Word Recognition in Noise among Young and Older Listeners: A Combined Behavioral and Electrophysiological Study

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Word Recognition in Noise among Young and Older Listeners: A Combined
Behavioral and Electrophysiological Study

by

Victoria A. Williams-Sanchez

A dissertation submitted in partial fulfillment of the requirement for the degree of
Doctor of Philosophy
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DEDICATION

I dedicate my dissertation work to my family. My family made my success both possible and rewarding. This work is especially dedicated to my sweet daughter, Adelina Rose Sanchez. Adelina, may you set your goals high and accomplish all of your dreams.
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Abstract

Word recognition is based on the complex interplay of bottom up processing of acoustic input and corresponding top-down processing based on linguistic redundancies (i.e., contextual cues). Friedrich and Kotz (2007) investigated the timeline of integrating top-down and bottom-up processes among young adults with normal hearing using sentences presented in quiet. As a follow-up study, also with young adults with normal hearing (Experiment 1 of this dissertation), we used sentences embedded in multi-talker background noise and found similar results to Friedrich and Kotz (2007); but, with the use of principal component analysis (PCA) unveiled additional effects of phonological and semantic integration of spoken sentences presented in background noise. These past studies provide evidence of the time course of bottom-up and top-down mechanisms among young adult listeners in quiet and in noise; however, it is unknown if a similar pattern would be present among older adult listeners, which was the primary goal of the dissertation.

In Experiment 2, we aimed to elucidate the time-course, and behavioral and neural correlates of word recognition primed by speech-in-noise in older adults with near normal hearing (i.e., thresholds ≤ 25 dB-HL through 3000 Hz and minimal high frequency hearing loss). Older adults often report difficulty understanding speech in the presence of background noise. Degradation in peripheral and central auditory processing along with age-related cognitive decline has been hypothesized as reasons why older adults struggle in the presence of noise.
1.1 Hearing and healthy aging

As we grow older, our ability to communicate via spoken language is a cornerstone of healthy aging (IOM, 2014). Spoken language communication is important for remaining cognitively and socially engaged with those around us. Age-related hearing loss, one of the most common chronic health conditions in the elderly, results in difficulty with speech understanding and leads to reduced spoken language communication interactions.

Age-related hearing loss is sensorineural in nature and has two distinct components which impact negatively on the ability to recognize speech: audibility and distortion (Plomp, 1977). The audibility component is quantified clinically by intensity level (in dB HL) that is needed to hear a pure tone or the ability to recognize words presented in quiet (Killion, 2002). There is a predictable and linear relationship between increasing pure-tone thresholds and decreasing speech recognition performance in quiet (Wilson & McArdle, 2005). The audibility component of a hearing loss is usually corrected with amplification. In contrast, the distortion component of sensorineural hearing loss is nonlinear and unpredictable, and manifests itself as a reduced ability to understand speech, especially in background noise and regardless of the presentation level (Killion, 2002). Thus, it is this distortion component of age-related hearing loss that is most debilitating.

CHAPTER ONE:
INTRODUCTION & LITERATURE REVIEW

1.1 Hearing and healthy aging
Although much of the difficulty that older adults have with understanding speech in noise can be attributed to the distortion component of SNHL and the effects of energetic masking of acoustic speech cues, decrements in higher level auditory processing, which can occur with or without peripheral damage, are also believed to contribute to poor performance (Fitzgibbons & Gordon-Salant, 1996; Schnieder & Pichora-Fuller, 2000). In particular, auditory processing difficulties are believe to impact negatively on the ability to differentiate target speech from other competing speech, resulting in an informational masking effect that can impact an older adult’s speech understanding, regardless of peripheral auditory status (for review, Fitzgibbons & Gordon-Salant, 2010; Wingfield & Stine-Morrow, 2000). Problems of speech understanding in noise, whether the noise is energetic or informational, are further exacerbated in older individuals due to declines in several cognitive processes. These cognitive processes include working memory capacity, inhibitory control, and processing speed (e.g., Van der Linden et al., 1999). Whatever the cause, when older adults are unable to effectively engage in spoken language communication due to reduced speech recognition abilities, particularly in noise, they can become socially isolated, and social isolation is known to be an important driver of morbidity and mortality in older adults.

The relative contribution of the peripheral auditory, auditory processing and cognitive factors that contribute to the speech-in-noise perceptual difficulties of older individuals are not well understood (CHABA, 1988; Humes, 1996; Humes, Kidd, & Lentz, 2013). Thus, increasing our knowledge of how older adults understand speech in noise, whether or not auditory thresholds are within the normal range, is the focus of the present dissertation, and is relevant from a public health perspective.
1.2 Speech understanding: Defining word recognition

Speech understanding is studied from different perspectives and by multiple disciplines, such as hearing scientists, speech scientists, linguists, cognitive psychologists, and engineers. This multi-disciplinary interest in speech understanding has led to a large corpus of terminology used to discuss similar topics. Likewise, throughout the literature there are many methods used to quantify speech understanding, from the micro-perspective of capturing the discrimination abilities of the dynamic temporal and spectral acoustic cues of a speech signal, to macro-prospective of quantifying the comprehension of discourse. It is important to clarify the definition of speech understanding being used in any investigation, and more so, to define the measurement of interest.

It is generally accepted that the term speech understanding is used as an umbrella term and may be referring to the discrimination of two speech sounds, the identification of a word in a closed-set of items, the recognition of a word from an open set, or the comprehension of the meaning of a message (for review see, Humes & Dubno, 2010). In this dissertation the focus is on word recognition, which occurs when the listener activates a lexical entry in his or her mental lexicon that is believed to correspond to the word that was produced by the speaker. The mental lexicon is described as the permanent storage of word knowledge in memory (McQueen, 2005).

There are several models of auditory word recognition that attempt to describe how the mental lexicon is organized, accessed, and how words are ultimately recognized (see Frauenfelder & Tyler, 1987; McQueen, 2005; for reviews). While there are many differences in the models, they all describe the three core representational levels as shown in Figure 1.1 – phonological, lexical and semantic. The phonological level is accessed via the acoustic/phonetic input making initial contact with phonological representations. The phonological representations
activate a set of word candidates in memory, or the lexical representations. Subsequently, the lexical representations need to be discriminated amongst until a single entry is selected and associated with its semantic representation (for reviews see, McQueen, 2005; Jusczyk & Luce, 2002). The question remains, however, as to whether the process of word recognition is an exclusively feed-forward process, with perception leading to recognition or if it is a mixture of feed-forward and feed-back flows such that perception is influenced by phonological mapping and/or by surrounding context. Indeed, linguistic context serves as a redundant source of information, which as described below, is essential to the ability to recognize words in a background of noise.

Figure 1.1 A basic schematic that highlights the three core levels of representation within the mental lexicon that are required for word recognition: phonological, lexical, and semantic.
1.3 A communication model: Implication for word recognition

While the focus of this work is on spoken word recognition in noise, it is important to remember that word recognition is just one aspect of human spoken communication which is clearly a complex, transactional, and social process. In examining the effects of age on word recognition in noise by adults, with or without hearing loss, however, the simple communication model proposed by Shannon (1948) is very applicable. Shannon, and his colleague Weaver, were engineers working at the Bell Telephone Laboratories, who proposed a set of theorems to account for effective transmission of messages via the radio or telephone. Subsequently, the Shannon-Weaver model, shown in Figure 1.2, provided the basis for the development of information or communication theory as a way of examining any system in which a message is sent from a source to a receiver, including by speech and hearing scientists examining factors affecting face-to-face spoken language communication between a speaker and a listener (McQueen, 2005; Wilson & McArdle, 2008).

Figure 1.2 Example schematic of the Shannon-Weaver communication model.
In this model, the “source” is the person producing the message in face-to-face spoken language communication\(^1\). The message is transmitted, first through speech production which creates and modulates an acoustic (and visual) signal, and then through the air, which serves as the transmission channel. The effective transmission of the signal through the channel to the receiver, which in this case is the listener, can be impeded by noise, which currently is often used as a metaphor for any problems associated with effective listening. Thus noise can be external, such as occurs when we try to converse in a noisy restaurant; or, it can be internal to either the speaker or the listener. Noise can arise from the speaker, for example, if articulation errors are made, speech is produced very rapidly, or the speech productions are heavily accented. Noise can be introduced by the listener at the point of decoding if, for example, there is a loss of acuity or an inability to selectively attend to the speaker such as might occur when there is informational masking and cognitive decline. Noise could also be introduced at the destination, which refers to the person’s understanding of the message. For example, when a person experiences neurological damage to the receptive language processing areas in the brain secondary to a stroke, the message may be effectively decoded, but the words many not be understood. Similarly, if a listener does not know a particular language, for example Spanish, the speaker may clearly articulate a message such as “¿Cómo te llamas?” in a quiet room, and the listener may have normal hearing and be neurologically intact, but the words will not be recognized and thus the message will not be understood.

To summarize thus far, when the Shannon-Weaver communication model is applied to face-to-face spoken language communication, two factors can be identified as important for effective word recognition. First, there is the capacity to effectively transmit information, or the

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\(^1\) Note that there is a visual speech signal too but this is not the focus of present study.
channel capacity, which in this context is dependent on the speaker’s cognitive-linguistic competence and speech production abilities, the acoustic environmental conditions, and the auditory-perceptual abilities and cognitive-linguistic competence of the listener. The higher the channel capacity, the greater the likelihood, that spoken words will activate the phonological, lexical, and semantic levels of processing and words will be effectively recognized. Second, as noise (external or internal) increases the likelihood that spoken words will be effectively recognized decreases.

1.4 Entropy and redundancy in the communication model

While both external and internal noise can negatively impact on speech understanding, and, more specifically, word recognition, it is also important to consider the implications of the concepts of entropy and redundancy as described in the Shannon-Weaver communication model (1948). In simple terms, entropy refers to the unpredictability of information being sent from the speaker to the listener. As an example, consider the Speech Perception in Noise (SPIN) test (Kalikow, Stevens, & Elliott, 1977; Bilger et al., 1984) in which a listener is required to recognize the last word in a spoken sentence. The SPIN test is comprised of sentences which are classified as low-predictability (LP) or high-predictability (HP). An example of a LP sentence is, “I had not thought about the GROWL”. As the word GROWL is very unpredictable from the preceding syntactic-semantic linguistic context, the sentence has high entropy for the recognition of the last word. In contrast in the HP sentence, “The watchdog gave a warning GROWL”, the last word could be predicted based on the preceding semantic-syntactic context; and thus, the sentence would be described as having low entropy.
The concept of entropy is counterbalanced with the concept of *redundancy*, where less entropy implies more redundancy (Shannon, 1948). Redundancy refers to the fact that in any form of communication, there is more information available than is needed for the receiver to understand the message when no noise is present. However, when there is noise, the redundancies increase the likelihood that the message will still be understood. So for example, in noise it is easier to recognize the word GROWL in a HP and high redundancy sentence than in a LP and high entropy sentence, as the semantic-syntactic linguistic context in the former serve as redundant sources of information that enhances the probability the word will be recognized even when the acoustic signal lacks clarity. As in other communication systems there is a great deal of redundancy in spoken language communication (Miller, 1951; Bocca & Callearo, 1963; Wilson & McArdle, 2008), and relevant to the present study are those sources of information which activate and/or constrain the phonological, lexical, and semantic representations available for the task of word recognition in noise.

1.5 Sources of information for word recognition in noise

Listeners have phonetic, phonological, lexical, syntactic, semantic and pragmatic sources of information, or redundancies, which can be used in the recognition process. At the phonetic level redundancy is illustrated by the many-to-one mapping of acoustic cues onto phonetic contrasts and by the presence of cue-trading relationships (Klatt, 1989). At the level of phonology, redundancy is provided by the combinatorial rules that organize sound sequences into words, also referred to as a probability phonotactics (Vitevitch & Luce, 1999). Lexical redundancy refers to the influences of word familiarity, word, frequency and neighborhood density, such that more familiar words, words which occur more frequently, and those from less
dense neighborhoods being easier to access in the mental lexicon than words that are less familiar, occur less frequently or are from denser neighborhoods (Luce & Pisoni, 1998). Redundancy is also provided by semantic, syntactic and pragmatic linguistic contextual constraints. Semantic redundancy refers to the meaning of words or concept of phrases stored within the mental lexicon. Syntactical combinational rules guide how words can be used in sentences (Boothroyd & Nittrouer, 1988). Lastly, pragmatic information deals with the sensible and realistic properties of the spoken message. Indeed, as discussed by Suleiman (1980) redundancies are inherent in any language, and because communication never takes place under optimum conditions, but rather in the presence of internal and external noises, redundancies are requisite to the conservation of the information being transmitted from a source to a receiver. Of interest in the present dissertation are the mechanisms by where a listener makes use of the linguistic-contextual redundancies within a speech message to assist word recognition in the presence of noise; and, whether or not age influences those mechanistic pathways. The use of the redundancies in this dissertation is also referred to as the use of top-down processing as further discussed in the next section.

1.6 Bottom-up and top-down processing streams: Identifying the underlying mechanisms of word recognition in noise

Recall that in the process of auditory word recognition, listeners must access their mental lexicons, whose architecture consists of three levels: phonological, lexical and semantic representations. In some models of spoken word processing, activation of the phonological, lexical and semantic word information stored in memory spreads from the bottom–up, with no information flow in the opposite direction, such that speech sounds activate words and words
activate meaning representations (Norris, McQueen, & Cutler, 2000; Marslen-Wilson, 1987; Marslen-Wilson & Zwitserlood, 1989). Other models postulate that information flow is interactive or distributed such that information flows in both directions, with words receiving activation from both bottom–up and top–down mechanisms (Gaskell & Marslen-Wilson, 1997; McClelland & Elman, 1986). Thus, as illustrated in Figure 1.3, not only do words become activated by bottom-up decoding of acoustic input, the top-down processing stream activate words base on the linguistic-contextual redundancies that create expectations or predictions for what is likely to be heard.

![Figure 1.3](image.png)

**Figure 1.3** Bottom-up and top-down processing streams on the core representations of word recognition.

Of course, as illustrated in Figure 1.4, top-down processing is dependent not only on linguistic-contextual information but also on non-auditory and non-language cognitive abilities that are also subject to age-related declines, including the executive functions of working memory (Bialystok, Craik, & Luk, 2008; Just & Carpenter, 1992) and inhibitory control.
(Bialystok et al., 2008; Hasher & Zacks, 1988), as well as information processing speed (Salthouse, 1996). In contrast, the use of linguistic-contextual cues in word recognition is spared in older adults, with older adults appearing to make greater use of context than younger ones in adverse listening conditions (see Pichora-Fuller, 2008, for a comprehensive review). Thus, in the case of word recognition in noise it is possible that older listeners are making greater use of spared conceptual and semantic knowledge for word recognition when noise and/or hearing loss degrades the bottom-up information. The present dissertation was interested in elucidating how bottom-up processing of the acoustic speech signal and top-down linguistic-contextual influences interact as the listener accesses phonological, lexical and semantic representations during word recognition in noise.

**Figure 1.4** A schematic of speech processing. *Bottom-up processing* is illustrated by the blue arrows. *Top-down processing* is illustrated by the red arrows. The green levels of speech processing has its own function (distinct color) but remains directly linked and modulated (bidirectionally) by executive/cognitive processes (all shades of green).
In quiet conditions, the mechanistic pathway listeners use seem to include both bottom-up and top-down processing streams to recognize words (Friedrich & Kotz, 2007; Davis, Ford, Kherif, & Johnsrude, 2011), but if the listening environment is degraded (i.e., noisy) or if the listener is impaired (e.g., age-related hearing loss, cognitive decline) the reliance on these streams, or the underlying mechanisms, changes (Pichora-Fuller, 2008; Davis, Ford, Kherif, & Johnsrude, 2011). Exactly how the interplay between bottom-up and top-down processes adapt in adverse listening conditions is unknown. Thus, in the present study with its overarching goal of increasing our knowledge of how older adults understand speech in noise, the individual and collective influences of bottom-up and top-down processing streams on word recognition in noise were examined. In the next sections, the methodological approaches that can be used to explore the dynamic interplay between the two processing streams are described.

1.7 Examining word recognition in noise: The behavioral approach

There is a vast amount of research dedicated to investigating the word recognition in noise performance of listeners, young and old, with and without hearing loss (e.g., Akeroyd, 2008; Wilson and McArdle, 2008). The use of behavioral analysis provides a measure of the speed and accuracy of perceptual performance that allows researchers to see how an experimental manipulation can directly affect word recognition performance. Commonly, word recognition in noise performance can be quantified by accuracy, reaction times, or the signal-to-noise ratio level needed for a specified level of performance.

These behavioral measures are informative but they miss out on capturing the underlying processes that occur (Hagoort & Kutus, 1995; Luck, 2005). That is, while quantifying performance is important, there is also a need to understand the mechanisms of how listeners
utilize bottom-up and top-down processing in real-time while accomplishing a word recognition in noise task. Understanding real-time processing may be particularly important in older listeners, who may achieve similar accuracy scores compared to younger listeners, but who may be using a very different mechanism to achieve the same level of accuracy, and differences in approaches may have implications for the types of interventions that might be utilized to address speech understanding in noise difficulties among the elderly.

1.8 Studying word recognition in noise: The neurophysiological approach

Neurophysiological approaches include various techniques to either directly or indirectly image the structure and/or function of the nervous system and neural activity. Basically there are two tactics: first, there is structural imaging, including hemodynamic measures [e.g., positron emission tomography (PET) and functional magnetic resonance imaging (fMRI)], that provide excellent spatial resolution but poor temporal resolution, and, second, functional imaging, including electroencephalography (EEG), and event-related potentials (ERPs), that provide poor spatial resolution but excellent temporal resolution (Luck, 2005). The temporal precision of ERPs provide both a “continuous” and “real time” measures, which make it possible to monitor the immediate consequences of a particular experimental manipulation at multiple time points (Hagoort & Kutas, 1995; Luck, 2005). Through looking at the three main aspects of ERPs: 1) time course 2) amplitude and 3) distribution across the scalp, one can make inferences about the “...timing, degree of engagement, and functional equivalence of the underlying cognitive processes” (Otten & Rugg, 2005, p. 5). There is a need for precise temporal resolution when investigating speech understanding considering the rapidly changing and complex nature of
spoken words. Likewise, ERPs can be time-locked to specific events of interest even if those events are embedded in-between other events. It is advantageous to unveil processes occurring in real time and are influenced less by offline response strategy because it allows for the evaluation of the underlying mechanism(s). Lastly, ERPs can also be analyzed componentially, and many ERP components are reliably linked with very specific cognitive processes (Handy, 2005).

Although the use of neurophysiological measures (i.e., ERPs) has several advantages, their use also has some limitations. The functional significance of an ERP component can be less clear compared to the functional significance of a behavioral response (Luck, 2005). An ERP component, such as the N400 response, which is of interest in the present study, does not tell us about the recognition of a particular word compared to having the participant repeat back the word of interest. Thus, it is more difficult to interpret ERP responses compared to behavioral metrics, such as percent correct or reaction time. Some amount of inference is always necessary when interpreting physiological measures of perception/cognition, but some measures are easier to interpret than others.

1.9 Combining behavioral and neural methods to study word recognition in noise

Since both behavioral measures of performance and ERP measures have limitations, the most logical approach would be a collaboration of methods or multi-methodology and an interdisciplinary approach to answer complex processing such words in noise recognition. A combination of both behavioral and neural correlates of word recognition in noise provides the most thorough insight into the construct being studied and manipulated. This is why a new research gold standard was stated requesting that behavioral and electrophysiological data are
obtained together (Picton et al., 2000). Furthermore, with regards to the hearing discipline, some have termed this innovative interdisciplinary multi-methodical research as auditory cognitive neuroscience (Arlinger et al., 2009).

A few researchers have implemented this novel research design with regards to speech understanding in noise, however, focusing more on the use of early occurring electrophysiological potentials such as the complex auditory brainstem response (cABR; Anderson & Kraus, 2010) and earlier latency responses such as the P1-N1-P2 complex (Billings et al., 2013). To elaborate, the cABR and P1-N1-P2 complex were shown to correlate with speech-in-noise performance where individuals with poor speech-in-noise also had degraded neural encoding in the brainstem and cortex. Although the work from the Kraus’ and Billings’ labs did show some relations between earlier electrophysiological potentials and speech-in-noise performance the relationships were weak. One explanation for these findings could be possibly because the early neural potentials evaluated were associated with detection perception and do not take into consideration the interplay of both bottom-up and top-down processing which is required in word recognition especially in the presence of noise. Furthermore, the earlier evoked potentials tell us about the brain’s response to the onset of sound and something of the basic properties of the sound. Additionally, the early potentials can be measured without any active participation of the listener. But, because of the perceptual-only nature of the earlier evoked responses they contribute little to our understanding of the complex interplay between phonological, lexical and semantic processing, the building blocks of successful word recognition in noise.

For a comprehensive study of word recognition in noise both behavioral and ERP correlates must be obtained in a paradigm requiring the listener to actively participate in a
listening task requiring a decision. No study to date has investigated the interplay of bottom-up and top-down processes of word recognition in noise using both behavioral and electrophysiological measures. Such an approach is necessary to allow for elucidating the identification of the underlying mechanisms used during a word recognition in noise task.

1.10 Purpose, questions and hypotheses of this dissertation

Older adults have difficulty understanding speech in noise, which leads to a decrease in spoken communication interactions, decrease in health-related quality of life, and increase in social isolation, all of which is a relevant public health concern. Thus, the primary objective is the examination of the effects of aging on word recognition in noise, specifically the interplay between bottom-up and top-down processing. Word recognition requires the activation of phonological, lexical, and semantic representations within the mental lexicon. It is generally agreed upon that bottom-up and top-down processing streams are activated during word recognition in quiet. Also, in quiet among young listeners, there is research that supports the parallel, interactive, or simultaneous bottom-up and top-down mechanisms. It is unknown if the same mechanisms occur in noise (bottom-up & top-down interactive processing) and if these mechanisms occur within the same time course. Thus, our first question is: How does noise affect bottom-up & top-down processing, specifically the activation of phonological, lexical semantic representations among young normal hearing listeners?

Uncovering the bottom-up and top-down processing in noise mechanisms among young listeners then allows us to ask our second question: How does aging affect word recognition in noise processing mechanisms, specifically the activation of phonological, lexical, and semantic
representations? The complex interaction of noise and age effects requires a sensitive methodological approach. Behavioral approach gives us accuracy and reaction times; however, the underlying processes or the mechanisms are still not known; therefore, collecting neurophysiological evidence can tell us about the online processes that occur. A combined behavioral and neurophysiological approach is best. Thus we can understand the mechanisms through judgment rankings and neural modulations and timecourse of the mechanisms through reaction times and latencies of neural modulations. Our hypotheses queried that word recognition in noise will activate phonological, lexical, and semantic representations using both bottom-up and top-down processing streams simultaneously. The mechanisms will be similar to those found by Friedrich & Kotz (2007) whom investigated processing in quiet. We also hypothesized there would be differences in the use of bottom-up and top-down processing streams between younger and older adults during a word recognition in noise task. The behavioral performance of the older adults will be similar to the young adults, however, the mechanisms driving word recognition in noise among older adults would be different.

1.11 Organization of the dissertation

This dissertation involved the completion of two distinct, but related experiments. The first experiment, within Chapter 2, investigated the bottom-up and top-down processing of words embedded in noise among young listeners with normal hearing. We simultaneously examined behavioral performance with an online physiological measure in order to quantify the integration of bottom-up and top-down processing during a word recognition primed by speech-in-noise. Next, Chapter 3 describes the second experiment that utilized the same methodological approach to investigate word recognition primed by speech-in-noise, but, among older adults with near
normal hearing. Chapter 4 brings together the results of the two experiments to address the effects of aging on processes of word recognition in noise. The final chapter, Chapter 5, highlights the work completed and the theoretical, research, and clinical and research implications of the findings. The results of this dissertation further our understanding of the effects aging, age-related hearing decline, and top-down and bottom-up processing of words embedded in noise.
CHAPTER TWO:
EXPERIMENT 1: WORD RECOGNITION PRIMED BY SPEECH-IN-NOISE AMONG YOUNG ADULT LISTENERS

2.1 Introduction

Word entries in the mental lexicon are comprised of phonological, lexical, and semantic representations. As information is extracted from a continuous speech signal, the phonological, lexical and/or semantic representations associated with a number of different word entries may become activated. The more consistent a word's phonological, lexical, and/or semantic representations are with the information extracted from the utterance, the more strongly activated those representations are thought to become. Some word entries attract greater activation than others, and the word entry that attracts the greatest activation strength is selected – that is, the word is ultimately recognized (for review see, McQueen, 2005).

Whether or not a word entry becomes activated as continuous speech is processed, and, if so, how strongly activated it becomes, depends on at least two major processing streams. The first is the bottom-up processing stream that starts with decoding based on phonological goodness-of-fit. Specifically, a phonological representation of an utterance is built as acoustic information comprising the speech signal is perceived. The surfacing phonological representation activates the lexical representation for a number of different words (Luce & Pisoni, 1998). The more closely a word's lexical representation matches the emerging phonological representation, i.e., the better its goodness-of-fit with the phonological representation built from
the speech signal (Marslen-Wilson & Zwitserlood, 1989), the greater the activation strength it
accrues and the more likely it is to be recognized.

The second processing stream, top-down, can strongly influence word recognition in
continuous speech because of linguistic-contextual priming – syntactical, semantic, and
pragmatic. Contextual priming is a phenomenon whereby prior information (when available) can
create expectancies about forthcoming information. Of interest here is semantic priming - an
effect that can result in the lexical representations of words attracting activation based upon the
activation of semantic representations extracted from the context within the utterance.

In at least some models of word recognition (e.g., Gaskell & Marslen-Wilson, 1997),
information processed from the bottom-up stream and information processed from the top-down
stream dually influence the activation level of word entries in the mental lexicon. That is,
bottom-up streams may activate the phonological and lexical representations and top-down
streams may activate the semantic and lexical representation of that same word, resulting in what
is assumed to be an additive effect on the activation level of the word entry. Although other
factors too can influence the activation and selection of a word – such as the word's frequency,
the number of activated neighbors, and the frequency of neighboring words (Marslen & Wilson,
1989; Luce & Pisoni, 1998) – the individual and collective influence of bottom-up and top-down
influences on word recognition primed by speech in noise were the focus of this dissertation and
Experiment 1.

Previous research by Friedrich and Kotz (2007) examined the immediacy with which
bottom-up decoding and top-down contextual priming influenced the activation of word entries
in the mental lexicon as clear and continuous speech was processed by young adults with normal
hearing to test two hypotheses. One hypothesis was that words initially become activated in the
mental lexicon via bottom-up decoding only, with contextual priming influencing the strength with which specific word entries become activated only after their initial activation via the bottom-up pathway. An alternative hypothesis was that word entries initially become activated in the mental lexicon as a function of both bottom-up and top-down streams (i.e., parallel processing). In order to test these hypotheses, Friedrich and Kotz examined behavioral responses and event-related potentials (ERPs) elicited from young adults who were required to hear a sentence with a truncated final word as a prime, followed by a printed probe word. For example, the young listener would hear, “To light up the dark she needed her can-“. Then a printed probe word appeared immediately after each sentence. The probe word matched the prime segment completely (e.g., candle), or in other words was “identical” to the putative sentence-final word; or, the probe word matched only in form (e.g., candy), and was thus “phonologically-related”; or, it matched only the sentence meaning (e.g., lantern) and was “semantically-related”. Finally, printed probes could be “unrelated” (e.g., number) matching neither to the form or the meaning of the putative sentence-final word, providing a control condition. The behavioral task required the participants to indicate with a “yes” or “no” response, as quickly as possible, whether or not the printed probe word matched the sentence meaning to provide both judgment and reaction time data. ERP activity beginning at the printed probe word onset was examined and the researchers identified a right-lateralized, positive-going ERP component that peaked in amplitude at ~220 milliseconds (ms) after word onset (P220). Of particular relevance, the P220 amplitude was modulated by both identically and phonologically-related, bottom-up conditions and semantically-related, or top-down, conditions. A different, left-lateralized positivity peaked in amplitude at ~250 ms after word onset (P250) which was modulated by identically or phonologically-related words only. The amplitude of still another ERP component (N400) was
modulated by identically-related words only. These results suggest that while both phonological and semantic influences are processed through (i.e., registered in, evaluated by) one mechanism at a relatively early latency (indexed by P220), phonological representations are also independently processed through another mechanism at roughly the same latency (indexed by P250); followed by an even later process that seems to reflect integration of phonological, lexical, and semantic cues (indexed by N400).

Friedrich and Kotz (2007) concluded that the behavioral data provided additional support for the ERP results – that is, neither semantics nor phonology (i.e., the meaning and the form) could be ignored in the speech recognition process. They based this conclusion on the fact that reaction times were fastest for the identically-related probes in which the phonology was congruent with the auditory segment of putative sentence-final word and the probe’s meaning was related to the sentence meaning. In other words, acceptance of the identical words profited from both an initial phonological activation of lexical representations which were readily integrated with semantically activated lexical representations. Reaction times were slowest for the acceptance of a semantically-related printed probe such as lantern in the example above, would not have been activated by the auditory prime “can”. More specifically, the auditory prime would have automatically activated lexical representations whose form was congruent with “can...” but which could be but not necessarily be related to the meaning of the sentence (i.e., activates lexical items such as candle and candy). Thus the “yes/no” decision about the relationship of the printed probe word to the sentence meaning could not be made until phonologically-activated lexical representations such as candy were inhibited and those such as candle were integrated with the selection of a meaning-matched lexical representation at a later stage of processing. According to Friedrich and Kotz, responses to semantically-related probes
are biased towards processing by “inhibited integration”. The rejection of phonologically-related, but semantically-unrelated probe words, resulted in a slightly faster reaction time as the “yes/no” response is biased towards the automatic activation of phonologically congruent lexical representations which are more quickly inhibited when activated semantic representations do not match the sentence meaning. Friedrich and Kotz posit that responses to phonologically-related probes are biased towards an earlier automatic activation. Finally, reaction times for unrelated probes, which match neither phonologically nor semantically activated lexical representations, occur relatively quickly as the response is neither biased by automatic activation or facilitated integration.

The effects reported by Friedrich and Kotz (2007) are consistent with distributed models of word recognition (for review see, McQueen 2005). Distributed word recognition models support simultaneous bottom-up and top-down mechanistic processes during word recognition. It is important to emphasize, however, that the effects reported by Friedrich and Kotz were found for word recognition in clearly audible continuous speech. Word recognition accuracy is known to decline in noise, particularly when linguistic-contextual information is not available (Kalikow, Stevens, & Elliott, 1977; Bilger, Neutzel, Rabinowitz & Rzeczowski, 1984). When linguistic-contextual information is available, however, decrements in word recognition caused by noise can be at least partially offset (McArdle, Wilson, & Burks, 2005; Kalikow, Stevens & Elliott, 1977). Thus Experiment 1 was designed to investigate whether or not the bottom-up and top-down mechanistic pathways identified by Friedrich and Kotz operate differently in noise. In addition, the data obtained in Experiment 1 with young adults with normal hearing provided the comparable results that allowed for addressing the primary research question of this dissertation.
which focused on understanding the inter-play between bottom-up decoding and top-down linguistic-contextual information in word recognition primed by speech-in-noise by older adults.

Based on the findings reported by Friedrich and Kotz (2007) three research questions were addressed in Experiment 1. The first was whether not, as occurs in quiet, bottom-up mechanisms continues to occupy a unique processing stream for word recognition primed by speech in noise and/or whether or not top-down mechanisms continue to have an additional, unique processing stream(s) in noise. The former would suggest that additional resources are always allocated toward building a phonological representation of a word - whether in clear quiet speech or in noise - an expected result. The latter would indicate that additional resources are allocated toward top-down processing when semantic-contextual information is available. The second question was whether or not, as occurs in quiet, bottom-up and top-down processing continue to also share a mechanistic pathway for word recognition primed by speech in noise. A shared processing stream would point to a common mechanism involved in word recognition that is relatively tolerant of degradation, while absence of a shared processing stream might suggest that the mechanisms underlying independent bottom-up and top-down processes take over in word recognition when the input is degraded. The final question concerned the time-course of bottom-up versus top-down processing. Whereas in clear speech both streams seem to activate lexical representations immediately and simultaneously, it is possible that in noise the streams operate along a different time-course; perhaps reflecting different levels of efficiency, listening effort, and/or attention to how phonological versus semantic information can be processed.
2.2 Method

2.2.1 Design

A within-group repeated measures design was utilized. We completed a behavioral and neural correlate approach to investigate the mechanisms and time-course of bottom-up and top-down processing on word recognition primed by speech in noise; and, whether these influences occupy shared and/or independent processing streams during word recognition primed by speech in noise by young listeners (YL) with normal hearing. This experiment, as a part of the larger dissertation work, was approved by the Institutional Review Board at the University of South Florida (USF).

2.2.2 Participants

To determine the number of participants of this experiment and in Experiment 2 described in the next chapter, the number of probe conditions, proposed effect sizes to be detected between performance in the probe conditions, and the methods to be used in the statistical analyses were taken into account. The proposed effect sizes were calculated based on our previous completed projects as well as data from the literature. All sample size calculations assume a significance level of 0.05 and a power of 0.80 and concluded that a minimum of 15 participants in each experiment would provide adequate power.

Fifteen YL participants (12 females, 3 males) who were native speakers of American English, with no known neurological or cognitive problems, were recruited from USF through word-of-mouth. Participants were between 21 to 30 years of age (mean age = 25.6, SD = 4.79). Participants were required to have no known history of middle ear disease and air conduction thresholds ≤ 25 dB HL between 250 and 8000 Hz with no greater than a 15 dB HL difference
between ears from 500 to 4000 Hz. All testing occurred in an Industrial Acoustics Company (IAC), double-walled, sound-treated booth with audiometric data obtained using an Interacoustics AC40 audiometer (SN:0290212001) calibrated to appropriate ANSI standards (American National Standards Institute, 2004) and stimuli presented by insert-ear (ER-3A) eartips. As there were no statistically significant differences in pure tone thresholds at any frequency for any participant Figure 2.1 shows the mean audiometric thresholds, collapsed across ears, for the participants. Individual audiometric thresholds for each ear and demographic data are provided in Appendix A.

**Figure 2.1** Young listeners (YL) mean audiogram collapsed across ears with standard deviation error bars shown.
2.2.3 Stimuli

The auditory stimuli were a subset of the Revised Speech Perception in Noise (SPIN) test materials (R-SPIN; Bilger, Nuetzel, Rabinowitz, & Rzeczkowski, 1984). The R-SPIN is comprised of eight lists, each with equal difficulty, variance, and reliability (Bilger et al., 1984). The R-SPIN test requires participants to listen to a series of sentences and repeat back the final word of each sentence. Half of the items were created as high-predictability (HP) sentences, in that they contain a word or two that are semantically associated with the final word (e.g., *Raise the flag up the POLE*). The other half are low-predictability (LP) sentences, in that the sentence context before the target final word provides syntactic, but not semantic, clues about the final word (e.g., *Peter has considered the POLE*). The sentences are presented simultaneously with multi-talker babble (MTB). MTB has been shown to represent realistic situations in which speech is hard to understand and provides greater separation of individuals with essentially equivalent hearing abilities who have good word recognition abilities from those with poor word recognition performance (e.g., speech spectrum noise) (Wilson et al., 2007).

In the current study, 192 carefully selected HP R-SPIN sentences were utilized in the test paradigm to obtain the behavioral and electrophysiological data as described below. The HP R-SPIN sentences were digital copies taken from the R-SPIN CD distributed by the University of Illinois. The durations of the sentences ranged from 1.3 to 2.4 sec with an average duration of 1.72 seconds. The 192 sentences were divided equally into three groups of 64 sentences each to create probe conditions similar to those utilized in the Friedrich and Kotz (2007) study – i.e., Phonological, Identical, and Semantic. Within each of these three conditions, the sentences were further divided during data collection such that a printed probe presented for half of the sentences was “related” to the sentence final word and “unrelated” for the other half to generate a
“neutral” probe condition. The R-SPIN HP stimuli used are shown in Appendices B, C, and D as a function of the three conditions, along with the probe words used.

2.2.4 Test Paradigm

Figure 2.2 illustrates a schematic of the test paradigm utilized to obtain both behavioral and electrophysiological data. A Dell computer with E-Prime 1.1 (Schneider et al., 2002) software was used to control stimulus presentation. On each trial of the task, participants were presented with a sentence at 8 dB signal to noise ratio (SNR) presented binaurally from experimental software (E-Prime) routed to Tucker-Davis Technology mixer to insert-earphones (ER-3A). The level of the HP R-SPIN sentence, also referred to as the signal, was fixed at 60 dB SPL and the level of the babble was set 8 dB lower as described in the R-SPIN manual (Bilger, 1984). The selected SNR was based on data from Pearsons et al (1977) that indicated that 8 dB SNR was the median SNR “encountered across a wide range of real-life situations” (Bilger, 1984a, p. 8).

Directly after the stimulus sentence ended, the E-Prime software was programmed to present a printed token probe word for 300 ms. The screen then went blank for another 300 ms after which the question - “How closely related is the written word to the sentence you heard?” - was shown on the screen along with for response alternatives: (1) Not Related; (2) Somewhat Related; (3) Related; and, (4) Highly Related. The printed token probe word matched the spoken sentence final word by: (1) having the same initial consonant, or consonant cluster, and subsequent vowel (Phonologically-Related to the prime); (2) being exactly the same (Identical to the prime); or, (3) sharing the same meaning (Semantically-Related to the prime). In addition, randomly, on half of the trials within each of the three conditions (i.e., Phonological, Identical
and Semantic) a printed probe word was presented which was “Unrelated” to the sentence final word, resulting in a total of six probe types being utilized within the testing paradigm.

![Figure 2.2](image.jpg)

**Figure 2.2.** Schematic representation of the test paradigm.

### 2.2.5 Procedure

Participants were seen for one session lasting 60-90 minutes. After informed consent was obtained and it was determined that an individual met inclusion criteria the experimental task was completed. Testing was completed in an IAC, double-walled, sound-treated booth with participants seated in a comfortable chair at a 90 cm viewing distance from a 43 cm LCD monitor (60 Hz refresh, 1024 × 768 resolution) monitor. Stimuli were presented binaurally through ER-3A inserts. After hearing a stimulus sentence the participant was shown the printed probe on the monitor followed by the judgment question and response alternatives. The participant’s task was to indicate how “related” the written probe was to the entire sentence by selecting on push-button response box a number from 1 to 4, with as described above: 1 = Not Related, 2 = Somewhat Related, 3 = Related, and 4 = Highly Related. Participants were
instructed to provide their responses as quickly as possible. This procedure allowed for the collection of the behavioral data analyzed in this experiment. Specifically, this was (a) the degree of relatedness of each probe to each stimulus measured on a Likert-scale of 1 (not related) to 4 (highly related); and, (b) the time it took for the participant to make the relatedness judgment or the “reaction time” measured in seconds. The relatedness responses and reaction times were saved to E-Prime for subsequent analysis.

During the behavioral test paradigm, continuous EEG activity was recorded from 64 Ag/AgCl electrodes at standard 10/20 locations in a nylon Quikcap (Neuroscan), with a vertex midline electrode position halfway between Cz and CPz as reference. Four additional electrodes were placed on the outer canthus of each eye and on the supra and infraorbital ridges of the left eye to monitor eye movement and blink activity. The ongoing EEG was recorded using Neuroscan™ (Scan 4.2) with a SynAmps2 amplifier and sampled at 500 Hz with a 100 Hz low pass filter (time constant: DC). Electrode impedances were kept below 5 kΩ for most electrodes.

2.2.6 EEG to ERP data extraction and neural correlate identification

The ongoing EEG was separated into epochs of 900 ms (-200 ms before probe word onset to 700 ms after). Eye movement artifacts were corrected for each participant by subjecting the EEG data to independent components analysis (ICA), identifying components that match a predefined template and removing these components from each trial if it reduced the overall EEG variance for that trial (Glass et al., 2004; see Maxfield et al., 2010 for detailed description of ICA). After ICA correction, channels with fast-average amplitude exceeding 200 µV (large drift) or differential amplitude exceeding 100 µV (high-frequency noise) was marked as bad. For trials with less than 3 bad channels, EEG activity at those channels was replaced using spherical
spline interpolation (Ferree, 2000). Any trial with more than three bad channels (5% of the total number of channels) was rejected. Data were then averaged separately for each stimulus type (Phonologically-Related, Phonologically-Unrelated, Identically-Related, Identically-Unrelated, Semantically-Related, and Semantically-Unrelated), low-pass filtered at a corner frequency of 40 Hz with a 48 dB/octave roll-off, re-referenced to averaged mastoids, truncated to a critical interval of -100 – 600 ms, and baseline corrected (-100 to 0 ms).

To facilitate objective neural correlate identification and help address component overlap, the averaged waveforms were submitted to temporal principal component analysis (PCA) derived from the covariance matrix (Dien et al., 2010), followed by unrestricted Varimax rotation (Kayser & Tenke, 2003). The temporal PCA generates a set of temporal factors, or "virtual time windows", each of which is defined by a set of loadings. The scores associated with each "virtual time window" capture the ERP activity during that time window, at each electrode, in each condition, in each participant. This approach is defined by a data-driven correlational analysis and produced distinctive PCA components (temporal factor loadings) and corresponding weighting coefficients (temporal factor scores), which describe the variance contributions of temporally and spatially overlapping ERP components more efficiently than conventional ERP measures (Kayser & Tenke, 2003; Beauducel et al., 2000).

To limit the focus of the analysis, only temporal factors accounting for at least 1% of the variance were targeted (see Kayser & Tenke, 2003; Foti et al., 2009). Temporal factor scores were analyzed in two steps. In a first pass, scores at five midline electrodes (i.e., Fpz, Fz, Cz, Pz, Oz) were analyzed, separately for each temporal factor, using multivariate analyses of variance (MANOVA) with Electrode entered as a within-subjects factor with five levels, Condition entered as a within-subject factor with three levels (Phonological, Identical, Semantic), and
Relatedness entered as a within-subject factor with two levels (related, unrelated). Second, for each temporal factor, a topographic analysis was carried out using scores at 40 electrodes covering the left and right hemispheres, at two levels of dorsality (superior, inferior), and two levels of anteriority (anterior, posterior). In Figure 2.3, the outlined areas show which electrodes were used in each region of interest. These scores were analyzed by MANOVA with laterality entered as a within-subjects factor with two levels (left, right), dorsality entered as a within-subjects factor with two levels (superior, inferior), anteriority entered as a within-subjects factor with two levels (anterior, posterior), condition entered as a within-subjects factor with three levels (Phonological, Identical, Semantic conditions), and relatedness entered as a within-subject factor with two levels (related, unrelated). MANOVAs were two-sided with an alpha level of 0.05. F-statistics were exact. Statistically significant effects were followed with Bonferroni-corrected pairwise comparisons when appropriate.

2.3 Results

2.3.1. Organization of results section

In order to determine if word recognition primed by speech in noise among YL with normal hearing shared the same processing streams as word recognition primed by clear speech in quiet as reported by Friedrich and Kotz (2007), it was necessary to first examine the behavioral data. Both the judgment data indicating the degree of the relatedness of the printed probe to the spoken sentence meaning and the reaction time data are presented. This is followed by a detailed examination of the ERP components.
Figure 2.3 Headmap showing region of interest electrodes used for the principle component analysis.
2.3.2 Judgment ratings

The responses to the question - "How closely related is the written word to the sentence you heard?" - were examined to ascertain whether or not the last words in the stimulus sentences were priming the printed probe words in the expected manner. If this was the case, then for the Identically-Related probes, the majority of responses were expected to be 4 (i.e., highly related) with perhaps a few being 3 (i.e., related). For the Semantically-Related probes it was expected that participants would be relatively equal in selecting either the response alternative 2 (i.e., somewhat related) or the response alternative 3 (i.e. related). For the Phonological condition, both Related and Unrelated probes, as well as for the Unrelated probes for the Semantic and Identical conditions, were expected that the majority of responses would be 1 (i.e., not related).

The means of the responses for each of the six probe types (i.e., Phonological-Related; Phonological-Unrelated; Identical-Related; Identical-Unrelated; Semantic-Related; Semantic-Unrelated) are shown in Figure 2.4. Visual inspection of the data supported the expected pattern of results. That is, the highest mean score was obtained for the Identically-Related probes. With a mean equal to 3.97 (SD = 0.89) indicating that the majority of responses were “Highly Related” (i.e., 4). The mean score for the Semantic-Related probes equaled 2.72 (SD = 1.90) suggesting that on the majority of the trials participants judged the printed probe word to be “Related” (i.e., 3) to the sentence meaning, with some trial responses indicating that the printed probe was only “Somewhat Related” (i.e., 2). The mean scores were very close to 1 indicating that the probes were “Not Related” to the sentence meaning for the Phonological condition, for both related words with a mean of 1.01 (SD = 1.20) and for unrelated words, which also had a mean of 1.01 (SD = 1.40). Finally, the data for both the Identical-Unrelated probes (M = 1.02, SD = 0.89) and
the Semantic-Unrelated probes \((M = 1.01, SD = 1.04)\) indicated that participants judged them appropriately as not being related to the sentence meaning. Demonstrating that the priming was working as expected was important as it allows for the conclusion that the behavioral reaction time data and the ERP data are valid for addressing the research questions.

![Bar chart showing relatedness judgments](image)

**Figure 2.4** Young Listeners (YL) mean degree of relatedness judgments on a 4 point Likert scale and standard deviations for both Related and Unrelated probes in each of the three experimental conditions (Phonological, Identical, and Semantic).

### 2.3.3 Judgment task reaction times

Participants were asked to make their relatedness judgments as quickly and accurately as possible. Figure 2.5 shows the mean reaction times (RT) and standard deviations for each probe type. As was expected based on the findings reported by Friedrich and Kotz (2007) the longest
reaction time was for the Semantically-Related probe task with a mean of 1.44 sec. (SD = 0.62). Although it was expected that the Identically-Related probe would have the shortest reaction time, the mean of 0.61 sec. (SD = 0.19) was essentially equivalent to that of the Phonologically-Related probe condition, with a mean of 0.60 sec (SD = 0.24). It was expected that the reaction times for all three Unrelated probe tasks would be longer than that for the Identically-Related probes but shorter than the Semantically-Related ones and this was the case, with the means for the Phonological, Identical, and Semantic conditions equaling 0.69 seconds (SD = 0.40), 0.68 sec (SD = 0.44), and 0.62 sec (SD = 0.28), respectively. To determine if observed reaction times were significantly different as a function of Condition, Relatedness, or their interaction the data were subjected to a repeated-measures analysis of variance (ANOVA). Both the main effect of Condition ($F(2, 14) = 15.96, p < 0.01$, partial eta square = 0.53) and the main effect of Relatedness ($F(1, 14) = 17.14. p < 0.01$, partial eta square = 0.55) were statistically significant. Post-hoc t-tests with Bonferonni corrections revealed that the mean reaction time for the semantic condition ($M = 1.03; SE = 0.11$) was significantly longer than for either the Identical ($M = 0.64, SE = 0.07$) or the Phonological ($M = 0.64, SE = 0.08$) conditions, and that the difference between the latter two conditions was not significant. Reaction times for the related probe tasks were significantly longer with a mean equal to 0.88 sec. (SE = 0.08) than that of the Unrelated probe tasks ($M = 0.66, SE = 0.08$). Finally, the interaction between condition and relatedness was found to be significant ($F(2, 14) = 28.62, p < 0.01$, partial eta square = 0.67). Post-Hoc analysis with Bonferroni-corrected $t$-tests revealed that the difference between the Related and Unrelated probes was significant for the Semantic condition ($t(14) = 7.2, p < 0.01$) but not for the Identical condition ($t(14) = -0.60, p = 0.56$) or the Phonological condition ($t(14) = 1.48, p = 0.16$).
Figure 2.5. Young Listeners (YL) mean reaction time durations (in seconds) for each of the conditions (Phonological, Identical, Semantic) as a function of Related vs. Unrelated probe types. Standard deviations error bars are shown.

2.3.4 Neural correlates

Grand average waveforms for each condition are shown at 21 electrodes in Figure 2.6, 2.7, and 2.8. For each figure the gray line represents the Related condition (i.e., Phonological, Identical, Semantic) while the black line represents the Unrelated condition. Visual inspection reveals a grossly similar pattern of ERP activity between conditions from probe word onset to the end of the epoch.
Figures 2.6 Grand average waveforms for the Phonologically-Related probes compared to the Unrelated probes.
Figure 2.7 Grand average waveforms for the Identically-Related probes compared to the Unrelated probes.
Figure 2.8 Grand average waveforms for the Semantically-Related probes compared to the Unrelated probes.
2.2.5 PCA results

Figure 2.9 shows that the unrestricted temporal PCA produced 71 temporal factors (top panel), but only seven temporal factors (TFs) accounted for at least 1% of the variance in the data set (bottom panel). As seen in the bottom panel of Figure 2.9, these seven peak latencies ranged from 122 ms to 600 ms after probe onset. Statistically significant effects were not detected for TF160, thus, the six remaining temporal factors TF122, TF212, TF333, TF464 and TF600 ms, are described in the next sections. For each of these peak latencies the midline analysis is described first followed by the topographic regions of interest analysis.

![Figure 2.9](image_url)

**Figure 2.9** Young Listeners (YL) temporal factor (TF) loadings. Top panel shows all 71 TF loadings while the bottom panel shows the 7 TF loadings that explain at least 1% of variance.
2.3.5a: TF122 effects. TF122 variance (3.0%) at midline electrodes was affected by an interaction of Electrode, Condition, and Relatedness ($F\ (8,112) = 2.33, p = 0.02$, partial eta-squared $= 0.14$). Bonferroni-corrected t-tests detected a Relatedness effect at FPz ($p = 0.02$) for the Phonological condition. Looking at FPz grand average waveform from Figure 2.6, around 122 ms a negative going wave is observed and the Phonologically-Related probe words were more negative versus the Unrelated-probe words.

Topographically, TF122 variance was not affected by Electrode, Condition, or Relatedness ($F\ (2,28) = 1.23, p = 1.02$, partial eta-squared $= 0.04$.)

2.3.5b: TF212 effects. TF212 variance (12.85%) at midline electrodes was affected by an interaction of Condition and Relatedness ($F\ (2,28) = 3.09, p = 0.00$, partial eta-squared $= 0.26$). Bonferroni-corrected t-tests detected a Condition by Relatedness effect across all midline electrodes ($p < 0.01$) for the Phonological condition. As shown in Figure 2.6, throughout the midline the Phonologically-Related probe responses differed from the Unrelated probe responses. The frontal midlines had a less positive-going amplitude for the Phonologically-Related versus the Unrelated-probe words. The posterior midline electrodes (Pz and Oz), however, had a reversed effect where the Phonologically-Related condition resulted in a more negative going amplitude than the unrelated condition.

Topographically, T212 variance was affected by an interaction of Anteriority, Dorsality, Condition, and Relatedness ($F\ (2, 28) = 4.52, p = 0.02$, partial eta-squared $= 0.24$). Bonferroni-corrected t-tests detected a Relatedness effect for the Phonological condition at the anterior/superior ($p = 0.05$) and posterior/superior ($p = 0.04$) regions. As shown in Figure 2.6,
both anterior- and posterior-superior regions were less positive for the Phonologically-Related probes versus the Unrelated probes.

2.3.5c: TF270 effects. TF270 variance (1.2 %) at the midline electrodes was affected by an interaction of Condition and Relatedness ($F(2, 28) = 3.43, p = 0.01$, partial eta-squared = 0.31). Bonferroni-corrected t-tests detected a Relatedness effect across all midline electrodes for the Phonological ($p = 0.05$) and for the Identical conditions ($p = 0.04$). As seen in Figure 2.6, the Phonologically-Related probe words were more positive meaning they resulted in a less negative-going amplitude versus the Unrelated-probe words that had a deeper negativity. This effect can be seen in the grand average waveforms most notably at Cz (see Figure 2.6). The opposite was detected for the Identical condition where Identically-Related probes were more negative than the Unrelated probes. Although this effect is not visibly apparent in the grand average waveforms the underlying componentry may explain the PCA results after the other layers of variance were removed.

Topographically, TF270 variance was affected by an interaction of Dorsality, Condition, and Relatedness ($F(2, 28) = 5.59, p = 0.01$, partial eta-squared = 0.29). Bonferroni-corrected $t$-tests detected a Relatedness effect for the Identical condition at the inferior ($p = 0.01$) and superior ($p = 0.02$) regions. Again, the PCA analysis reports a more negative response for the Identically-Related probes than the Unrelated. In Figure 2.7, the Identically-Related waves are more positive; however, the slope changing from a positive deflection to a negative deflection is steeper and thus more negative at both inferior and superior regions.

2.3.5d: TF378 effects. TF378 variance (34.6 %) at the midline electrodes was affected by an interaction of Electrode, Condition and Relatedness ($F(8, 112) = 4.68, p = 0.01$, partial eta-
squared = 0.25). Bonferroni-corrected $t$-tests detected a Relatedness effect across all midline electrodes for the Identical condition (FPz, $p = 0.01$; Fz, $p < 0.01$; Cz, $p < 0.01$; Pz, $p < 0.01$; Oz, $p < 0.01$) and for the Semantic condition at electrodes Cz ($p = 0.01$) and Pz ($p = 0.03$).

Throughout the midline Identically-Related probe words had a more positive-going amplitude versus the Unrelated probe words. This effect can be seen in the grand average waveforms throughout the midlines (see Figure 2.7). The same was seen for the Semantic condition at Cz and Pz. In Figure 2.8 at electrode Cz and Pz, the Semantically-Related probe words had a more positive-going amplitude versus the unrelated-probe words.

Topographically, TF378 variance was affected by an interaction of Dorsality, Condition, and Relatedness ($F(2, 28) = 18.00$, $p < 0.01$, partial eta-squared = 0.56). Bonferroni-corrected $t$-tests detected a Relatedness effect for the Identical condition at the inferior ($p < 0.01$) and superior ($p < 0.01$) regions. As seen in Figure 2.7, the Identically-Related probes had a more positive deflection compared to the Unrelated probes at both inferior and superior regions. A Relatedness effect was also seen for the Semantic condition at the superior region ($p = 0.04$). With Semantically-Related probes resulting in a more positive-going amplitude than Unrelated condition.

2.3.5e: TF464 effects. The TF464 variance (1.76 %) at midline electrodes was affected by an interaction of Condition and Relatedness ($F(2, 28) = 6.06$, $p = 0.01$, partial eta-squared = 0.63). Bonferroni-corrected $t$-tests detected a Relatedness effect across all midline electrodes for the Semantic condition ($p < 0.01$). Throughout the midline, Semantically-Related probe words had a less negative-going amplitude versus the Unrelated probe words. This effect can be seen in the grand average waveforms throughout the midlines (see Figure 2.8).
Topographically, TF464 variance was affected by an interaction of Condition and Relatedness ($F(2, 28) = 6.89, p < 0.00$, partial eta-squared = 0.33). Bonferroni-corrected $t$-tests detected a Relatedness effect for the Semantic condition ($p = 0.01$) and Phonological condition ($p= 0.03$). As seen in Figure 2.8, for the Semantic condition and across all regions the Semantically-Related probes resulted in a less negative-going amplitude compared to the Unrelated probes. The opposite was seen for the Phonological condition. As seen in Figure 2.6, across all areas of interest, but very robust in some electrodes such as F5, the Phonologically-Related probes resulted in a more negative amplitude than the Unrelated probes.

2.3.5f: TF600 effects. TF600 variance (39.0 %) at the midline electrodes was affected by an interaction of Electrode, Condition and Relatedness ($F(8, 112) = 5.68, p = 0.02$, partial eta-squared = 0.264). Bonferroni-corrected $t$-tests detected a Relatedness effect across all midline electrodes for the Semantic condition (FPz, $p = 0.04$; Fz, $p < 0.01$; Cz, $p < 0.01$; Pz, $p < 0.01$; Oz, $p = 0.05$) and for the Phonological condition at electrode site Cz ($p = 0.01$). Throughout the midline Semantically- and Phonologically-Related probe words caused a more positive-going amplitude versus the Unrelated-probe words. This effect can be seen in the grand average waveforms throughout the midlines, as seen Figures 2.8 and 2.7, respectively.

Topographically, TF600 variance was affected by an interaction of Anteriority, Condition, and Relatedness ($F(2, 28) = 12.00, p = 0.01$, partial eta-squared = 0.33). Bonferroni-corrected $t$-tests detected a Relatedness effect for the Semantic condition at the anterior ($p = 0.01$) and posterior ($p = 0.01$) regions. As seen in Figure 2.8 and similar to the midline effects, the Semantically-Related probes had a more positive deflection compared to the Unrelated probes at both anterior and posterior regions.
2.4 Discussion

The purpose of Experiment 1 was to determine if the mechanistic pathways utilized during word recognition primed by speech-in-noise among YL with normal hearing was the same or different than those identified by Friedrich and Kotz (2007) for the recognition of words primed by clear speech in quiet. Recall that Friedrich & Kotz identified three major processing mechanisms reflecting: (1) an interactive or shared neural pathway between bottom-up and top-down processing streams; (2) an independent or unique bottom-up processing stream; and, (3) a neural correlate that was interpreted as the integration of bottom-up and top-down processing. The neural correlates of word recognition primed by speech in noise identified in this experiment are discussed first, followed by a discussion of the ERP and behavioral data as it relates to the identification of mechanistic pathways and their similarity and difference to those that Friedrich and Kotz identified for word recognition primed by clear speech in quiet.

2.4.1 Neural correlates of word recognition primed by speech-in-noise

Neural correlates of word recognition primed by speech-in-noise were identified. The waveforms across most electrode sites had some peak latency similarities for all conditions which can be visualized in Figures 2.6, 2.7, and 2.8. Reviewing the literature for similar ERP waveform morphology we found comparable deflections. Temporally, the first deflection was a negative deflection at a latency of about 120 ms (N1); followed by the P2, a positive deflection at about 225 ms. More distinct for the Unrelated probes there was a prolonged negative deflection, a possible processing negativity (PN) or N400, peaking in the 350 – 500 latency range and
lasting more than 200 ms. Meanwhile, for the Identical and Semantically-Related probes the waveforms showed a positivity after 350 ms instead of a PN. Lastly for all Related probes the waveforms also had a slow positive deflection from baseline peaking at about 600 ms range which may be a late positive component (LPC).

Although the visual inspection of the waveforms are interesting, due to the large data set from this high-density electrode montage and various conditions as well as the unavoidable overlapping componentry complication we will focus on the statistically significant effects discovered by the unrestricted PCA. Figure 2.10 displays the significant temporal factors (TFs) as a function of latency and in terms of modulating phonological, lexical, and semantic representations. Temporally the first correlate was the TF122, which was modulated by the Phonologically-Related probes, along the midline and showed a more negative-going amplitude for Phonologically-Related probe words. The time course of this effect is consistent with a N1 or N100 component (Key, Dove, & Maguire, 2000). N1 typically has maximum negativity occurring over the left frontal and central regions of the scalp (Jerger, Martin & Fitzharris, 2014). N1 is thought to be generated in the extrastriate visual cortex (Mangun, Hillyard, & Luck, 1993). In other research N1 has been reported and proposed to index early perceptual processing that is sensitive to attentional manipulations (Hillyard, Vogel, & Luck, 1998; Key, Dove, and Maguire, 2000), reflects orientation of attention to stimulus location/spatially (Luck, Heinze, Mangun, & Hillyard, 1990) and is related to motor readiness (Key, Dove, and Maguire, 2000). The more negative-going amplitude for the Phonologically-Related probes may have developed due to the participants focusing their attention to the visual presentation of the probe word and starting to recognize that although the initial orthographic phonemes were indeed present as expected it was not the last word of the sentence they just heard.
Following the N1, the Phonologically-Related probes also modulated a positivity, detected by the TF212 effect, through the midline and anterior/posterior region of the scalp. The TF212 positivity was less positive, or attenuated, for the Phonologically-Related probes. The scalp distribution as well as the latency of the TF212 is consistent with the P2 component. The topographic distribution of the P2 is characterized by a positive shift at the frontal sites around 150-200 ms after stimulus onset (Heslendfeld et al., 1997; Kenemans et al., 1993; Van der Stelt et al., 1998) that can be slightly more right hemisphere (Jerger, Martin, & Fitzharris, 2014) and a large negativity, approximately 200 ms following stimulus onset at the occipital sites (Talsma & Kok, 2002).

Visual P2 is thought to be more involved in later stages of stimulus processing, and are related to cognitive processes of stimulus evaluation, selective attention, and conscious discrimination (Kok, 2000). Specifically, the P2 component has been shown to index the encoding of visual features, particularly in working memory (Lefebvre, Marchand, Eskes, & Connolly, 2005; Wolach & Pratt, 2001), and the posterior P2 may reflect feedback from higher visual areas (Kotsoni, Csibra, Mareschal, & Johnson, 2007). The TF212 reduction in positivity may reflect the YL participants processing of the Phonologically-Related probe words and recognizing that the probe word was not the last word in the sentence they just heard. At this step they may be assessing the phonological similarities with words stored in their working memory or the phonological representations within their mental lexicons.
Figure 2.10. Graph illustrating the Temporal Factor (TF) loadings across time and if they modulated Phonological, Lexical, and/or Semantic representations.
Both Phonologically- and Identically-Related conditions had modulations identified in the TF270 effect, however, reverse effects were seen in each condition. Throughout the midlines and superior and inferior regions (dispersed throughout the scalp), the Phonologically-Related and Unrelated probes show a general negative deflection with the difference being the Phonologically-Related probes were positive, or less negative, compared to the Unrelated probe response. The scalp distribution as well as the latency is consistent with the N2 component. The N2 component known for peaking between 200 and 350 ms after stimulus onset is maximally negative over the frontal and posterior regions (Key, Dove, & Maguire, 2000; Jerger, Martin, & Fitzharris, 2014). Folstein and Van Petten (2008), in a review of N2 effects elicited in visual modality, proposed that posterior N2 indexes orienting of visual attention while frontal N2 indexes cognitive control. Also, N2 is reported as a marker of deviation from what you expect (Key et al., 2000) and has previously been reported for Phonological deviations (N250; Hagoort & Brown, 2000).

As mentioned there was a reverse finding for the TF270 effect for the Identical condition. Here, the Identically-Related probes were more negative than the Unrelated probes. The less negative deflection for the Identically-Related probe words is most like the P250 as reported by Friedrich & Kotz (2007). Friedrich & Kotz reported a modulation in the P250 differentiated form-matching words and form-mismatching words and interpreted their finding as being the result of activation of multiple form-matching candidates. Similarly, our TF270 could also be interpreted as relating to the bottom-up activation and competition of multiple lexical entries.

Both Identical probes and Semantically-Related probes modulated the TF378. This modulation could mean that YL had access to whole word (lexical representation) and meaning (semantic representation) as early as 378ms. Through the midlines, superior and inferior regions,
thus, topographically wide spread, the Identical probes and Semantically-Related probes conditions were more positive. Although the Related probes modulated a large positivity the paired Unrelated probes showed a robust negativity which was also topographically wide spread. At first glance our TF378 could resemble a P300 effect, however, our interpretation of this correlate is a Cz centered P400 that is known to respond to semantic congruity manipulation and reflects a general sequential expectancy system (Dien et al., 2010). Whereas the P300 responds to overall probability (Donchin, 1981) of a stimulus the P400 responds most to the local expectancy of a stimulus, as in sequential probabilities (Dien et al., 2010). The P400 is suggested to have a major source in the medial parietal region. Similar to literature (Dien et al., 2010) our P400 was more positive for congruent endings when the probe words were Identical or Semantically-Related to final word of the sentence heard.

Next, the Semantically-Related probes modulated in the TF464 throughout the midline electrodes. The midline electrodes showed a reduced negativity for the Semantically-Related probes compared to a deep and prominent negativity seen for the Unrelated probes. Semantics relate to the meaning of words and holding meaning in memory to do a task, which was expected of the YL in this experiment. Topographically the Semantically-Related probes elicited a more positive response and the Unrelated probes showed a more negative amplitude which may indicate a reduction in processing because the Semantically-Related probes were activated in the mental lexicon by the sentence context.

For the TF464 topographic results, reverse effects were seen with Phonologically-Related probes being more negative than the Unrelated probes. This additional negativity may reflect late inhibition where the YL participants recognized that the words overlap in sound but have to ignore the overlap because it does not relate to meaning. For both the Semantic and Phonological
conditions the modulation of the TF464 neural correlate is most likely an N400 effect also
known as the Processing Negativity (PN) component related to word processing. The PN peaks
between 400 – 500 ms (Jerger, Martin, & Fitzharris, 2014). Jerger and colleagues describes the
PN reflecting the sum of at least four cognitive processes overlapping in time, but reflecting
evoked activity over different regions of the head. These four cognitive processes are attention,
phonological processing, working memory, and semantic processing (Jerger, Martin, &
Fitzharris, 2014). The observed modulations for both Semantic and Phonologic conditions may
indicated a shared processing mechanism that is evaluating both phonological representations
(bottom-up streams) and semantic representation (top-down streams), all of which supports the
interactive theory of word recognition even while embedded in noise.

Finally significant neural modulations were captured by the TF600 effect, which
indicated more positive relatedness effect for the Semantically-Related condition at all midline
electrodes and anterior/posterior regions and the Phonologically-related condition at midline
electrode Cz only. The related conditions were more positive and most likely representative of a
late positive component (LPC). The LPC is a slow positive deflection from baseline peaking in
the 600- 900 ms range. LPC is technically defined by the difference between targets and non-
targets, but it is often the case that the target (related condition) waveform alone is referred to as
the LPC. The LPC has been reported to be component that reflects the degree of difficulty in
making the decision whether or not a target word has been heard. More specifically, the LPC
reflects the degree of difficulty in making the decision whether or not a target word has been
heard (Jerger, Martin, & Fitzharris, 2014) and the LPC has been shown to modulate based on
task difficulty, namely, the easier the decision the earlier and larger the evoked positivity. Thus,
significant modulation of the TF600 for the Semantically-related and Phonologically-related
conditions could indicate that the probe words were activated in the mental lexicon due to the sentence context and thus the task of relating the probe word to the sentence previously heard was easier.

2.4.2. **Word recognition primed by speech-in-noise and quiet: Similar or different mechanistic pathways?**

Although our behavioral data indicated that semantic representations take longer to process than the other conditions and that the Phonologically-Related probe words were almost exactly treated like the Unrelated probes with regards to judgment ranking and RT, these results do not explain the underlying mechanisms and the neurophysiological results paint a very different and interesting picture of the processing that occurred before the behavioral response was completed. As ERPs activate automatically, as the probe word is perceived on the screen, and are modulated automatically by the priming context. This is interesting because the ERPs obtained showed neural modulation to the Phonological condition and both Phonological, Identical, and Semantic conditions modulated processing effort differently than the Unrelated probes.

Overall the neurophysiological data showed that YL had access to both phonological, lexical and semantic representations; thus, YL made use of all the information provided from the spoken sentence embedded in noise. Furthermore, YL were continuously able to process sound and context (phonological, lexical, and semantic) information picked up under noise and continue the processing late into the probe word reading. One of our first goals of this experiment was whether not, as occurs in quiet, bottom-up mechanisms continue to occupy a unique processing stream for word recognition in noise and/or whether or not top-down
mechanisms continue to have an additional, unique processing stream(s) in noise? Indeed, phonological neural correlates where uniquely modulated early on (indexed by the TF122 and TF212), but lexical and semantic neural correlates were also modulated simultaneously (indexed by the TF270 and TF348). This suggests that mechanistic pathways always allocated toward building a phonological representation of a word - whether in clear quiet speech or in noise, but also suggests that that additional resources are allocated toward building top-down mechanisms when semantic-contextual information is available and can aid recognition.

Friedrich and Kotz (2007) results suggest that while both bottom-up and top-down influences are processed through (i.e., registered in, evaluated by) one mechanism at a relatively early latency (indexed by P220), bottom-up influences are also independently processed through another cognitive mechanism at roughly the same latency (indexed by P250); followed by an even later process that seems to reflect integration of bottom-up and top-down cues (indexed by N400). Thus Experiment 1 was designed to investigate whether or not the bottom-up and top-down mechanistic pathways identified by Friedrich and Kotz operate differently in noise. The present experiments results showed that Phonological modulations were seen early on (TF122) followed by lexical modulations starting around 270 ms. This may indicated the flow from the bottom up stream directly to the lexical level of representation. Also, semantic representations were modulated around 378ms meaning the top-down was not activated until after whole word or lexical modulation was completed but a shared lexical and semantic mechanistic pathway was utilized.

The present experiment’s results are consistent with distributed models of word recognition (for review see, McQueen 2005), which accommodate simultaneous bottom-up and top-down influences on auditory word recognition; however, possibly at a later time course than
was found by Friedrich & Kotz (2007). This answers one of our final questions, which was concerned with the time-course of bottom-up versus top-down processing. Whereas in clear speech both seem to activate phonological, lexical and semantic representations immediately and simultaneously, it appears that in noise, processing mechanisms operate along a different time-course; perhaps reflecting different levels of efficiency in, listening effort, and/or attention to how phonological versus semantic information can be processed. Listening effort is reflected in both the depth and duration of the negativity of the TF424 or PN component and the onset, height, and duration of the positivity of the LPC. Collectively the PN and LPC components collectively reflect an important dimension of real-life auditory experience, listening effort. Listening effort was reduced for the Related conditions indicating that both Phonological and Semantic priming activated words in the mental lexicon and aided the recognition process.

In sum, the results of the present study support the conclusion made by Friedrich and Kotz (2007) that neither phonological nor semantic information are ignored by young adults with normal hearing during speech recognition, whether recognition is occurring in quiet or in noise. While the data presented here suggest that the time course of processing is lengthened in noise, it is likely, as Friedrich and Kotz postulated, that both bottom-up automatic activation of phonological and lexical representations and the integration of top-down semantic information which can facilitate or inhibit the earlier activated lexical entries, are both important for word recognition primed by speech-in-noise. This suggests that in older adults, who may have less robust phonological activation due to peripheral hearing loss and/or greater susceptibility to the effects of background noise, as discussed in Chapter 1, the mechanistic pathways may differ. This possibility is explored in Experiment 2 which is described in the next chapter. In addition to elucidating the mechanisms associated with word recognition, the results obtained in
Experiment 1 with young adults with normal hearing provided the comparative data that allowed for addressing the primary research question of this dissertation which focused on understanding the inter-play between bottom-up decoding and top-down linguistic-contextual constraints in auditory word recognition primed by speech-in-noise by older adults.
CHAPTER THREE:
EXPERIMENT 2: WORD RECOGNITION PRIMED BY SPEECH-IN-NOISE AMONG OLDER ADULT LISTENERS

3.1 Introduction

In the process of auditory word recognition, listeners must access their mental lexicons via the stored phonological, lexical and semantic representations. Two processing streams, bottom up and top-down are involved in the word recognition task. The presence of background noise makes recognizing words challenging for all listeners, but the challenges of understanding speech in noise are exacerbated in older listeners.

As age-related hearing loss reduces the audibility of speech cues and background noise results in energetic and/or informational masking, it is not surprising that older adults with hearing loss report problems with understanding speech in noise. Even when audibility is accounted for, however, older adults have difficulty in adverse listening environments (Dubno et al., 1984; Humes & Chrisotophenson, 1991). This phenomenon is illustrated by the psychometric functions shown in Figure 3.1 as reported by Stuart & Phillips (1996). In examining these plots of recognition performance (%) as a function of signal to noise ratio [SNR (dB)], there are two obvious distinctions between the three groups of listeners. The psychometric functions for both the older listeners with normal hearing and those with hearing loss are shifted to the right
(requiring better SNR for equivalent performance of that of the younger listeners), as expected, and the psychometric function for the older listeners with hearing loss shows the greatest separation for the YL group. Second, the slopes of the psychometric functions for the two older listener groups are more gradual than that of the younger listeners, with again, as expected, the shallowest slopes for the older listeners with hearing loss (Wilson & Strouse, 1999). These observations indicate that while older listeners with hearing loss are more impacted by noise than older listeners with normal hearing, all older listeners are more affected by noise than younger ones, as seen by the decrease in speech-in-noise performance as well as a decrease in the homogeneity in responses illustrated by the more gradual slopes of the functions for the older listener groups.

**Figure 3.1** Speech recognition in noise performance among young normal-hearing listeners, older normal-hearing listeners, and older hearing-impaired listeners. Adapted from Stuart & Phillips (1996).

Although the exact mechanisms behind the difficulties that older adults experience with recognizing speech embedded in background noise are not known, there are two possible factors beyond the contributions of peripheral hearing status, which are believed to play a role. These
are changes in central-auditory processing and declines in cognitive abilities (CHABA, 1998; Tun et al., 2012). Indeed, research findings support peripheral and central proposals of age-related decline, with evidence that as individuals age there is associated degradation in the cochlea and supporting cells, loss of neural synchrony coding that reduces the abilities of older listeners with hearing losses to differentiate a target speaker from other competing talkers, as well as declines in cognitive factors, which can impact older listeners even without a hearing loss, that are required for comprehension (Alain et al., 2001; Pichora-Fuller & Souza, 2003; Summers & Leek, 1998; Schneider & Pichora-Fuller, 2000; Koehnke & Besing, 2001; Gordon-Salant et al., 2008; Wilson & McArdle, 2008; Plomp, 1977).

As speech understanding in noise is based on a complex interaction of bottom-up processing of the acoustic input and corresponding top-down processing based on knowledge of linguistic-contextual constraints, as well as non-auditory, non-linguistic cognitive factors, there are aging models of language processing that have been proposed trying to account for the interplay of age-related declines in peripheral hearing acuity, central auditory processing, and cognitive operations (Burke and Shafto, 2008). Impaired recognition of spoken words may be based on an inadequate level of function at various processing stages of (a) perceptual operations (i.e., phonological analysis, segregation of the speech stream, lexical identification), (b) encoding in working memory, and (c) understanding the input at the conceptual and discourse levels (Wingfield et al., 2005). In line with this, age-related deficits in word recognition become manifest especially under conditions of high mental workload in combination with acoustically demanding listening situations, while differences between older and younger listeners are often quite small in simple tasks (e.g., speech-recognition in quiet where hearing loss is the
predominant predictor of performance, they become magnified when noise is present (see Humes, 2007, for review).

Although the bottom-up processing stream can be degraded due to the signal not being encoded effectively due to peripheral hearing loss, central changes which may occur with or without loss of pure tone sensitivity and noise itself, there is evidence, that older listeners can compensate for the degradation via a shift in the use of top-down linguistic-contextual processing (for review, Schneider et al., 2010), as illustrated in Figure 3.2. Indeed the results of behavioral studies suggest that older adults may even outperform younger ones in using sentential context to reduce ambiguity, suggesting that they use linguistic-contextual information more efficiently to support communication in challenging listening situations (Pichora-Fuller, 2008; Sheldon et al., 2008).

As linguistic knowledge (part of the so-called “crystallized intelligence”, Cattell, 1987; Baltes et al., 1980) is well preserved into older adulthood, compensation by using linguistic-contextual information could offset declines in bottom-up processing, at least in situations when available attentional and memory resources are sufficient to allow for top-down processing to occur (Wingfield et al., 2005). Such would be the case in a paradigm where the linguistic-context was used to prime the recognition of the last word in a sentence as was done in Experiment 1 of this dissertation. In that experiment, bottom-up and top-down processing during word recognition by young listeners (YL) with normal hearing was explored. The results provided evidence of the mechanisms and time course of speech processing in noise among young adult listeners; however, it was still unknown if aging would result in a similar or different pattern, as older adults are known to make more use of linguistic-contextual information than do young
adults during the speech recognition in noise process (Pichora-Fuller, 2008; Pichora-Fuller & Singh, 2006).

![Diagram showing Core Levels of Representation for OLs]

**Figure 3.2.** Schematic illustrating the possible compensation mechanism completed by Older Listeners (OLs) when performing a word recognition in noise task.

Recall that the work presented in this dissertation was motivated by the need to understand the mechanisms and time course of word recognition primed by speech-in-noise in older listeners so that improved interventions could be developed which would help keep older adults engaged in spoken communication interactions. Thus the experiment described in this chapter was designed to identify the underlying mechanisms for word recognition primed by speech-in-noise in older adults; and, in the next chapter (Chapter 4), the results obtained in Experiment 2 are compared to those obtained in Experiment 1 with YL. In this way, the effects of aging on the mechanistic pathways supporting word recognition primed by speech in noise can be elucidated.
3.2 Method

The design, stimuli, behavioral task, procedure, and electrophysiological data extraction utilized in Experiment 2 were essentially the same as in Experiment 1 and are described in detail in Chapter 2. There was one difference in the methods of the two experiments and that was that an off-line assessment of word recognition in noise was obtained in the present experiment. This assessment is described after the participant characteristics are presented.

3.2.1 Participants

Seventeen OL participants (12 females, 5 males) were recruited from flyers posted on the campus of the University of South Florida (USF), word-of-mouth, and through contacting with permission individuals who had participated in previous studies in the Department of Communication Sciences & Disorders at USF. Recruitment methods were approved by the USF IRB. The participants were ranged in age from 55 to 72 years (mean age = 63.2, SD = 6.2).

Individual audiometric thresholds for each ear and demographic data are provided in Appendix E. Audiometric performance as function of frequency is shown in Figure 3.3. Participants met the following audiologic criteria: (1) air conduction thresholds at 500 - 2000 Hz ≤ 45 dB HL in both ears; (2) no air conduction threshold > 75 dB HL between 3000 and 4000 Hz in both ears; (3) no greater than a 15 dB HL difference between ears from 500 to 4000 Hz; and, (4) no history of middle ear disease. As the speech-in-noise measures utilized in this study are only available in English, all participants reported English as their first and primary language. In addition, as self-
reported by the participant, participants with known cognitive or neurological impairments were excluded.

![Older Listeners Mean Audiogram](image)

**Figure 3.3.** Older listeners (OL) combined ears mean audiogram with standard deviation bars shown.

### 3.2.2 Words in Noise (WIN) test

The WIN test was used to quantify the word recognition in noise performance for each participant (Wilson, 2003). The WIN test uses 70 of the 200 NU-6 monosyllabic words presented binaurally with fixed MTB at 80-dB SPL and the speech varies from 24 (104-dB SPL) to 0 db SNR (80-dB SPL) in 4-dB decrements, with 5 words presented at each level. The WIN provides the 50% threshold or dB SNR level derived by the Spearman-Karber equation (Finney, 1952).
3.3 Results

3.3.1 Organization of results section

The results are organized in a similar manner to the presentation of the results for Experiment 1, with the addition of the WIN results which are provided next.

3.3.2 Words in Noise (WIN) test

OL WIN performance, reported by the 50% threshold in the unit form of dB SNR or the amount of signal over the noise required to achieve 50% recognition (Finney, 1952) ranged from 7.6 – 1.2 dB SNR. The individual WIN scores are reported in Appendix E. Participants’ right ear mean WIN threshold was 4.5-dB SNR (SD = 2.8) and left ear mean threshold was 5.2-dB SNR (SD = 2.7).

3.3.3 Judgment ratings

As with the YL, the OL’s responses to the question – “How closely related is the written word to the sentence you heard?” were examined to ascertain whether or not the last words in the stimulus sentence were priming the printed probe words in the expected manner (see Chapter 2 for expected relatedness responses and explanation). The mean scores and standard deviation for six probe word conditions are shown in Figure 3.4. The mean score for the Phonologically-Related probes was 1.08 (SD = 1.10) and mean Unrelated score was 1.04 (SD = 1.20). The Identically-Related probes had a mean score of 3.72 (SD = 1.61) while the mean score for Unrelated probes was 1.05 (SD = 0.97). Also having a higher-related ranking, the mean score for
the Semantically-Related probes was 2.69 (SD = 1.92) and the paired Unrelated probes score was 1.03 (SD = 1.01). The mean judgment scores demonstrated that the priming was working as expected.

### 3.3.4 Judgment task reaction times

Figure 3.5 shows the mean RT (durations presented in seconds) per condition. As with the YL, it was expected that RTs would be the lowest/fastest for the Related probes and longer for Unrelated probes. The mean RT for the Phonologically-Related probes was 0.80 seconds (SD = 0.90) and 0.75 (SD = 0.62) for the Phonologically-Unrelated probes. The RT for the Identically-Related probes had a mean of 1.08 seconds (SD = 1.13) while the Identically-Unrelated probes were slightly slower with a mean of 0.69 seconds (SD = 1.12). Having the longest RT, the mean RT for the Semantically-Related probes was 1.85 seconds (SD = 1.9) while the Semantically-Unrelated probes mean was 0.95 (SD = 0.84). The shortest, or quickest reaction times were seen for the Unrelated probes.

The Longest reaction times were seen for the Semantically-Related probes compared to Semantically-Unrelated probes. Reaction times were significantly affected by Relatedness ($F(1,16) = 30.28$, $p=0.00$, partial eta square = 0.65), and Condition ($F(2, 16) = 10.28$, $p < 0.01$, partial eta square = 0.39). Although the interaction between Relatedness and Condition failed to reach a strict criterion for statistical significance ($F(2,16) = 3.48$, $p = 0.06$), partial eta square indicated that the interaction was accounting for a substantial amount of the variance equaling 0.18.
Figure 3.4 Older Listener (OL) mean relatedness judgment responses per condition: Phonological, Identical, and Semantic. Standard deviation bars are shown.

Figure 3.5 Older Listeners (OL) mean reaction times (seconds) per condition (Phonological, Identical, Semantic) with standard deviations error bars shown.
Given the magnitude of the effect size and the fact that the interaction for the YL was significant, we elected to examine the within Condition differences in Relatedness via a post-hoc analysis with Bonferroni-corrected t-tests. A significant effect of Relatedness for the Semantic condition \((t (16) = 3.7, p < 0.01)\) was observed with the Semantically-Related probes having longer reaction times than the Semantically-Unrelated probes. The Identical \((t (16) = 2.12, p = 0.46)\) and Phonological \((t (16) = 1.73, p = 0.10)\) Conditions by Relatedness were not significantly different.

### 3.3.5 Neural Correlates

Grand average waveforms for each Condition are shown at 21 electrodes in Figure 3.6, 3.7, and 3.8. For each figure the gray line represents the Related-probe response while the black line represents the Unrelated-probe response. Visual inspection reveals a grossly similar pattern of ERP activity between Conditions from probe word onset to the end of the epoch.

### 3.3.6 PCA analysis results

PCA analysis was performed to the reduce data and identify time and scalp distributions that varied based on condition. Unrestricted temporal PCA produced 71 temporal factors (TFs), but only five TFs accounted for at least 1% of the variance in the OL data set. As shown in Figure 3.9, these five peak latencies ranged from 138ms to 600ms after probe onset and each TF will, hereafter, be labeled by its peak latency (e.g., TF138, TF202, TF306, TF424 and TF600).
Figure 3.6. Older Listeners’ (OL) grand average waveforms for the Phonological condition.
Figures 3.7. Older Listeners’ (OL) grand average waveforms for the Identical condition.
Figures 3.8. Older Listeners’ (OL) grand average waveforms for the Semantic condition.
Statistically significant effects were not detected for TF138; however, visual inspection of the grand averages would suggest that this TF is related to N1 correlate, but that it was not modulated by the priming/probe conditions. The four significantly modulated TFs (TF202, TF306, TF424 and TF600) are reported next first describing the modulations throughout the midline analysis then discussing topographic effects.

Figure 3.9 Older Listeners (OL) temporal factor (TF) loadings. Top panel shows all 71 TF loadings while the bottom panel shows the 5 TF loadings that explain at least 1% of variance.
3.3.6a: TF202 effects. TF202 variance (9.2 %) at the midline electrodes was affected by an interaction of Condition and Relatedness \((F(2,28) = 8.46, p < 0.01, \text{partial eta-squared} = 0.35)\). Bonferroni-corrected t-tests detected a Relatedness effect across all midline electrodes for Identically-Related probes \((p < 0.01)\). Identically-Related probes had an attenuated positivity versus the Unrelated probes. This effect can be seen in the grand average waveforms (see Figure 3.7). Topographically, TF202 variance was affected by a interaction of Dorsality, Condition, and Relatedness \((F(2,28) = 5.71, p < 0.01, \text{partial eta-squared} = 0.26)\). Bonferroni-corrected t-tests detected a Relatedness effect for the Identical condition at the inferior \((p = 0.01)\) and superior \((p= 0.01)\) regions. As seen in Figure 3.7, and similar to the midline modulations, both inferior and superior regions had an attenuated positivity that can be seen for the Identically-Related probes compared to the Unrelated probes.

3.3.6b: TF306 effects. TF306 variance (34.6 %) at the midline electrodes was not affected by an interaction of Electrode, Condition and/or Relatedness. However, topographically, TF306 variance was affected by a interaction of Laterality, Dorsality, Condition, and Relatedness \((F(2,28) = 3.46, p = 0.05, \text{partial eta-squared} = 0.18)\). Bonferroni-corrected t-tests detected a Relatedness effect for the Identical condition at the left/inferior region \((p = 0.03)\). As seen in Figure 3.7, the left inferior regions were more negative for the Identically-Related probes compared to the Unrelated probes.

3.3.6c: TF424 effects. TF424 variance at midline electrodes was affected by an interaction of Electrode, Condition and Relatedness \((F(2,28) = 5.22, p = 0.01, \text{partial eta-squared} = 0.25)\). Bonferroni-corrected t-tests detected a Relatedness effect at Fpz for the Semantic condition \((p = 0.05)\). At Fpz, Semantically-Related probes resulted in a more positive response or a less negative-going amplitude, versus the Unrelated probes. This attenuated
deflection effect can be seen in the grand average waveforms at Fpz (see Figure 3.8). Also, Bonferroni-corrected t-tests detected a Relatedness effect at Fz ($p = 0.03$), Cz ($p = 0.01$), Pz ($p < 0.01$), and Oz ($p = 0.01$) for the Identical condition. Throughout these midline electrodes, the Identically-Related probes had positive or less negative-going amplitude versus the Unrelated probes. This attenuated deflection effect can be seen in the grand average waveforms at Fz, Cz, Pz, and Oz (see Figure 3.7).

Topographically, TF424 variance was affected by two interactions. First, there was an interaction of Dorsality, Condition and Relatedness ($F(2,28) = 9.27, p = 0.01$, partial eta-squared = 0.37). Bonferroni-corrected t-tests detected a Relatedness effect for the Semantic condition at the inferior region ($p = 0.01$) and for the Identical condition at the inferior ($p = 0.04$) and superior regions ($p = 0.01$). As seen in Figure 3.8, for the Semantic condition at the inferior region of interest the Semantically-Related probes results in positive or a less negative amplitude compared to the Unrelated probes. As seen in Figure 3.7, for the Identical condition, located at both the inferior and superior regions, the Identical probes resulted in a more positive or less negative-going deflection compared to the Unrelated condition. The second interaction was an effect of Anteriority, Condition, and Relatedness ($F(2,28) = 3.90, p = 0.03$, partial eta-squared = 0.20). Bonferroni-corrected t-tests detected a Relatedness effect for the Semantic condition at the anterior region ($p = 0.01$) and Identical condition affect at both anterior ($p = 0.03$) and posterior regions ($p = 0.02$). As seen in Figure 3.8, for the Semantic condition, the anterior section showed that the Semantically-Related probes resulted in a less-negative going amplitude compared to the Unrelated probes. Similarly and as seen in Figure 3.7, for Identically-Related probes at both anterior and posterior regions were more less negative compared to Unrelated probes.
3.3.6d: TF600 effects. TF600 variance (49.5 %) at the midline electrodes was affected by an interaction of Electrode, Condition and Relatedness ($F(2,28) = 4.12, p = 0.02$, partial eta-squared = 0.21). Bonferroni-corrected t-tests detected a Relatedness effect for the Semantic condition at Cz ($p = 0.03$), Pz ($p = 0.03$) and Oz ($p = 0.04$), and for the Identical condition at electrode sites FPz ($p = 0.03$), Cz ($p = 0.02$), Pz ($p = 0.01$) and Oz ($p = 0.02$). Throughout most of the midline electrodes Semantically-Related and Identically-Related probes caused a more positive-going shift in amplitude versus the Unrelated-probe words. This effect can be seen in the grand average waveforms throughout the midlines in Figures 3.8 for the Semantic condition and in Figure 3.7 for the Identical condition.

Topographically, TF600 variance was affected by an interaction of Laterality, Anteriority, Condition, and Relatedness ($F(2,28) = 2.28, p = 0.02$, partial eta-squared = 0.22). Bonferroni-corrected t-tests detected a Relatedness effect for the Semantic condition at the right posterior ($p = 0.04$) and a Relatedness effect for the Identical condition at the right posterior ($p = 0.01$) region. As seen in Figures 3.8 and 3.7 and similar to the midline effects, the Identically-Related and Semantically-Related probes caused a more positive deflection compared to the Unrelated probes at both right posterior regions.

3.4 Discussion

The purpose of Experiment 2 was to determine the mechanistic pathways utilized during word recognition primed by speech-in-noise among OL with minimal hearing loss. The neural correlates of word recognition primed by speech-in-noise identified in this experiment are
discussed first, followed by a discussion on the ERP and behavioral data as it relates to the identification of the mechanistic pathways.

3.4.1 Neural correlates of word recognition primed by speech-in-noise

Neural correlates of word recognition primed by speech-in-noise were identified. The waveforms across most electrode sites had some peak latency similarities for all conditions. Reviewing the literature for similar ERP waveform morphology and scalp distribution comparable components were identified. In the present experiment, the waveforms showed a negative deflection of about 120 ms (possible N1); followed by a positive deflection at about 225 ms (possible P2). More distinct for the Unrelated probes, but only at certain electrodes, there was a prolonged negative deflection, a possible processing negativity (PN) or N400, peaking in the 350 – 500 latency range and lasting more than 200 ms. The Identically- and Semantically-Related probes generated waveforms that also had a slow positive deflection from baseline peaking in the 600 ms range which may be a late positive component (LPC). Visual inspection also revealed that the ERP activity had typical aging effects with some increased latencies and decreased amplitudes.

The aging literature has repeatability reported that N1 peak declines and the peak latency increases slightly as well as any hemisphere asymmetries disappear. Likewise, with age the P2 latency increases more than the N1 but amplitude is not greatly influenced. Early ERP components are usually found to be less affected by age than later ERP components, where latencies typically increases more and amplitudes decrease with advancing age (Anderer et al., 1996; Schiff et al., 2008). This suggests a higher influence of aging on later (cognitive) processes than on early (perceptual and pre-attentive) ones (Jerger, Martin, & Fitzharris, 2014). The PN
and LPC components change substantially with age with amplitude declines and latency increases (Jerger, Martin, & Fitzharris, 2014). For our grand average waveforms there seems to be latency shifts and amplitude decreases throughout the whole waveform.

Due to the large data set from this high-density electrode montage and various conditions as well as the unavoidable overlapping componentry complication we will focus on the statistically significant effects discovered by the unrestricted PCA. Figure 3.10 illustrates the significant temporal factors as function of latency and in terms of modulating Phonological, Lexical, and Semantic representations. Obvious from Figure 3.10 there were no significant Phonological modulations detected from the PCA. However, there were Lexical and Semantic modulations which will be described in detail below.

Figure 3.10 Graph illustrating the Temporal Factor (TF) Loadings across time and if they modulated Phonological, Lexical, and/or Semantic representations.
The first temporal loading, TF202, identified a positivity that was more positive for the Identically-Related probes. The scalp distribution as well as the latency of the TF202 is consistent with the P2 component. The topographic distribution of the P2 is characterized by a positive shift at the frontal sites around 150-200 ms after stimulus onset (Heslendfeld, et al., 1997; Kenemans et al., 1993; Van der Stelt et al., 1998) that can be slightly more right hemisphere (Jerger, Martin, & Fitzharris, 2014) and a large negativity, approximately 200 ms following stimulus onset at the occipital sites (Talsma & Kok, 2001).

Visual P2 is thought to be more involved in later stages of stimulus processing, and are related to cognitive processes of stimulus evaluation, selective attention, and conscious discrimination (Kok, 2000). Specifically, the P2 component has been shown to index the encoding of visual features, particularly in working memory (Lefebvre, Marchand, Eskes, & Connolly, 2005; Wolach & Pratt, 2001), and the posterior P2 may reflect feedback from higher visual areas (Kotsoni, Csibra, Mareschal, & Johnson, 2007). The TF202 positivity modulation may reflect the OL participants efficient processing of the Identically-Related probe word and recognizing that the probe word was the last word in the sentence they just heard. Therefore, as the Identical probe word is a direct match to the last word of the sentence they just heard the attenuated P2 may indicate that the Identical probe was easier to visually recognize and the word via priming by the sentence in noise was successfully activated the listener’s mental lexicon.

The next significant modulation was the found in the TF306 effect. The TF306 effect was only found for the Identical condition and was a left lateralized modulation where Identical probes resulted in a more negative response than Unrelated probes. The timecourse and scalp distribution of the TF306 effect is most similar to the left anterior negativity (LAN) effect which is described as a possible index of morphosyntactic processing (Hahne & Friederici, 2002;
Coulson, King, & Kutas, 1998). Other researchers report the LAN effect may index processes which differentiate language processing from the detection of anomalous events. Furthermore, some have suggested that the LAN indexes some aspect of working memory usage (Coulson et al., 1998; Kluender & Kutas, 1993) although variations in experiments make it difficult to report if the LAN indexes cognitive operations which are exclusively morphosyntactic, it is generally accepted that this ERP component may index operations specific to verbal and auditory working memory. Thus, we interpret our TF306 as a possible LAN and may indicate that OL had multiple lexical activations with varying morphosyntactic representations. The multiple lexical activations may occur because of the degraded bottom-up stream increasing the uncertainty around the morphosyntactic pieces. The Identical probe word then serves as a confirmatory process reducing the verbal working memory load, because a final lexical item is the fully recognized.

Next, Semantically-Related and Identically-Related probes had modulations detected in the TF464 that were widespread across the scalp. The TF464 effect indicated a reduced negativity for the Related probes for both Semantic and Identical conditions. Also, there were deep and prominent negativity seen for the Unrelated probes. The time course and scalp distribution of attenuated negativity is exemplar of an N400 correlate or also referred to as a Processing Negativity (PN). The N400/PN component is related to expectancies, such as word expectancies during word recognition, and peaks between 400 – 500 ms (Kutas & Federmeier, 2011; Jerger, Martin, & Fitzharris, 2014). Expected words such as Identical probes and Semantically-Related probes produce a less or shallower response while unexpected, and, in our case, Unrelated probes, produce a large PN. Jerger and colleagues (2014) describes the PN reflecting the sum of at least four cognitive processes overlapping in time, but reflecting evoked
activity over different regions of the head. These four cognitive processes are attention, phonological processing, working memory, and semantic processing (Jerger, Martin, & Fitzharris, 2014). Listening effort is reflected in both the depth and duration of the negativity of the PN component. Therefore, the TF464 effect reflects that the Related probe words were processed more efficiently than the Unrelated words.

The final effect, the TF600, is most likely a correlate reflecting the late positive component (LPC), which is a slow positive deflection from baseline peaking in the 600-900ms range, the TF600 was modulated by the Identical and Semantic Conditions. The LPC has been reported to be component that reflects the degree of difficulty in making the decision whether or not a target word has been heard. And, listening effort is reflected by the onset, height, and duration of the positivity of the LPC. Specifically, the easier the decision, the earlier and larger the evoked positivity which was the case for the Related probes compared to the Unrelated probe responses.

3.4.2 Word recognition primed by speech-in-noise: Older Listeners’ mechanistic pathways

Although our behavioral data indicated that semantic representations take longer to process than the other conditions and that the Phonologically-Related probe words were almost exactly treated like the Unrelated probes with regards to judgment rankings and RTs, these results do not explain the underlying mechanisms and the neurophysiological data can elucidate these pathways.

Overall OL had access to lexical and semantic representations but they did not robustly activate phonological representations from the incoming acoustic/phonetic sounds because the
Phonologically-Related probes failed to strongly activate phonological neighbors within the mental lexicon. This does not mean that phonological representations were not activated, just they were not activated as strongly to modulate ERP activity. The lack of significant phonological priming might be support for loss of phonological awareness/memory in older adults. Therefore a unique and independent bottom-up mechanism was not identified. The influence of top-down processing in the OLs many reflect a tendency to draw on intact cognitive resources as a means of compensating for the perceptual decrements associated with normal aging. They might have relied on the top-down mechanism to disambiguate a degraded signal or multiple lexical words that compete for recognition. We would suggest that bottom-up pathway activated multiple lexical representations causing ambiguity and then the top-down influence was required to resolve and select the final word.

The overarching goal of this dissertation was to compare the mechanistic pathways for word recognition primed by speech in noise among OLs to YLs. The following chapter, Chapter 4, will directly compare the behavioral and neurophysiological data obtain between the two groups.
CHAPTER FOUR:
COMPARING THE BEHAVIORAL AND NEURAL CORRELATES OF WORD RECOGNITION PRIMED BY SPEECH-IN-NOISE AMONG YOUNG AND OLDER ADULT LISTENERS

The overarching goal of this dissertation was to examine the effects of aging on the interplay between bottom-up and top-down processing of information during probe word recognition which was primed by speech-in-noise. In this chapter the data obtained with the young listener (YL) group in Chapter 2 are compared to the data obtained with the older listener (OL) group in Chapter 3 in order to elucidate the effects of age on speech-in-noise priming. Prior to examining the behavioral and ERP data the group demographic and audiological characteristics are compared.

4.1 Comparison of demographic and audiological variables between the young and old listener groups

The general inclusion and exclusion criteria for the participants in both Experiment 1 (Young Listeners, YL, n = 15) and Experiment 2 (Older Listeners, OL, n = 17) were the same. Thus, all individuals had a negative history of neurological disorders, otological diseases, ototoxic drug use, head trauma and/or and speech and language disorders. In addition all participants were native monolingual speakers of English. As would be expected the groups differed significantly on age with the mean age of the YL group 25.06 years (SD = 3.10) being
significantly lower \( t(30) = 25.50, p < 0.01 \) than the mean age \( (M = 63.35, SD = 5.02) \) of the OL group.

The mean pure-tone audiograms of the two groups are presented in Figure 4.1. It can be seen that on average, the YL group presented with normal hearing sensitivity whereas the OL group presented with normal hearing though 2000 Hz, with an average mild sloping loss between 3000 and 8000 Hz. Further examination of the data with a two-way ANOVA, with one between group factor (Age Group) and one within groups factor (Frequency) revealed, a significant main effect of Age Group \( (F(1,30) = 31.40, p < 0.01, \text{partial eta squared} = 0.51) \), with the mean for the YL equal to 13.67 dB (SD = 3.11) and the mean for the OL group equal to 34.71 (16.48). Thus, despite meeting the criteria for essentially normal hearing, collapsed across all audiometric frequencies the OL group exhibited an essentially mild hearing loss. The main effect of frequency also was significant \( (F(7,210) = 22.17, p < 0.01, \text{partial eta squared} = 0.43) \) as perhaps, more importantly, was the interaction between Age Group and Frequency \( (F(7,210) = 112.10, p < 0.01, \text{partial eta squared} = 0.28) \). Post hoc Bonferroni adjusted \( t \)-tests confirmed that the OL had significantly poorer thresholds for 3000 Hz \( (t(30) 3.71, p < 0.01) \), 4000 Hz \( (t(30) 3.83, p < 0.01) \), 6000 Hz \( (t(30) 5.62, p < 0.01) \), and 8000 Hz \( (t(30) 4.86, p < 0.01) \). While the maximum thresholds at these frequencies for the YL group did not exceed 20.0 dB, the maximums for the OL group were 25.0, 65.0, 52.5, and 70.0, for 3K, 4K, 6K and 8K Hz, respectfully. Using 25 dB as the lower limit of normal hearing, Table 4.1 shows the number of participants in the OL group who exhibited mild (26-40 dB), moderate (41-55 dB) and severe (56-70 dB) hearing losses at 4000, 6000, and 8000 Hz. These data are provided to illustrate that only a small number of the older participants had normal hearing throughout the audiometric frequency range. This pattern of high-frequency hearing loss is typical in studies which attempt
to include older samples with essentially normal hearing. Thus, while differences discussed later in this chapter in processing mechanisms may in fact be due to “aging” the potential contribution of high-frequency hearing loss cannot be entirely ruled-out.

![Young & Older Listeners Mean Audiogram](image)

**Figure 4.1** Young Listeners (YL; diamonds) and Older Listeners (OL; squares) mean audiogram collapsed across ears with standard deviation error bars shown.
Table 4.1  Number of older listeners with high frequency thresholds indicating hearing loss. The high frequencies (4000, 6000, and 8000 Hz) are shown from left to right while the categorical degrees of hearing loss from mild (26-40), moderate (41-55), and severe (56-70) are listed down the left hand side of the table.

<table>
<thead>
<tr>
<th>Intensity (dB)</th>
<th>Frequency (Hz)</th>
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<tbody>
<tr>
<td></td>
<td>4000</td>
</tr>
<tr>
<td>26-40</td>
<td>3</td>
</tr>
<tr>
<td>41-55</td>
<td>3</td>
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<tr>
<td>56-70</td>
<td>1</td>
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<tr>
<td>Total</td>
<td>7</td>
</tr>
<tr>
<td>% of Sample</td>
<td>41%</td>
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4.2 Comparison of judgment ratings for the YL and OL groups

Figure 4.2 shows the mean judgment ratings and standard deviations for the YL group (left panel) and the OL group (right panel). Visual inspection of results in the two panels reveals a similar pattern for both groups. Discussed in detail in Chapters 2 and 3, the findings indicate that the priming of the probe words functioned as expected for both age groups. Specifically, Identically-Related probes were most likely to be rated as “4 – very related”; Semantically-Related probes most likely to be rated as “3 – Related” or “2 – Somewhat Related”; and, Phonologically-Related probes and all unrelated probes were most likely rated as “1 – not related”. Based on these findings, it was concluded that priming was working as expected for both younger and older listener groups, supporting the validity of the reaction time and ERP results.
4.3 Comparison of judgment ratings for the YL and OL groups

Figure 4.3 shows the mean reaction times and standard deviations for the YL group (left panel) and the OL group (right panel). From the figure it can be observed there was a similar pattern of reaction times between groups. Both YL and OL groups’ reaction times for the Semantically-Related primes were the longest (slowest). Both groups’ reaction times were fast for all of the Unrelated Conditions and for the Phonologically-Related probes. The only observable difference was the mean reaction times for the Identical-Related probes which was longer for the OL as compared to the YL group. To determine whether this or any other differences between groups was statistically significant the data were subjected to a two-way mixed ANOVA with one between factor (Age Group) and two within factors (Condition, Relatedness).
As expected based on the analyses for each group separately presented in Chapter 2 for the YL and Chapter 3 for the OL, the main effects of Condition \((F(2, 60) = 21.75, p < 0.01,\) partial eta-squared = 0.42) and Relatedness \((F(1, 30) = 4.25, p < 0.01,\) partial eta-squared = 0.62) remained significant. Post-hoc Bonferroni \(t\)-tests confirming that the mean RT for the Semantic condition \((M = 1.24, SE = 0.10)\) was significantly higher than for the other two conditions with no difference between the Phonological and Identical conditions’ mean reaction times. For Relatedness, the mean for the related probes \((1.08, SE = 0.07)\) was higher than for the unrelated ones \((M = 0.72, SD = 0.07)\). While neither the two-way interaction between Group and Condition \((F(2, 60) = 0.75, p = 0.57,\) partial eta-squared = 0.02) or Group and Relatedness \((F(1, 60) = 3.85, p = 0.06,\) partial eta-squared = 0.11) reached statistical significance, the interaction
between Condition and Relatedness was statistically significant ($F (2, 60) = 14.86, p < 0.01$, partial eta-squared = 0.33). Post-hoc Bonferroni adjusted t-tests ($t (32) = 5.62, p < 0.01$) revealed that within the Semantic condition, the mean for the Related probes ($M = 1.70, SD = 0.86$) was significantly higher than the mean for the Unrelated probes ($M = 0.81, SD = 0.65$); and, for the Identical and Phonological conditions the differences between the Related and Unrelated probes were not statistically significant. Interestingly, and perhaps most important, the three-way interaction of Group X Condition X Relatedness ($F (2, 60) = 2.01, p = 0.14$, partial eta-squared = 0.06) reached statistical significance.

In sum, the lack of finding any statistically significant differences in the reaction time measures as a function of age group does not necessarily indicate that the same processing strategies are being utilized in the word recognition task. That is, other researchers have reported that when YL and OL perform equivalently on various perceptual and cognitive tasks, there is more widespread activation in older brains than in younger brains, with one interpretation being that this reflects compensatory processing (Aydelott et al., 2010; Arlinger et al., 2009; Pichora-Fuller and Singh, 2006). Thus, the behavioral results alone are insufficient for elucidating whether or not the YL and OL groups are using the same mechanistic pathways while performing a word recognition primed in noise task. We now turn to a comparison of the neurophysiological data to address the question of the potential effects of age on the complex inter-play of bottom-up and top-down processing for word recognition primed in noise.
4.4 Comparing neurophysiological results between the YL and OL groups

The neurophysiological results were compared in two ways. First, differences and similarities in the grand average waveforms were examined to provide a descriptive analysis of the waveform morphology across the two groups. Then, the PCA analyses were compared in order to determine if the underlying mechanisms were the same or different in the two age groups.

4.4.1 Grand average waveforms

The grand average waveforms for both the YL and OL groups, across most electrode sites, had some peak amplitude and latency similarities for all three conditions (Phonological, Identical, and Semantic). Similarities can be visually identified by examining the grand average head montages for both YL and OL groups for the Phonological condition (Figure 2.6 and Figure 3.6), Identical condition (Figure 2.7 and Figure 3.7) and the Semantic condition (Figure 2.8 and Figure 3.8). To simplify the comparisons, Figure 4.4 is provided as an example, at electrode site Pz, and allows us to zoom in and demonstrate the similarities and differences between the groups for all conditions. As can be seen in Figure 4.4, although the morphology was similar between the two groups the amplitudes and latencies of peaks for the OL group show typical morphological changes reported in other aging studies. Evaluating the morphological difference between the YL and OL for each condition, each relatedness, and each probe at each electrode is an unrealistic task. Thus the focus of the comparison between the YL and OL group is on the componentry that was revealed by the unrestricted PCA.
Figure 4.4 Grand average waveform morphology at electrode site Pz for young listeners (YL, top panel) and older listeners (OL, bottom panel) for different priming conditions (Phonological, Identical, and Semantic) where the gray line represents the Related-probe response and the black line represents the Unrelated-probe response.

4.4.2 Neural Correlate comparisons

Figure 4.5 illustrates the significant temporal factors (TFs) as function of latency and in terms of modulating phonological, lexical, and semantic representations. The TFs shown in black are from the YL PCA, while the white TFs were isolated from the OL PCA. The most notable difference between the TF from the YL group and OL group is the lack of significant phonological modulations detected from the PCA of the OL. We interpret this finding to suggest that the OL group failed to robustly activate phonological representations and instead their mechanistic pathways allocated resources towards building lexical and semantic representations. Before reporting overall conclusions of mechanisms let us discuss the differences and similarities of the PCA correlates temporally.
The first correlate to have statistically significant modulations was the TF122 for among the YL group, which modulated phonological representations, and was interpreted as an N1 response to orthographic phonologically similar probe words. Interesting, the PCA for the OL group did return a TF138, a negativity observed in a similar duration and scalp distribution via visual inspection of the grand averages that would suggest to be attributed to N1 correlate but that it was not modulated by the priming conditions. This leads to speculation that although both groups have an N1 response, the OL groups N1 response was not significantly modulated by the priming and probe condition thus further supporting the conclusion that phonological representations were not strongly activated during priming spoken sentence in noise. Visual inspection of these early deflections reveals that the ERP activity had typical aging effects with some increased latencies and decreased amplitudes. Indeed, the aging literature has reported that the N1 peak declines and the peak latency increases slightly, as well as having any hemispheric asymmetries disappear when younger and older groups are compared (e.g., Jerger, Martin, & Fitzharris, 2014).

Following the N1 response both groups showed a positivity most likely attributed to a P2 which for the YL group modulated during the phonological condition (TF 212) and the phonological and Identical conditions (TF270); while the OL group Identical condition had a P2 modulation (TF202). Likewise, with aging the P2 latency increases more than the N1 latency, but P2 amplitude is not as reduced as is the N1 amplitude. Early ERP components are usually found to be less affected by age than later ERP components, where latencies typically increase more and amplitudes decrease more with advancing age (Anderer et al., 1996; Schiff et al., 2008).
Figure 4.5 Graph illustrating the Temporal Factor (TF) Loadings across time and if they modulated phonological, lexical, and/or semantic representations. The TFs shown in black are from the young listeners (YL) PCA while the white TFs were isolated from the older listeners (OL) PCA.

This suggests a higher influence of aging on later (cognitive) processes than on early (perceptual and pre-attentive) ones (Jerger, Martin, & Fitzharris, 2014), which was evidenced in the comparison of the observed morphology of YL and OL groups in the present study, as discussed below. Unlike the YL group which showed a Cz-centered P400, the OL group did modulate a proposed N400 or PN. The YL group had a N400 and PN too, but this was seen at 464 for both the Semantic and Phonological condition.
Following the course temporally, as seen on Figure 4.5, both YL and OL groups showed a similar mechanistic pathways where both Identical and Semantic conditions modulated a proposed N400 or Processing Negativity. Specifically, the YL had an early (TF378) modulation and continued to significantly modulate the component TF464. The OL group only had a modulation detected by the TF424. The difference in the N400 between the YL and OL groups for all three unrelated conditions showed a more robust processing negativity (PN) for OL group as compared to the YL group. In contrast both the YL and OL groups showed a slow positive deflection that was most robust for the Identically- and Semantically-Related probes, which was interpreted in Experiments 1 and 2 to be a late positive component or an LPC. As expected, however, when comparing the YL and OL waveforms the LPC for the older participants had a shallower amplitude and an increased latency relative to the LPC for the YL (Jerger, Martin, & Fitzharris, 2014). For example, it can be seen in Figure 4.4 for the Identical condition the probe word modulation for the YL was very robust from 300 – 600ms but greatly reduced for the OL where the gray and black lines barely deviate from each other. This observation, along with a similar one for Semantic condition suggests that the related neural correlates were not as robustly modulated for the OLs as for the YLs, a conclusion which is strengthened further by the Phonological condition, in which the related responses were identical to the unrelated responses for OL but not the YL group. Collectively the PN and LPC components reflect an important dimension of real-life auditory experience, listening effort.

In sum, the YL had a strong early bottom-up mechanism and continued to modulate phonological representations via top-down mechanisms through 600 ms. On the other hand, the OL group failed to strongly activate phonological representations and relied more on the top-down processing mechanism to clear up any lexical ambiguities.
4.5 Summary of Results

The results of the comparison of the data from the YL and OL can be summarized as follows:

1. The validity of the RT and electrophysiology data is supported by the demonstration that the behavioral relatedness judgments supported a conclusion that the priming was working as expected for the YL and OL.

2. The RT data was essentially equivalent for the YL and the OL. Although both groups were able to complete the task with equivalent performance, consideration of the behavioral data alone does not provide information about whether or not the two age groups were utilizing similar or different underlying processing strategies in completing the task.

3. Neural correlates of word recognition primed by speech-in-noise were identified for both YL and OL groups. The YL had a strong early bottom-up mechanism and continued to modulate phonological representations via top-down mechanisms. On the other hand, the OL group failed to strongly activate phonological representations and relied more on the top-down processing mechanism to clear up any lexical ambiguities.

The overall relation of these results to the literature and their implications for future research and clinical practice are discussed in Chapter 5.
CHAPTER FIVE:
SUMMARY AND CONCLUSIONS

The present study was motivated by the fact that the most common complaint amongst older adults with hearing loss is difficulty with understanding speech in background noise. Although the peripheral hearing loss associated with aging results in a reduction in the audibility of the acoustic speech signal, thus making recognition difficult, the addition of noise appears to impact older adults more than younger ones (Humes, 1996; Dubno et al., 1984; Humes & Chrisotophenson, 1991; Stuart & Phillips, 1996). In fact, even amongst older adults with essentially normal hearing, many complain that they can hear but not understand the spoken words in noisy and reverberant environments (Stuart & Phillips, 1996).

Word recognition, the focus of the present study, involves accessing three core representational levels in the mental lexicon – phonological, lexical, and semantic. As discussed in Chapter 1, in auditory word recognition, phonological representations are accessed through the acoustic/phonetic input making initial contact. The phonological representations then activate a set of lexical representations or word candidates that are stored in long-term memory. As a number of lexical candidates might be activated, they need to be discriminated amongst until a single entry is selected and associated with its semantic representation (for reviews see, McQueen, 2005; Jusczyk & Luce, 2002). Researchers interested in word recognition seek to
understand whether the process of accessing the representational levels is an exclusively feed-forward one, with perception leading to recognition or if it is a mixture of feed-forward and feedback flow of information, such that perception is influenced by phonological mapping and/or by linguistic context. The use of linguistic-contextual information during word recognition is spared in aging, and is believed to play an important role in the ability of an older adult to understand speech in noise (Pichora-Fuller & Singh, 2006).

While the focus of the work reported here is on understanding the potential effects of age on the inter-play between bottom-up and top-down processing during word recognition in noise, it is important to recall, as illustrated in Figure 1.4, that more generalized cognitive functions, such as working memory and inhibition, along with speed-of-processing, must be sufficiently functioning in order for the top-down spread of linguistic-contextual information to occur. Unfortunately, as the peripheral auditory mechanism can be impacted negatively by aging, the executive functions of working memory and inhibition, as well as processing speed, also are subject to the negative effects of aging. Thus, increasing our understanding of the underlying mechanisms of bottom-up and top-down information flow and integration during word recognition is an important step in for the eventual development of targeted interventions for older adults, who may or may not have peripheral hearing losses and/or may not be experiencing cognitive declines that impact on speech recognition and in noise.

The overarching goal of the research presented here was thus to elucidate the effect of age on the complex interaction between bottom-up processing of the acoustic input and corresponding top-down processing based on linguistic-contextual constraints, with a focus on the task of word recognition primed by speech-in-noise. The study utilized a multi-methods approach involving both a behavioral task and late-latency
event-related potentials in an experimental paradigm that was based loosely on previous work reported by Friedrich and Kotz (2007). These investigators examined how bottom-up decoding and top-down linguistic-contextual priming influenced the activation of word entries in the mental lexicon as clear and continuous speech was processed by young adults with normal hearing. Their results indicated that: (a) bottom-up mechanisms occupy a unique processing stream during word recognition primed by speech in quiet; (b) top-down mechanisms also have a unique processing stream during word recognition primed by speech in quiet; and, (c) there is a third processing stream, in which both bottom-up and top-down processes share a mechanistic pathway. Further, Friedrich and Kotz reported that the time course in which the mechanisms they identified were activated was immediate and simultaneous. As a whole, the results supported a distributed model of word recognition in which bottom-up and top-down mechanistic processes are acting simultaneously (McQueen, 2005).

Based on the Friedrich and Kotz findings the present study aimed to determine if the same or different mechanistic pathways existed for the recognition of words which were primed by speech-in-noise, first in young listeners (YL) with normal hearing, in order to provide a baseline of optimal performance (Experiment 1), and then in older listeners (OL) with essentially normal hearing, in order to determine the effects of aging (Experiment 2). Further, the time course of bottom-up and top-down processing was examined, as it was believed possible that the presence of noise could alter the time-course observed in quiet, perhaps by impacting the level of efficiency, listening effort and/or attention. The neural correlates identified in each experiment along with those of Friedrich and Kotz are summarized in Table 5.1
Table 5.1. Neural correlate results placed within mechanistic pathways identified. The first column reports the findings from Friedrich & Kotz (2007) while the second and third columns report the findings from Experiment 1 and Experiment 2, respectively.

<table>
<thead>
<tr>
<th>Pathway</th>
<th>Friedrich &amp; Kotz (2007)</th>
<th>Experiment 1 – Young Listeners in noise</th>
<th>Experiment 2 – Older Listeners In noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom Up</td>
<td>P250</td>
<td>TF212</td>
<td>None Identified</td>
</tr>
<tr>
<td>Pathway</td>
<td></td>
<td>TF270</td>
<td></td>
</tr>
<tr>
<td>Top Down</td>
<td>N400</td>
<td>TF378</td>
<td>TF202</td>
</tr>
<tr>
<td>Pathway</td>
<td></td>
<td></td>
<td>TF306</td>
</tr>
<tr>
<td>Shared</td>
<td>P220</td>
<td>TF464</td>
<td>TF424</td>
</tr>
<tr>
<td>Pathway</td>
<td></td>
<td>TF600</td>
<td>TF600</td>
</tr>
</tbody>
</table>

It can be seen that for YL utilizing a prime in noise the same three mechanistic pathways were identified as in Friedrich and Kotz using a prime in quiet, again supporting a distributed model of word recognition. There were, however, differences in the time course when primed with speech in quiet and primed with speech in noise, with a slower shared processing stream for the latter, which may be attributed to a slower completion of the bottom-up processing stream prior to integration with the top-down stream. This interpretation, however, is made with caution because there were slight differences in the experimental task (e.g., lack of a truncated prime, different judgment...
The most dramatic finding occurred for the OL group who only had two mechanistic pathways. The unique bottom-up pathway did not result in any significant neuro-modulations. One possible explanation for this finding is that the participations had some type of degradation, either peripheral, or cognitive, or perhaps both. Thus due to the degradation the participants allocated the resources available to build a stronger lexical representation via the top-down unique and the shared mechanistic pathways, rather than to three separate pathways, one of which would be dependent on strongly activated phonological representations. Support for this interpretation comes from the fact that the OL, while representative of older individuals with “normal hearing” in the literature had, on average, across the audiometric frequency range an essentially mild hearing loss. This was due to the hearing thresholds of the majority of participants at 4000 Hz and above. Unfortunately, purely cognitive assessments were not obtained in this study, thus we do not know if there were any declines in executive functioning and/or processing speed. Future research should include cognitive assessment and should manipulate the degree of hearing loss of participants in order to provide greater clarification of the factors which resulted in the lack of the unique bottom-up processing stream.

In sum, the results of the two experiments in comparison with the data published by Friedrich and Kotz (2007) showed that neither phonological nor semantic information is ignored by the YL group during speech recognition, whether recognition is occurring in quiet or in noise. Older listeners, however, do not have strongly activated phonological representations during word recognition primed by speech-in-noise. Recall, however, that
the YL and OL group had the same reaction time performance on the behavioral task. Together the behavioral and electrophysiological performance suggests that the bottom-up mechanism degrades with age while the top-down mechanism can be used to compensate.

In terms of theories postulated to explain changes in word recognition with aging, the data reported here are in keeping with the decline compensation theory described by Wong and colleagues (2010). This theory posits that when there is a decline in a sensory system a compensatory counterbalance is needed in order to maintain appropriate recognition. Despite the fact that the participants would be considered as having “normal hearing” for their age, there was a statistically significant difference between the YL and OL groups when thresholds were collapsed across the audiometric frequency range. Indeed for the pediatric population it has been recommended that audiologists use a 15 dB HL cut-off for normal hearing and consider thresholds with in the 16-25 dB HL range as reflecting a “minimal hearing loss” (Bess et al., 1998). Further it has been argued that 15 dB HL rather 25 dB HL should be considered the upper limit of normal hearing sensitivity (Martin and Champlin, 2000). Martin and Champlin (2000) reported that over half a million hearing-aid purchasers had pure tone averages (PTAs) that were less than 25dBHL and still sought assistance for dealing with their hearing impairments is distinct evidence that many people, who may be told that their hearing is normal based on their PTA, would clearly testify that this is not the case. In addition as the OL group likely had better thresholds when younger than they did during this experiment, based on known progression of hearing loss in older adults (e.g., Lin et al., 2011), there are likely physiological changes occurring that could impact the ability of the auditory system to
decode and transmit the incoming acoustic signal of the early neural transmissions. Recall from Chapter 1 that other laboratories have shown that early evoked potentials can be reflective of speech understanding in noise difficulties in older populations (Billings et al., 2013; Anderson & Kraus, 2010)

Furthermore, the results of Experiment 2 are also important for providing additional confirmation of previously reported findings indicating that older adults are able to effectively make use of linguistic-contextual information or redundancies via top-down processing. The use of linguistic-contextual compensation, however, comes at the cost of increase listening effort as discussed in Chapter 4. Recall that the processing negativity (PN) and late processing complex (LPC), which combined reflect listening effort, was larger for the OL as compared to the YL. The larger the combined PN/LPC the greater the listening effort expended. Several behavioral studies have shown that older adults require more effortful processing than younger adults to understand speech (Pichora-Fuller, 2008; Wingfield & Tun, 2007), and the data presented here provide mechanistic confirmation of the behavioral observations.

Understanding underlying mechanisms that govern the inter-play between bottom-up and top-down streams is particularly important in older listeners, who may achieve similar accuracy scores compared to younger listeners, but who may be using a very different mechanism to achieve the same level of accuracy. It is feasible that the use differences mechanistic pathways may have implications for the types of interventions that might be utilized to address speech understanding in noise difficulties among the elderly. In terms of implications for clinical practice, the finding that even with only high frequency hearing losses, ranging from mild to moderate, older individuals, as a group,
utilize different processing mechanisms than do younger adults, suggests that an older listener’s concerns and complaints need to be taken as evidence of real-world problems by the audiologist. All too often, an audiologist might say to a person with an average audiogram such as the one shown for the OL group in Chapter 3, that the hearing is “essentially normal” and that the problem is only “mild”. Instead, depending on cognitive abilities and lifestyle, there may be significant functional listening problems. Counseling should allow for an acknowledgement of the real-world problems being reported and hearing tactics or communication strategies, such as sitting with one’s back to the noise, or learning how to effectively ask for clarifications, could be introduced. While perhaps not candidates for traditional hearing aids, individuals presenting with problems understanding speech in noise greater than would be predicted based on presenting with a mild high frequency hearing loss, could be offered some type of assistive technology to improve the signal-to-noise ratio in specific environments. Certainly, the one thing the clinician should be cautioned against doing is simply dismissing the person with a statement such as “Oh you are normal for your age”. As discussed above, this recommendation was also made by Martin & Champlin (2000).

An interesting question from these experiments arises. That is, can we identify individuals who early on are starting to not use the bottom-up pathway and provide intervention to keep this pathway as equally strong as the top-down? Would the use of mild gain hearing aids earlier than typical keep the bottom-up neural mechanism engaged? It may be the case that the significant individual differences seen in acclimatization to hearing aids (Turner et al., 1996) might be related to individual differences in the reliance on bottom-up and top-down mechanisms. For example, acclimatization might be faster
for an individual whom still has a heavy reliance of bottom-up mechanisms, while acclimatization might be much longer for those older adults whom have transitioned to highly rely on top-down mechanisms. Hearing aid uptake, report of usage and benefit might also be very different if the acclimatization process is different. Such that slower acclimatization might need longer trial periods with hearing aids or more focused auditory rehabilitation programs that strengthen the bottom-up pathways. Clearly further research will help to answer these questions, and if knowledge of bottom-up and top-down mechanistic pathways can better guide intervention, then efforts towards developing clinical feasible evaluation methods would be warranted.

While the results of this study are compelling, certain limitations need to be acknowledged. First, generalization of the results to older adults with varying degrees of hearing loss needs to be made with caution. Indeed, as indicated above, future research should include individuals with varying degrees of hearing losses. Second, because cognitive abilities were not measured some of the interpretations presented here are more speculative than they might have had cognitive assessments been included. Certainly cognitive assessments should become a routine part of all studies of auditory aging. Third, our task involved priming a written probe with speech presented in noise. Thus, we did not actually obtain our behavioral and electrophysiological measures while a person was actively engaged in auditory word recognition. However, cross-modal priming in word recognition experiments is common (e.g., Buchwald & Winters, 2005; Badgaiyan et al., 1999) and inferences can be reliably made. Last, while the lack of the unique bottom-up pathway was attributed to the effects of aging with speech-in-noise priming, we do not know if older listeners would exhibit the pathway when primed with speech in quiet.
Whether the lack of the pathway is due to increased degradation of the acoustic speech signal due to a combination of noise with mild to moderate high frequency hearing losses across participants, or do to a the hearing losses alone is not known. With these limitations in mind, the following conclusions can be drawn:

1. Young and old listeners have essentially equivalent reaction time performance for a word recognition relatedness judgment when primed by speech in noise and presented a probe that was either Phonologically, Identically, or Semantically Related by the last word in a high predictability sentence.

2. Relatedness judgments are longest to make by both YL and OL groups for Semantic probes, suggesting more complex processing than for Identical or Phonological probe words.

3. Although YL and OL groups may exhibit the same behavioral results, the mechanistic pathways that are used to obtain the same performance can differ.

4. YL use the same three mechanistic pathways when priming is in noise as when it is in quiet: (a) an interactive or shared neural mechanism between bottom-up and top-down processing streams; (b) an independent or unique bottom-up mechanism; and, (c) a mechanism reflecting the integration of bottom-up and top-down processing.

5. OL use only two mechanistic pathways when priming is in noise (a) an interactive or shared neural mechanism between bottom-up and top-down processing streams; (b) a mechanism reflecting the integration of bottom-up and top-down processing. The greater use of top-down and shared pathway in the OL has implications for both future research and clinical practice.
REFERENCES


Ferree, T. C. (2000). Spline interpolation of the scalp EEG. Secondary TitleEGI.


Appendix A: Young listeners’ (YL) demographic data.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Gender</th>
<th>Age</th>
<th>Left Ear Hearing Thresholds</th>
<th>Right Ear Hearing Thresholds</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>250</td>
<td>500</td>
</tr>
<tr>
<td>1</td>
<td>F</td>
<td>22</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>21</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>F</td>
<td>23</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>F</td>
<td>30</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>F</td>
<td>28</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>F</td>
<td>27</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>7</td>
<td>M</td>
<td>26</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>8</td>
<td>F</td>
<td>21</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>9</td>
<td>F</td>
<td>23</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>M</td>
<td>22</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>11</td>
<td>F</td>
<td>24</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>12</td>
<td>F</td>
<td>24</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>13</td>
<td>F</td>
<td>29</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>14</td>
<td>F</td>
<td>29</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>15</td>
<td>F</td>
<td>27</td>
<td>5</td>
<td>15</td>
</tr>
</tbody>
</table>

| Average |        | 25.07 | 10.00 | 15.67 | 10.67 | 11.00 | 12.67 | 15.00 | 15.67 | 14.67 | 9.67 | 12.00 | 10.67 | 10.67 | 13.33 | 13.33 | 13.33 | 12.67 |
| SD      |        | 3.00  | 4.63  | 4.58  | 4.17  | 4.31  | 4.58  | 3.27  | 3.20  | 3.99  | 6.29 | 5.39  | 5.75  | 6.18  | 5.94  | 12.85 | 10.15 | 16.72 |
**Appendix B: Phonological Condition SPIN sentences**

<table>
<thead>
<tr>
<th>HP-SPIN Sentence</th>
<th>Prime Word</th>
<th>Phonological Probe Word</th>
<th>HP-SPIN Sentence</th>
<th>Prime Word</th>
<th>Unrelated Probe Word</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stir your coffee with a</td>
<td>spoon</td>
<td>spool</td>
<td>A zebra has black and white</td>
<td>stripes</td>
<td>coil</td>
</tr>
<tr>
<td>Let's decide by tossing a</td>
<td>coin</td>
<td>coil</td>
<td>The mouse was caught in the</td>
<td>trap</td>
<td>dice</td>
</tr>
<tr>
<td>The doctor prescribed the</td>
<td>drug</td>
<td>drum</td>
<td>The papers were held by a</td>
<td>clip</td>
<td>drum</td>
</tr>
<tr>
<td>The cow gave birth to a</td>
<td>calf</td>
<td>cast</td>
<td>The swimmer dove into the</td>
<td>pool</td>
<td>cloth</td>
</tr>
<tr>
<td>We heard the ticking of the</td>
<td>clock</td>
<td>cloth</td>
<td>The house was robbed by a</td>
<td>thief</td>
<td>spool</td>
</tr>
<tr>
<td>Mary wore her hair in</td>
<td>braids</td>
<td>brakes</td>
<td>Playing checkers can be</td>
<td>fun</td>
<td>cast</td>
</tr>
<tr>
<td>We're lost so let's look at the</td>
<td>map</td>
<td>math</td>
<td>Get the bread and cut me a</td>
<td>slice</td>
<td>brakes</td>
</tr>
<tr>
<td>My son has a dog for a</td>
<td>pet</td>
<td>peg</td>
<td>The sleepy child took a</td>
<td>nap</td>
<td>sprain</td>
</tr>
<tr>
<td>Unlock the door and turn the</td>
<td>knob</td>
<td>notch</td>
<td>Drop the coin through the</td>
<td>slot</td>
<td>crab</td>
</tr>
<tr>
<td>Bob stood with his hands on his</td>
<td>hips</td>
<td>hill</td>
<td>They fished in the babbling</td>
<td>brook</td>
<td>math</td>
</tr>
<tr>
<td>The cigarette smoke filled his</td>
<td>lungs</td>
<td>lunch</td>
<td>The fruit was shipped in wooden</td>
<td>crates</td>
<td>seams</td>
</tr>
<tr>
<td>The door was opened just a</td>
<td>crack</td>
<td>crab</td>
<td>The burglar escaped with the</td>
<td>loot</td>
<td>hill</td>
</tr>
<tr>
<td>Kill the bugs with this</td>
<td>spray</td>
<td>sprain</td>
<td>He rode off in a cloud of</td>
<td>dust</td>
<td>notch</td>
</tr>
<tr>
<td>How much can I buy for a</td>
<td>dime</td>
<td>dice</td>
<td>You cut the wood against the</td>
<td>grain</td>
<td>deaf</td>
</tr>
<tr>
<td>Watermelons have lots of</td>
<td>seeds</td>
<td>seams</td>
<td>The cop wore a bullet-proof</td>
<td>vest</td>
<td>lunch</td>
</tr>
<tr>
<td>The sailor swabbed the</td>
<td>deck</td>
<td>deaf</td>
<td>Paul took a bath in the</td>
<td>tub</td>
<td>kiln</td>
</tr>
<tr>
<td>The boy gave the football a</td>
<td>kick</td>
<td>kiln</td>
<td>Maple syrup is made from</td>
<td>sap</td>
<td>throne</td>
</tr>
<tr>
<td>The storm broke the sailboat's</td>
<td>mast</td>
<td>mad</td>
<td>The thread was wound on a</td>
<td>spool</td>
<td>mad</td>
</tr>
<tr>
<td>The glass had a chip on the</td>
<td>rim</td>
<td>rich</td>
<td>The crook entered a guilty</td>
<td>plea</td>
<td>barn</td>
</tr>
<tr>
<td>Tree trunks are covered with</td>
<td>bark</td>
<td>barn</td>
<td>A bear has a thick coat of</td>
<td>fur</td>
<td>dine</td>
</tr>
<tr>
<td>I've got a cold and a sore</td>
<td>throat</td>
<td>throne</td>
<td>The cookies were kept in a</td>
<td>jar</td>
<td>rich</td>
</tr>
<tr>
<td>The airplane went into a</td>
<td>dive</td>
<td>dine</td>
<td>The stale bread was covered with</td>
<td>mold</td>
<td>cane</td>
</tr>
<tr>
<td>The boy took shelter in a</td>
<td>cave</td>
<td>cane</td>
<td>How long can you hold your</td>
<td>breath</td>
<td>comb</td>
</tr>
<tr>
<td>The boat sailed along the</td>
<td>coast</td>
<td>comb</td>
<td>Air mail requires a special</td>
<td>stamp</td>
<td>beg</td>
</tr>
<tr>
<td>The gambler lost the</td>
<td>bet</td>
<td>beg</td>
<td>The shipwrecked sailors built a</td>
<td>raft</td>
<td>chick</td>
</tr>
<tr>
<td>Ruth had a necklace of glass</td>
<td>Beads</td>
<td>beef</td>
<td>I cut my finger with a</td>
<td>knife</td>
<td>fleece</td>
</tr>
<tr>
<td>The sick child swallowed the</td>
<td>Pill</td>
<td>pinch</td>
<td>Greet the heroes with loud</td>
<td>cheers</td>
<td>tag</td>
</tr>
<tr>
<td>John's front tooth had a</td>
<td>Chip</td>
<td>chick</td>
<td>Our seats were in the second</td>
<td>row</td>
<td>peg</td>
</tr>
<tr>
<td>Our cat is good at catching</td>
<td>Mice</td>
<td>mime</td>
<td>The shepherd watched his flock of</td>
<td>sheep</td>
<td>mime</td>
</tr>
<tr>
<td>The Admiral commands the</td>
<td>Fleet</td>
<td>fleece</td>
<td>A rose bush has prickly</td>
<td>thorns</td>
<td>beef</td>
</tr>
<tr>
<td>That job was an easy</td>
<td>Task</td>
<td>tag</td>
<td>My jaw aches when I chew</td>
<td>gum</td>
<td>trash</td>
</tr>
<tr>
<td>The railroad train ran off the</td>
<td>Track</td>
<td>trash</td>
<td>Bob was cut by the jackknife's</td>
<td>blade</td>
<td>pinch</td>
</tr>
</tbody>
</table>
### Appendix C: Identical Condition SPIN sentences

<table>
<thead>
<tr>
<th>HP-SPIN Sentence</th>
<th>Prime Word</th>
<th>Identical Probe Word</th>
<th>HP-SPIN Sentence</th>
<th>Prime Word</th>
<th>Unrelated Probe Word</th>
</tr>
</thead>
<tbody>
<tr>
<td>The plow was pulled by a an</td>
<td>ox</td>
<td>ox</td>
<td>Hold the baby on your lap</td>
<td>ox</td>
<td></td>
</tr>
<tr>
<td>The old train was powered by</td>
<td>steam</td>
<td>steam</td>
<td>The dog chewed on a bone</td>
<td>steam</td>
<td></td>
</tr>
<tr>
<td>The war was fought with armored</td>
<td>tanks</td>
<td>tanks</td>
<td>The witness took a solemn oath</td>
<td>tanks</td>
<td></td>
</tr>
<tr>
<td>They tracked the lion to his</td>
<td>den</td>
<td>den</td>
<td>The scarf was made of shiny silk</td>
<td>coach</td>
<td></td>
</tr>
<tr>
<td>The super highway has six</td>
<td>lanes</td>
<td>lanes</td>
<td>For dessert he had apple pie</td>
<td>lanes</td>
<td></td>
</tr>
<tr>
<td>No one was injured in the</td>
<td>crash</td>
<td>crash</td>
<td>He killed the dragon with his sword</td>
<td>chunks</td>
<td></td>
</tr>
<tr>
<td>The natives built a wooden</td>
<td>hut</td>
<td>hut</td>
<td>The baby slept in his crib</td>
<td>feast</td>
<td></td>
</tr>
<tr>
<td>The wedding banquet was a</td>
<td>feast</td>
<td>feast</td>
<td>The sport shirt has short sleeves</td>
<td>crash</td>
<td></td>
</tr>
<tr>
<td>This nozzle sprays a fine</td>
<td>mist</td>
<td>mist</td>
<td>Household goods are moved in a van</td>
<td>shock</td>
<td></td>
</tr>
<tr>
<td>The ship's Captain summoned his</td>
<td>crew</td>
<td>crew</td>
<td>The teacher sat on a sharp tack</td>
<td>crew</td>
<td></td>
</tr>
<tr>
<td>Follow this road around the</td>
<td>bend</td>
<td>bend</td>
<td>Please wipe your feet on the mat</td>
<td>bend</td>
<td></td>
</tr>
<tr>
<td>My T.V. has a twelve-inch</td>
<td>screen</td>
<td>screen</td>
<td>Your knees and your elbows are joints screen</td>
<td>screen</td>
<td></td>
</tr>
<tr>
<td>The girl swept the floor with a</td>
<td>broom</td>
<td>broom</td>
<td>The meat from a pig is called pork</td>
<td>broom</td>
<td></td>
</tr>
<tr>
<td>Her cigarette had a long</td>
<td>ash</td>
<td>ash</td>
<td>The lion gave an angry roar</td>
<td>sponge</td>
<td></td>
</tr>
<tr>
<td>The pond was full of croaking</td>
<td>frogs</td>
<td>frogs</td>
<td>Her entry should win first prize</td>
<td>mist</td>
<td></td>
</tr>
<tr>
<td>The team was trained by their</td>
<td>coach</td>
<td>coach</td>
<td>The airplane dropped a bomb</td>
<td>rent</td>
<td></td>
</tr>
<tr>
<td>It's getting dark, so light the</td>
<td>lamp</td>
<td>lamp</td>
<td>The fur coat was made of mink</td>
<td>lamp</td>
<td></td>
</tr>
<tr>
<td>He wiped the sink with a</td>
<td>sponge</td>
<td>sponge</td>
<td>Cut a piece of meat from the roast</td>
<td>dart</td>
<td></td>
</tr>
<tr>
<td>The heavy rains cause a</td>
<td>flood</td>
<td>flood</td>
<td>Bob wore a watch on his wrist</td>
<td>flood</td>
<td></td>
</tr>
<tr>
<td>The landlord raised the</td>
<td>rent</td>
<td>rent</td>
<td>The secret agent was a spy</td>
<td>belt</td>
<td></td>
</tr>
<tr>
<td>Instead of a fence, plant a</td>
<td>hedge</td>
<td>hedge</td>
<td>Ann works in the bank as a clerk</td>
<td>hedge</td>
<td></td>
</tr>
<tr>
<td>He was hit by a poisoned</td>
<td>dart</td>
<td>dart</td>
<td>A chimpanzee is an ape</td>
<td>ash</td>
<td></td>
</tr>
<tr>
<td>We swam at the beach at high</td>
<td>tide</td>
<td>tide</td>
<td>The bandits escaped from jail</td>
<td>tide</td>
<td></td>
</tr>
<tr>
<td>On the beach we play in the</td>
<td>sand</td>
<td>sand</td>
<td>The doctor charged a low fee</td>
<td>sand</td>
<td></td>
</tr>
<tr>
<td>His pants were held up by a</td>
<td>belt</td>
<td>belt</td>
<td>The candle flame melted the wax</td>
<td>hut</td>
<td></td>
</tr>
<tr>
<td>To open the jar, twist the</td>
<td>lid</td>
<td>lid</td>
<td>The singer was mobbed by her fans</td>
<td>lid</td>
<td></td>
</tr>
<tr>
<td>The marksman took careful</td>
<td>aim</td>
<td>aim</td>
<td>She hated to vacuum the rug</td>
<td>aim</td>
<td></td>
</tr>
<tr>
<td>The bottle was sealed with a</td>
<td>cork</td>
<td>cork</td>
<td>They played a game of cat and mouse</td>
<td>cork</td>
<td></td>
</tr>
<tr>
<td>That animal stinks like a</td>
<td>skunk</td>
<td>skunk</td>
<td>Tighten the belt by a notch</td>
<td>skunk</td>
<td></td>
</tr>
<tr>
<td>The bad news came as a</td>
<td>shock</td>
<td>shock</td>
<td>Cut the bacon into strips</td>
<td>frogs</td>
<td></td>
</tr>
<tr>
<td>He caught the fish in his</td>
<td>net</td>
<td>net</td>
<td>Throw out all this useless junk</td>
<td>net</td>
<td></td>
</tr>
<tr>
<td>Cut the meat into small</td>
<td>chunks</td>
<td>chunks</td>
<td>A round hole won't take a square peg</td>
<td>den</td>
<td></td>
</tr>
</tbody>
</table>
## Appendix D: Semantic Condition SPIN sentences

<table>
<thead>
<tr>
<th>HP-SPIN Sentence</th>
<th>Prime Word</th>
<th>Semantic Probe Word</th>
<th>HP-SPIN Sentence</th>
<th>Prime Word</th>
<th>Unrelated Probe Word</th>
</tr>
</thead>
<tbody>
<tr>
<td>His plan meant taking a big risk</td>
<td>risk</td>
<td>chance</td>
<td>The beer drinkers raised their mugs</td>
<td>beer</td>
<td>pests</td>
</tr>
<tr>
<td>They drank a whole bottle of gin</td>
<td>gin</td>
<td>beer</td>
<td>Wipe your greasy hands on that rag</td>
<td>beer</td>
<td>beer</td>
</tr>
<tr>
<td>The rude remark made her blush</td>
<td>blush</td>
<td>cringe</td>
<td>Paul hit the water with a splash</td>
<td>light</td>
<td></td>
</tr>
<tr>
<td>He was scared out of his wits</td>
<td>wits</td>
<td>mind</td>
<td>The cushion was filled with foam</td>
<td>chance</td>
<td></td>
</tr>
<tr>
<td>The watchdog gave a warning growl</td>
<td>growl</td>
<td>bark</td>
<td>The guests were welcomed by the host</td>
<td>mind</td>
<td></td>
</tr>
<tr>
<td>The ducks swam on the pond</td>
<td>pond</td>
<td>lake</td>
<td>The flood took a heavy toll</td>
<td>cringe</td>
<td></td>
</tr>
<tr>
<td>Ruth poured the water down the drain</td>
<td>drain</td>
<td>pipe</td>
<td>The car drove off the steep cliff</td>
<td>bark</td>
<td></td>
</tr>
<tr>
<td>She shortened the hem of her skirt</td>
<td>skirt</td>
<td>dress</td>
<td>The sand was heaped in a pile</td>
<td>ducks</td>
<td></td>
</tr>
<tr>
<td>The policemen captured the crook</td>
<td>crook</td>
<td>thief</td>
<td>The farmer baled the hay</td>
<td>mast</td>
<td></td>
</tr>
<tr>
<td>She faced them with a foolish grin</td>
<td>grin</td>
<td>smile</td>
<td>We shipped the furniture by truck</td>
<td>hole</td>
<td></td>
</tr>
<tr>
<td>Use this spray to kill the bugs</td>
<td>bugs</td>
<td>pests</td>
<td>That accident gave me a scare</td>
<td>arm</td>
<td></td>
</tr>
<tr>
<td>He tossed the drowning man a rope</td>
<td>rope</td>
<td>line</td>
<td>The king wore a golden crown</td>
<td>lake</td>
<td></td>
</tr>
<tr>
<td>The doctor X-rayed his chest</td>
<td>chest</td>
<td>arm</td>
<td>The nurse gave him first aid</td>
<td>flock</td>
<td></td>
</tr>
<tr>
<td>The workers are digging a ditch</td>
<td>ditch</td>
<td>hole</td>
<td>Mr. Brown carved the roast beef</td>
<td>pipe</td>
<td></td>
</tr>
<tr>
<td>Raise the flag up the pole</td>
<td>pole</td>
<td>mast</td>
<td>The soup was served in a bowl</td>
<td>dress</td>
<td></td>
</tr>
<tr>
<td>We saw a flock of wild geese</td>
<td>geese</td>
<td>ducks</td>
<td>The lonely bird searched for its mate</td>
<td>thief</td>
<td></td>
</tr>
<tr>
<td>How did your car get that dent</td>
<td>dent</td>
<td>scratch</td>
<td>He hit me with a clenched fist</td>
<td>line</td>
<td></td>
</tr>
<tr>
<td>Spread some butter on your bread</td>
<td>bread</td>
<td>toast</td>
<td>A bicycle has two wheels</td>
<td>smile</td>
<td></td>
</tr>
<tr>
<td>The judge is sitting on the bench</td>
<td>bench</td>
<td>court</td>
<td>The duck swam with the white swan</td>
<td>court</td>
<td></td>
</tr>
<tr>
<td>The rancher rounded up his herd</td>
<td>herd</td>
<td>flock</td>
<td>The detectives searched for a clue</td>
<td>toast</td>
<td></td>
</tr>
<tr>
<td>The widow’s sob expressed her grief</td>
<td>grief</td>
<td>pain</td>
<td>The steamship left on a cruise</td>
<td>scratch</td>
<td></td>
</tr>
<tr>
<td>The candle burned with a bright flame</td>
<td>flame</td>
<td>light</td>
<td>Ruth poured herself a cup of tea</td>
<td>pain</td>
<td></td>
</tr>
<tr>
<td>He got drunk in the local bar</td>
<td>bar</td>
<td>pub</td>
<td>She made the bed with clean sheets</td>
<td>pub</td>
<td></td>
</tr>
<tr>
<td>The bloodhound followed the trail</td>
<td>trail</td>
<td>scent</td>
<td>She wore a feather in her cap</td>
<td>scent</td>
<td></td>
</tr>
<tr>
<td>Football is a dangerous sport</td>
<td>sport</td>
<td>game</td>
<td>The bread was made from whole wheat</td>
<td>game</td>
<td></td>
</tr>
<tr>
<td>I ate a piece of chocolate Fudge</td>
<td>Fudge</td>
<td>cake</td>
<td>The cabin was made of logs</td>
<td>cake</td>
<td></td>
</tr>
<tr>
<td>At breakfast he drank some Juice</td>
<td>Juice</td>
<td>milk</td>
<td>The sandal has a broken strap</td>
<td>milk</td>
<td></td>
</tr>
<tr>
<td>The bride wore a white Gown</td>
<td>Gown</td>
<td>dress</td>
<td>He's employed by a large firm</td>
<td>dress</td>
<td></td>
</tr>
<tr>
<td>I can't guess so give me a Hint</td>
<td>Hint</td>
<td>clue</td>
<td>To store his wood he built a shed</td>
<td>clue</td>
<td></td>
</tr>
<tr>
<td>The dealer shuffled the Cards</td>
<td>Cards</td>
<td>deck</td>
<td>The fireman heard her frightened scream</td>
<td>deck</td>
<td></td>
</tr>
<tr>
<td>Tom fell down and got a bad Bruise</td>
<td>Bruise</td>
<td>cut</td>
<td>The chicks followed the mother hen</td>
<td>cut</td>
<td></td>
</tr>
<tr>
<td>Lubricate the car with grease</td>
<td>grease</td>
<td>oil</td>
<td>Let's invite the whole gang</td>
<td>oil</td>
<td></td>
</tr>
</tbody>
</table>
### Appendix E. Older listeners’ (OL) demographic data.

| Gender | Age | 250  | 500  | 1000 | 2000 | 3000 | 4000 | 6000 | 8000 | 250  | 500  | 1000 | 2000 | 3000 | 4000 | 6000 | 8000 | LE  | RE  |
|--------|-----|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|-----|-----|
| 1      | M   | 65   | 15   | 25   | 15   | 25   | 25   | 30   | 15   | 20   | 10   | 10   | 15   | 25   | 30   | 30   | 2.8 | 4.4 |
| 2      | M   | 55   | 10   | 15   | 10   | 10   | 20   | 20   | 10   | 15   | 15   | 10   | 15   | 15   | 15   | 15   | 15   | 15   | 2.8 | 2.8 |
| 3      | F   | 56   | 20   | 15   | 20   | 20   | 20   | 25   | 20   | 20   | 25   | 20   | 20   | 25   | 20   | 20   | 30   | 30   | 2.0 | 0.4 |
| 4      | F   | 60   | 15   | 20   | 10   | 25   | 20   | 10   | 10   | 10   | 10   | 25   | 15   | 15   | 15   | 15   | 15   | 10   | 7.6 | 3.6 |
| 5      | M   | 64   | 10   | 15   | 5    | 10   | 25   | 65   | 50   | 50   | 15   | 15   | 10   | 5    | 15   | 65   | 45   | 55   | 6.0 | 6.0 |
| 6      | F   | 67   | 25   | 20   | 10   | 10   | 20   | 35   | 35   | 10   | 10   | 5    | 20   | 20   | 15   | 10   | 35   | 1.2 | 1.2 |
| 7      | M   | 58   | 25   | 20   | 10   | 10   | 25   | 25   | 25   | 40   | 15   | 15   | 10   | 10   | 25   | 25   | 35   | 45   | 10.0 | 7.9 |
| 8      | F   | 66   | 10   | 5    | 10   | 5    | 15   | 15   | 25   | 25   | 10   | 15   | 10   | 15   | 15   | 15   | 20   | 25   | 6.0 | 4.4 |
| 9      | F   | 67   | 10   | 10   | 10   | 15   | 15   | 30   | 35   | 45   | 15   | 15   | 15   | 15   | 20   | 25   | 25   | 35   | 1.2 | 2.8 |
| 10     | M   | 72   | 15   | 20   | 25   | 20   | 20   | 45   | 55   | 70   | 25   | 20   | 15   | 10   | 15   | 40   | 50   | 70   | 3.6 | 2.8 |
| 11     | F   | 64   | 15   | 20   | 15   | 20   | 15   | 20   | 30   | 25   | 5    | 10   | 10   | 10   | 15   | 25   | 35   | 20   | 5.2 | 6.8 |
| 12     | F   | 70   | 25   | 15   | 10   | 20   | 25   | 45   | 45   | 45   | 25   | 15   | 15   | 15   | 20   | 15   | 30   | 30   | 4.0 | 4.6 |
| 13     | F   | 69   | 10   | 15   | 15   | 20   | 25   | 50   | 50   | 50   | 15   | 15   | 15   | 20   | 25   | 40   | 35   | 60   | 7.6 | 5.2 |
| 14     | M   | 64   | 10   | 10   | 10   | 10   | 15   | 25   | 45   | 35   | 10   | 5    | 10   | 15   | 10   | 40   | 30   | 15   | 7.6 | 7.6 |
| 15     | F   | 57   | 5    | 15   | 5    | 10   | 15   | 15   | 15   | 15   | 5    | 10   | 10   | 5    | 15   | 20   | 20   | 20   | 6.8 | 4.4 |
| 16     | F   | 60   | 5    | 15   | 10   | 15   | 25   | 35   | 25   | 30   | 10   | 5    | 15   | 10   | 25   | 30   | 30   | 45   | 7.9 | 6.0 |
| 17     | F   | 63   | 25   | 25   | 10   | 10   | 10   | 20   | 30   | 50   | 20   | 20   | 0    | 5    | 0    | 15   | 25   | 50   | 6.8 | 7.6 |
| Average|     | 63.35 | 15.0 | 16.67 | 12.22 | 15.00 | 19.44 | 28.89 | 32.50 | 34.44 | 14.72 | 14.44 | 12.50 | 13.33 | 16.67 | 26.94 | 28.33 | 35.00 | 5.26 | 4.62 |
| SD     |     | 4.87 | 6.86 | 5.14 | 5.21 | 5.94 | 5.66 | 14.41 | 12.28 | 16.35 | 6.29 | 5.39 | 5.75 | 6.18 | 5.94 | 12.85 | 10.15 | 16.72 | 2.59 | 2.21 |
ABOUT THE AUTHOR

Dr. Victoria Williams-Sanchez was born and raised in California. She had a vibrant childhood with her loving parents, Ken and Pat, and older brother, Ryan. When Victoria was in elementary school she learned Signing Exact English and it was at that very young age Victoria knew she wanted to be an advocate for individuals with hearing impairment. With this goal in mind, Victoria completed her undergraduate degree at the University of California, Santa Barbara (UCSB) focusing her studies on hearing and health sciences. It was at UCSB when Victoria met Jeff Danhauer, Ph.D., a Hearing and Speech Science professor, that exposed Victoria to not only a successful clinical practice but allowed her to join in on his research projects. Under Dr. Danhauer’s guidance Victoria achieved her first lead-author publication and this accomplishment lit a scientific fire underneath her that has not faded. Victoria’s research interests include auditory cognitive neuroscience, speech perception, aging, and auditory rehabilitation (e.g., hearing aids, assistive listening devices, outcomes). Victoria’s passion is the ear-brain system. More specifically, she investigates how factors reduce speech recognition such as a noisy background, hearing loss, aging, and/or trauma, or, enhance speech recognition such as audio-visual input, cognitive compensation, hearing aids, signal-to-noise improvements and/or auditory training. Although Victoria is very passionate about her profession and research she loves her family even more. Victoria calls Florida home now and forever with her husband, Glenn Sanchez, and their daughter Adelina Rose Sanchez.