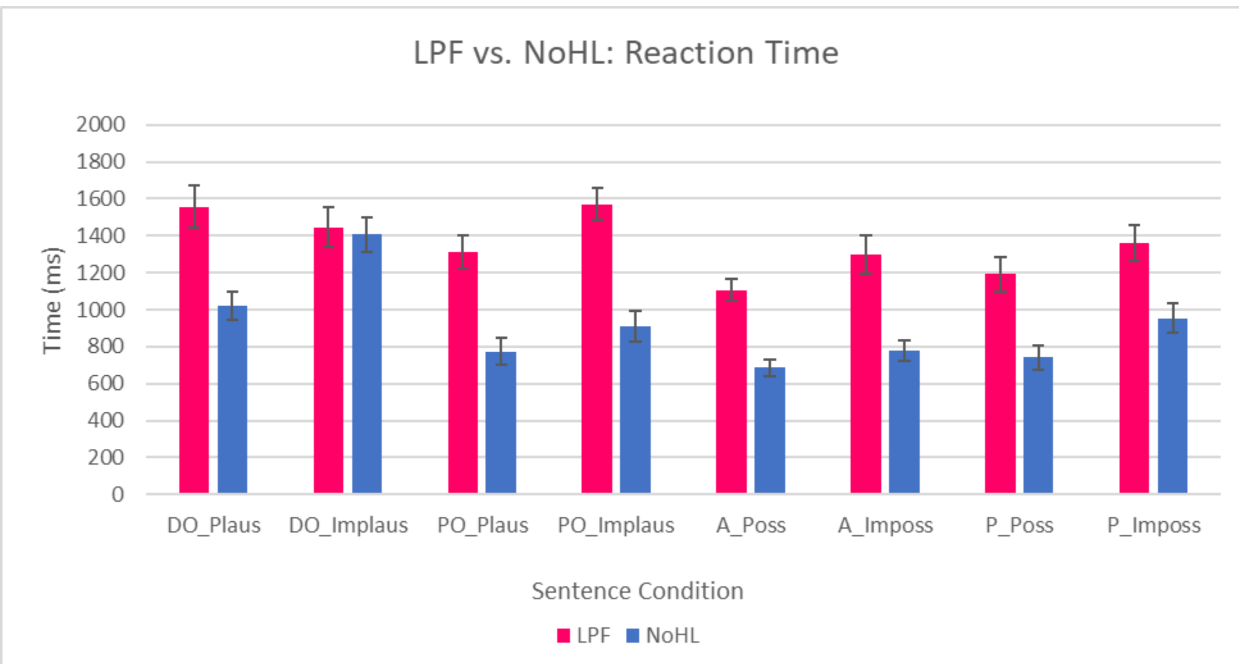


**Figure 8: LPF vs. NoHL, Reaction Time**

### 4.3.3 Broadened Auditory Filters vs. Low Pass Filtered

For double object and prepositional object sentences, there was no main effect of group. There was a main effect of structure. Participants had higher reaction times for DO (mean: 1622 ms) than PO sentences (mean: 1414 ms, F=11.3, p<.002). There was also a main effect plausibility. Participants had higher reaction times for implausible (mean: 1618 ms) than plausible sentences (mean: 1418 ms, F=9.5, p<.004). There were no significant interactions.

For the active and passive structures, there was no main effect of group. There was a main effect of structure. Participants had higher reaction times for passives (mean: 1334ms) compared to actives (mean: 1182ms, F=7.5, p<.009). There was also a main effect of plausibility. Participants had higher reactions times for impossible (mean: 1387 ms) compared to possible sentences (mean: 1129 ms, F=15.8, p<.001). There were no significant interactions.

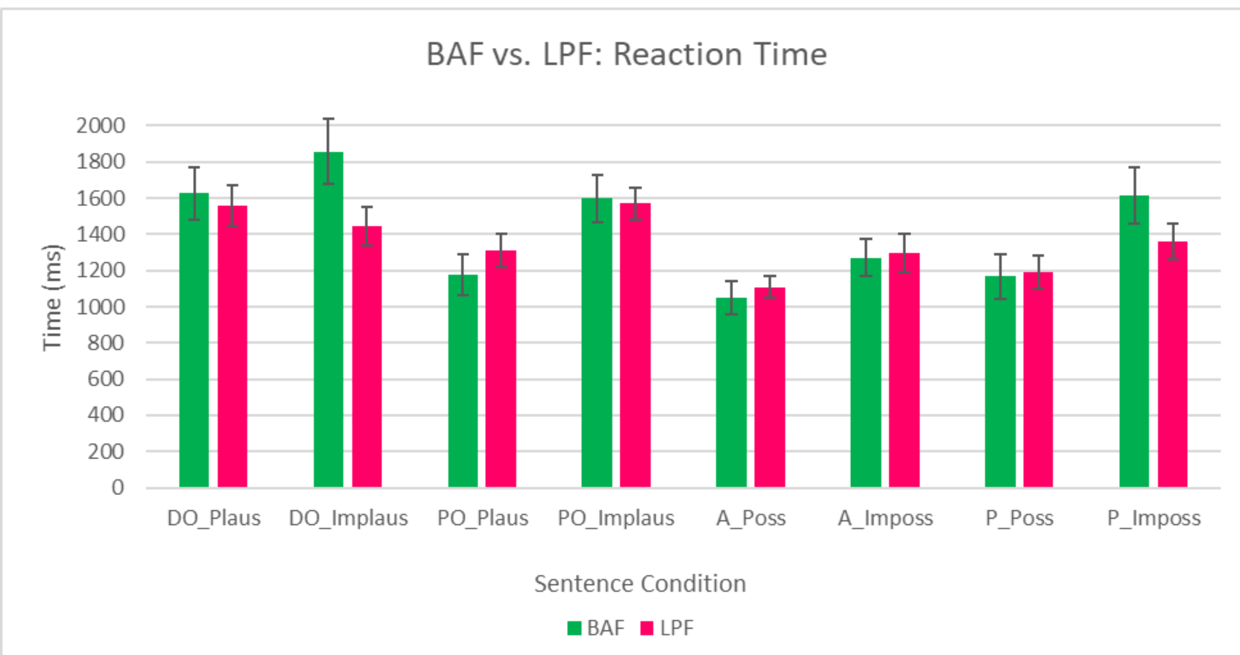


**Figure 9: BAF vs. LPF, Reaction Time**

### 4.3.4 Broadened Auditory Filters vs. Vocoded

For the double object and prepositional object structures, there was a main effect of filter. Participants had higher reaction times for the BAF (mean: 1569 ms) compared to the vocoded condition (mean: 1220 ms, $F=18.0$, $p<.001$). There was also a main effect of structure. Participants had higher reaction times on the DO (mean: 1551 ms) compared to PO sentences (mean: 1238 ms, $F=16.8$, $p<.001$). Finally, there was a main effect of plausibility. Participants had higher reaction times for implausible (mean: 1509 ms) compared to plausible structures (mean: 1279 ms, $F=12.2$, $p<.002$). There were no significant interactions.

For the active and passive structures, there was a main effect of filter. Participants had higher reaction times for the BAF (mean: 1270 ms) compared to the vocoded only condition (mean: 1050 ms, $F=12.4$, $p<.002$). There was no main effect of structure. Finally, there was a main effect of plausibility. Participants had higher reaction times for impossible (mean: 1264 ms) compared to possible sentences (mean: 1056 ms, $F=12.8$, $p<.002$). There were no significant interactions.

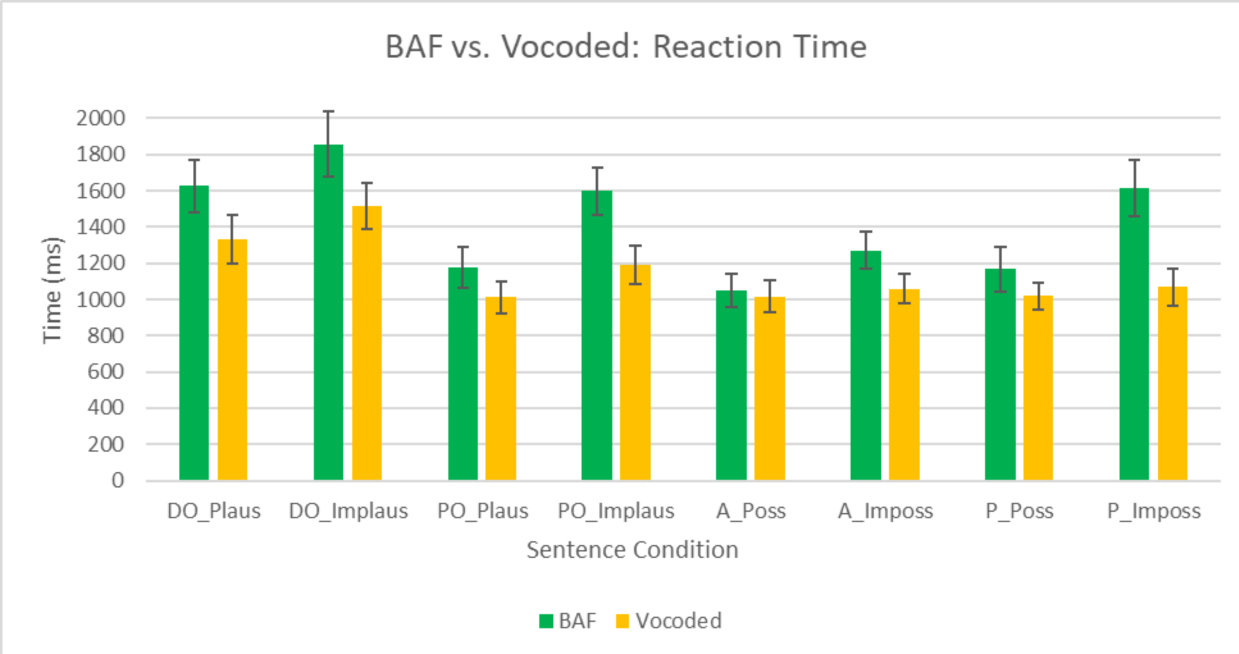


**Figure 10: BAF vs. Vocoded, Reaction Time**

### 4.3.5 Summary of Reaction Time Data

Overall, both the BAF and LPF groups had longer reaction times than the NoHL group. The LPF group and the BAF group were not significantly different. Participants had longer reaction times in the BAF condition than in the vocoded condition. All groups acted in a way consistent with the hypotheses set forth in which they had higher reaction times for DOs compared to POs and passives compared to actives as well as improbable compared to probable sentences. Significant interactions were only found when comparing the LPF and NoHL group. The NoHL group was more influenced by structure. This is expected as it is likely that when the syntactic structure of the sentence is intact (i.e., no noise present), participants are more likely to be influenced by syntax. There was also a three-way interaction in which participants were more influenced by plausibility in the DO compared to PO structures, but this was stronger for the NoHL group.

## 4.4 EYE-TRACKING

The following measures were collected on eye-tracking: mean latency to fixate on the target image after the POD and the sentence-offset, the mean number of fixations after the POD and the sentence-offset, the proportion of gazes at the target image after the POD and the sentence offset, and the proportion of *first* fixations at the target image following disambiguation.

The mean latency of first target fixation represents how long it took for participants to gaze at the target image after a particular part of the sentence (the POD or sentence-offset). This was a measure of how quickly after hearing a critical point in the sentence participants were able to identify the sentence's literal syntax and choose an interpretation based on that syntax. The lower the latency, the easier it was for participants to identify the target image. It was predicted that latency would be higher in conditions where uncertainty was higher (i.e., DO-impossible) or if the group had a higher degree of uncertainty (i.e., BAF and LPF vs. NoHL). This measure was only collected on trials where participants' response was correct (faithful to the literal syntax). Because eye-tracking was expected to mirror accuracy data, it was hypothesized that the LPF filter group would take longer to fixate on images than the BAF group for the active/passive condition but the same amount of time for the DO/PO condition.

The mean number of fixations represents the number of fixations on both the target and competitor image following a particular part of the sentence (the POD or sentence-offset) until the participant's response. This was a measure of how much competition there was between the faithful and unfaithful interpretation of the sentence with more fixations meaning there was more competition between the literal and non-literal interpretations. It was predicted that the number of fixations would be greater in conditions where uncertainty was higher (i.e., DO-impossible) and in the group with higher uncertainty about the perceived linguistic signal (i.e., BAF and LPF). Because eye-tracking was expected to mirror accuracy data, it was hypothesized that the LPF filter group would take longer to fixate on images than the BAF group for the active/passive condition but the same amount of time for the DO/PO condition.

The proportion of gazes represents the proportion of gazes to the target image following a particular part of the sentence (the POD or sentence-offset) until the participant's response. This was a measure of how much competition there was between the faithful and unfaithful interpretation of the sentence. A lower proportion means more competition from the competitor image. It was predicted that the proportion of gazes towards the target image would be lower in conditions where there is more uncertainty (i.e., DO-impossible) or in the group with higher uncertainty about the perceived linguistic signal (i.e., BAF and LPF). Because eye-tracking was expected to mirror accuracy data, it was hypothesized that the LPF filter group would take longer to fixate on images than the BAF group for the active/passive condition but the same amount of time for the DO/PO condition.

The measure of proportion of gazes is distinct from the mean number of fixations towards the target image in that participants may show equal proportions of gazes while having a different mean number of gazes. For example, participants may gaze at the target image 2 times and the competitor image 2 times resulting in a proportion of .5 of the gazes towards the target image. They may also gaze at the target image 10 times and the competitor image 10 times. This too would result in a proportion of .5 of the gazes towards the target image; however, the second situation exemplifies more competition between the target and competitor image even though both proportions are equal. Therefore, these proportion of gazes data complement the mean number of gazes data.

Finally, proportion of first target fixations after the POD represents the proportion of first fixations following the POD that were on the target. This is a measure of how likely it is that the first picture gazed at following the POD is the target image. A lower number means there was more competition between the faithful and non-faithful interpretation of the syntax. Because eye-tracking was expected to mirror accuracy date, it was hypothesized that the proportion would be lower when there was higher uncertainty (i.e., DO-impossible) and for the group with more uncertainty (i.e., BAF or LPF). The proportion was also expected to be lower for the LPF group compared to the BAF group when in the active/passive condition but not the DO/PO condition.

The following section contains tables showing each variable and the significant main effects (group, structure, and plausibility). After each table, there is a section summarizing the results and explaining any significant interaction effects.

### 4.4.1 Broadened Auditory Filters vs. No Hearing Loss

*Summary of Main Effects:*

There were only two significant main effect of group. For the latency to fixate on the target image after the sentence offset in the DO/PO condition, the BAF group took longer (mean: 1080 ms) than the NoHL group (mean: 918 ms, $p<.005$). For proportion of fixations to the target image, the BAF group showed a higher proportion of fixations to the target image (.56) than the NoHL group (.47, $p<.002$).

For the DO/PO condition, participants sometimes showed significantly more uncertainty in the PO condition than the DO condition. For example, they showed more mean fixations in the PO compared to DO condition. However, the proportion of fixations to the target image shows that a higher proportion of fixations after the POD were to the target for POs compared to DOs. Participants also took significantly longer to fixate on the target image for the PO structure (mean: 1347 ms) compared to the DO structure (1126 ms) after the POD. This is the opposite of what was expected. For the active/passive condition, participants consistently showed more uncertainty in the passive compared to active condition in latency, mean number of fixations, and proportion of fixations to target measures.

*Interaction Effects:*

**Latency to Fixate on Target Image:**

*After POD*: For the DO/PO condition, there was an interaction between structure and group ($F=12.8$, $p<.002$). The NoHL group was more influenced by structure than the BAF group ($F=10.1$, $p<.004$). There was also a group by plausibility interaction. Participants in the BAF group were more influenced by plausibility than the NoHL group. For the active/passive condition, there was a significant interaction between structure and group (F=8.3, p<.006). The NoHL group was more influenced by structure than the BAF group.

*After Sentence Offset*: For the DO/PO condition, there was a group by plausibility interaction (F=11.8, p<.002). The BAF group was more influenced by plausibility than the NoHL group. For the active/passive condition, there was a group by structure interaction (F=11.1, p<.003). Participants in the BAF group were more influenced by sentence structure than the NoHL group.

**Mean Number of Fixations:**

*After POD:* For the DO/PO condition, there were no significant interaction effects. For the active passive condition, there was a group by structure interaction (F=14.3, p<.001). Participants in the NoHL group were more influenced by structure than the BAF group. There was also a group by plausibility interaction (F=23.4, p<.001). Participants in the BAF group were more influenced by plausibility than the NoHL group. There was also a structure by plausibility interaction (F=13.1, p<.002). Participants were more influenced by plausibility in the passive compared to active condition. Finally, there was a three-way structure by plausibility by group interaction (F=18.7, p<.001) suggesting that plausibility influenced actives more than passives and this effect was larger for the BAF than the NoHL group. This is not what was expected given that Nunn (2016) found that participants with NoHL tended to be more influenced by structure and plausibility than LPF.

*After Sentence Offset:* For the DO/PO condition there were no significant interaction effects. For the active/passive condition, there was a structure by plausibility interaction (F=36.8, p<.001). Participants were more influenced by plausibility in the passive compared to active condition.

There was also a three-way structure by plausibility by group interaction ($F=53.4$, $p<.001$). Again, it appears as if plausibility influenced the active structure more than the passive and that this effect was larger for the BAF group than the NoHL group.

**Table 10: BAF vs. NoHL, Eye-tracking**

| BAF vs. NoHL | DO/PO | | | Active/Passive | | |
|---|---|---|---|---|---|---|
| Measure | Effect | Mean | Significance | Effect | Mean | Significance |
| Latency - POD (ms) | NoHL | 1293 | ns | NoHL | 1077 | ns |
| | BAF | 1181 | | BAF | 872 | |
| | DO | 1126 | p<.0125 | Active | 675 | p<.001 |
| | PO | 1347 | | Passive | 1274 | |
| | Plaus | 1122 | p<.001 | Poss | 914 | ns |
| | Implaus | 1352 | | Imposs | 1035 | |
| Latency - sent-off (ms) | NoHL | 918 | p<.005 | NoHL | 724 | ns |
| | BAF | 1080 | | BAF | 811 | |
| | DO | 1127 | ns | Active | 675 | p<.001 |
| | PO | 871 | | Passive | 860 | |
| | Plaus | 889 | p<.000 | Poss | 708 | ns |
| | Implaus | 1108 | | Imposs | 826 | |
| Mean # Fix - POD | NoHL | 6.4 | ns | NoHL | 5.4 | ns |
| | BAF | 6.1 | | BAF | 5.3 | |
| | DO | 5.7 | p<.001 | Active | 4.4 | p<.001 |
| | PO | 6.8 | | Passive | 6.2 | |
| | Plaus | 5.9 | p<.001 | Poss | 4.6 | p<.001 |
| | Implaus | 6.7 | | Imposs | 6.0 | |
| Mean # Fix - sent-off | NoHL | 5.2 | ns | NoHL | 4.3 | ns |
| | BAF | 5.0 | | BAF | 4.4 | |
| | DO | 5.8 | p<.001 | Active | 4.5 | ns |
| | PO | 4.4 | | Passive | 4.2 | |
| | Plaus | 4.6 | p<.001 | Poss | 3.9 | p<.001 |
| | Implaus | 5.5 | | Imposs | 4.7 | |
| Proportion Fix - POD | NoHL | 0.64 | ns | NoHL | 0.67 | ns |
| | BAF | 0.62 | | BAF | 0.68 | |
| | DO | 0.59 | p<.001 | Active | 0.70 | p<.005 |
| | PO | 0.66 | | Passive | 0.66 | |
| | Plaus | 0.66 | p<.002 | Poss | 0.64 | p<.001 |
| | Implaus | 0.60 | | Imposs | 0.71 | |
| Proportion Fix - sent-off | NoHL | 0.67 | ns | NoHL | 0.72 | ns |
| | BAF | 0.63 | | BAF | 0.71 | |
| | DO | 0.59 | p<.001 | Active | 0.70 | ns |
| | PO | 0.71 | | Passive | 0.73 | |
| | Plaus | 0.68 | p<.001 | Poss | 0.69 | ns |
| | Implaus | 0.62 | | Imposs | 0.73 | |
| Proportion First Fix -POD | NoHL | 0.47 | p<.002 | NoHL | 0.56 | ns |
| | BAF | 0.56 | | BAF | 0.61 | |
| | DO | 0.48 | ns | Active | 0.67 | p<.001 |
| | PO | 0.54 | | Passive | 0.51 | |
| | Plaus | 0.56 | p<.0125 | Poss | 0.53 | p<.001 |
| | Implaus | 0.47 | | Imposs | 0.65 | |

**Proportion of Fixations:**

*After POD:* For the DO/PO condition there were no significant interaction effects. For the active/passive condition, there was a group by plausibility interaction (F=17.1, p<.001). Participants in the NoHL group were more influenced by plausibility than the BAF group.

*After Sentence Offset:* For the DO/PO condition, there were no significant interactions. For the active/passive condition, there was a group by plausibility interaction (F=9.9, p<.003). Participants in the NoHL group were more influenced by plausibility than the BAF group.

*First Fixations After POD:* For the DO/PO condition, there was a structure by group interaction (F=6.6, p<.0125). Participants in the NoHL group were more influenced by structure than the BAF group. For the active/passive condition there were no significant interactions.

### 4.4.2 Low Pass Filtered vs. No Hearing Loss

*Summary of Main Effects:*

There were main effects of group in all measures except proportion of first fixations to target image. Overall, participant in the LPF group showed higher degrees of uncertainty.

For the DO/PO condition, participants showed variable degrees of uncertainty for the different structures. For example, participants took significantly longer to fixate on the target image in the PO condition (mean: 1690 ms) than the DO condition (mean: 1149, p<.001) after the POD but longer to fixate on the DO (mean: 1149 ms) compared to PO (mean: 947 ms, p<.001) after the sentence offset. The similar pattern was displayed in the mean number of fixations data. In the proportion of fixations data, the participants consistently showed significantly more first fixations to the target for the PO compared to DO conditions. For the active/passive condition, participants consistently showed more uncertainty for the passive compared to active conditions. In terms of plausibility, participants showed higher degrees of uncertainty for improbable sentence structures. However, for the proportion of fixations data in the active/passive condition, participants showed a higher proportion of fixations to the target in the passive compared to active condition.

*Interaction Effects:*

**Latency to Fixate of Target Image:**

*After POD:* For the DO/PO and active/passive conditions, there were no significant interactions.

*After Sentence Offset:* For the DO/PO and active/passive conditions, there were no significant interactions.

**Mean Number of Fixations:**

*After POD:* For the DO/PO condition, there was an interaction between group, structure, and plausibility (F=10.5, p<.003). Participants were more influenced by plausibility in the DO compared to PO condition and this effect was larger for the NoHL compared to LPF group. For the active/passive condition, there were no significant interactions.

*After Sentence Offset:* For the DO/PO condition, there was an interaction between structure and group (F=13.4, p<.001). The NoHL group's number of fixations was more influenced by the different sentence structures than the LPF group. Finally, there was a three-way interaction between group, structure, and plausibility (F=10.3, p<.003). Participants were more influenced by structure for the DO compared to PO and this was stronger for the NoHL compare to LPF group. For the active/passive condition there were no interactions.

**Table 11: LPF vs. NoHL, Eye-tracking**

| LPF vs. NoHL | DO/PO | | | Active/Passive | | |
|---|---|---|---|---|---|---|
| Measure | Effect | Mean | Significance | Effect | Mean | Significance |
| Latency - POD (ms) | NoHL | 1293 | p<.010 | NoHL | 1077 | p<.001 |
| | LPF | 1546 | | LPF | 1377 | |
| | DO | 1149 | p<.001 | Active | 843 | p<.001 |
| | PO | 1690 | | Passive | 1611 | |
| | Plaus | 1390 | ns | Poss | 1191 | ns |
| | Implaus | 1450 | | Imposs | 1263 | |
| Latency - sent-off (ms) | NoHL | 918 | p<.001 | NoHL | 724 | p<.001 |
| | LPF | 1179 | | LPF | 1022 | |
| | DO | 1149 | p<.001 | Active | 843 | ns |
| | PO | 947 | | Passive | 903 | |
| | Plaus | 1006 | ns | Poss | 810 | p<.001 |
| | Implaus | 1091 | | Imposs | 936 | |
| Mean # Fix - POD | NoHL | 6.5 | ns | NoHL | 5.4 | p<.003 |
| | LPF | 7.4 | | LPF | 6.3 | |
| | DO | 6.2 | p<.001 | Active | 4.7 | p<.001 |
| | PO | 7.7 | | Passive | 7.0 | |
| | Plaus | 6.8 | ns | Poss | 5.6 | p<.002 |
| | Implaus | 7.1 | | Imposs | 6.1 | |
| Mean # Fix - sent-off | NoHL | 5.2 | p<.003 | NoHL | 4.3 | p<.001 |
| | LPF | 6.4 | | LPF | 5.4 | |
| | DO | 6.2 | p<.001 | Active | 4.8 | ns |
| | PO | 5.4 | | Passive | 4.9 | |
| | Plaus | 5.6 | ns | Poss | 4.5 | p<.001 |
| | Implaus | 6.0 | | Imposs | 5.2 | |
| Proportion Fix - POD | NoHL | 0.64 | p<.001 | NoHL | 0.67 | p<.001 |
| | LPF | 0.55 | | LPF | 0.63 | |
| | DO | 0.55 | p<.001 | Active | 0.68 | p<.001 |
| | PO | 0.63 | | Passive | 0.63 | |
| | Plaus | 0.62 | p<.001 | Poss | 0.60 | p<.001 |
| | Implaus | 0.57 | | Imposs | 0.71 | |
| Proportion Fix - sent-off | NoHL | 0.67 | p<.001 | NoHL | 0.72 | p<.001 |
| | LPF | 0.56 | | LPF | 0.65 | |
| | DO | 0.55 | p<.001 | Active | 0.68 | ns |
| | PO | 0.68 | | Passive | 0.69 | |
| | Plaus | 0.64 | p<.001 | Poss | 0.64 | p<.001 |
| | Implaus | 0.59 | | Imposs | 0.73 | |
| Proportion First Fix - POD | NoHL | 0.47 | ns | NoHL | 0.56 | ns |
| | LPF | 0.50 | | LPF | 0.55 | |
| | DO | 0.44 | ns | Active | 0.63 | p<.001 |
| | PO | 0.53 | | Passive | 0.48 | |
| | Plaus | 0.51 | ns | Poss | 0.47 | p<.001 |
| | Implaus | 0.46 | | Imposs | 0.65 | |

**Proportion of Gazes to Target:**

*After POD:* For the DO/PO and active/passive conditions, there were no significant interactions.

*After Sentence Offset:* There was an interaction between group and plausibility ($F=13.8$, $p<.001$). Participants in the LPF group were more influenced by plausibility information than participants in the NoHL group. For the active/passive condition, there were no significant interaction effects.

*First Fixations After POD:* For the DO/PO and active/passive conditions, there were no significant interactions.

### 4.4.3 Broadened Auditory Filters vs. Low Pass Filtered

*Summary of Main Effects:*

The LPF groups showed higher degrees of uncertainty than the BAF group in measures of latency to fixate on target image after POD (active/passive condition), mean number of fixations to target image after POD and sentence offset (active/passive and DO/PO condition), and proportion of gazes to the target image after sentence offset (active/passive and DO/PO).

For the DO/PO condition, participants showed variable degrees of uncertainty for the different structures. For example, participants took significantly longer to fixate on the target image in the PO condition (mean: 1481 ms) than the DO condition (mean: 1149, $p<.001$) after the POD but longer to fixate on the DO (mean: 1199 ms) compared to PO (mean: 1032 ms, $p<.001$) after the sentence offset. The similar pattern was displayed in the mean number of fixations data. In the proportion of fixations data, the participants consistently showed significantly more first fixations to the target for the PO compared to DO conditions after the sentence offset. For the active/passive condition, participants showed consistently higher degrees of uncertainty for the passive compared to active sentences.

Overall, participants generally showed significantly higher degrees of uncertainty for improbable compared to probable sentences. However, participants showed slightly longer latency to fixate on target images for active/passive possible (mean: 1069 ms) than active/passive impossible sentences (mean:1043, p<.01). They also showed more first fixations to the target image for active/passive impossible (mean: .66) compared to active/passive possible (mean: .52, p<.001). All other main effects of plausibility were as expected.

*Interaction Effects:*

**Latency to Fixate of Target Image:**

*After POD:* For the DO/PO condition, there was a significant group by structure interaction (F=9.4, p<.005). Participants in the LPF group were more influenced by structure than the BAF group. For the active/passive condition there were no significant interactions.

*After Sentence Offset:* For the DO/PO and the active/passive conditions, there were no significant interactions.

**Mean Number of Fixations:**

*After POD:* For the DO/PO condition, there were no significant interaction effects. For the active/passive condition, there was a significant group by plausibility interaction (F=52.7, p<.001). Participants in the BAF group were more influenced by plausibility than the LPF group. There was also a structure by plausibility interaction (F=13.4, p<.001). Participants were more influenced by plausibility in the active compared to passive condition. This is not as expected as

**Table 12: BAF vs. LPF, Eye-tracking**

| BAF vs. LPF | DO/PO | | | Active/Passive | | |
|---|---|---|---|---|---|---|
| Measure | Effect | Mean | Significance | Effect | Mean | Significance |
| Latency - POD (ms) | LPF | 1546 | ns | LPF | 1377 | p<.001 |
| | BAF | 1084 | | BAF | 736 | |
| | DO | 1149 | ns | Active | 787 | p<.001 |
| | PO | 1481 | | Passive | 1326 | |
| | Plaus | 1392 | ns | Poss | 1069 | p<.01 |
| | Implaus | 1239 | | Imposs | 1043 | |
| Latency - sent-off (ms) | LPF | 1179 | ns | LPF | 1022 | ns |
| | BAF | 1053 | | BAF | 815 | |
| | DO | 1199 | p<.0125 | Active | 833 | p<.002 |
| | PO | 1032 | | Passive | 1004 | |
| | Plaus | 1058 | p<.0125 | Poss | 842 | ns |
| | Implaus | 1173 | | Imposs | 995 | |
| Mean # Fix - POD | LPF | 7.4 | p<.002 | LPF | 6.3 | p<.0125 |
| | BAF | 6.1 | | BAF | 5.3 | |
| | DO | 6.0 | p<.001 | Active | 5.0 | p<.001 |
| | PO | 7.4 | | Passive | 6.6 | |
| | Plaus | 6.4 | p<.006 | Poss | 5.1 | p<.001 |
| | Implaus | 7.1 | | Imposs | 5.6 | |
| Mean # Fix - sent-off | LPF | 6.4 | p<.001 | LPF | 5.4 | p<.009 |
| | BAF | 5.0 | | BAF | 4.3 | |
| | DO | 6.1 | p<.002 | Active | 5.0 | ns |
| | PO | 5.3 | | Passive | 4.8 | |
| | Plaus | 5.3 | p<.005 | Poss | 4.5 | p<.001 |
| | Implaus | 6.0 | | Imposs | 5.3 | |
| Proportion Fix - POD | LPF | 0.55 | p<.001 | LPF | 0.63 | p<.004 |
| | BAF | 0.62 | | BAF | 0.68 | |
| | DO | 0.54 | p<.001 | Active | 0.68 | p<.006 |
| | PO | 0.62 | | Passive | 0.63 | |
| | Plaus | 0.63 | p<.001 | Poss | 0.63 | p<.003 |
| | Implaus | 0.53 | | Imposs | 0.67 | |
| Proportion Fix - sent-off | LPF | 0.56 | p<.001 | LPF | 0.65 | p<.008 |
| | BAF | 0.63 | | BAF | 0.71 | |
| | DO | 0.54 | p<.001 | Active | 0.68 | ns |
| | PO | 0.65 | | Passive | 0.68 | |
| | Plaus | 0.65 | p<.001 | Poss | 0.66 | ns |
| | Implaus | 0.54 | | Imposs | 0.69 | |
| Proportion First Fix - POD | LPF | 0.50 | ns | LPF | 0.55 | ns |
| | BAF | 0.56 | | BAF | 0.61 | |
| | DO | 0.53 | ns | Active | 0.64 | p<.001 |
| | PO | 0.53 | | Passive | 0.53 | |
| | Plaus | 0.56 | ns | Poss | 0.52 | p<.001 |
| | Implaus | 0.50 | | Imposs | 0.66 | |

one would think participants would be more influenced by plausibility in the structures they were less certain about (i.e., passives) compared to actives. This effect was driven by the BAF group. Finally, there was a three-way interaction between structure, plausibility, and group ($F=15.7$, $p<.001$). Again, it appears that plausibility influenced participants more in the active than passive condition and this effect was larger for the BAF group than LPF group.

*After Sentence Offset:* For the DO/PO condition, there were no significant interaction effects. For the active/passive condition, there was a significant structure by plausibility effect ($F=37.6$, $p<.001$). Participants were more influenced by plausibility in the active compared to passive condition. This effect, again, was driven by the BAF group. Finally, there was a three-way structure by plausibility by group interact ($F=46.5$, $p<.001$). Again, it appears that plausibility influenced participants more in the passive compared to active condition and that this effect was larger for the BAF compared to LPF group.

**Proportion of Fixations to Target:**

*After POD:* For the DO/PO condition, there were no significant interaction effects. For the active/passive condition, there was a significant plausibility by group interaction ($F=11.0$, $p<.002$). Participants in the LPF group were more influenced by plausibility than the BAF group.

*After Sentence Offset:* For the DO/PO condition, there were no significant interaction effects. For the active/passive condition, there was a significant group by plausibility interaction ($F=8.7$, $p<.005$). The LPF group was more influenced by plausibility than the BAF group.

*First Fixations After POD:* For the DO/PO and active/passive conditions, there were no significant interaction effects.

### 4.4.4 Broadened Auditory Filters vs. Vocoded

*Summary of Main Effects:*

Participants performance significantly differed in the BAF and vocoded only condition in the DO/PO condition only for measures of mean number of fixation between images and proportion of fixations to target image. When in the BAF condition, participants showed higher levels of uncertainty than the vocoded only condition for these measures.

For the DO/PO condition, participants showed higher degrees of uncertainty for the PO (4.0) compared to DO condition (2.9, p<.001) in the mean number of fixations after POD. They also showed a higher number of first fixations to the target image for POs compared to DOs both after the POD and sentence offset. For the active/passive condition, participants showed more uncertainty for the passive than active sentences as measured by latency after POD, mean number of fixations after the POD, and proportion of first fixations to target after POD.

Overall, for the DO/PO and active/passive condition, participants showed more uncertainty for improbable sentences compared to probable sentences across measures. However, for the proportion of first fixations to target after POD, participants showed a higher proportion of gazes to the target after improbable (mean: .71) compared to probable active/passive condition (mean: .58, p<.002). This is not as expected and the reason behind this finding is unknown.

*Interaction Effects:*

**Latency to Fixate of Target Image:**

*After POD:* For the DO/PO condition, there was a filter by plausibility interaction (F=31.6, p<.003). Participants were more influenced by plausibility when listening to sentences in the

BAF condition than vocoded condition. For the active/passive condition, there were no significant interactions.

*After Sentence Offset:* For the DO/PO and active/passive conditions, there were no significant interactions.

**Mean Number of Fixations:**

*After POD:* For the DO/PO condition, there were no significant interactions. For the active/passive condition, there was a structure by plausibility interaction ($F=27.0$, $p<.001$). Participants were more influenced by plausibility in the active compared to passive condition. There was also a plausibility by filters interaction ($F=15.4$, $p<.001$). Participants were more influenced by plausibility in the BAF compared to vocoded condition.

*After Sentence Offset:* For the DO/PO condition, there were no significant interactions. For the active/passive condition, there was a significant structure by plausibility interaction ($F=13.6$, $p<.002$). Participants were more influenced by plausibility in the passive compared to active conditions. There was also a structure by filter interaction ($F=41.4$, $P<.001$). Participants were more influenced by structure in the vocoded compared to BAF condition. There was a plausibility by filter interaction ($F=10.4$, $p<.004$). Participants were more influenced by plausibility in the BAF compared to vocoded condition. Finally, there was a three-way structure by plausibility by filter interaction ($F=23.9$, $p<.001$). Participants were more influenced by plausibility in the active than passive condition and this effect was larger in the BAF compared to vocoded condition.

**Table 13: BAF vs. Vocoded, Eye-tracking**

| BAF vs. Vocoded | DO/PO | | | Active/Passive | | |
|---|---|---|---|---|---|---|
| Measure | Effect | Mean | Significance | Effect | Mean | Significance |
| Latency - POD (ms) | BAF | 1181 | ns | BAF | 872 | ns |
| | Vocoded | 906 | | Vocoded | 805 | |
| | DO | 1042 | ns | Active | 671 | p<.001 |
| | PO | 1045 | | Passive | 1005 | |
| | Plaus | 930 | ns | Poss | 789 | ns |
| | Implaus | 1158 | | Imposs | 888 | |
| Latency - sent-off (ms) | BAF | 1080 | ns | BAF | 810 | ns |
| | Vocoded | 773 | | Vocoded | 741 | |
| | DO | 1042 | ns | Active | 671 | ns |
| | PO | 811 | | Passive | 880 | |
| | Plaus | 828 | ns | Poss | 707 | p<.0125 |
| | Implaus | 1024 | | Imposs | 845 | |
| Mean # Fix - POD | BAF | 6.1 | p<.005 | BAF | 7.5 | ns |
| | Vocoded | 5.4 | | Vocoded | 4.1 | |
| | DO | 5.3 | p<.008 | Active | 6.1 | p<.001 |
| | PO | 6.2 | | Passive | 5.5 | |
| | Plaus | 5.4 | p<.009 | Poss | 5.2 | p<.001 |
| | Implaus | 6.1 | | Imposs | 6.5 | |
| Mean # Fix - sent-off | BAF | 4.5 | p<.003 | BAF | 7.8 | ns |
| | Vocoded | 4.2 | | Vocoded | 5.8 | |
| | DO | 5.3 | p<.001 | Active | 6.1 | ns |
| | PO | 3.9 | | Passive | 7.5 | |
| | Plaus | 4.1 | p<.003 | Poss | 4.8 | p<.001 |
| | Implaus | 5.0 | | Imposs | 8.8 | |
| Proportion Fix - POD | BAF | 0.62 | ns | BAF | 0.68 | ns |
| | Vocoded | 0.7 | | Vocoded | 0.7 | |
| | DO | 0.59 | p<.001 | Active | 0.72 | ns |
| | PO | 0.68 | | Passive | 0.68 | |
| | Plaus | 0.68 | p<.003 | Poss | 0.68 | ns |
| | Implaus | 0.59 | | Imposs | 0.72 | |
| Proportion Fix - sent-off | BAF | 0.63 | p<.009 | BAF | 0.71 | ns |
| | Vocoded | 0.70 | | Vocoded | 0.75 | |
| | DO | 0.59 | p<.001 | Active | 0.72 | ns |
| | PO | 0.75 | | Passive | 0.74 | |
| | Plaus | 0.71 | p<.003 | Poss | 0.72 | ns |
| | Implaus | 0.62 | | Imposs | 0.74 | |
| Proportion First Fix - POD | BAF | 0.56 | ns | BAF | 0.61 | ns |
| | Vocoded | 0.55 | | Vocoded | 0.68 | |
| | DO | 0.56 | ns | Active | 0.72 | p<.001 |
| | PO | 0.55 | | Passive | 0.58 | |
| | Plaus | 0.60 | ns | Poss | 0.58 | p<.002 |
| | Implaus | 0.51 | | Imposs | 0.71 | |

**Proportion of Fixations to Target:**

*After POD:* For the DO/PO condition there was a significant structure by plausibility interaction ($F=8.9$, $p<.006$). Participants were more influenced by plausibility in the DO compared to PO condition. For the active/passive condition, there was a plausibility by filter interaction ($F=10.9$, $p<.003$). Participants were more influenced by plausibility in the vocoded compared to the BAF condition.

*After Sentence Offset:* For the DO/PO condition, there was a significant structure by plausibility interaction ($F=7.6$, $p<.01$). Participants were more influenced by plausibility for the DO compared to PO sentences. For the active/passive condition, there were no significant interactions.

*First Fixations After POD:* For the DO/PO and active/passive conditions, there were no significant interactions.

### 4.4.5 Summary of Eye-tracking Data

When comparing the BAF and LPF groups to the NoHL group, the BAF group showed more uncertainty as measured via eye-tracking in only two measures. The LPF group showed higher degrees of uncertainty in most eye-tracking measures. In this way, the BAF group acted more similarly to the NoHL group than the LPF group did. The LPF group showed higher degrees of uncertainty than the BAF group in four significant main effects of group. Participants showed more uncertainty in the BAF compared to vocoded condition.

Participants tended to show higher degrees of uncertainty in the PO compared to DO condition. This is unexpected, however, participants also showed a higher proportion of fixations to the target for PO compared to DO sentences. Participants were more uncertain for passives compared to actives. Finally, participants were more uncertain for improbable compared to probable sentences.

When comparing the BAF and LPF groups to the NoHL group, participants with simulated hearing loss were more influenced by plausibility than participants with NoHL. Participants with NoHL were more influenced by structure than participants with simulated hearing loss. This is as expected because in the face of noise, it is likely participants rely on a probability heuristic. In the absence of noise, when the syntactic structure is preserved, participants are likely to be influenced more by sentence structure.

When comparing the BAF and NoHL groups, there were two significant three-way interactions. Participants were more influenced by plausibility in the active compared to passive condition and this was larger for the BAF compared to NoHL group. When comparing LPF and NoHL, there were two significant three-way interactions. Participants were more influenced by plausibility in the DO compared to PO condition and this effect was larger for the NoHL compared to LPF group. This is the opposite pattern of the BAF interaction. Finally, when comparing the groups with simulated hearing loss to the NoHL group, the BAF group had more significant interactions in the active/passive condition and the LPF group in the DO/PO condition.

When comparing BAF to LPF, participants in the LPF group were more influenced by structure. The LPF group was more influenced by plausibility in a majority of significant group by plausibility interactions. Participants were more influenced by plausibility in active compared to passive sentences. This was unexpected and will be discussed in section 5.4. There were two significant three-way interactions in which participants were more influenced by plausibility for actives compared to passives and this was larger for the BAF group.

When comparing participants when listening to BAF vs. vocoded stimuli, participants were more influenced by plausibility in the BAF compared to vocoded condition. Participants were more influenced by structure in the vocoded compared to BAF condition. Participants were more influenced by plausibility in the passive compared to active condition. There was a significant three-way interaction in which participants were more influenced by plausibility in the active compared to passive condition and this was larger for the BAF compared to vocoded group.

# 5.0 DISCUSSION

This study aimed to answer the following questions:

1. How will sentence structure and plausibility influence fidelity to a perceived linguistic signal?
2. How does the absence or presence of broadened auditory filters affect one's fidelity to a perceived linguistic signal?
3. How does absence or presence of broadened auditory filters affect one's consideration of target and non-target interpretations of the sentence, as measured through eye-tracking and reaction time data?
4. How does individuals with broadened auditory filter's (BAF) performance on the Gibson task compare to people with simulated reduced audibility of high frequency information (LPF) and individuals without simulated hearing loss (NoHL)?
5. How does individuals with simulated hearing loss' performance on the Gibson task compare to individuals with aphasia's performance?

The discussion will explore how the results answer these questions.

## 5.1 APPLICATION TO THE NOISY CHANNEL MODEL

### 5.1.1 Edit Distance

Gibson et al. (2013) predicted that participants would be more faithful to the literal syntax when more edits were required to switch between alternate interpretations. This was evident in higher accuracy scores for actives and passives compared to DOs and POs. This finding was true for all groups: BAF, LPF, and NoHL.

### 5.1.2 Types of Edits

Gibson et al. (2013) predicted that language users would be more faithful to a sentence where the listener must assume a word was unintentionally inserted as opposed to deleted. The results were consistent with this prediction for the DO/PO alteration. Participants were more faithful to the POs compared to DOs. Results showed an opposite pattern for actives and passives. Participants were less faithful to passives compared to actives despite a response unfaithful to a passive requiring you to assume two words were inserted that were not intended. These results, however, were not unexpected. Gibson et al. (2013), Gibson et al. (2015), and Warren et al. (2017) found that typical language users and people with aphasia were more faithful to actives compared to passives. There are several possible explanations of this finding that may be specific to the population being considered.

When discussing typical language users, Gibson et al. (2013) explains this discrepancy in the model as an effect of structural frequency. People are more likely to rely on plausibility information for the less common passive structure compared to the common active structure. This might also explain why participants have profoundly low scores for DOs compared to POs. In addition to being consistent with the insertion/deletion effect, DOs are a less frequent syntactic structure relative to POs (O'Grady & Lee, 2005). This highlights the importance of considering multiple linguistic factors that can be contributing to one's uncertainty about linguistic information including edit distance, type of edit, plausibility among other factors like structural frequency.

Gibson et al. (2015) and Warren et al. (2017) explain why people with aphasia were less faithful to actives compared to passives. Warren at al. (2017) suggest the combination of low structural frequency and high complexity results in PWA having "lower quality representations" of passive sentences compared to active sentences. A low-quality representation means that people with aphasia are more uncertain about passives than actives resulting in more unfaithful interpretations.

When thinking about the participants in the present study, Warren et al.'s (2017) explanation does not apply. This is because the people in this study had a simulated hearing loss. This means that they did not have any history of communication disorders that may influence the quality of their syntactic representations. Low structural frequency could play a role, but it is also possible that additional factors contributed to this effect. Possible explanations specific to simulated hearing loss are explained below:

(1) Passives, in the face of hearing loss, are more susceptible to noise. This is because they contain more easily reduced function words than actives (i.e., “was” and “by”). These function words are cues for the syntactic structure of the sentence. In the face of more noise, i.e., simulated hearing loss, these words are more difficult to hear. This increases uncertainty about the structure and the likelihood one would rely on semantic priors.

While this explanation may explain why people listening to LPF speech performed more poorly on this task, it would not explain why people with BAF did. This is because the BAF group is not expected to have increased difficulty hearing easily reduced function words compared to other words. All words should be smeared relatively equally. In addition, this explanation would suggest that people would perform more poorly on POs compared to DOs because POs contain more easily reduced function words (i.e., “to”). This however, is not the case.

(2) Individuals with simulated hearing loss are already expending a majority of their processing resources to simply perceive a sentence. This leaves fewer processing resources available to parse more linguistically complex structures like passives. As a result, people with simulated hearing loss are more likely to rely on semantic information as a processing heuristic. This is consistent with research that finds people with hearing loss take longer to parse a given sentence, particularly if that sentence is more complex or of lower structural frequency (Carroll & Ruigendijk, 2013; Larsby et al., 2005; McCoy et al., 2005; and Wendt, Kollmeir, & Brand, 2015). This may also help explain why Leibold et al. (2014) found that children and adults listening to low-pass filtered speech were more likely to assume the plural marker they heard was not intended. For example, participants were more likely to assume “dogs” was intended as “dog” than to assume “dog” was intended as “dogs”. Perhaps linguistic complexity plays a role

in how people make decisions in the face of uncertainty. In addition to being sensitive to plausibility information, users are also sensitive to relative complexity of an alternate interpretation. Whether it means assuming the more complex passive was an active or the noun plus plural marker was only a noun, the present data suggests that participants with simulated hearing loss default to more simple interpretations in the face of decreased processing resources.

### 5.1.3 Plausibility

In terms of plausibility, results were consistent with Gibson et al.'s (2013) prediction that participants would be more faithful to probable compared to improbable sentences for the DO/PO structures. This is because participants are more likely to think a sentence was distorted when it does not align with their world knowledge. For the DO/PO structure, participants in the LPF and BAF groups were more influenced by plausibility than participants in the NoHL group and vocoded condition. This aligns with the assertion that people with hearing loss may be more likely to rely on plausibility information due to increased noise to their language processing mechanism. This coincides with Amichetti et al.'s (2016) findings that people with hearing loss tend to rely on probability heuristics to compensate for decreased available processing resources, a consequence of increased noise.

Interestingly, however, for actives/passives, there were no significant effects of plausibility in accuracy data and participants with BAF or listening to LPF speech did not rely more on plausibility information than participants with NoHL. However, reaction time data and eye-tracking data showed significant main effects of plausibility in which participants were more uncertain for impossible actives/passives than possible actives/passives. Perhaps this is because for the passive sentences, participant's decisions were driven by the low structural frequency and complexity of the structure resulting in equally low accuracy scores for passives regardless of plausibility.

### 5.1.4 In the Face of Noise

Participants with simulated hearing loss, both BAF and LPF, were less faithful to the literal syntax than people with no hearing loss. This was consistent with Gibson et al.'s (2013) prediction that in the face of noise, people would be less likely to rely on the literal syntax. It is also consistent with the Warren et al. (2017) finding that PWA were less likely than controls to rely on the literal syntax, and furthermore that their degree of sentence-comprehension impairment on a standardized language-assessment measure was predictive of how often they chose interpretations consistent with the literal syntax. The results indicate that both aspects of cochlear hearing loss result in increased reliance on plausibility information even though the simulations have different perceptual effects on the acoustic signal. This is consistent with findings that people with aphasia, a different type of noise than hearing loss, are also more likely to be unfaithful to the literal syntax. Noise, regardless of the type, influences our reliance on linguistic input. This holds true when the noise is constant (i.e., a person with aphasia) or simulated and only present temporarily. It also holds true when the noise influences the ability to hear high frequency information in speech and when it influences our certainty about spectral information. This will be further explored in section 5.3.

Eye-tracking measures showed that in the absence of noise, the NoHL groups tended to be more influenced by structure as evident in significant group by structure interactions. In the face of noise (LPF and BAF groups), participants tended to be more influenced by plausibility. The LPF and BAF group were also more influenced by plausibility in accuracy measures. This aligns with expectations as it is more likely that when listening to intact acoustic information and thus, intact structural information, participants would rely more on syntactic structure. In the face of noise, when the acoustic signal carrying syntactic structure is impaired, participants rely more on plausibility information.

## 5.2 MEASURES OF UNCERTAINTY

Reaction time data is a measure of how long it takes participants to decide which illustration best represents the sentence heard. Reaction time data can be said to be a measure of participant uncertainty as it is likely a participant takes longer to decide between illustrations for a sentence they are uncertain about. Eye-tracking data is also a measure of uncertainty. Taking longer to fixate on the target image means a participant is less certain about which image represents the literal syntax. More gazes between images suggests more uncertainty about which image represents the literal syntax. The BAF and LPF groups had higher reaction times than the NoHL group. This suggests that the perceptual consequences of cochlear hearing loss simulated in these two groups made participants less certain about the sentences they were perceiving. In terms of eye-tracking data, the LPF group showed higher degrees of uncertainty across measures than the

NoHL group. The BAF group, however, was not significantly different from the NoHL group in a majority of measures. It appears that the LPF group is more uncertain relative to the NoHL group than the BAF group is relative to the NoHL group. This suggests that reduced audibility of high frequency information drives uncertainty in people with hearing loss.

For reaction time data, there were no significant interactions between the BAF and NoHL group. However, there were interactions between the LPF and NoHL group for the DO/PO structure. The LPF group was less influenced by structure than the NoHL group. There was also a three-way interaction between group, structure, and plausibility in which the NoHL and LPF groups were more influenced by plausibility in the DO compared to PO condition and this was stronger for the NoHL group. This may reflect that individuals with LPF reached ceiling in terms of available processing resources. The LPF group showed consistently high reaction times across conditions regardless of the accuracy for a given sentence construction. For example, for the DO/PO alteration, individuals with LPF have robust differences in accuracy between DO possible (mean: .86) and DO impossible constructions (mean: .19) but have disproportionately similar reaction times (mean: 1556 ms, 1447 ms respectively). The NoHL group, on the other hand, had smaller differences between DO plausible (mean: .89), DO implausible (mean: .71) and proportional reaction times (mean: 1019 ms, mean: 1406 ms). When the NoHL group was less accurate and likely more uncertain, they had longer reaction times. The LPF group, on the other hand, had relatively high reaction times regardless of the given sentence condition's accuracy. This is further supported by the three-way interactions found for the DO/PO condition for mean number of fixations after POD and sentence offset. This interaction showed that participants in the NoHL group were more influenced and able to adapt the number of fixations between images than the LPF group. Individuals listening to LPF stimuli showed high reaction times and mean number of fixations to images across all conditions while the NoHL group was able to adapt their reaction time depending on how uncertain they were about a given sentence condition. Thus, reaction time data shows that the LPF group is at ceiling in terms of available processing resources as evident by reaction time and eye-tracking measures.

When looking at eye-tracking data comparing the BAF and NoHL group, it appears as if the BAF group was not at ceiling in terms of available processing resources. Like the NoHL group they were able to adapt the allocation of resources based on the sentence condition as evident by a group by plausibility by structure interaction in which both groups were influenced by plausibility more in the active compared to passive condition, but this was stronger for the BAF compared to NoHL group.

Eye-tracking and reaction time data both show that the BAF group is more like the NoHL group than the LPF group is. This suggests that the perceptual consequence of cochlear hearing loss, reduced audibility of high frequency information, contributes more to uncertainty experienced by people with hearing loss than the perceptual consequences of broadened auditory filters.

It is also important to address whether eye-tracking and reaction time measures are an index of uncertainty, processing resources, or both. Eye-tracking and reaction time are measures of uncertainty. Participants who are more uncertain consider alternate interpretations more as evident in eye-tracking measures like more fixations between images or longer reaction times. However, is this also a measure of processing resources? It may be likely that these two are related as someone who is more uncertain must exert more processing resources to consider alternate interpretations or keep alternate interpretations active. However, more direct measures, like pupil dilation, a reliable measure of cognitive effort (Johnsen, 2016), may aid to supplement this data and make the distinction clearer.

When thinking about uncertainty in the BAF group, it would also be interesting to look at relative uncertainty in the BAF group over the time course of the experiment. When listening to BAF speech, participants are able to adapt and recover intended meaning relatively easily. The BAF group likely adapted to the simulation over time resulting in diminished uncertainty. It would be interesting to see whether the group was generally more uncertain at the beginning of the experiment and how it changed over time. This could shed light on how people adapt to changes in the linguistic signal that only temporarily influence certainty, like an unfamiliar accent. It would be interesting to see how people with long-standing communication disorders adapt to uncertainty as opposed to temporary uncertainty. Do people with long-term uncertainty become more uncertain over time because they realize the input to their language processing mechanism is more unreliable? Or are there some aspects that they become more certain about as they learn how to recover intended meaning?

An unexpected result in the eye-tracking data was in the mean number of fixations after the POD—there was a main effect of structure, in which participants had more fixations for PO than DO structures. This was evident in comparisons between the BAF and NoHL group and LPF and NoHL group. This is opposite of the accuracy data, which showed lower accuracy scores for DO compared to PO sentences. This is surprising because Gibson et al. (2013) claims individuals should be more faithful to the literal syntax (and thus, should show less competition between alternate interpretations) when an edit involves an insertion rather than a deletion. This effect is only present after the POD. This could be because of the high uncertainty for this structure due to the edit distance of one. Perhaps, participants remained uncertain about this structure until the sentence offset keeping the alternate interpretation active until hearing the final noun phrase and confirming their interpretation. This is supported by the data showing that although participants showed more fixations for POs, a higher proportion of their fixations were to the target for POs compared to DOs. This suggests that while they were more uncertain, they were leaning towards an interpretation that was consistent with the literal syntax.

## 5.3 ASPECTS OF COCHLEAR HEARING LOSS

This study aimed to better understand how different aspects of cochlear hearing loss, reduced audibility of high frequency information and reduced spectral clarity, contributed to certainty about perceived linguistic information. The noise experienced by the BAF group can be said to be a result of simulation of broadened auditory filters. This is evident in the within subject comparisons between the vocoded and broadened auditory filter stimuli. Differences in performance showed that the uncertainty experienced in the BAF condition was not an effect of listening to vocoded speech, but rather, of listening to vocoded speech simulating auditory filters broadened by a factor of 3. In terms of accuracy, participants were less faithful to the literal syntax in the BAF compared to the vocoded condition. Participants also showed higher degrees of uncertainty in both reaction time and eye-tracking measures across sentence conditions in the BAF compared to vocoded condition. Furthermore, in the filter by plausibility and filter by structure interactions, the BAF vs. vocoded had results similar to the BAF vs. NoHL comparison. Participants were more influenced by structure in the vocoded condition as indicated by one out of one significant filter by structure interactions while participants were more influenced by plausibility in the BAF condition in two out of three filter by plausibility interactions.

It was predicted that people with simulated broadened auditory filters would perform differently on some structures than people with speech that had been low pass filtered. For the DO/PO structure, it was predicted the BAF and LPF group would perform similarly. This is because performance by PWA and the LPF group was similar for DOs and POs suggesting this structure is highly susceptible to uncertainty despite the degree or type of noise. For the active/passive condition, it was predicted that the BAF group would perform better than the LPF group. This is because groups with different types and degrees of noise (PWA and LPF) have shown more varied performance on this structure. Because the noise experienced by the BAF group causes uncertainty but does not interfere with the ability to identify consonants and is readily adapted to, they were predicted to out-perform the LPF group. Participants with simulated aspects of cochlear hearing loss, regardless of the particular simulation, were less faithful to the literal syntax. However, the results showed the opposite than expected pattern on sentence structures. Overall, in terms of accuracy, the BAF group outperformed the LPF group on DO/PO sentences but had no significant difference in performance on active/passive sentences. Possible explanations of these findings are below.

The LPF group and PWA could be performing more poorly on the DO/PO structures than the BAF group because the noise experienced by LPF and PWA are creating equally high amounts of uncertainty for this structure. This might be because the perceptual uncertainty experienced by the LPF group specifically targets the audibility of easily reduced function words like “to.” “To” is critical in differentiating between a DO and a PO. PWA are also expected to have relatively high degrees of uncertainty about this structure due to their language impairment. Not only does the increased noise to their language processing mechanism make them less faithful to a sentence with an edit distance of one, but the low structural frequency of DOs relative to POs would further decrease performance (O’Grady & Lee, 2005). The BAF group likely outperformed the LPF group because the perturbation of the linguistic signal influenced certainty about spectral information but not the ability to identify words essential to recognizing the sentence structure.

Interestingly, while the LPF group showed lower accuracy scores for the DO/PO construction, they did not have significantly higher reaction times than the BAF group. Thus, while the BAF group did not show more uncertainty for DOs and POs in measures of accuracy, they were as uncertain in measures of reaction time. This is further supported by significant main effects of group in which the LPF and BAF group had higher reaction times than the NoHL group. When looking at eye-tracking, the LPF group showed more uncertainty than the BAF group across measures and structures. This suggests that the LPF group showed both overt (i.e., accuracy) and covert (i.e., reaction time and eye-tracking) measures of uncertainty. For covert measures of uncertainty, the BAF group had decreased accuracy compared to the NoHL group but not the LPF group. They did, however, show covert signs of uncertainty in reaction time data. These comparisons show that different aspects of cochlear hearing loss can create different degrees of uncertainty about perceived linguistic input that manifest differently in behavioral measures. Just because a group shows less overt signs of uncertainty does not mean they are not covertly uncertain. Furthermore, groups that show more overt signs of uncertainty tend to show more covert signs of uncertainty.

For the active/passive condition, the LPF group and BAF group showed no statistically significant difference in accuracy. The BAF group did not outperform the LPF group as expected. This is not believed to be a ceiling effect because while the LPF group already had relatively high accuracy ~90% for the active impossible and passive possible/impossible conditions, higher accuracy was possible as evident by the 98% accuracy in the active possible condition. Thus, while the degradation to the linguistic signal experienced by the LPF group was significant enough to cause significantly decreased performance on the DO/PO condition it was not for the active/passive condition. This is likely because the active/passive is a more reliable structure. The edit distance of two means that a higher degree of noise is necessary to push an individual to an interpretation that is not faithful to the literal syntax. The data for PWA suggests that the language impairment caused by aphasia is significant enough to significantly influence fidelity to actives/passives.

While the LPF and BAF group did not show significant differences in performance on actives and passives in accuracy or reaction time data, they did show differences in eye-tracking data. The LPF group was more uncertain than the BAF group. This suggests that while the LPF group did not have what appeared to be any difference in certainty in the accuracy data, the more fine-tuned eye-tracking data shows a significant difference in how the LPF group and BAF group considered alternate interpretations. This underlines the importance of occult impairments that may not be easily diagnosable but can influence the amount of cognitive resources that are being expended in cognitive-linguistic tasks. Often, clinical measurements of impairment only measure accuracy i.e., did a client point to the correct image after hearing a sentence or word. This type of measurement is only sensitive to impairments that are evident in overt behaviors. It is not sensitive to times in which a patient may be uncertain but select the correct answer. Uncertainty, however, is still clinically significant. Patients who are uncertain must exert more cognitive resources on a given task leaving less resources available for higher level cognitive processing, even if their accuracy data is relatively unaffected. When hearing active/passive sentences, the perceptual consequence of hearing loss that is experienced by LPF may influence an individual's certainty about a perceived sentence leaving less cognitive resources available for higher level linguistic processing. Similarly, when listening to DO/POs, the perceptual consequence of cochlear hearing loss that smears spectral information (BAF) may make a language user more uncertain about spectral information while preserving accuracy, again leaving less cognitive resources available for higher level processing.

Another interesting trend observed in the eye-tracking data was that the BAF group showed more significant interaction effects in the active/passive condition compared to the DO/PO condition while the LPF group showed more interactions in the DO/PO condition compared to active/passive. The most interesting of these was the three-way interactions between structure, plausibility, and group for the mean number of fixations after the POD and sentence offset. Comparing the LPF and NoHL group, the three-way interactions appeared to show that for the DO/PO structure, participants were more influenced by plausibility in the DO compared to PO structure and that this effect was stronger for the NoHL group. This was interpreted as the LPF group reaching ceiling in terms of available processing resources. While the NoHL group was able to adapt number of fixations to the target image relative to each sentence, the LPF group showed high number of fixations across sentences. For comparisons between the BAF and NoHL group, the three-way interactions appeared to show that the groups were more influenced by structure in the active compared to passive condition and that this effect was stronger for the BAF group. This is the opposite of the three-way interactions for the LPF vs. NoHL groups. Here, the simulated hearing loss group is more influenced than the no hearing loss group. This suggests that while the LPF group was at ceiling in terms of available processing resources for the DO/PO construction, the BAF group was approaching ceiling for the active/passive condition. As a result, they showed higher number of fixations for some structures and not others while the NoHL group had a relatively low and relatively stable mean number of fixations for each sentence condition.

This finding, however, raises the questions as to why there were no significant three-way interactions for the LPF vs. NoHL condition in the active/passive condition. Wouldn't they too be approaching ceiling in terms of uncertainty? One contributing factor may be that that the BAF group actually had fewer mean number fixations for conditions they were more certain about than the NoHL group (i.e., active possible). However, when they were more uncertain, they had many more fixations than the NoHL group. This amplified the differences between structure and plausibility for the BAF vs. NoHL comparison. Perhaps, because the BAF group was able to adapt to the acoustic perturbations caused by the simulated broadened auditory filters they were left with little uncertainty for some conditions. However, they were still aware that there was increased noise to their language processing mechanism. Thus, when a structure conflicted more with their syntactic and semantic priors, they showed higher uncertainty than the NoHL group.

Overall, the results show that the perceptual consequence of hearing loss that causes reduced audibility of high frequency information profoundly influences the audibility of easily reduced function words like “to”, “was”, and “by”. This has profound effects when edit distance is small like in the DO/PO structures. For structures with larger edit distances, like actives and passives, reduced audibility of higher frequency information may cause increased uncertainty as evident in eye-tracking and reaction time data. This may draw from an individual’s cognitive resources leaving less available resources to do higher level cognitive-linguistic tasks.

The perceptual consequences of broadened auditory filters less severely influences an individual’s certainty about linguistic information than reduced audibility of high frequency information. Despite higher overall accuracy scores, broadened auditory filters caused increased uncertainty as measured by reaction time and eye-tracking data. Again, this could pull from available processing resources making higher level cognitive-linguistic tasks more challenging. Furthermore, participants listening to simulated broadened auditory filters for active/passive sentences showed levels of uncertainty equal or lower to that of the NoHL group when a sentence aligned with their semantic and syntactic priors. However, when encountering a sentence that conflicted with these priors, they showed disproportionately high measures of uncertainty in mean number of fixations to the target image. This suggests that people experiencing broadened auditory filters have high degrees of occult uncertainty that is especially evident in sentences that conflict with their semantic and syntactic priors.

One implication of the difference in performance between the LPF and BAF group is that researchers must carefully consider how they simulate hearing loss in research studies. Not all simulations of hearing loss are equal and different aspects of cochlear hearing loss influence our overt and covert uncertainty about a perceived linguistic signal differently. If hearing loss is simulated with one aspect and not another, it should be considered how other aspects of cochlear hearing loss may have influenced performance differently. Further research on how the combined effects of different aspects of cochlear hearing loss (i.e., BAF plus LPF) influence certainty about a linguistic signal would inform us on how people with true hearing loss make linguistic decisions given that the acoustic signal is perturbated in multiple ways.

## 5.4 COMPARISONS TO PEOPLE WITH APHASIA

When comparing individuals with simulated hearing losses and people with aphasia, data showed that people experiencing BAF outperformed PWA on DO/PO and active/passive sentences. The LPF group outperformed PWA on active/passive sentences but performed similarly on DO/POs. Thus, it is not that any uncertainty, regardless of type, influences faithfulness to DOs and POs equally but rather that some types of uncertainty influence this structure profoundly. It appears the language impairments experienced by PWA and the audibility of “to” makes people very uncertain about DOs and POs. Reduced spectral clarity, however, does not influence this structure as much. Similarly, the linguistic impairment experienced by PWA greatly influences faithfulness to actives/passives. The aspects of cochlear hearing loss examined in this study, however, do not influence faithfulness to actives/passives to the same degree. Given that it is possible for people with different types of uncertainty to act similarly on a structure (i.e., PWA and LPF on DO/POs), is it possible that some other kind of peripheral noise can influence certainty about passives/actives equally. It is expected that this type of noise would have to require expenditure of cognitive resources that would negatively influence the participant's ability to parse more complex and less frequent linguistic structures like passives.

Overall, the comparison of LPF, BAF, and PWA shows that the relationship between type and degree of uncertainty and linguistic structure is complex. Not all syntactic structures are influenced equally by any type of noise and not all types of noise influence the perceived meaning of a structure equally. One must consider how noise experienced by a language user influences the integrity of the perceived linguistic structure and available cognitive resources for parsing of complex linguistic structures and making decision between the literal and non-literal interpretations of the syntax.

There was also an interesting effect that played out across populations and across different measures. When looking at accuracy data and eye-tracking data for LPF, BAF, and PWA, participants show relatively high degrees of uncertainty in the active impossible condition. The manifestation of this uncertainty varies depending on the degree of noise to the language processing mechanism. PWA show this effect in overt measures of accuracy. Their accuracy for active impossible is nearly as low as their accuracy for passive impossible. LPF also show this effect in overt measures of accuracy. Their accuracy for active impossible sentences is slightly lower than their accuracy for passive impossible. The LPF group shows this effect in eye-tracking: a covert measure of uncertainty. The three-way interaction between structure, plausibility, and group for mean number of fixations after POD and sentence offset show that both groups were more influenced by plausibility for actives compared for passives and that this

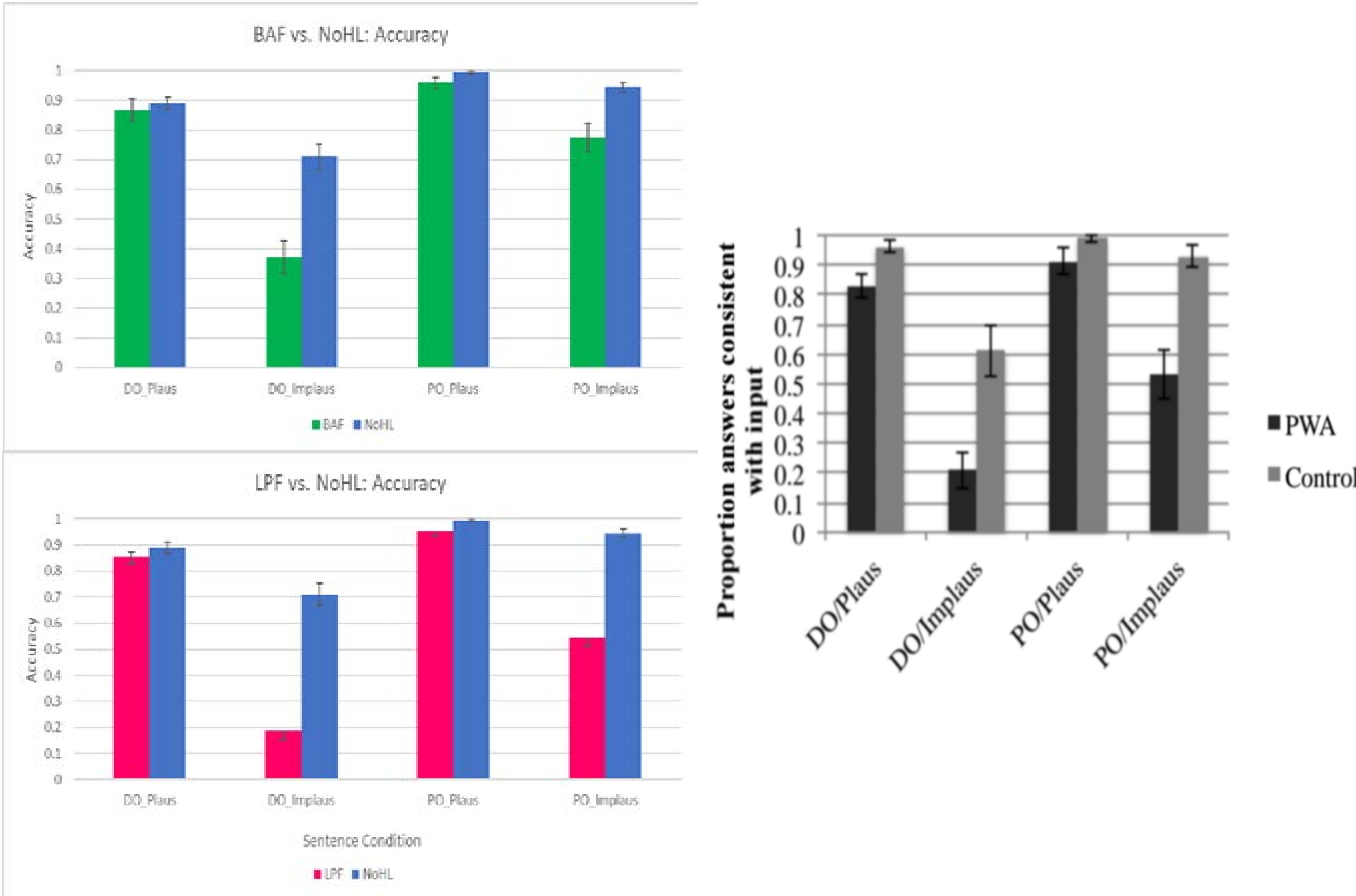


**Figure 11: Comparisons with PWA, DO/PO**

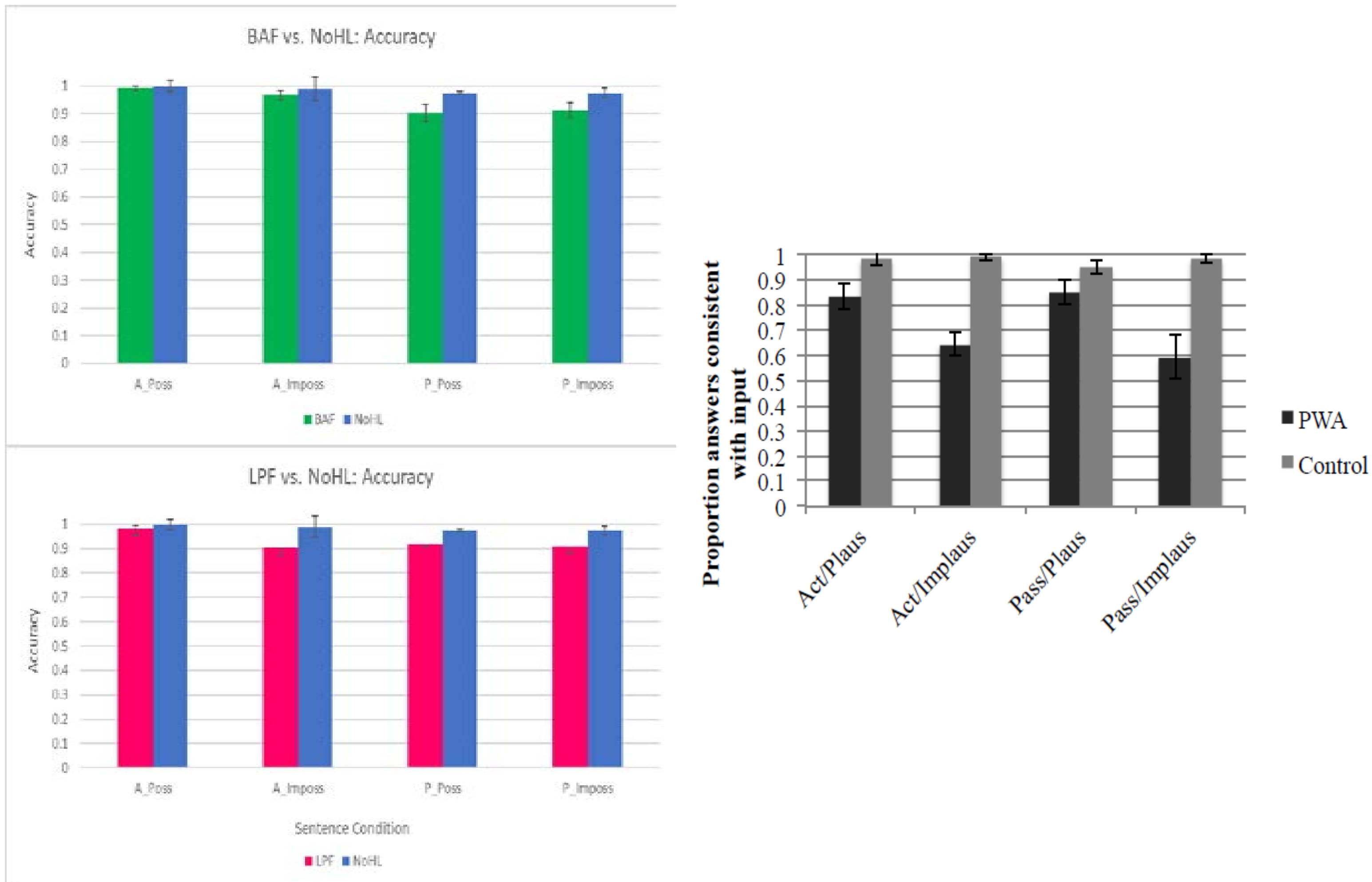


**Figure 12: Comparisons with PWA, Active/Passive**

effect was larger for the BAF compared to NoHL group. The BAF group showed more mean fixations to the target image for active impossible compare to active possible. Here we see another measure of increased uncertainty about active impossible sentences. The reason behind this heightened uncertainty for a common syntactic structure is unknown. Further research examining what happens cognitively when a person encounters a semantically improbable variation of a common syntactic structure should be conducted. One possible explanation is that this is the manifestation of the insertion/deletion effect in a common syntactic structure. According to the noisy channel model, participants should show higher degrees of uncertainty in active impossible than passive impossible sentences. This is because to interpret a passive impossible as a possible sentence, one must assume the perceived words “was” and “by” were not intended. On the other hand, to interpret an active impossible as possible, one must assume the words “was” and “by” were not perceived but intended. The latter is more probable. This effect may be the complex interaction between frequency of syntactic structure and the insertion/deletion effect. This suggests that we must carefully consider how language may be grapple with conflicting semantic and syntactic priors.

# 6.0 CONCLUSION

Participants in all groups acted in a way consistent with the noisy channel model. They were less faithful to the literal syntax when a sentence required fewer edits to switch to an alternate interpretation (DO/POs vs. active/passive), when an edit required a deletion as opposed to insertion (DO vs. PO), for improbable compared to probable sentences, and in the face of more noise (BAF/LPF vs. NoHL). Participants showed higher degrees of uncertainty in both reaction time and eye-tracking measures for sentences that were more likely to be corrupted by noise. Participants in the LPF group showed higher degrees of uncertainty than the BAF group for the DO/PO sentences but not for the active/passive sentences. This suggests that reduced audibility of high frequency information profoundly effects certainty about double object and prepositional object sentences. Both broadened auditory filters (BAF group) and reduced audibility of high frequency information (LPF group) caused participants to be equally unfaithful to active/passive sentences. The LPF group, however, showed higher degrees of uncertainty in this condition as measured through eye-tracking data. This underlies the importance of occult uncertainty that may draw from an individual's cognitive resources. Participants in the LPF group performed similarly to PWA in the DO/PO condition while the BAF group outperformed PWA. Both the LPF group and BAF group outperformed PWA in the active/passive condition. This suggests that

that the relationship between type and degree of noise and syntactic structure is complex. Not all types of syntactic structures are influenced equally by any type of noise and not all types of noise influence the perceived meaning of a structure equally.

## BIBLIOGRAPHY


Amichetti, N., White, A., Wingfield, A. (2016). Multiple solutions to the same problem: utilization of plausibility and syntax in sentence comprehension by older adults with impaired hearing. *Frontiers in Psychology, 7*, 1-13.

Aylett, M., & Turk, A. (2004). The smooth signal redundancy hypothesis: a functional explanation for relationships between redundancy, prosodic prominence, and duration in spontaneous speech. *Language and Speech, 47*(1), 31-56.

Baer, T., & Moore B. (1993a). Effects of spectral smearing on the intelligibility of sentences in noise. *The Journal of the Acoustical Society of America, 94,* 1229-1241.

Baer, T., & Moore, B. (1993b). Effects of spectral smearing on the intelligibility of sentences in the presence of interfering speech. *The Journal of the Acoustical Society of America, 95* (4), 2277-2280.

Bak, T. H., & Hodges, J. R. (2003). Kissing and dancing—a test to distinguish the lexical and conceptual contributions to noun/verb and action/object dissociation. Preliminary results in patients with frontotemporal dementia. *Journal of Neurolinguistics, 16*(2), 169–181.

Bhargava, P., Baskent, D. (2012). Effects of low-pass filtering on intelligibility of periodically interrupted speech. *The Journal of the Acoustical Society of America, 131* (2), 87-92.

Boothroyd, A., Bethany, M., Gong, J., Ostroff, J. (1996). Effects of spectral smearing on phoneme and word recognition. *The Journal of the Acoustical Society of America, 100* (3), 1807-1818.

Carminati, M., van Gompel, R., Scheepers, C., & Arai, M. (2008). Syntactic Priming in Comprehension: The Role of Argument Order and Animacy. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 34* (5), 1098-1110.

Carroll, R., & Ruigendijk, E. (2013). The effects of syntactic complexity on processing sentences in noise. *Journal of Psycholinguistic Research, 42*, 139-159.

Carter, C., Yorkston, K., Strand, E., & Hammen, V. (1996). Effects of Semantic and Syntactic Context on Actual and Estimated Sentence Intelligibility of Dysarthric Speakers in

Robin, D., Yorkston, K., & Beukelman, D., *Disorders of Motor Speech: Assessment, Treatment, and Clinical Characterization* (pp. 67-87). Baltimore, MD: Brookes Publishing Company.

Desloge, J., Reed, C., Braida, L., Perez, Z., & Delhorne, L. (2010). Speech reception by listeners with real and simulated hearing impairment: Effects of continuous and interrupted noise. *The Journal of the Acoustical Society of America, 128* (1), 342-359.

Duquesnoy, A. J. (1983). Effect of single interfering noise or speech source upon the binaural sentence intelligibility of aged persons. *The Journal of the Acoustical Society of America, 74* (3), 739-743.

Ferriera, F. (2003). The misinterpretation of noncanonical sentences. *Cognitive Psychology, 47,* 164-203.

Fletcher, H. (1940). Auditory Patterns. *Reviews of Modern Physics, 12* (1), 47-65.

Folstein, M. F., Folstein, S. E., McHugh, P. R. (1975). “Mini-mental state”. A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research, 12,* (3), 189-98.

Gelfand, S. (2010). *Hearing: An Introduction to Psychological and Physiological Acoustics.* London, England: Informa Healthcare.

Gelfand, S., Ross, L., Miller, S. (1987). Sentence reception in noise from one versus two sources: Effects of aging and hearing loss. *The Journal of the Acoustical Society of America, 83* (1), 248- 256.

Gibson, E., Bergen, L., & Piantadosi, S. (2013). Rational integration of noisy evidence and prior semantic expectations in sentence interpretation. *Proceedings of the National Academy of Sciences, 110,* (20), 8051-8056).

Gibson, E., Sandberg, C., Fedorenko, E., Bergen, L., & Kiran, S. (2015). A rational inference approach to aphasic language comprehension. *Aphasiology.*

Hornsby, B., Ricketts, T. (2003). The effects of hearing loss on the contribution of high- and low- frequency speech information to speech understanding. *The Journal of the Acoustical Society of America, 113* (3), 1706-1717.

Howard, D., & Patterson, K. E. (1992). *The Pyramids and Palm Trees Test: A test of semantic access from words and pictures*. Thames Valley Test Company.

Johnsen, A. (2016). *Comprehension and effort for vocoded speech varying in syntactic complexity.* (Master's thesis).

Larsby, B., Hallgren, M., Lyxell, B., & Arlinger, S. (2005). Cognitive performance and perceived effort in speech processing asks: Effects of different noise backgrounds in normal-hearing and hearing- impaired subjects. *International Journal of Audiology 44,* 131-143.

Leek, M., Dorman, M., & Summerfield, Q. (1987). Minimum spectral contrast for vowel identification by normal-hearing and hearing-impaired listeners. *The Journal of the Acoustical Society of America, 81* (1), 148-154.

Leibold, L., Hodson, H., McCreery, R., Calandruccio, L., Buss, E. (2014). Effects of low-pass filtering on the perception of word-final plurality markers in children and adults with normal hearing. *American Journal of Audiology, 23* (3), 351-358.

Levy, R. (2008). A noisy-channel model of rational human sentence comprehension under uncertain input. *Proceedings of the 2008 Conference of Empirical Methods in Natural Language Processing,* 234-243.

Levy, R., Bicknell, K., Slattery, T., Rayner, K. (2009). Eye movement evidence that readers maintain and act on uncertainty about past linguistic input. *Proceeding of the National Academy of Sciences, 106* (50), 21086-21090.

Levy, R. (2011). Integrating surprisal and uncertain-input models in online sentence comprehension: formal techniques and empirical results. *Proceedings of the 49$^{th}$ Annual Meeting of the Association for Computational Linguistics,* 1055-1065.

McCoy S., Tun, P., Colangelo M., Stewart, R., & Wingfield, A. (2005). Hearing loss and perceptual effort: Downstream effects on older adults' memory for speech. *The Quarterly Journal of Experimental Psychology, 58A* (1), 22-33.

Moore, B. (1995). Frequency analysis and masking in Moore, B., *Hearing (*pp.161-205). Orlando, FL: Academic Press.

Moore, B. (1996). Perceptual consequences of cochlear hearing loss and their implications for the design of hearing aids. *Ear & Hearing, 17* (2), 133-161.

Nunn, K. (2016). *The Noisy Channel Model and Sentence Processing in Individuals with Simulated Hearing Loss* (Unpublished undergraduate thesis). University of Pittsburgh, Pittsburgh.

O'Grady, W., & Lee, M. (2005). A mapping theory of agrammatic comprehension deficits. *Brain and Langauge, 92,* 91-100.

Olsen, W., Hawkins, D., & Van Tasell, D. (1987). Representations of the Long-Term Spectra of Speech. *Ear and Hearing, 8* (5).

Owen E., Benedict, M., & Schubert, E. (1972). Consonant and Phonemic Errors Associate With Pure-Tone Configurations and Certain Kinds of Hearing Impairment. *Journal of Speech and Hearing Research, 15,* 308-322.

Raven, J. (1956). Coloured Progressive Matrices: Sets A, Ab, B. London: H.K. Lewis and Co., Ltd.

Sher, O., & Owens, E. (1974). Consonant Confusions Associated With Hearing Los Above 2000 Hz. *Journal of Speech and Hearing Research, 17,* 669-681.

Swinburn, K., Porter, G., Howard, D. (2004). *Comprehensive Aphasia Test*. Psychology Press.

Tanenhaus, M. K., Spivey-Knowlton, M.J., Eberhard, K., & Sedivy, J. C. (1995). Integration of visual and linguistic information in spoken language comprehension. *Science,* 268: 1632-1634.

ter Keurs, M., Festen, J., Plomp, R. (1992). Effect of spectral envelope smearing on speech perception I. *The Journal of the Acoustical Society of America, 91* (5), 2872-2880.

Warren, T., Dickey, M. W., & Liburd, T. L. (2017). A rational inference approach to group and individual-level sentence comprehension performance in aphasia. Cortex, 92, 19–31.

Wendt, D., Kollmeier, B., Brand, T. (2015). How hearing impairment affects sentence comprehension: using eye fixations to investigate the duration of speech processing. *Trends in Hearing, 19,* 1-18.

Wingfield, A., McCoy, S., Peelle, J., Tun, P., & Cox, L. (2006). Effects of Adult Aging and Hearing Loss on Comprehension of Rapid Speech Varying in Syntactic Complexity. *Journal of American Academy of Audiology, 17,* 487-497.