The Effects of Brain Injury and Talker Characteristics on Speech Processing in a Single-Talker Interference Task

A DISSERTATION
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF THE UNIVERSITY OF MINNESOTA
BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

Mary R.T. Kennedy

July 2011

Acknowledgements

I owe immeasurable thanks to my advisor, Mary Kennedy, for shepherding me through the past eight years with patience, wisdom, and an admirable sense of humor.

Thanks also to my committee – Chad Marsolek, Ben Munson, and Peggy Nelson – each of whom were unfailingly generous with their help, support, and flexibility throughout this process.

I could not have completed this dissertation without the technical assistance and expert advice of Edward Carney, Sarah Angerman, and Paula Chesley.

Thank you to my labmates Katy O'Brien, Jocelyn Yu, Mike Peterson, Shelley Johnson, Daniel DeLapp, Olivia Matthys, Krystle Baumgarten, Pradeep Ramanathan, and Hsin-Huei Chiou. Each of them made crucial contributions to this project, from recruiting and testing participants to checking reliability to sharing their own dissertations.

Thank you to Sarah Angerman (again), Jay Sasisekaran, Laura Crocker, and Yu-Wen Chen for taking the time to help me create my experimental stimuli.

I'm also very grateful to my extensive support system, including many of those already mentioned, as well as my parents and my dissertation group (Susan Park Anderson, Bess Borchert, Alvina Kittur, and Katrina Schleisman). Thank you all for lending your ears, commiserating, and helping me keep things in perspective.

Finally, I want to express my profound thanks to my research participants. I am particularly grateful to those people with brain injury who generously dedicate time, energy, and effort to projects like this one that do not help them personally, just because the work may someday indirectly benefit others who experience TBI.

Dedication

This dissertation is dedicated to Rabbi Yosi Gordon, to add to his collection.

Abstract

People who have experienced traumatic brain injury (TBI) often report increased difficulty processing speech than they experienced before their injuries; and this difficulty is not always accompanied by impaired performance on standardized tests of language, auditory processing, or other cognitive factors. Unfortunately, there is a paucity of research directly addressing this issue. Prior studies have mostly focused on measures of characteristics such as attention (e.g. Schmitter-Edgecombe & Nissley, 2000), dichotic listening (e.g. Meyers, Roberts, Bayless, Volkert, & Evitts, 2002), and masking release (e.g. Krause, Nelson, & Kennedy, 2009) in people with TBI. All of these factors may play their part in functional listening tasks, but separately they cannot capture the complex task of speech processing (e.g. Wilson 2003). The goal of this dissertation is to build on existing work to explore and compare the issue of speech processing after brain injury across several levels: sentence repetition with single-talker interference, using targets spoken by native- and non-native-accented speakers of English; standardized testing of cognition and auditory processing; and semi-structured interviews about participants' subjective experiences with complex speech processing.

This study comprised two experiments. The purpose of Experiment 1 was to demonstrate the effects of simulated peripheral hearing loss on performance on the sentence repetition task. Participants in Experiment 1 were 30 healthy young adults, 15 of whom completed the sentence repetition task with stimuli that were filtered with a 1400 Hz low-pass filter to simulate peripheral hearing loss. The other 15 participants completed the task with unfiltered stimuli. The purpose of Experiment 2 was to compare adults with and without TBI on the (unfiltered) sentence repetition task, and included 13 people in each participant group. Groups were matched for age, education, and estimated verbal IQ within each experiment. Dependent variables for the sentence repetition task were accuracy and subjective effort. Participants in Experiment 2 also completed a battery of standardized tests and a semi-structured interview about their subjective experiences with speech processing.

Results of Experiment 1 showed that the filtered group was less accurate and reported greater effort than the unfiltered group, and the filtered group showed greater effects of speaker accent. Results of Experiment 2 demonstrated that the TBI group had poorer accuracy than controls, but not significantly higher effort. As predicted, the TBI group also reported more subjective difficulty with complex speech processing than healthy controls, but there was no direct correlation between interview reports and accuracy on the sentence repetition task. Comparisons between the TBI group of Experiment 2 and the filtered group of Experiment 1 suggest that, although the TBI group did show impaired performance on the speech processing task, their performance was not consistent with the peripheral auditory effects that were modeled in Experiment 1. This suggests that the speech processing difficulty experienced by people with TBI cannot be explained by bottom-up processing (e.g. energetic masking) alone.

Further research is needed in order to better understand the nature of speech processing problems after TBI, the ultimate goal of which is to be able to develop therapies and strategies that will allow people with TBI to communicate successfully even in difficult circumstances.

Table of Contents

List of Tables

List of Figures

Introduction

"I have to think hard when talking to people."

"There's so much other noise that my brain doesn't know what to listen to."

These quotes are examples of how some people who have experienced traumatic brain injury (TBI) describe their difficulties with speech processing. This type of problem may hinder a person's participation in social activities and their performance on complex listening tasks. This phenomenon is acknowledged by TBI researchers such as Musiek, Baran, and Shinn (2004) and Bergemalm and Lyxell (2005), who note that "every-day problems (e.g. keeping track of a conversation, listening to a conversation in noisy environments) are frequently reported by patients" (p. 40). Unfortunately, there is a paucity of research directly addressing this issue. Prior studies have mostly focused on measures of selective attention, dichotic listening, and masking release. While all of these may play a role in functional listening tasks, separately they may not be able to capture the complex task of speech processing (e.g. Wilson, 2003). The goal of this dissertation is to provide direct evidence regarding whether people with TBI have deficits in speech processing and, if so, to determine what cognitive factors contribute to those deficits.

Project Overview

Research about speech processing after TBI is important for several reasons. The Centers for Disease Control (CDC) estimates that at least 1.7 million civilians sustain a TBI in the United States every year; of those, roughly 275,000 are hospitalized (Faul, Xu, Wald, & Coronado, 2010). This dissertation is part of a growing body of research seeking to better understand the effects of TBI in the post-acute or chronic phase of recovery. In this phase, people with TBI re-integrate into the communication realms of family and community as well as rehabilitation, assisted living, school, and work. This type of speech processing research can help clinicians and people with TBI to anticipate possible challenges, and may eventually lead to treatments or strategies to help people with TBI function more effectively and independently, and to communicate more successfully with caretakers and others. In addition, studying the mechanisms of disordered speech processing can provide insight into the normal variation that occurs in speech processing among the uninjured population.

The design of the dissertation project comprises two experiments, and is discussed in detail in the Methods section. Experiment 1 compared two groups of healthy controls in a single-talker interference sentence repetition task; one group heard sentences that were low-pass filtered at 1400 Hz, while the other group heard the same stimuli with no filter. The low-pass filtering was intended to approximate the effects of a peripheral hearing loss (e.g. Fabry & Van Tasell, 1986; Wang, Reed, & Bilger, 1978). Experiment 2 compared a group of adults with TBI to a healthy control group that was matched for age, education, and estimated verbal IQ. Experiment 2 participants also completed a set of standardized tests of auditory processing and cognitive abilities such as working memory and processing speed, as well as a semi-structured interview about their subjective experience of speech processing in challenging situations.

Background

As of the beginning of 2005, the CDC estimated that there are approximately 3.2 million people in the U.S. living with long-term disability due to TBI (Zaloshnja, Miller, Langlois, & Selassie, 2008). One recent definition, developed to support consistency in research, states that TBI is "an alteration in brain function, or other evidence of brain pathology, caused by an external force" (Menon, Schwab, Wright, & Maas, 2010). An open or penetrating brain injury occurs when the external force breaches the bone of the skull; a closed or non-penetrating injury occurs when the skull remains intact. The neurophysiological and behavioral effects of non-penetrating injuries can be quite diffuse relative to penetrating or focal injuries, due to mechanisms such as axonal shearing, intracranial pressure, and contra-coup impacts (e.g. Constantinidou & Kennedy, in press).

The alteration of brain function in Menon et al.'s (2010) definition can comprise loss of consciousness or altered consciousness, neurological deficits, loss of memory for information before or after the event, and altered mental states. After a mild TBI, all symptoms may resolve after a period of days or weeks, whereas with mild-complicated, moderate, or severe injuries, effects are likely to linger much longer (e.g. Carroll et al., 2004).

Researchers have found numerous and varied effects of brain injury that may continue for years to decades after injury, both by subjective report (Mazaux, Masson, Levin, Alaoui, Maurette, & Barat, 1997; van Zomeren & van den Burg, 1985) and based on standardized assessments (Dikmen, Machamer, Winn, & Temkin, 1995; Klein, Houx, & Jolles, 1996). Among the effects commonly observed after TBI are difficulty with short-term memory (e.g. Hanten & Martin, 2000; Rios, Perianez, & Munoz-C'espedes, 2004), regulation of attention (e.g. Rueda, Posner, & Rothbart, 2004), processing speed (e.g. Madigan, DeLuca, Diamond, Tramontano, & Averill, 2000; Nicholas & Brookshire, 1995; Spikman, van Zomeren, & Deelman, 1996), auditory processing (Bergemalm & Borg, 2001), and executive functions (e.g. Kennedy, Carney, & Peters, 2003; Kennedy & Coelho, 2005). Any or all of these may arguably impact speech processing in challenging situations.

In addition to trauma, other forms of acquired brain injury (ABI) can have similar effects on cognition and communication; the broader term ABI includes events such as stroke, aneurysm (e.g. Evitts, Nelson, & McGuire, 2003), tumor resection, and anoxia as well as TBI. For the sake of participant recruitment, and because of its emphasis on functional outcomes rather than on specific etiology or mechanisms of deficits, the current study's inclusion criteria allowed for acquired injury as well as TBI. Only one participant in the current study had ABI and not TBI, and for the sake of simplicity the remainder of this dissertation will predominantly discuss TBI.

Traumatic Brain Injury and Speech Processing

There are several areas of evidence to support the hypothesis that individuals with TBI will have more difficulty than healthy controls with complex speech processing. Three areas most relevant to the current study are central auditory processing, processing speed, and attention. The theory underlying the dissertation experiments is that, due to the complexity and redundancy inherent in both the tasks and the processing involved (e.g. Cooke, Garcia Lecumberri, & Barker, 2008; Oxenham & Simonson, 2009), impairments in any one of these areas are unlikely to have a one-to-one relationship with functional communication deficits. Rather, it is the combination of deficits associated with brain injury that may hinder some individuals' ability to process speech in challenging environments. This complexity, and the heterogeneity of injuries and experiences of individuals with TBI, necessitates the use of both quantitative and qualitative measures. Thus both quantitative measures of speech processing and qualitative measures from interviews are used in this project.

Central Auditory Processing

Intuitively, auditory processing – how auditory information is processed by the ear and brain – must play a key role in the processing of speech. Many researchers consider peripheral and central auditory processes separately: peripheral audition involves the outer, middle, and inner ear and auditory nerve, while central audition comprises the auditory pathway within the brainstem and cerebral cortex (e.g. Peelle, Johnsrude, & Davis, 2010). Both have to function in order for a listener to process speech.

Peripheral auditory problems include conductive and sensorineural hearing loss; peripheral auditory processing is affected by energetic masking, in which the spectral energy of the interfering signal masks that of the target (see Table 1). Central auditory processing includes functions of the brainstem, measured by auditory brainstem response (ABR) (e.g. Bergemalm & Lyxell, 2005), and more central areas. In contrast to peripheral processing, which is affected by energetic masking, central auditory processing is also affected by informational masking, in which phonological or semantic information from the interfering signal can mask that of the target (e.g. Oxenham & Simonson, 2009;

Schneider, Li, & Daneman, 2007).

As Lagace, Jutras, and Gagne (2010) point out, auditory assessments of speech perception in noise may be useful in assessing central auditory processing. They are writing from the perspective of evaluating Auditory Processing Disorder (APD), a disorder whose nature is debated among clinicians and researchers (American Speech-Language-Hearing Association, 1996; Jerger, 2009; Moore, 2006). Nevertheless, there is consensus that further explanation is needed for the complaints that are attributed to APD, including in individuals with TBI.

One study that supports both auditory processing difficulties for people with brain injury and the potential for treatment is a case report by Musiek et al. (2004). A 41-year-old woman experienced difficulty processing speech more than a year after concussion. The authors assessed peripheral and central auditory functioning and found that, although her peripheral hearing was normal, several measures of central auditory processing, including dichotic digits and compressed speech, were “outside of the range of normal.” The patient participated in intensive auditory rehabilitation with several components: behavioral and metacognitive strategies such as reading aloud, asking communication partners to speak slowly and clearly, and anticipating problem situations; and auditory components such as auditory memory training, auditory speech discrimination training, and temporal sequence training. The client completed much of the therapy independently, and when she was re-tested seven months after her initial evaluation, her scores on several of the measures of central auditory processing had improved to normal or near-normal. In contrast, auditory brainstem response measures remained the same before and after therapy. Musiek et al. also report subjective improvements, quoting the participant as saying, “I can talk, listen (and think) while the radio is on and people are talking around me. This was impossible after my accident and has greatly improved, though not recovered 100%” (p. 130).

In this dissertation, the different designs of Experiment 1 and Experiment 2 were developed to distinguish between peripheral and central auditory effects, the latter of which are predicted to be more pronounced in individuals with brain injury than in healthy controls. This is because, absent peripheral hearing loss, the diffuse neurological changes following TBI are predicted to include regions and functions related to central auditory processing.

Energetic and informational masking.

Studies about auditory masking come largely from the field of audiology, with relevant contributions also coming from perceptual psychology. The three concepts related to masking that are most relevant to the current project are energetic masking, informational masking, and masking release (see Table 1). With energetic masking, a masking sound acoustically covers the masked sound, making it inaudible. When one sound is completely masked by another, the first sound is not detectable to the listener; in experiments, the masker is often broad-spectrum noise, such as white noise or pink noise. White noise contains equal energy at all frequencies, whereas pink noise is logarithmically distributed to contain equal energy at each octave. An everyday example of energetic masking would be part of a conversation becoming inaudible when a large and noisy vehicle drives by. Audiologists use masking during hearing assessments by playing masking noise in one ear in order to isolate responses from the other ear. As

Stickney, Zeng, Litovsky, and Assmann (2004) explain, energetic masking comprises two or more sounds that overlap to create a peripheral effect.

Informational masking, in contrast, is described as a central as opposed to a peripheral phenomenon that inhibits the ability to process sound (Oxenham, Fligor, Mason, & Kidd, 2003). An everyday example would be when the conversation of a neighboring student makes it difficult to for a listener to follow the speech of the lecturer. As explained by Schneider et al. (2007),

> Both kinds of distracting sound sources [noise and speech] produce interference at the auditory periphery (activate similar regions along the basilar membrane), and this kind of interference is called energetic masking. However, in addition to energetic masking, meaningful sound sources, such as competing speech, can and do interfere with the processing of the target speech at more central levels (phonetic and/or semantic), and this kind of interference is often called informational masking. (p. 478).

Although a sufficiently loud, consistent noise (e.g. a jet engine) can completely mask speech, it is often possible to understand speech if the masking noise is fluctuating (e.g. a noisy restaurant). This ability to piece together intelligible speech in modulated as opposed to steady noise is called release from masking.

Nelson, Jin, Carney, and Nelson (2003) and Nelson and Jin (2004) described the phenomenon of energetic release from masking in detail using gated (modulated, or periodic) noise. In a comparison between people with normal hearing and cochlear implant (CI) users, they found that normal-hearing listeners had significant release from masking at various signal-to-noise ratios (SNR), especially with a modulation frequency of 8 Hz. This means that the listeners were able to understand the speech signal much better with noise that was modulated at 8Hz than with steady noise of the same intensity. However, individuals with cochlear implants – and normal-hearing participants listening to cochlear implant simulations – did not benefit from modulation of the masker, even when the signal was 16 dB louder than the noise. The authors proposed three likely components of masking release for cochlear implant users: informational masking, spectral resolution, and auditory fusion/segregation. Informational masking is a complex topic discussed in greater detail below but, for the purposes of explaining masking release for CI users, it was described as "threshold elevation due to non-energetic factors such as signal uncertainty, masker-stimulus similarity, or distraction from extraneous sounds" (Nelson & Jin, 2004).

Nelson and Jin (2004) conducted a second experiment in which the stimulus sentences themselves were gated (i.e. interrupted by periodic bursts of silence) without including background noise. Procedures were similar to those of the first experiment, and the authors found that the performance of normal-hearing listeners improved with increasing gate frequency, meaning more frequent, briefer periods of silence disrupting the speech signal. Cochlear implant and simulation listeners, in contrast, showed very poor speech perception across gating frequencies. Overall, Nelson and Jin concluded that cochlear implant and simulation listeners are not successful with auditory fusion of interrupted speech but do gain masking release benefits from increased spectral information.

Cullington and Zheng (2008) also compared CI users, people with normal hearing, and people listening to CI simulations in the presence of noise, single-talker, and multiple-talker interference. They found that, although the simulation listeners performed similarly to the CI users in noise-masker conditions, the simulation was not as successful in matching real CI-users' performance in the single-talker interference task.

Nelson and Jin's (2004) methodology provided the basis for the procedures used by Krause, Nelson, and Kennedy (2009), who examined whether the experience of masking release was the same for individuals with and without ABI. Listeners repeated sentences in different masking conditions, including steady noise, gated noise at 8 Hz and 16 Hz, gated speech at 4 Hz with no noise, and single-talker interference (two voices at the same time). The authors hypothesized that deficits of masking release might be related to reduced processing speed. Moreover, if there were differential effects of spectral masking after brain injury compared to the performance by uninjured controls, it would be expected that gated noise conditions would be at least as affected as gated speech or single-talker interference conditions in this experiment. Although no significant group differences were found in accuracy (i.e. ability to accurately repeat sentences in different masking conditions), regressions showed that some processing speed measures correlated significantly and positively with listening accuracy, but only for gated speech and single-talker interference conditions and not for steady or gated noise-masking conditions. This suggests that, in some situations, faster processing speed was associated with better sentence repetition performance; the fact that the correlations occurred in the gated speech and single-talker interference but not in the gated masking conditions suggests that informational masking rather than spectral masking was more significant in the performance of individuals with TBI in that experiment. In addition, the experiment showed a significant overall effect of subjective effort between groups, with the TBI group reporting greater effort than the control group.

Brungart (2001) found informational masking predominant over energetic masking in an experiment comparing phrase repetition in the presence of single-talker interference and speech-spectrum-shaped noise in healthy adults. Speech-spectrum-shaped noise is that in which the temporal and/or spectral characteristics are manipulated to mimic those of a speech sample. The authors found masking effects in the speech interference conditions beyond those of the same signal-to-noise ratios (SNRs) in the speech-shaped-noise conditions; in addition, for most conditions, performance was better in a modulated (gated) noise condition than in the two-talker condition. Moreover, Brungart points out that the different-sex talker condition showed the least masking, indicating that the effects found by Krause et al. (2009), whose single-talker interference condition used opposite-sex talkers, could have been even more pronounced had they used same-sex talkers for interference. Altogether, this evidence suggests the dominance of informational masking over energetic masking effects in the single-talker interference task.

Other work has demonstrated additional mechanisms of release from informational masking. Of the multiple factors involved in informational masking – and in release from informational masking – arguably one of the most important is the capacity for stream segregation, which is the ability to separate complex auditory input into two or more perceptual “streams.” For example, Freyman, Balakrishnan, and Helfer (2001) demonstrated that normal-hearing listeners had better comprehension in one- and two-talker interference tasks when the talkers were perceived as spatially different compared to when the voices came from the same location. They also showed that informational masking became less of a factor with an increasing number of voices; in other words, the more voices that make up the interference, the more similar their masking characteristics are to a non-speech noise masker. Arbogast, Mason, and Kidd (2005) found similar release from masking with spatial separation, and additionally compared the phenomenon in normal and hearing-impaired listeners. They found that people with sensorineural hearing loss did experience release from informational masking, but to a significantly lesser extent than those with normal hearing, a finding that is particularly relevant to Experiment 1 of the current project. In a set of three experiments, Freyman, Balakrishnan, and Helfer (2004) also found increased release from informational masking with both spatial separation and increased number of talkers, both independently and in combination; in addition, they demonstrated masking release benefits from providing a preview of target sentences.

The findings of three more studies provide critical information on the contrast between informational and energetic masking that bear on the current project. Brungart, Simpson, Ericson, and Scott (2001) conducted a study with two-, three-, and four-talker interference in various combinations of gender and intensity. They found improved performance when the target and masking voices were qualitatively different and worsened performance when the target and masking voices were qualitatively similar. Performance was most often best when the target and masking voices were different sexes and, with negative SNRs, different intensities also helped with release from masking. In an interesting effect that the authors called "odd-sex distraction," having more than one same-sex masking voice combined with a single opposite-sex masker actually led to poorer performance than did the same number of maskers all of the same sex as the target. In other words, two male and one female masker caused more interference for a male target than three male maskers. The authors attributed this to a type of informational masking in which the salience of the masker distracts the listener from attending to the target. It is possible to expect a related effect in the proposed study, in the non-native speaker target/native speaker masker (NNS-ns) condition; the salience of the masker may make it more difficult to ignore than in the opposite (NS-nns) condition, in which the target itself is the more cognitively salient signal.

Stickney et al. (2004) specifically addressed energetic and informational masking in cochlear implant listening in an experiment using a procedure similar to that of Brungart (2001). They found that single-talker interference led to poorer performance than speech-shaped noise, indicating the effect of informational masking: since the two signals were the same in spectral energy, the additional interference in the single-talker condition must be due to informational masking. In addition, participants with normal hearing showed the greatest masking effects when the masking voice was the same as the target voice, demonstrating the combination of energetic masking and informational masking.

Finally, in a study of different types of masking, Oxenham and Simonson (2009) used high- and low-pass filters to compare masking release effects in steady noise, speech-modulated noise, and single-talker interference tasks. Based on earlier studies suggesting that both temporal and pitch information are important for masking release, they predicted that these factors would play an important role in participant performance in their experiments. However, counter to predictions, the authors demonstrated that masking release was not significantly affected by the temporal fine structure of pitch information. Rather, they suggested that how much perceptual redundancy is present in the target governs the amount of masking release the listener will experience. The phenomenon of perceptual redundancy can be argued to encompass everything from spatial location to spectral overlap to semantic similarity or listener interest; thus, Oxenham and Simonson's work, along with the studies discussed above, contribute support to the idea that informational masking operates on multiple perceptual and cognitive levels.

Dichotic listening.

One of the most common ways that researchers have measured central auditory processing is through dichotic listening tasks (e.g. Harris, 1994; Levin et al., 1989). As explained by Meyers, Roberts, Bayless, Volkert, and Evitts (2002), in a dichotic listening task the participant wears stereo headphones and simultaneously hears one word in one ear and a different word in the other ear. The words are usually matched for number of syllables, and the listener is asked to repeat one or both words. Roberts et al. (1994) developed the Dichotic Word Listening Test (DWLT) to standardize the procedure for testing dichotic listening. They tested adults and children with and without TBI, as well as healthy adults from both the U.S. and Canada and from both rural and urban areas. They found that adults with brain injury performed significantly worse than those without. However, they also found significant differences among the adult control subgroups, which they speculated might be partly related to the bilingualism of some of the Canadian participants. Furthermore, socioeconomic status was not controlled for in the study, and has been shown to affect dichotic listening task performance. These caveats make it clear that dichotic listening tasks cannot be interpreted as simple tests of central auditory processing; nevertheless, there has been other research suggesting that accuracy on such tasks is adversely affected by brain injury.

Meyers et al. (2002) followed up the Roberts et al. (1994) study by adding 200 additional healthy controls to the original group of 136 in order to develop better norms for the DWLT short form (30 items). They found that age had a significant negative correlation with dichotic listening, and they published means and 5^{th} percentile cutoff scores for age groups ranging from 16 to 69 based on their findings. In their second experiment, Meyers et al. examined a database of individuals with TBI and stroke who had taken the test. The TBI participants were divided based on duration of unconsciousness into mild, moderate, and severe; the stroke participants were divided into right and left cerebrovascular accident (CVA) groups. The TBI and stroke participants were compared to a group of 36 healthy controls, a subset of the 336 from the first experiment that completed the same neuropsychological test battery as the TBI and stroke groups. Consistent with the first experiment, Meyers et al. found a significant effect of age in the second experiment. In addition, they found that DWLT scores correlated significantly with duration of LOC (i.e. severity of injury) such that those with more severe injuries had poorer dichotic listening scores. Although no control participant "failed" the test by scoring lower than the 5^{th} percentile (Roberts et al., 1994), 70% of the TBI group in the Meyers (2002) study failed at least one of the three measures used, with more severely injured participants failing more frequently than those with more mild injuries. In the stroke groups, there were predictable laterality effects; more participants with right CVA failed the test, and overall the RCVA group did more poorly than the left CVA group. Indeed, 89% vs. 55%, respectively, failed at least one measure, compared to the 70% failure rate for the TBI group. The authors concluded that dichotic listening may be a useful tool for neuropsychological evaluation but caution that there are clearly numerous mechanisms behind poor dichotic listening performance after ABI.

Importantly, while researchers including Roberts and Meyers have demonstrated dichotic listening consequences of brain injury, and others such as Schneider and Oxenham have discussed the importance of informational masking in speech processing, no one has yet connected the two concepts in a functional experiment. One goal of this dissertation is to explicitly compare a speech processing task with measures of central auditory processing, including dichotic listening.

Some evidence exists for the possibility of therapeutic intervention to improve dichotic listening after TBI. In addition to the case study by Musiek et al. (2004) discussed earlier, Yokota-Adachi, Kershner, Jutai, and Knox (2003) found that after musical attention training, an adolescent with brain injury showed improved performance on a dichotic listening task for CV syllables. Neither of these studies, however, addressed whether either deficits or improvements in dichotic listening were directly related to ecologically valid speech processing tasks.

Processing Speed

Processing of speech is a highly time-sensitive task. Speaking rates of 140 words per minute are typical (e.g. Tun, Wingfield, Stine, & Mecsas, 1992), equivalent to several words per second. Findings from current research have concluded that individuals with

TBI have slower speed of processing than those without TBI. For example, Madigan et al. (2000) explored the issue of processing speed in individuals with TBI as it impacts visual and auditory modalities, finding deficits particularly in auditory processing speed. They used a variation of the Paced Auditory Serial Addition Task (PASAT), a test of working memory that places increasing demands on processing speed with each subtest.

Other studies are more indirectly relevant to the connection between general processing speed and speech processing. Hinton-Bayre, Geffen, and McFarland (1997) showed that tests of processing speed were sensitive to post-acute mild brain injury in a group of rugby players. One of the tasks they used, although not a measure of speech processing, measured another aspect of language processing: participants read sentences and rated whether they were sensible or nonsensible. The other task in that study was a symbol-digits task, in which participants had to decode symbols from a key. This is similar to one of the “attention” tasks on the Repeatable Battery for the Assessment of Neuropsychological Status (R-BANS) (Randolph, Tierney, Mohr, & Chase, 1998), a neuropsychological screening battery used in the current study.

In a study of speaking rate in children and adolescents with TBI, (Campbell & Dollaghan, 1995) used syllable duration and clinical judgments to measure speed of articulation and average duration of within-utterance pauses during natural speech as a measure of language processing time. They showed that slowing of articulation and language processing both contributed independently to slower speech rates among participants. Although their study addressed expressive and not receptive skills, the dual effects of motor and cognitive factors are suggestive for the current project.

Further support for the prediction of processing speed effects on speech processing can be found in the study of masking release and ABI by Krause et al. (2009). In that study, participants repeated sentences in different noise masking conditions, and correlations were found between processing speed and sentence repetition accuracy.

Studies of speech processing in elderly people with normal hearing are another source of data supporting the role of processing speed in speech processing. Dubno, Horwitz, and Ahlstrom (2002) found several differences between younger and older subjects in speech recognition in noise, independent of audibility. The greatest differences between older and younger adults occurred with temporally challenging listening tasks, specifically speech processing in fluctuating rather than steady-state noise. With this finding, they broach the idea that speed of processing may influence individuals' ability to process speech in disadvantageous conditions such as those in the current experiment.

The work of Tun et al. (1992) comparing older and younger adults is also relevant here. They used a dual-task paradigm, in which participants immediately recalled sentences at varying speech rates while simultaneously performing a visual picture recognition task. The older adults' performance on immediate memory for sentences was more affected by increasing speech rates than was that of the younger adults, suggesting reduced speed of processing for the older versus the younger group. There was no interaction between age and speech rate on accuracy in either task, suggesting that both groups were able to divide their attention with similar efficiency. The fact that slowed processing in Tun et al.'s study was demonstrated using a sentence repetition task further supports the link between speech processing and overall processing speed.

Another time-sensitive element of speech processing occurs when listeners adapt or adjust to a difficult or unfamiliar speech pattern. This is called accommodation, which is the ability of a listener to adapt to an unfamiliar or difficult signal over time. Studies have shown that accommodation occurs very quickly for normal listeners. For example, Clark and Garrett (2004) showed that healthy adults can improve their performance in processing accented speech with less than a minute of exposure. Davis, Johnsrude, Hervais-Adelman, Taylor, and McGettigan (2005), also demonstrated this type of accommodation for noise-vocoded speech. Although research has not been done to directly link accommodation with processing speed, it is discussed here as a speed-based phenomenon that is potentially sensitive to the speed of processing of the listener.

There are two measures in this dissertation that processing speed would be predicted to affect. First, reduced processing speed is predicted to be associated with reduced accuracy in the sentence repetition task. Second, individuals with TBI are predicted to accommodate to the challenging listening tasks more slowly; in other words, more trials would be required before they reached ceiling, particularly in the conditions in which the target talker was a non-native speaker. Participants with TBI may also describe more subjective difficulty "catching up" in day-to-day conversational contexts compared to healthy controls.

Effort

Increased mental effort is another frequent complaint following brain injury. Effort is difficult to operationalize, but may be related to self-regulation of attention, allocation of cognitive resources, simple subjective difficulty, or – more likely – some combination of factors. Researchers have attempted to measure effort in various ways, including direct self-report measures such as rating scales (Fraser, Gagne, Alepins, & Dubois, 2010; Krause et al., 2009) and indirect measures such as performance differences within a dual-task paradigm (Sarampalis, Kalluri, Edwards, & Hafter, 2009) or fMRI localization of brain areas differentially activated during more difficult speech comprehension tasks, (Davis & Johnsrude, 2003; Peelle, Eason, Schmitter, Schwarzbauer, & Davis, 2010).

Rating effort on a 1-to-10 scale in a sentence repetition task, the group of listeners with ABI in Krause, et al.'s (2009) study showed greater effort overall compared to matched controls, with group differences most pronounced in the single-talker interference condition. In addition, studies using surveys and interviews have shown that students returning to college after brain injury report that studying requires greater effort compared to before their injuries (Kennedy & Krause, 2011; Kennedy, Krause, & Turkstra, 2008).

Effort reports do not always match performance in speech processing tasks, however. In a dual-task study about noise reduction (NR) algorithms for hearing aids, Sarampalis et al. (2009) gauged effort in normal-hearing listeners by noting differential performance on a working memory task that was conducted simultaneously with a speech perception in noise (SPIN) word repetition test. In addition to repeating the final word of each sentence in the SPIN test, participants were asked to maintain those words in memory and repeat them again after each block of eight sentences. The study found that even when the NR algorithm did not demonstrably improve speech intelligibility for listeners, it *did* reduce the cognitive effort of listening, and participants often stated that the new algorithms led to improved ease of listening, sound quality, and speech understanding. In a second experiment, the researchers found differential effects on processing speed with and without the NR algorithms. They conclude that, even though the algorithms did not significantly improve listeners' performance on the speech processing tasks, "NR, by doing some of the processing normally done by a listener, may free resources for other, simultaneous tasks" (p. 1239).

In a similar study, Fraser et al. (2010) used a dual-task experiment to show that visual cues decreased the effort required to process speech in noise compared with an audio-only condition. In contrast to previous studies, the two tasks used by Fraser et al. were in two different modalities: while speech recognition (in auditory only or auditory-visual modality) was the primary task, the secondary task required tactile pattern recognition. In addition to the accuracy and processing speed measures, Fraser et al. gave participants a self-rating questionnaire after each condition, asking them to rate both their performance and their level of effort on each task from 0 to 100% effort. Results showed that the audiovisual condition of the speech recognition task required less effort than the audio-only condition. In addition, as with the study of Sarampalis et al. (2009), there was no relationship between effort ratings and actual dual task performance in the auditory-only condition. However, there was a negative correlation between effort rating and performance in the audio-visual condition, such that lower accuracy scores were associated with higher effort ratings.

The work of these researchers supports the value of measuring subjective effort in the current study. In addition to quantitative ratings of effort, thematic analysis of interview responses is also predicted to show group differences relative to listening accuracy and effort. It is predicted that there would be an overall effect of effort between groups, such that individuals with TBI would report greater effort required for the challenging listening tasks. Speed/performance trades-offs, potentially manifested in greater perceived effort, are discussed further in the section on attention below.

Attention

Attention is one of the cognitive factors most relevant to the consideration of how individuals with TBI process complex auditory information. It is a complex, multi-faceted cognitive factor, and researchers debate to what extent its different aspects can be studied independently of each other or of other cognitive issues such as processing speed. Driver (2001) provides a convenient overview describing selective attention in particular, which involves attending to a target while ignoring a distracting stimulus. This is the aspect of attention most relevant to the current study, because the single-talker interference task could be described as a selective attention task (as well as a stream-segregation task, as discussed above).

Individuals with TBI frequently demonstrate various difficulties with attention, including reporting everyday experiences of distractibility and difficulty with multitasking (e.g. Cicerone, 1996). Studies related to distractibility include Knight, Titov, & Crawford (2006), who showed that visual and auditory distractions affected prospective memory – the ability to recall and carry out a plan – in participants with TBI more than in controls. Veltman, Brouwer, Van Zomeren, and Van Wolffelaar (1996) found divided attention among the executive function deficits observed in a group of 20 people in subacute recovery (<6 months) after severe closed-head injuries. Schmitter-Edgecombe and Nissley (2000) conducted a study of people with severe TBI who were at a chronic recovery stage (>1 year post injury). Participants were shown two lists of 28 five- to seven-letter words and then given word-stem cues to recall them. One list was used in the full-attention condition, in which the study phase only involved reading the word list; the second list was studied in divided-attention condition, in which participants simultaneously performed an even/odd decision task for numbers. A third list appeared in the testing phase without having been studied, as a baseline condition. The researchers contrasted between controlled and automatic recall with a two-part recall test. With "inclusion" items, participants were told to complete the word stem cues using words they had studied; with "exclusion" items, they were told to avoid words they had studied and provide only new words. Words from the studied lists that were provided in response to "exclusion" cues were assumed to represent automatic and not controlled recall, because participants would only provide them based on implicit recall in the absence of explicit recall. Accuracy results showed that divided attention load impacted performance on controlled but not automatic memory more so for the TBI group than for healthy controls. In other words, the individuals with TBI were no different from controls in their implicit recall of items studied during the distraction condition, but they were less accurate for controlled-recall items.

Telling, Meyer, and Humphreys (2010) investigated basic visual distractibility in healthy controls and individuals with frontal lobe injury using an eye tracker. Participants were shown a target word followed by an array of four pictures, and were told to press a button indicating whether the target was present or absent among the pictures. The eye tracker recorded participants' gazes as they looked at the pictures, which, in addition to the target or foil item, included semantically related and unrelated distracters. Participants with frontal-lobe injuries had more first initial gazes to distracters and fewer to target items, had more false-positive errors on trials where targets were absent, and were slower to look away from distracters than controls were. Although Telling et al. used the visual rather than auditory domain, their study is analogous to the current project in several ways. First, participants in the current study hear a sample of which voice to attend for each block of sentences in the single-talker interference task; this is comparable to the visual "search template" discussed by Telling et al., which participants may use to facilitate finding target images within an array. Also, the rapid initial discrimination involved in target selection for attention in the current study is similar to the early visual saccades discussed by Telling et al. In other words, the effect of frontal lobe injury on participants' ability to quickly and accurately identify targets while ignoring distracters in a the visual domain supports the hypothesis that similar difficulties may be found in related auditory tasks such as those in the current study.

Several studies have claimed that reduced processing speed can account for nearly all differences between groups with and without TBI on attention tasks (e.g. Ponsford & Kinsella, 1992; Spikman et al., 1996), and – as discussed above – reduced processing speed is one of the most commonly reported sequelae of TBI. However, there seems to be some agreement that this link is not as clear when it comes to supervisory control or regulation of attention – what Rueda, et al. (2004) call "executive attention." The more fundamental types of attention are arguably more automatic processes, even if they may be slower in people with TBI. For example, in their anatomical approach to areas of attention, Posner and Petersen (1990) identified orientation, detection, and vigilance as the primary types of attention processes. Indeed, these areas may be impaired in individuals with severe or acute brain injury (e.g. Stuss et al., 1999). From a cognitive rehabilitation standpoint, however, Sohlberg and Mateer (2001) separate attention into possible areas of deficit including sustained attention (similar to vigilance), selective attention (called “focus” by some others), alternating attention, and divided attention. Any of these types of attention may, in some circumstances, require supervisory control. In other words, the individual may need to deliberately control his or her attention in order to complete a task (e.g. prioritize attending to one task over another), particularly if there are contextual requirements involved, which make the process of developing automaticity much more difficult.

It is in these supervisory attention control conditions that deficits may occur for individuals with TBI that are over and above those caused by reduced processing speed; instead, they would fall under the category of self-regulation. The current study is not designed to directly test self-regulation. However, if the hypothesized group differences are found, a future course of study is planned that will specifically focus on the self-regulatory aspects of complex speech processing.

Schneider et al. (2007) conceive of difficulty with a single-talker interference task as a problem with alternating attention, or switching. They state that difficulties with scene analysis or linguistic interference as well as energetic masking can cause problems in switching attention when a conversation requires the listener to attend to multiple speakers. Whether or not it is truly an alternating attention problem, the three factors they cite are certainly relevant. Energetic and informational masking, as well as scene analysis (in terms of stream segregation), were discussed in the section above on auditory processing. Semantic and linguistic interference are also relevant to the current study, in that all interfering signals consist of speech in the language of the listener, rather than noise or speech in other languages. Schneider et al. sum up the role of attention in speech processing in a single-talker interference task nicely:

> [A] person must be able to focus their attention on one auditory stream (voice) in order to extract the meaning from that stream, while simultaneously inhibiting the processing of information from other auditory streams, or, if the information from the second stream is processed, prohibiting it from interfering with the processing of the targeted voice. (p. 582)

There is existing evidence that attention plays a role in auditory stream segregation, which is the ability to separate a single stream of auditory information into two meaningful components. Carlyon, Cusack, Foxton, and Robertson (2001) studied stream segregation in healthy adult listeners. They used tone sequences in which a pair of tones at frequencies A and B could be perceived as either a single “galloping” ABA-ABA pattern, or as two separate streams of A and B, depending on the rate of presentation and other factors. Stream segregation, the perception that the tone pairs are two separate patterns, builds up over time. In Carlyon et al.’s study, participants were asked to press one button when they heard a single stream and another button when they heard two streams. This task was done with and without the presence of distracters, and sometimes after instructions to ignore or attend to features of the distracter signal. The researchers found that the buildup of stream segregation could be limited by manipulating attention. This means that when attention was directed away from the streaming signal, the time at which it was perceived to switch from one stream to two was delayed.

In a clinical application, Carlyon et al. (2001) performed additional experiments comparing among participants with right hemisphere brain damage (RHD) with left visual neglect, those with RHD but no neglect, and healthy controls. Left neglect is a phenomenon in which some people who have experienced damage to the right cerebral hemisphere have difficulty attending to stimuli on the contralateral (left) side. The authors found an asymmetry of results for the group with neglect but not for the other two groups: participants with neglect showed reduced stream segregation for stimuli that were presented to their left ears compared with those presented to their right ears. The results overall strongly suggest that attention plays a role in the perception of auditory streaming. However, the authors do not directly demonstrate the connection between the experimental tasks and functional communication effects.

Pitt and Samuel (1990) took a step closer to everyday speech processing by studying phoneme monitoring in words and pseudowords. By controlling the location of target phonemes within their stimuli, they implicitly manipulated the expectations – and attentional focus – of listeners. They found faster response times for phonemes that were in the expected location, suggesting a performance benefit from attention. This effect was somewhat stronger in the nonword condition, suggesting that it was easier for participants to focus narrowly on monitoring phonemes in nonwords than words. In addition, they found that adding a distracter semantic evaluation task resulted in poorer performance on the phoneme-monitoring task. Gordon, Eberhart, and Rueckl (1993) and Francis and Nusbaum (2002) also noted the importance of attention in speech. Gordon et al. showed that engaging in dual tasks affected how different acoustic cues were weighted in phoneme identification; and Francis and Nusbaum showed that attention plays a role in learning new phonemic categories.

In addition to research on healthy adults, there have been numerous studies exploring the role of attention in communication for various clinical populations, such as people with aphasia (e.g. Erickson, Goldinger, & LaPointe, 1996; Sohlberg & Mateer, 2001). Among the recent literature about attention difficulties in people with aphasia are studies on selective and divided attention (e.g. Murray, Holland, & Beeson, 1997) and on switching (Chiou & Kennedy, 2007). In order to compare focused and divided attention in adults with and without mild aphasia, Murray et al. asked participants to complete semantic and lexical decision tasks as well as a tone discrimination task. Each was done in isolation and in selective and divided attention conditions with secondary stimuli. In other words, participants were asked to either complete the primary task while ignoring the secondary task (selective attention, or what the authors call "focused attention") or to do the primary task first and the secondary task second (divided attention). Secondary stimuli included verbal and nonverbal conditions. Participants with aphasia were more affected by the presence of secondary stimuli than controls. In addition, semantic judgment for all groups was more affected by verbal than nonverbal secondary tasks, which is consistent with what would be predicted based on the discussion of informational masking earlier in this introduction. The fact that people with aphasia had greater difficulty than controls in the selective attention condition is relevant to the current study because the single-talker interference task is also a selective attention task, in which participants must repeat back one voice while ignoring the other.

In order to study the phenomenon of switching in adults with and without aphasia, Chiou and Kennedy (2007) conducted a study using four go/no-go tasks, in which both modality of presentation (visual vs. auditory) and task rules could be switched, sometimes predictably and sometimes unpredictably. All participants did better when the modality switching was predictable when there was no rule switching; but when rule-switching was involved, predictability of modality switching had no effect. This meant that knowing the switching pattern from visual to auditory presentation and back in advance improved performance when response rules were consistent, but not when there was rule switching. In addition, participants with aphasia performed more poorly with regards to speed, accuracy, and ability to adopt new rules after switching. Switching is relevant to this dissertation study because participants must attend to first one speaker, then the other speaker in the two single-talker interference blocks of the experiment.

In summary, previous research has shown that attentional changes can affect performance on a speech processing task in healthy adults. In addition, attention effects have been demonstrated in TBI and other clinical populations as well. These findings suggest that attentional deficits of adults with TBI may impact their speech processing performance in the current study, which specifically demands controlled, selective attention and switching.

Non-Native Accented Speech

There have been many studies exploring the intelligibility of non-native speakers (NNS) speaking English. Some have included both native speaker (NS) and NNS listeners, while others, like the proposed study, focus only on NS listeners. It is important to note the distinctions among language proficiency, comprehensibility, intelligibility, and accentedness. Language proficiency comprises factors such as vocabulary size and accuracy and complexity of receptive and expressive syntax. Comprehensibility relates to how easily the message can be understood, whereas intelligibility is a more fine-grained measure of whether individual words can be understood. A person with dysarthria might have reduced intelligibility but relatively preserved comprehensibility; in contrast, a person with fluent aphasia might be fully intelligible and yet his or her intended meaning might be incomprehensible.

Non-native accent can occur based on any of a variety of factors that affect expressive language, and may or may not be independent of proficiency, comprehensibility, and intelligibility. Munro and Derwing (1999) specifically examined phonemic, grammatical, and prosodic variation in speakers of Chinese-accented English. Both comprehensibility and accentedness were subjectively measured on 1-to-9 scales, while intelligibility was measured based on sentence transcription. Many participants showed negative correlations between comprehensibility and accentedness, such that higher accentedness ratings were associated with lower comprehensibility. However, these two were often not correlated with the objective intelligibility measure, and the authors emphasized that a “heavy” accent can still be highly intelligible. They also showed that prosodic errors in the study had more influence on accent and comprehensibility ratings than did phonemic or grammatical errors. McHenry (2011) also demonstrated the wide variability of intelligibility ratings in a study using speakers with dysarthria: she found no significant patterns related to age, gender, or education level in accounting for the variability of ratings among listeners.

Munro and Derwing (1999) also emphasize the importance of distinguishing between accentedness and intelligibility or comprehensibility because efforts at “accent reduction” may not actually have any impact on whether a speaker becomes more intelligible or comprehensible. Along similar lines, Munro and Derwing (1995) found that, although comprehensibility was significantly related to processing speed (i.e. listeners were faster at a sentence verification task with sentences they rated as more comprehensible), accentedness was not.

Studies of listening to non-native accented speech in noise have shown that the intelligibility of non-native speech is more affected by background noise than native speech (Rogers, Dalby, & Nishi, 2004; Wilson & Spaulding, 2010). This is consistent with the concept of reduced signal redundancy discussed by Oxenham and Simonson (2009) – because NNS contains less redundancy than NS, it is more susceptible to energetic masking effects.

Several previous studies are relevant to the topic of the effects of native versus non-native speech in a single-talker interference task. In a study exploring perception of spatial separation in a two-talker interference task, Freyman et al. (2001) included a condition which used the voices of two native speakers of Dutch, speaking both Dutch and English. Consistent with the predictions of the current study, their results suggested that when the native Dutch speakers spoke English, it led to equal energetic masking but less informational masking compared to the masker spoken by native English speakers.

Van Engen and Bradlow (2007) conducted a study relevant to the question of informational masking in which participants listened to English target sentences in the presence of two or six interfering talkers speaking English or Mandarin. Whereas there was no language effect in the six-talker condition, native listeners experienced more masking with English babble than with Mandarin babble in the two-talker-babble condition. This suggests that the six-talker stimuli's "greater spectral and temporal density" led to increased energetic masking and minimized the effect of informational masking; the converse was true for the two-talker condition. Although all speakers in the current project spoke English, the results of Van Engen and Bradlow (2007) provide support for the hypothesis that informational masking would be greater when the interfering talkers are native speakers.

Research on intelligibility in dialect variations is also indirectly related to the current study. For example, Clopper and Bradlow (2008) found that the effects of moderate amounts of noise on intelligibility were different for different dialects of American English. In addition, with increasing noise, listeners became poorer at classification of the dialects, even when sentences remained intelligible. The authors note that "at more difficult noise levels, participants cannot effectively adapt to dialect variation in the acoustic signal and cross-dialect differences in intelligibility emerge for all listeners, regardless of their dialect" (p. 175). This difficulty with adaptation in a noisy situation may be comparable to what listeners experience during the single-talker interference conditions in the current study.

Although the current study compares the performance of monolingual native listeners repeating native- and non-native-accented speakers, there is an overlapping literature about speech perception for non-native *listeners*, which shows some similar consequences to those of native listeners listening to NNS. For example, Smiljanic and Bradlow (2007) found that native and non-native listeners benefit similarly from clear speech over plain speech by both native and non-native speakers. Clear speech is a mode of speech that is automatically produced by speakers in adverse conditions, and incorporates a range of features such as widened pitch variation, slowed rate, and exaggerated contrasts among phonological categories (Smiljanic & Bradlow, 2007). Conversely, Bradlow and Alexander (2007) suggest that non-native listeners are less able to use higher-level compensatory information in challenging listening conditions. In other words, non-native listeners are able to take advantage of contextual information, but need greater signal clarity than native speakers in order to do so. Cooke et al. (2008) and Lecumberri and Cooke (2006) also showed that non-native listeners experience greater effects of both energetic and informational masking than native listeners. Shi (2010) studied native listeners and bilingual listeners with different ages of acquisition of their second language. He found that non-native speakers, even those who learned their second language before the age of seven, were more vulnerable than monolingual listeners to effects of acoustic degradation on their ability to use context in sentence repetition. All these studies further support the idea, discussed also by Oxenham and Simonson (2009), that reduced redundancy in the signal – or reduced ability on the part of the listener to take advantage of redundancy – leads to greater masking effects.

Research on the speech perception of non-native listeners is directly relevant to the current study based on the premise that both non-native listeners and native listeners listening to non-native speech face similarly increased cognitive loads. One “top-down” cognitive factor that affects speech perception is listener expectations. For example, in an experiment in which participants listened to sentences in single- or mixed-talker blocks, Magnuson and Nusbaum (2007) showed that listeners had slower responses during mixed-talker blocks but that, for speakers with similar voices and vowel spaces, this slowing disappeared when listeners believed they were only listening to a single talker.

One study suggesting that attention plays a role in the comprehension of difficult or unfamiliar (e.g. accented) speech is Pallier, Sebastian-Galles, Dupoux, Christophe, and Mehler (1998). The authors found that monolingual Spanish speakers actually benefited more than bilingual speakers from transcribing compressed Catalan as training for compressed Spanish. One explanation for this is that the monolingual speakers had to concentrate more in order to transcribe an unfamiliar language, and perhaps this intensified their training benefit. In addition, Francis and Nusbaum (2002) showed that attending to different dimensions (or adjusting the weighting of different dimensions) is crucial for learning new phonemic categories.

This dissertation incorporates a number of factors based on the existing research about non-native speech intelligibility. For example, the current study focuses on intelligibility, not proficiency, comprehensibility, or accentedness. By using the IEEE sentence corpus and providing sentences rather than using spontaneous speech, the study side-steps the issue of speaker proficiency. Intelligibility is more important than comprehensibility in repeating the IEEE sentences, because they are designed to be grammatical but not predictable, and scoring is based only on keywords correct and not overall meaning. Listeners were not asked to rate speaker accentedness.

Based on the work of Rogers et al. (2004), Wilson and Spaulding (2010), and Oxenham and Simonson (2009) regarding redundancy, in the current study it is hypothesized that the NNS target conditions will be more susceptible to informational masking effects; and, moreover, that lack of redundancy will have a greater effect on the performance of the TBI group than on that of healthy controls. Finally, the fact that attention can affect the ability to process speech in challenging situations in general, and in unfamiliar language specifically (Francis & Nusbaum, 2002; Pallier et al., 1998), suggests that NNS intelligibility is likely to be affected by attention. Moreover, because individuals with TBI are known to have deficits of attention, it is reasonable to expect that survivors of TBI may have greater difficulty with the proposed experimental task than healthy controls.

Why Mixed Methods?

Historically, scientists avowed allegiance to either quantitative or qualitative methods. These camps were at times so oppositional that proponents of quantitative methods would dismiss the work of qualitative researchers as unscientific while advocates of qualitative methods would dismiss quantitative work as being ecologically invalid and ignoring the importance of individual variation (Cresswell & Plano Clark, 2007). Much has been written about the utility of mixing quantitative and qualitative methods. As Cresswell, Plano Clark, Gutmann, and Hanson (2003) point out, the complexities of social phenomena, including communication, make them particularly suited to study using mixed methods. In the current project, a qualitative component is included in the form of a semi-structured interview in order to supplement the primary, quantitative component of the experiment. Mixing methods in this way combines convergence and explanation: in other words, the results of the qualitative portion of the study will be used both to *provide an additional perspective* on the phenomenon in question (e.g. Cresswell & Plano Clark, 2007) and to *provide explanation* for the quantitative results (e.g. Morse & Niehaus, 2009). More specifically, participants' subjective descriptions of their experience with listening to speech in challenging situations may provide further – and perhaps more nuanced – support for the findings of their performance on the quantitative listening task. In addition, discrepancies or complexities observed in the quantitative data may be explained by details present in the qualitative interviews.

A further advantage to employing a mixed-methods approach is that it allows an investigation of potential deficits at all three levels of the World Health Organization's International Classification of Functioning, Disability, and Health (World Health Organization, 2001). In the World Health Organization classification, assessments of such basic abilities concerned with body structures and "low-level" functions are described as body/function-level abilities. Examples include motor movement of the legs or verbal naming of pictures, and difficulties with this level of task are referred to as impairments. In contrast, difficulties with activity-level tasks are called limitations, such as difficulty with walking or talking on the telephone. Finally, participation-level measures describe a person's ability to function within his or her environment or social context, and problems on that level are called restrictions. For example, climbing stairs to get to class or carrying on a conversation in a crowded restaurant are participation-level tasks. The sentence-repetition component of this experiment, while not a truly activity-level task, is intended to model real-world behaviors so as to be a better measure of activity-level performance than existing standardized tests.

One goal of this dissertation is to build on existing work to expand on the issue of speech processing after brain injury using body/function-, activity-, and participation-level measurements (standardized testing, sentence repetition, and interviews, respectively). Specifically, the body/function-level part of the study uses standardized assessments of memory, language, attention, dichotic listening, and other abilities relevant to speech processing. The activity-level portion of the study involves participants listening to and repeating target speakers with single-talker interference; target and interfering talkers are one native-accented and one non-native-accented speaker of English. Finally, the study explores participation-level speech processing effects using semi-structured interviews to gather subjective information. The study uses a mixed-methods design to accommodate this combination of quantitative and qualitative data collection and analysis.

By studying the effects of one type of challenging listening situation on the speech processing of those with and without TBI, and attempting to correlate those effects with impairment- and participation-level abilities, the current study has the potential to shape future research as well as to suggest ways of improving communication for brain injury survivors. The choice to study the experience of monolingual listeners interacting with non-native speakers has wide-ranging practical implications for modern U.S. society.

Research Questions and Hypotheses

Overall, despite the heterogeneity of brain injuries and brain injury sequelae, it is possible to paint a general picture of deficits that may affect the processing of speech in challenging situations such as the current experimental task. Research has found that individuals with TBI often experience deficits in central auditory processing, accompanied by difficulties with processing speed and attention regulation. Research on informational masking suggests that reduced access to signal redundancy increases the difficulty of auditory speech stream segregation. Finally, research on the intelligibility of non-native speech reinforces the importance of informational redundancy for accurate comprehension, and suggests that typical listeners adjust very quickly to unfamiliar speech.

This experiment is the first to explicitly attempt to test the associations between impairment-, activity-, and participation-level measures of speech processing: these measures are standardized assessments, the experimental sentence-repetition task, and semi-structured interview, respectively. It has been found in various areas of TBI research (e.g. Wilson, 2003) that day-to-day challenges encountered by high-functioning TBI survivors are not always reflected on impairment-level assessments; for this reason, the contribution of the qualitative component of the study is crucial. By comparing the results of the interview portion of the study with the standardized testing and experimental listening task results, a more thorough description of the effects of brain injury on speech processing is developed than has been possible before. In addition, comparisons between the filtered group in Experiment 1 and the TBI group in Experiment 2 will offer further insight into the nature of the speech processing difficulties faced by people with TBI. The combination of all these factors makes it possible to develop research questions and hypotheses predicting the outcomes of the experiments in this dissertation.

Experiment 1: Filtered vs. unfiltered speech (healthy controls only).

Research questions.

- Is the filtered group less accurate than the control group with the sentence repetition task?
- Are participants less accurate in the NNS than the NS target speaker condition?
- Is there an interaction between group and target speaker (i.e. is the filtered group more susceptible to target effect than the control group?)
- Does the filtered group report greater effort than the control group with the sentence repetition task?

Hypotheses.

1. Within-group differences

- Accuracy will be lower in the non-native target/native masker (NNS-ns) block than in the native target/non-native masker (NS-nns) block; and lower in the alone condition than the attend condition.
- Subjective effort will be greater for the NNS-ns block than the NS-nns block; and greater in the attend condition than the alone condition.

2. Between-group differences

- Accuracy will be lower for the filtered speech group than the unfiltered speech group.
- Subjective effort will be greater for the filtered speech group than the unfiltered speech group.

3. Interactions

- There will be group-by-condition interactions such that the filtered group will obtain less benefit from the NS target than the unfiltered group.

Experiment 2: TBI vs. healthy controls (unfiltered speech only).

Quantitative research questions.

1. Accuracy

- Is the TBI group less accurate than the control group with the sentence repetition task?
- Are participants less accurate for the NNS than the NS target?
- Is there an interaction between group and target speaker (i.e. is the TBI group more susceptible to target effects than the control group?)
- Was the TBI group more likely than the control group to repeat interfering words?

2. Effort

- Does the TBI group report more effort than the control group with the sentence repetition task?
- Do participants report more effort for the NNS than the NS target?
- Is there an interaction between group and target (i.e. is the TBI group more susceptible to target effects than the control group?)

3. Accommodation

- Does the control group accommodate faster than the TBI group? In other words, do they improve more over the course of the experiment, resulting in order effects?

4. Standardized tests

- Are there correlations between standardized tests or demographic factors and sentence repetition accuracy?

Quantitative hypotheses.

1. Within-group differences

- Accuracy will be lower and subjective effort greater for the NNS target than the NS target.
- Accuracy will be lower and subjective effort greater in the attend condition than the alone condition.

2. Between-group differences

- Accuracy will be lower and subjective effort greater for the TBI group than the healthy control group.
- Accommodation effects will be reduced for the TBI group compared to the healthy control group.

3. Interactions

- There will be group-by-condition interactions such that the decrements in accuracy and effort across conditions will show different patterns for the TBI group than the healthy control group. Specifically, the more challenging listening conditions (i.e. NNS target in the attend condition) will affect the TBI group significantly more than they will the control group.

4. Correlations

- Across groups, standardized measures of processing speed, attention, and/or working memory will be associated with performance on the experimental task (i.e., faster processing speed and better attention scores will predict better accuracy).
- Across groups, measures of central auditory processing will not predict accuracy on the experimental task.

Qualitative and mixed-methods research questions.

- Is there a difference in how the two groups subjectively describe their speech processing?
- To what extent do the interview reports (qualitative), standardized testing (quantitative), and listening task (quantitative) results converge?
- In what ways do the interview (qualitative) data help to explain the listening task (quantitative) results?
- Are there correlations between repetition accuracy and quantified interview data?

Mixed-method hypotheses.

- Interview reports of difficulty with listening to speech in challenging situations will converge or correspond with poorer performance and/or greater effort on sentence repetition tasks.
- Interview responses will reveal details of individual experience with challenging listening situations, including strategies to compensate for difficulties, which will augment and provide insight into performance on the sentence repetition task.
- Interview reports of difficulty with speech processing will show correlations with reduced accuracy in the sentence repetition task.

Methods

Overview

This dissertation project consisted of two experiments. Experiment 1 compared healthy adults without TBI or other neurological problems in filtered and unfiltered versions of the experimental sentence repetition task. Experiment 2 compared adults with and without TBI on the unfiltered listening task, and also included standardized testing and interview components.

Figure 1 shows a diagram of the overall study design. The disproportionate recruitment of control participants allowed Experiment 1 to compare filtered and unfiltered speech, and provided sufficient numbers so that a subgroup could be matched to the experimental group in Experiment 2 for age, education, and estimated verbal IQ.

General Procedures

All studies were approved by the University of Minnesota Institutional Review Board (IRB). Sessions took place at Shevlin Hall at the University of Minnesota with three exceptions, when standardized testing was conducted at participants' homes. The experimental sentence repetition task, hearing screening, and auditory processing tests took place in sound-treated booths; all other procedures took place in quiet laboratory rooms. Participants provided informed consent to participate, and were invited to take regular breaks throughout the procedures.

Participants were compensated for participating. Those who were recruited through the Psychology Department extra credit program were offered a choice between extra credit points and cash. For those who were paid in cash, for Experiment 1 and the first part of Experiment 2, they received five dollars plus an incentive of $0.05 per keyword correct for accuracy in the better of the two attend condition blocks of the sentence repetition task. Those who chose extra credit points also received the additional $0.05 per keyword incentive. With a possible total of 150 words, this equaled a total possible bonus of $7.50. This incentive system was used to encourage participants to perform their best, particularly in the very difficult attend condition for the filtered group of Experiment 1. All participants received a minimum of $7.50 in compensation (or $2.50 for those whose base compensation was extra course credit), regardless of their accuracy scores. For the second part of Experiment 2, comprising the standardized testing and interview, all participants were compensated $10 per hour.

Recruitment

Participants for Experiment 1 were largely recruited from undergraduate classes at the University of Minnesota–Twin Cities using in-class presentations, fliers, and online recruiting through the U of MN Department of Psychology website. The unequal number of male and female participants in this study is partly due to having recruited participants through classes in the Speech-Language-Hearing Science Department, whose student body is predominantly female. The undergraduate population at the U of M is roughly 53% female (Education-Portal.com), and within the SLHS Department the percentage of female students is much higher.

Several mechanisms were used in order to recruit participants for Experiment 2, which included a group of adults with brain injury and a group of healthy controls matched for age, education, and estimated verbal IQ. Some of the healthy controls were participants from Experiment 1 who were recruited to participate in Experiment 2 based on group matching of those three criteria (experimental task performance was not considered, as sentence repetition accuracy was not analyzed until later). Table 2 lists all healthy control participants, whether they completed the filtered or unfiltered version of the sentence repetition task, and in which studies their data were included. There were three participants who completed the experiment but whose demographics did not fit the demographic matching needs of either experiment; these participants' data were not included in analysis, and they are not listed in Table 2.

In addition to the methods used for Experiment 1, some participants were recruited from a database of prior research participants in the NeuroCognitive Communication Lab. These individuals were contacted via telephone or email. Additional recruitment was done via an advertisement placed in the Brain Injury Association of Minnesota (BIA-MN) electronic newsletter, and through word of mouth.

All potential participants were screened using an IRB-approved demographic questionnaire, either by email or over the telephone according to participant preference (see Appendix 1). Criteria for inclusion for all participants in both experiments was that they be between the ages of 18 and 65 and have no history of degenerative neurological disorder, learning disability, significant substance abuse, or hearing loss. Two participants did not disclose – or were not aware of – their hearing loss until after they had been recruited. These two participants completed the experimental sentence repetition task, but their data were not included in analysis, and they did not complete the standardized testing or interview.

All participants were monolingual English speakers with no more than four semesters of undergraduate second-language instruction. This criterion was chosen because four semesters is the minimum graduation requirement for undergraduates in the University of Minnesota College of Liberal Arts.

Inclusion criteria for the TBI group included having adult-acquired brain injury events such as TBI, stroke, aneurysm, tumor resection, and anoxic brain injury; and being six months or more post-onset or -injury (post-acute stage). Excluded diagnoses included injuries acquired in childhood (younger than 18), encephalitis, meningitis, epilepsy or other seizure disorder, and schizophrenia. As it happened, all but one participant in this group had a traumatic brain injury, one participant (#1) having an acquired brain injury due to a cerebral-spinal fluid (CSF) dysfunction. Potential participants were also excluded if they had dysarthria severe enough to compromise intelligibility in the sentence repetition task, or any aphasia beyond mild word-finding problems.

Participants

Participants in Experiment 1 were a group of 30 healthy young adults, aged 18–26. Their demographic information is shown in Table 3. As shown in the table, the groups were matched for age (unfiltered group mean 20.4 years; filtered group mean 20.8 years), education (unfiltered group mean 14.1 years; filtered group mean 14.3 years), and estimated verbal IQ (unfiltered group mean 107.1; filtered group mean 108.1). None of the group differences were significant for these characteristics.

Healthy participants who completed Experiment 1 were asked whether they would be willing to return for the additional testing and interview to be included in Experiment 2; all Experiment 1 participants agreed to this, and a subset from the unfiltered stimulus group was invited back to complete the additional tasks of Experiment

2. As mentioned above, this selection was based on creating a group to match the TBI group on age, education, and estimated verbal IQ.

Participants in Experiment 2 were twenty-six adults ranging in age from 18 to 59. Demographic information for participants in Experiment 2 is shown in Table 4. Two participants in the TBI group were disqualified due to hearing loss, and a third was eliminated from analysis due to procedural problems. These three participants are not listed in Table 4. As shown in the table, the groups were matched for age (control group mean 33.6 years, TBI group mean 39.2 years); education (control group mean 15.2 years, TBI group mean 14.6 years); or estimated verbal IQ (control group mean 112.5, TBI group mean 112.1) for Experiment 2. None of the group differences were significant for these factors.

Injury information specific to participants with TBI is shown in Table 5. The mean time post injury was 11.3 years, and ranged from 2 to 40 years. Nine of the 13 participants had experienced a severe TBI, one had a moderate TBI, two had mild-complicated injuries, and one experienced a CSF dysfunction resulting in intracranial hypotension and brain injury.

In addition to age, education, and estimated verbal IQ, more detailed demographic information was gathered for all participants during the initial screening. Questions were asked about participants' experience with foreign languages and musical expertise. The former is relevant because the study of non-English languages could provide benefit to listeners in the NNS-target conditions of the sentence repetition task. Information on musical training was gathered because research by Oxenham et al. (2003) indicated that a group of expert musicians experienced significantly less informational masking than nonmusicians on a complex stream segregation task. Musical history was not a factor in participant recruitment, so it is unlikely that any participants in this project would meet the rigorous standards of musical training used by Oxenham et al.; nevertheless, musical experience was considered as an exploratory demographic category.

Standardized Testing

A battery of standardized tests was given to all participants in Experiment 2 in order to understand the cognitive and linguistic functioning of participants (see Table 6). The rationale for testing these aspects of cognition (e.g. attention, processing speed, and memory) and auditory processing is discussed in the introduction section. All TBI participants and six of the 13 healthy control participants completed the auditory processing tests on the same day as the listening task. The remaining seven participants did the other standardized tests first, followed by the auditory processing tests at the end of the second session. This was done so that if there were any fatigue effects of doing the auditory processing tests at the end of the session, it would be similar across participants. In other words, the auditory processing tests were done either at the end of session 1 or at the end of session 2. The order of standardized tests was randomized across participants, with the exception of the National Adult Reading Test (NART), which was done at the beginning of session 1, for the purpose of matching estimated verbal IQ in both studies. Group differences for standardized tests were evaluated using simple one-way ANOVAs, and group means for each test are listed in Table 7. The full dataset of scores for each participant can be found in Appendix 2.

Standardized testing was conducted in a quiet room for the cognitive tests and in a sound-treated booth for tests of auditory processing. Participants were invited to take breaks as desired between each test.

Tests of cognition and communication.

The Repeatable Battery for the Assessment of Neuropsychological Status (RBANS) (Randolph et al., 1998) is a battery used to screen cognition and memory, including list learning, story learning, semantic fluency, naming, coding, and other tasks. It provides normed subtest scores of immediate and delayed memory, language, visuospatial skills, and attention. The TBI group scored significantly lower than the control group on total RBANS score. This is as predicted, given that the test is designed to assess areas commonly affected by TBI such as memory and attention. The only subtests that were significantly different between the groups were attention and language. The attention subtest of the RBANS comprises a timed "coding" task (writing numbers corresponding to a set of symbols) and a digit-span task. The language subtest includes a semantic fluency task (naming as many fruits and vegetables as possible in one minute) and simple picture naming. Because all participants were at ceiling for the picture naming task, the significant difference between groups in this case can be entirely attributed to the semantic fluency task, for which "language" is arguably a poor descriptor. The fact that the other RBANS subtests did not show significant deficits for the TBI group supports the assertion that the participants in this experiment were quite high-functioning.

The National Adult Reading Test (NART) (Nelson, 1982) is a measure commonly used to estimate premorbid intelligence. The test was administered to all participants in both Experiments 1 and 2 to enable group matching of verbal IQ. Groups were deliberately matched on estimated verbal IQ scores, derived from the NART.

Tompkins' Listening Span task (Tompkins, Bloise, Timko, & Baumgaertner, 1994) was used as a measure of verbal working memory. In this task participants hear a series of short statements and must (1) indicate whether each statement is true or false, and (2) remember the final word of each statement for reporting later. Final words are recalled in sets of two, three, four, and five sentences. While both groups were at ceiling on the true/false portion of this task, the control group was significantly more accurate than the TBI group on the ability to recall the sentences' final words.

The digits backward subtest of the Weschler Memory Scale–III (WMS-III) (Weschler, 1997) was used as an additional measure of working memory, to supplement the Listening Span task. The lack of group differences for this frequently used measure of working memory demonstrates that participants in this study's TBI group were high functioning, with deficits manifesting only on more complex, language-based tasks such as the Listening Span.

The Attention Process Training Attention Questionnaire (APT-II) (Sohlberg & Mateer, 1996) was administered to measure self-report of attention difficulties. Participants are presented with a list of statements such as "can't keep mind on activity or thought because mind keeps wandering," and "easily lose place if task or thinking interrupted" and are asked to check a box indicating how often the statement applies to their daily functioning, ranging from "not a problem or no change from before" to "is a problem *all the time* (affects most activities)." As predicted, people with TBI reported significantly more difficulty with attention than healthy controls.

The Behavioral Assessment of Dysexecutive Function Dex questionnaire (BADS) (Wilson, Alderman, Burgess, & Emslie, 1996) is a self-report questionnaire of executive functioning, similar in structure to the APT-II questionnaire. Participants check a box ranging from "never" to "very often" for a series of statements such as, "I have difficulty thinking ahead or planning for the future," or "I find it difficult to stop myself from doing something even if I know I shouldn't." It was predicted that, like the APT-II questionnaire, the BADS Dex questionnaire would show significant differences between the control and TBI groups, but this was not the case.

The Decision Speed subtest of the Woodcock-Johnson III Test of Cognitive Abilities (WJ-III) (Woodcock, McGrew, & Mather, 2001) was used as a measure of processing speed. In this test, participants are presented with a series of rows of simple pictures, and are asked to circle the two items in each row that "go together or are most alike." The TBI group was less accurate than the control group, indicating how many items participants were able to complete within three minutes.

The trail-making subtest of the Delis-Kaplan Executive Function System (D-KEFS Trails) (Delis, Kaplan, & Kramer, 2001) was used as another measure of executive functioning, specifically in the contrast between the switching item (connecting alternating numbers and letters) and non-switching items (connecting only numbers and only letters). There were significant differences between groups in the combined letter-sequence and number-sequence (no-switching) measure, and in the switching subtest. However, once motor speed (subtest 5) was taken into account, the two groups were almost identical, with the TBI group mean (and SD) standard score of 9.77 (2.0) and the control group score of 9.77 (1.7).

An abbreviated version of the Western Aphasia Battery (WAB) (Kertesz, 1982) was administered to participants in the TBI group, to ensure that they did not have aphasia. No participant with a diagnosis of aphasia was included in the study, though some reported occasional word-finding problems. No language errors were demonstrated by any participant on this abbreviated administration of the WAB.

In addition to the tests described above, all participants were given a hearing screening before the experimental listening task, in order to ensure that their hearing was within normal limits. Participants were screened at 20 dB at 500, 1000, 2000, and 4000 Hz.

Tests of auditory processing.

Each participant in Experiment 2 completed three tests of central auditory processing: the SCAN-A, the Masking Level Difference test (MLD), and the Gaps-in-Noise test (GIN).

The SCAN-A Test for Auditory Processing Disorders in Adolescents and Adults (SCAN-A) (Keith, 1986) is a test of auditory processing that consists of four different subtests involving word repetition. The first is the filtered word subtest, the second is the auditory figure-ground subtest (words are presented with a speech-like babbling noise in the background), the third is the competing words subtest (a dichotic listening test with different words presented in each ear), and the fourth is the competing sentences subtest (dichotic listening for sentences). Only the first three subtests were administered for this study. This was mostly due to time constraints: participants in the TBI group often took a full two hours to complete their first session, and adding the fourth SCAN-A subtest would have extended the time an additional 5 to 10 minutes. Also, the fourth subtest is a dichotic sentences task in which participants repeat back the sentences heard in one ear while ignoring sentences heard in the other ear. Given the overlapping content between subtest 4, subtest 3 (dichotic word repetition), and the experimental listening task (single-talker interference sentence repetition), it was felt that this subtest would not provide enough additional information to justify the extra time required.

The MLD test (Auditec, 1999) is designed to test central auditory processing at the level of the brainstem (e.g. Jiang, McAlpine, & Palmer, 1997). Listeners repeat spondee words that are presented with background noise; the words decrease in intensity until they become inaudible. The list is repeated twice: first in the SoNo condition, then in the SπNo condition, in which the phase of the noise is inverted relative to the signal. The test is designed so that a masking level difference of less than 5 dB between the two conditions indicates impaired functioning.

The GIN test (Musiek et al., 2005) was used as a test of gap detection, a measure of temporal auditory processing. The test is designed to measure the shortest gap of silence that listeners can hear within six-second periods of noise. Several different tests have been developed to test gap detection, including the Random Gap Detection Test (RGDT) (Keith, 2000), the Adaptive Test of Temporal Resolution (Lister, Roberts, Shackelford, & Rogers, 2006), and the GIN. Musiek (2005) found a significant difference in gap detection threshold between a healthy control group (4–5 ms) and a group of adults with central auditory system deficits (7–8 ms). Samelli and Schochat (2008) also tested the GIN on a group of 100 healthy young adults (age 18–31) and found 96% detection accuracy for gaps of 5 ms or longer. Finally, Zaidan, Garcia, Tedesco, and

Baran (2008) compared a group of young adults on the GIN and RGDT and found that the gap detection threshold was significantly better for the GIN, but that males performed better than females on both tests; in addition, they found no difference in thresholds between ears. They also found the GIN to be preferable for scoring and application.

Based on this previous research, the GIN was chosen as a measure of gap detection for the current study, but a modified version was used. The original test provides cutoff scores for “disordered” performance based on a series of four subtests with thirty-five items each. In each subtest, participants hear six-second bursts of broadband noise, punctuated by occasional “gaps” of silence. The number of gaps in each trial ranges from zero to three, and gaps are 2, 3, 4, 5, 6, 8, 10, 12, 15, or 20 ms in duration. Each duration occurs six times per subtest, and the full administration of the test takes about 40 minutes. This reason, as well as poor availability of norming data and inconvenient design for participant response, led to the decision to use a modified administration for the current study.

The method of participant responses on the GIN was altered in several ways. The scoresheet indicates both the duration of each gap and its relative position within the trial: early, middle, or late. The administrator is supposed to judge response accuracy based on the timing of when participants press a response button. The described button response system was not available for use in this study; moreover, the methodology would be problematic for use with groups with potentially different processing and motor speeds, such as the adults with and without TBI in this project. Therefore, an alternative response scheme was developed, in which participants counted the number of gaps they heard and reported the number to the experimenter after each trial. They were told at the beginning of the test that there might be zero, one, two, or three gaps in each item. In fact, this alternative method was used as a backup system by Samelli and Schochat (2008) on trials when participant button responses needed clarification. By participant report, and based on the six-second trial time and participants' performance on the assessments of working memory described elsewhere, short-term memory abilities were not judged to be a limiting factor in participants' ability to give responses in this way.

The other difficulty with conducting the GIN as designed is the time required for administration. Because the GIN was one component of a two-hour session including the experimental listening task and the two other auditory processing tasks described above, it was not reasonable to devote 40 minutes to this test alone. Respecting participants' schedules and avoiding fatigue and boredom were judged to outweigh the benefits of administering the entire test as designed. Instead, only the first of the four subtests was done, along with practice trials from the original design. Participants did ten practice items in the right ear first, ensuring that they understood and were able to complete the task; then the first 17 items of subtest 1 were administered to the right ear, and finally the remaining 18 items of subtest 1 were administered to the left ear (totaling 35).

Because of the modifications described here, the results of the modified GIN are used only for comparisons within this study; no conclusions are made in the Results section regarding how study participants compare to the norms published with the test.

Procedural Overview

Procedures for the project comprised four parts: the experimental sentence repetition task, standardized assessments of cognition and communication, tests of auditory processing, and the semi-structured interview. All participants completed the sentence repetition task and NART (for the purpose of matching estimated verbal IQ between groups), but only participants in Experiment 2 completed the rest of the standardized testing and the interviews. Figure 2 shows the procedure for Experiment 2 in more detail. All participants in both Experiment 1 and Experiment 2 completed the experimental listening task shown in the left-most column, but only participants with TBI and the matched control subgroup completed the standardized testing and semi-structured interview.

Participants in Experiment 1 were scheduled for a single session. Participants in the TBI group of Experiment 2 were scheduled for two research sessions, ranging from one day to 28 days apart, based on scheduling convenience. The mean time between sessions was 7.7 days (SD 7.3). The first session included the experimental sentence repetition task and standardized tests of auditory processing, and the second session included standardized testing and the semi-structured interview. One exception to this was participant #3 in the TBI group, who completed the testing in reverse order, with the standardized testing and interview at her residence, due to transportation problems. Of necessity, most participants from Experiment 1 who were invited back to complete the interview and testing for Experiment 2 completed the listening task first, and had a longer delay between the two sessions, ranging from five to 161 days. The mean time between sessions for controls was 58.2 days (SD 44.0). Of the 14 control participants recruited for Experiment 2, six of them completed auditory processing tests during session 1 (like the TBI group).

Stimuli

Listeners were asked to repeat back sentences from the IEEE corpus (IEEE, 1969), which consists of 72 blocks of sentences, with 10 sentences per block and five keywords per sentence. The sentences are designed to be syntactically and semantically correct but low-context. For example, when a listener hears "The birch canoe slid on the smooth ____" it is difficult to predict the final word "planks."

The order of presentation was randomized across participants, and block order within both the alone and attend conditions was counterbalanced across participants. This led to four possible sequences for the experiment, listed in Table 8. These orders were assigned to participants sequentially (e.g. the first participant scheduled did sequence I, the next did sequence II, and so on).

Recording.

Recordings for all the stimuli except practice sentences were made using an AKG C420 condenser microphone and a Marantz Professional CDR 300 CD recorder in a sound-treated booth. The sentences used in the practice block were recorded by two speakers different from those used in the main task, and were recorded using a laptop computer and microphone in quiet rooms. This difference in recording procedure was not a concern because the purpose of the practice block was to accustom participants to the task, and the data from practice responses were not to be considered in the analysis. Informal evaluation by two listeners determined that the practice sentences did not differ noticeably in quality from the experimental sentences.

All four speakers – two each for the practice and experimental blocks – were female. The target speaker in the practice block was a native speaker of mainstream-American English (NS), and the distracter was a speaker of Hindi-accented English (NNS). In the experimental blocks, one speaker was a native speaker of mainstream-American English (NS) and the other was a speaker of Mandarin-accented English (NNS). The two speakers for the experimental blocks were chosen to have similar mean fundamental frequencies. Fundamental frequency was scaled in equivalent rectangular bandwidth (ERB) (Hermes & van Gestel, 1991), as these have been shown to be better-correlated with judgments of vocal pitch than are measures in Hertz. Mean F0 was approximately 4.56 ERB and 4.51 ERB for the NS and NNS, respectively (ranges 2.3–5.0 and 1.7–5.3). Stimuli were presented as mono audio signals in order to maximize informational masking. As discussed in the introduction section, differences in sex, intensity, or spatial location can serve as cues for stream segregation, even in the presence of a negative SNR that would increase energetic masking (e.g. Brungart, 2001).

Stimulus selection.

For the purposes of this study, a total of 160 sentences from the IEEE corpus were used, consisting of 10 sentences x 2 speakers for practice; 10 sentences each for two alone condition blocks; and 30 sentences x 2 speakers each for two attend condition blocks. A list of all sentences and sentence pairs is provided in Appendix 3.

The first step in selecting the 160 sentences from the 720 available in the IEEE corpus was to eliminate from the list any sentence not beginning with “the.” This was done in an attempt to make sure that, in the attend condition, one voice would not be more salient or intelligible due to different sentence onsets. Next, the pool of sentences was restricted to those from six to nine words long, in order to limit the working memory burden potential in repeating longer sentences. These sentences were split into two sets for recording by the two volunteer speakers. Items were discarded in the few instances when the non-native-accented speaker made pronunciation errors that suggested she was not familiar with the word (as opposed to pronunciations simply consistent with her accent). Items were also discarded in a few cases when the recording levels for the native-accented speaker produced a recording artifact. This final step narrowed the pool to the requisite 160 sentences.

After the sentences were recorded, sentence pairs were created such that the keywords in each pair aligned to occur in the same sentence positions. For example, in the following sentence pair, the keywords (capitalized) for both sentences are the second, third, fourth, sixth, and seventh words:

The GRASS CURLED AROUND the FENCE POST.

The PLAY SEEMS DULL and QUITE STUPID.

Pairing sentences in this way was intended to increase the likelihood that keywords would acoustically overlap, rather than alternate, in the combined sound stream heard by participants.

It is worth noting that Helfer and Freyman (2009) developed a different set of stimuli that they specifically designed for speech interference experiments. In their TVM corpus, the listener is cued to the target sentence using a target name (Theo, Victor, or Michael). The authors found that cuing listeners with the name versus a voice sample made little difference in their ability to repeat the sentences. They also found that voices that are similarly affected by energetic masking can be differentially affected by informational masking. IEEE sentences rather than TVM sentences were used for this experiment for consistency with a precursor study about energetic masking release in adults with and without TBI (Krause et al., 2009).

Editing.

All sentences were converted to mono and sound files trimmed using Goldwave software (www.goldwave.com). Trimming was done by zooming to a window of approximately 0.05 sec around the sentence onset, and cutting silence up to the point of the first visible waveform.

The next step in the process of editing the stimuli was to match durations for each sentence pair. This was done by calculating the average duration for each pair using Praat software (Boersma & Weenink, 2011) and then lengthening the shorter sentence and shortening the longer sentence so both equaled the average. The experimenter and two independent listeners judged the naturalness of these duration-adjusted sentences and determined that lengthening or shortening the sentences up to 25% resulted in acceptably natural-sounding sentences. Sentence pairs whose differing lengths would have required greater than 25% duration adjustment were discarded and replaced with alternates.

The twenty sentences used in the alone condition were chosen from the pool of sentences that were either never paired or whose pairings were discarded because of mismatched durations. These “alone” sentences were shortened or lengthened in a pseudo-random pattern designed to mimic the distribution of duration manipulations among the paired sentences.

After duration adjustments were completed, 150 ms of silence was added to the beginning of each sentence file as a buffer between trial onset and sentence onset during the experimental procedure. The intensity of each sentence was then adjusted to 70 dB using Praat's intensity scaling tool. Finally, each sentence pair was combined into a single stereo .wav file, which was then compressed into a mono file for use in the experimental protocol.

For Experiment 1, a final step was required to develop stimuli for the filtered condition. All sentences and sentence pairs were filtered with a 1400 Hz low-pass band pass filter using Goldwave's batch processing function, which can apply the same process to multiple files. The purpose of this filtering was to simulate the effects of a peripheral hearing loss. Precedent for this procedure includes Wang et al. (1978), who found that, for CV and VC nonsense syllables with 1400 Hz low-pass filtering, listeners with normal hearing demonstrated consonant confusion similar to listeners with high-frequency hearing loss; they also found that 2800 Hz high-pass filtering produced results similar to those of listeners with flat or rising audiograms. Fabry and van Tassell (1986) showed similar findings based on a study whose participants each had one normal ear and one ear with hearing loss, using filtering as low as 7500 Hz. Oxenham and Simonson (2009) used low-pass filtering at 1200 Hz and high-pass filtering at 1500 Hz for their simulations. For the current study, pilot testing was done with low-pass filters at 1200, 1400, and 1600 Hz and a high-pass filter at 2800 Hz. The 1200 Hz filter resulted in accuracies near zero in the single-talker interference task, and the high-pass filter was reported by listeners to be annoying and difficult to listen to. Therefore, the 1400 Hz filter was chosen for this study based on a combination of maintaining consistency with previous research, sensitivity of measurement (keeping scores off floor), and positive listener experience.

Sentence Repetition Task Procedure

The experimental sentence repetition task was completed by all participants in both Experiment 1 and Experiment 2. Participants were seated in a sound-treated room and, before starting the experimental task, they were given a hearing screening using a screening audiometer to ensure that their hearing was within normal limits. The screening used a 20 dB signal at 500, 1000, 2000, 3000, and 4000 Hz. Participants #13 and #16 in the TBI group, and #11 in the control group, had thresholds of up to 30 dB for one ear at 4000 Hz, and participant #22 in the control group had a threshold of 30 dB at 4000 Hz in the right ear and 25 dB at 2000 Hz in the left ear. All other participants were able to detect the signal at 20 dB in both ears for all frequencies tested. Two participants in the TBI group were disqualified when the hearing screening revealed more significant hearing difficulties, but completed the listening task anyway so as not to have wasted their visit to the University. Data for these two participants are examined briefly in the Discussion section.

All experimental procedures were recorded using a digital audio recorder (either a Zoom Handy Recorder H2 or an Olympus WS-500M). The experimenter also scored the sentence repetition task on paper in real time. The procedure began with a screen of written instructions, accompanied by a simultaneous audio recording of the instructions. Participants pressed the space bar to advance from this screen, and the experimenter then asked if the participant had any questions. The next step was a sample audio file presented as an example of how loud the sentences would be in the upcoming experiment; participants were invited to indicate whether they wanted the sound louder, or quieter, or preferred it to stay the same. Loudness was initially set at approximately 70 dB for all participants, and the experimenter then adjusted the loudness as requested. At the end of this setup phase, participants were invited to ask any questions about the procedure.

Presentation of stimuli.

Stimuli in the sentence repetition task included five blocks of sentences: one practice and four experimental (see Figure 2). After having an opportunity to adjust the loudness of the stimuli, participants again pressed the space bar to indicate they were ready to proceed to the practice block. The time between the presentation of the "press the space bar when you are ready to continue" instruction and when the participant pressed the space bar to advance to the next trial was recorded by E-prime, but no other response time measures were gathered. Methods of measuring response time for this type of task often require participants to limit their movement, even with head-mounted microphones. Therefore, for the sake of naturalness and comfort, it was decided that precise response time measures were not a priority for this experiment.

Practice block.

The practice block consisted of 10 sentence pairs, spoken simultaneously by two female speakers. The purpose of the practice block was simply to familiarize participants with the single-talker interference protocol. After participants pressed the space bar to indicate that they were ready to begin, a screen displayed, "In the sentences coming up, you will hear two voices at the same time. Press the space bar and you will hear an example of the voice that you should listen to and repeat back." When participants pressed the space bar, a sample sentence of the target speaker was played. Next, the display read, “Now you will hear two voices at the same time. Remember, only repeat back the sentences spoken by the example voice you just heard. Just guess if you are not sure. Press the space bar when you are ready to continue.” When participants pressed the space bar this time, the first trial of the block was presented. Each auditory sentence presentation was accompanied by a visual display stating, “Listen and repeat.” This screen displayed for 2 seconds (with the 150 ms lag built in to the beginning of each sound file), followed by 2 seconds of a blank screen, followed by the prompt, “Press the space bar when you are ready to continue.”

Experimental blocks 1 and 2: alone condition.

Each of the first two experimental blocks comprised ten sentences, in counterbalanced order among participants, of the two experimental speakers in quiet (with no background noise or second speaker). Specific procedures were the same as for the practice block, but without the sample target voice because each block had only one speaker.

Experimental blocks 3 and 4: attend condition.

Each of the last two experimental blocks comprised thirty sentence pairs of both speakers (NS and NNS) at the same time. Participants were asked to repeat back only one of the speakers for the first block, and the other speaker for the second block, with order counterbalanced among participants. Specific procedures were the same as for the practice block.

Effort.

After each of the four blocks, participants were asked to rate the level of effort required to understand the target sentences on a visual scale from 0 (no effort) to 10 (extreme effort) by clicking with the computer mouse on the equal-appearing interval scale. Figure 3 shows the screen that was used for effort ratings. The experimenter also noted the participant’s responses on a paper form for later follow-up, shown in Appendix 4. After the conclusion of block 4 of the sentence repetition task, participants were shown the ratings they had made during the task. The experimenter verbally reviewed which ratings were for which block, and asked, “Can you please tell me more about what was behind your ratings?” The analysis presented here is based on the numerical ratings, but follow-up qualitative responses were audio recorded for future analysis.

Semi-Structured Interviews

The qualitative portion of this study comprised a semi-structured interview in which participants discussed their individual experiences of speech processing in challenging situations and, in the case of participants with TBI , if and how that experience has changed since their injury (see Appendix 5). All interviews were transcribed, and the utterances of the interviewees were parsed into quotations; a list of thematic codes was then developed based on these quotations, and each quote was labeled with one, two, or three appropriate codes. Both qualitative and mixed-methods results based on the interviews are presented in the next section.

The goal of the qualitative analysis was to determine whether the two participant groups reported different subjective experiences of complex speech processing. The mixed-methods analyses are used to help explain the quantitative results, and are also quantified for correlational analyses with the sentence repetition and cognitive testing data. Interviews were conducted on the same day as standardized testing (i.e. not on the same day as the experimental listening task) in order to minimize direct association of the two for the participants.

Analyses

Dependent variables in the sentence repetition task were accuracy and effort. Accuracy was measured as the proportion of key words correctly repeated (five possible per sentence; 50 total in each alone block and 150 in each attend block). Effort ratings from 0 to 10 were made after each block within the listening task, and were compared as raw numbers. In summary, quantitative dependent measures were accuracy (proportion) and subjective effort ratings (0–10). Independent variables were group (filtered vs. unfiltered in Experiment 1 and TBI vs. control in Experiment 2), target voice (NS vs. NNS), and condition (alone vs. attend).

Statistical analysis.

For both Experiment 1 and Experiment 2, the primary analysis used a three-way repeated measures ANOVA: group x target x condition, with presentation order (NS vs. NNS first in the attend condition) nested within group. Group was a between-subjects factor while target and condition were repeatable within-subjects factors. In addition, linear mixed-effects modeling was completed for Experiment 2 using item-by-item scoring of the experimental sentence repetition task. This method can account for random item effects (e.g. Baayen, Davidson, & Bates, 2008) which, in this case, were sentences and trial number, or order of item presentation. Exploratory correlations were calculated among sentence repetition accuracy and several demographic features and cognitive test scores. Linear regressions were performed to compare effort ratings and accuracy, to determine whether higher accuracy was associated with greater or lesser effort.

Qualitative analyses were conducted by identifying themes within transcribed interviews. As described above, quotes were tabulated from each interview, and up to three thematic codes were assigned to each quote. For the mixed-methods analysis, interview data were quantified by tabulating the total number of quotes for each participant, the number of times participants mentioned each theme, and the number of participants in each group who mentioned each theme. Finally, the number of specifically negative themes mentioned by each participant was counted for comparison between groups. Between-group comparisons were done using univariate ANOVA.

Reliability

All sentence repetition sessions and tests of auditory processing were administered by the principal investigator. Other standardized testing was completed by the principal investigator and two research assistants. Scoring was done by the author and a research assistant.

Reliability checking was done on 20–23% of test protocols (three per participant group). One undergraduate research assistant checked scoring on standardized tests and the sentence-repetition task; this involved rescoring all standardized tests of cognition for three participants per group, recounting responses on answer sheets for the sentence-repetition task for three participants per group, and rescoring the sentence-repetition task for three other participants in each group based on audio recordings of the experiment sessions. Inter-rater reliability for standardized test scoring was 98%; reliability for counting sentence repetition scores was 99.99%.

Another undergraduate research assistant assisted with transcribing and did reliability checking on three interviews per group. Reliability checking consisted of listening to the audio recording of the interview while reading the transcription and using Microsoft Word's "track changes" function to note discrepancies. The primary investigator checked for reliability on one of the research assistant's six transcriptions, and the research assistant checked for reliability on three of the principal investigator's 20 transcriptions. Inter-rater reliability for the interview transcriptions was 97.5%.

Finally, a graduate research assistant was given the list of 45 thematic codes for the semi-structured interviews, along with descriptions and examples of each code, and recoded quotes that the primary investigator had extracted from the interviews of three participants. Inter-rater reliability for this coding was 73%.

Results

Results from both experiments are summarized below. The purpose of Experiment 1 was to determine the effects of peripheral deficits on a sentence repetition task. This was accomplished by comparing accuracy and effort ratings on the sentence repetition task for healthy participants in groups presented with filtered versus unfiltered stimuli. The purpose of Experiment 2 was to determine the effects of TBI on the same sentence repetition task that was used in Experiment 1. This was done by comparing a group of adults with TBI to a group of age-, education-, and verbal IQ-matched healthy controls on the unfiltered version of the experimental sentence repetition task. In addition, Experiment 2 examined whether participants demonstrated accommodation to the task by measuring improvement over the course of the experiment; it also included exploratory correlations between sentence repetition accuracy and standardized tests of cognition and auditory processing. Finally, Experiment 2 included semi-structured interviews in which participants discussed their subjective experiences with complex speech processing.

Experiment 1

The primary research questions for Experiment 1 were whether a peripheral auditory deficit simulated with filtering would result in reduced accuracy or increased effort on the experimental sentence repetition task, whether participants were less accurate or reported more effort in the NNS than the NS condition, and whether there was an interaction between group and target such that the filtered group was more susceptible to target effects than the control group. Results for each condition are discussed in detail in the sections below. Because performances of the filtered group in the attend condition of Experiment 1 were initially near floor, these data were analyzed using randomized arcsine unit (RAU) transformation. In addition, during data collection, it was noted that many participants missed the same word spoken by the NNS ("rags" in the sentence The SMELL of BURNT RAGS ITCHES my NOSE). Therefore, this word was excluded from scoring. These modifications are reflected in Table 9 and Figure 4, which show the mean accuracies for each group in Experiment 1.

A three-way repeated-measures ANOVA was used to analyze the results of Experiment 1, in which group (filtered vs. unfiltered) was a between-subjects factor while target (NS vs. NNS) and condition (alone vs. attend) were repeatable within-subjects factors. The affect of block order was considered; a model incorporating order as a nested variable within groups showed that the effect of order was not significant. Therefore, order was not considered in the model reported here. Statistics for this analysis are shown in Table 10.

As shown in Table 10, there were significant main effects for group, condition, and target in Experiment 1, such that the unfiltered group had higher accuracy than the filtered group, the alone condition had higher accuracy than the attend condition, and the NS target had higher accuracy than the NNS target. In addition, there were significant two-way interaction effects for condition x group, target x group, and condition x target; and a three-way interaction effect for condition x target x group.

Figure 5 illustrates the three-way interaction between condition, target, and group for accuracy in Experiment 1. Pairwise comparisons for the components of the three-way interaction using two-sample *t*-tests assuming unequal variances showed numerous significant differences. Within the alone condition, the unfiltered group differed from the filtered group for the NS target, $t(14) = 7.96$, $p = 7.29 \times 10^{-7}$, and the NNS target, $t(15) = 26.27$, $p = 2.94 \times 10^{-14}$, where the unfiltered group was more accurate in both comparisons. For the filtered group in the alone condition, the NS target was significantly more accurate than the NNS target, $t(27) = 11.13$, $p = 6.82 \times 10^{-12}$, but this was not the case for the unfiltered group, where the same difference was only a trend toward significance, $t(25) = 1.45$, $p = 0.08$.

Within the attend condition, the unfiltered group was more accurate than the filtered group for both the NS target $t(22) = 15.21$, $p = 1.85 \times 10^{-13}$, and the NNS target, $t(22) = 20.20$, $p = 5.42 \times 10^{-16}$. Within the filtered group in the attend condition, the NS target was more accurate than the NNS target, $t(28) = 5.19$, $p = 8.32 \times 10^{-6}$, but, like the alone condition, for the attend condition there was no significant difference in accuracy between the NS and NNS target for the unfiltered group, $t(27) = 0.70$, $p = 0.24$. Between the alone and attend conditions, the alone condition was consistently significantly more accurate: for the unfiltered group NS and NNS targets, $t(14) = 10.42$, $p = 2.79 \times 10^{-8}$ and $t(15) = 12.39$, $p = 1.39 \times 10^{-9}$, respectively; and for the filtered group NS and NNS targets, $t(22) = 24.92$, $p = 6.44 \times 10^{-18}$ and , $t(18) = 20.07$, $p = 4.54 \times 10^{-14}$, respectively. With a simple Bonferroni correction, in which the significant *p* value is divided by the number of comparisons analyzed in the interaction the significant differences remained significant. In this case, twelve comparisons were required by the three-way interaction, resulting in an adjusted $p = 0.004$.

In summary, the explanation of the three-way interaction between condition, target, and group for Experiment 1 accuracy scores has several components. First, while the filtered group did significantly more poorly on the NNS target than the NS target in both conditions, the unfiltered group scores were essentially the same for each target. Second, as shown in Figure 5, this decrease in accuracy was more pronounced for the filtered group in the alone condition than in the attend condition, perhaps partly due to near-floor effects observed in the attend condition. In fact, the filtered group's accuracy dropped precipitously between the alone and attend condition, a difference of 66% for the NS target and 40% for the NNS target, compared to decreases of 34% and 32% for the unfiltered group.

In addition to accuracy, Experiment 1 also compared effort ratings. Table 11 and Figure 6 show the mean effort ratings for each group. Similar to the accuracy analysis, a three-way repeated-measures ANOVA was used to analyze the effort ratings in Experiment 1, in which group (filtered vs. unfiltered) was a between-subjects factor while target (NS vs. NNS) and condition (alone vs. attend) were repeatable within-subjects factors. Statistics for this analysis are shown in Table 12.

As shown in Table 12, there were significant main effects for group, condition, and target in the effort comparisons for Experiment 1, such that the filtered group reported greater effort than the unfiltered group, the attend condition required more effort than the alone condition, and the NNS target was more effortful than the NS target. In addition, there were significant two-way interaction effects for condition by target and condition by group. Figures 7 and 8 illustrate these interactions.

As shown in Figure 7, the condition by target interaction involves several significant differences. Two-sample t-tests assuming unequal variances revealed that the NNS target was more effortful than the NS target in the alone but not the attend condition, $t(58) = -4.03$, $p = 8.31 \times 10^{-5}$ and $t(57) = -1.01$, $p = 0.16$, respectively; and the attend condition was more effortful than the alone condition for both the NS and NNS targets, $t(40) = -11.25$, $p = 2.88 \times 10^{-14}$ and $t(42) = -6.50$, $p = 3.82 \times 10^{-8}$, respectively. The interaction, therefore, may stem from the fact that effort was uniformly high throughout the attend condition, whereas in the alone condition participants reported significantly higher effort for the NNS than the NS target.

For the condition by group interaction, as shown in Figure 8, all *t*-test comparisons were significant. The filtered group reported higher effort in both the alone and attend conditions, $t(58) = -7.82$, $p = 6.16 \times 10^{-11}$ and $t(45) = -4.70$, $p = 1.22 \times 10^{-5}$, respectively; and the attend condition was significantly more effortful for both the unfiltered and filtered groups, $t(48) = -13.28$, $p = 5.43 \times 10^{-18}$ and $t(36) = -8.43$, $p = 2.44 \times 10^{-10}$, respectively. Therefore, this interaction is less clear to explain than the condition by target interaction; however, the slope of change between groups appears higher for the alone condition than the attend condition. Therefore, the interaction may be due to greater effort effect in the alone condition compared to the attend condition. In other words, effort was similarly high for both groups in the attend condition, possibly a near-ceiling effect, whereas in the alone condition there was a larger increase in effort for the filtered group compared to the unfiltered group.

As with the accuracy analyses, Bonferroni corrections do not result in any changes in significance for the effort interaction *t*-tests in Experiment 1. In this case, four comparisons result in an adjusted significant $p = 0.0125$.

In summary, the findings of Experiment 1 support the hypotheses that participants in the filtered group would demonstrate poorer accuracy and higher effort than those in the unfiltered group. They also partly support the hypothesis that the NNS target would have lower accuracy and higher effort than the NS target: this was the case more so for the alone condition than for the attend condition. The prediction of a group by target interaction was supported, in that the filtered group was more adversely affected by the NNS target than was the unfiltered group. Moreover, the three-way interaction for accuracy scores suggests that the differential effect of NNS target for the filtered group was most pronounced in the alone condition, whereas in the attend condition both targets were near floor for the filtered group.

Experiment 2

In contrast to Experiment 1, which tested two groups of healthy adults with different types of stimuli, Experiment 2 tested two different groups, adults with and without TBI, using the same unfiltered stimuli. The first analysis paralleled the analysis used in Experiment 1, comparing mean sentence repetition accuracies and effort between conditions, groups, and targets using repeated-measures ANOVAs. Accuracies were also compared between the target and interfering speakers in the attend condition in order to more thoroughly assess group differences in the ability to ignore the interfering speaker while repeating the target. The second research question to be addressed was whether the control group learned or accommodated faster than the TBI group to the single-talker interference task and to the less-familiar, non-native accented speaker. Next, an exploratory correlation matrix was developed to examine whether standardized test results were associated with performance on the experimental sentence repetition task. Finally, results are presented based on qualitative and mixed-methods analyses of data from the semi-structured interviews that were conducted.

Sentence repetition task.

In order to assess whether mean accuracies were different between groups, conditions, or target speakers in Experiment 2, a three-way repeated-measures ANOVA similar to the one applied to data from Experiment 1 was used to analyze accuracy data from Experiment 2. As with Experiment 1, many participants missed the word “rags” during the NNS target block of the alone condition: in Experiment 2, only two participants in each group repeated it correctly. Therefore, the mean scores reflect proportions correct out of 49 words, excluding “rags,” in the NS alone block, in order to more precisely reflect the accuracy for each group. Mean accuracies for each group in each condition are shown in Table 13 and Figure 9.

Like in Experiment 1, presentation order was considered as a possible factor, but a model incorporating block order as a nested variable within group showed that the effect of order was not significant. Therefore, order was not considered in the primary model, a three-way repeated-measures ANOVA in which group (TBI vs. control) was a between-subjects factor while target (NS vs. NNS) and condition (alone vs. attend) were repeatable within-subjects factors. Results of this analysis are shown in Table 14.

As shown in Table 14, there were significant main effects for group, condition, and target in the accuracy comparisons for Experiment 2. The control group overall was more accurate than the TBI group; the alone condition was more accurate than the attend condition; and the NS target was more accurate than the NNS target. In addition, there was a significant interaction between condition and target and a trend toward significance for the condition x group interaction.

As shown in Figure 10, the condition x target interaction involves several significant differences. Two-sample *t*-tests assuming unequal variances revealed that, within both the alone and attend conditions, the NS target was more accurate than the NNS target, $t(31) = 1.84$, $p = 0.03$ and $t(49) = 1.95$, $p = 0.03$, respectively. In addition, the alone condition was significantly more accurate than the attend condition for both the NS and NNS target, $t(25) = 12.70$, $p = 1.06 \times 10^{-12}$ and $t(27) = 13.08$, $p = 1.70 \times 10^{-13}$, respectively. With Bonferroni corrections (modified $p = 0.0125$ criterion), only the alone vs. attend differences remain significant. This pattern of significant differences in the condition by target interaction may be explained by the greater decrease in accuracy between the NS and NNS targets for the attend condition compared to the alone condition. In the attend condition, there was a nearly 10% drop in accuracy for the NNS target, whereas in the alone condition both targets were near ceiling, with the NNS target only 1.5% lower than the NS target.

The condition by group interaction, which showed a trend toward significance, is illustrated in Figure 11. While the interaction is not significant, the pattern of responses here suggests that the TBI group may have had a greater decrement in accuracy with the attend condition than did the control group, though both groups showed significant decreases, $t(27) = 12.45$, $p = 5.30 \times 10^{-13}$ and $t(25) = 15.22$, $p = 1.90 \times 10^{-14}$, respectively.

Effort ratings were assessed in the same way as accuracy, first eliminating block order as a significant factor and then using a three-way repeated-measures ANOVA in which group (TBI vs. control) was a between-subjects factor and condition (alone vs. attend) and target (NS vs. NNS) were repeatable within-subjects factors. Means and standard deviations are reported in Table 15, and statistics from the ANOVA are presented in Table 16 and Figure 12.

As shown in Table 16, there were main effects for condition and target, with participants reporting higher effort in the attend condition and for the NNS target. However, there was no main effect for group, meaning that the TBI and control groups' reported effort scores were roughly equivalent to each other. In addition to the main effects, there was a significant interaction between condition and target. The interaction is shown in Figure 13.

As shown in Figure 13, several of the two-sample *t*-tests assuming unequal variances used to examine the interaction were statistically significant. In the alone condition, the NNS target had significantly higher effort ratings than the NS target, $t(45) = 5.12$, $p = 3.04 \times 10^{-6}$, but this was merely a trend in the attend condition, $t(49) = -1.42$, $p = 0.08$. The attend condition was significantly more effortful than the alone condition for both the NS and NNS targets, $t(46) = -13.07$, $p = 2.15 \times 10^{-17}$ and $t(48) = -8.46$, $p = 2.22 \times 10^{-11}$, respectively. The interaction may be explained by the fact that target speaker had a large impact on effort in the alone condition, whereas in the attend condition effort was similarly high for both targets. With a Bonferroni correction of the *p* criterion to 0.0125 for significance, the significant and non-significant findings held.

The results of the analyses of sentence-repetition accuracy and effort data from Experiment 2 support some of the research hypotheses, in that the attend condition was consistently less accurate and more effortful than the alone condition; and the TBI group was overall less accurate than the control group. However, the prediction of higher effort ratings from the TBI group was not supported, nor was the hypothesis that there would be a group by talker interaction in which the TBI group experienced a greater decrement of accuracy and increase of effort with the NNS target than did controls. The only result potentially supporting this type of interaction was a non-significant trend suggesting that the TBI group may have had a greater decrease in accuracy for the attend condition compared to controls.

Another research question for Experiment 2 was whether the TBI group was more likely than the control group to repeat interfering words. In order to consider this question, an analysis was completed to take into account not only words that were repeated from the target speaker, but also words that were repeated from the interfering or distracter voice. All participants repeated at least a few words from the “wrong” voice; some stated that they were aware that they were not repeating the target speaker and others did not. Experiment instructions included the statement, “Remember, only repeat back the sentences spoken by the example voice you just heard. Just guess if you are not sure.” Because of this, some participants may have deliberately refrained from repeating words if they knew them to be from the interfering voice; however, if they inquired, they were told that while they should try to repeat the target speaker, they should go ahead and say whatever words they were able to pick out.

In order to compare the TBI and control groups on their repetition of distractor words, difference scores were calculated for each participant: the proportion of target words repeated minus the proportion of interfering words repeated. Table 17 and Figure 14 show these differences. A two-way repeated-measures ANOVA was performed, with group (TBI vs. control) as a between-subjects factor and target (NS vs. NNS) as a within-subjects repeated factor. The statistics for this comparison are shown in Table 18. As shown in the table, the ANOVA revealed a main effect of target, such that the difference between the proportion of words repeated from the target versus the interfering speaker was significantly greater with the NS target than the NNS target. In other words, participants were more likely to repeat the “wrong” voice when their target was the NNS than when it was the NS. Contrary to the hypothesis, however, there was no significant difference between the groups, although there was a trend in the expected direction of the TBI group having a smaller target-minus-interfering difference, $p = 0.09$.

In addition to the analyses of accuracy and effort discussed above, the relationship between those two factors was also examined. For each group in each condition, effort was regressed against accuracy in order to determine whether reduced accuracy was associated with higher, lower, or no change in effort. Figure 15 shows that there was a spread of effort for both groups in the alone condition despite accuracies near ceiling; this is reflected in the regression analysis, which showed that there was no significant regression for either group, $R^2 = 0.07$, $F(1, 24) = 1.83$, $p = 0.19$, $\beta = -0.26$ for the control group, and $R^2 = 0.06$, $F(1, 24) = 1.43$, $p = 0.24$, $\beta = -0.24$ for the TBI group. In contrast, in the attend condition, greater effort was associated with poorer accuracy for both groups. Regression analyses showed significant negative associations between effort and accuracy in the attend condition for both the control group, $R^2 = 0.40$, $F(1, 24) = 16.22$, $p = 4.91\text{x}10^{-4}$, $\beta = -0.64$, and the TBI group, $R^2 = 0.32$, $F(1, 24) = 11.04$, $p = 0.003$, $\beta = -0.56$. These findings do not support the prediction that the TBI group would have higher effort ratings than the control group. However, it does support the assumption that more difficult speech processing demands – as reflected by reduced accuracy – were associated with greater effort on the part of participants. In other words, poor accuracy was not reflective of participants giving up on the task or failing to put forth effort.

Accommodation.

The next research question addressed in Experiment 2 was whether there were group differences in how participants accommodated to the less familiar (i.e. NNS) target. Two types of analysis were used to address the question of accommodation. First, regression analyses were performed for each group to determine whether there was a change in the number of keywords that were accurately repeated over the course of NNS target block. Second, linear mixed-effects modeling was used as an alternative mechanism to explore whether the order of trials played a significant role in repetition accuracy. These analyses were applied only to the attend condition because all participants were essentially at ceiling in the alone condition, so it would be difficult if not impossible to detect accommodation in that condition.

The first method for exploring whether participants' performance changed over time in the attend condition of the sentence repetition task was to regress accuracy over time (trials 1–30 over the NNS block). As shown in Figure 16, regressions were not significant for either the TBI group, $R^2 = 0.02$, $F(1, 28) = 0.55$, $p = 0.46$, $\beta = 0.006$, or the control group, $R^2 = 0.008$, $F(1, 28) = 0.21$, $p = 0.65$, $\beta = 0.005$. One limitation to this type of analysis is that, with only five possible keywords per trial, there is little possible variation in scores.

The second technique that was used to examine participants' accommodation during the experiment was linear mixed-effects modeling. As discussed in the methods section, linear mixed-effects modeling can provide an advantage over ANOVAs when there are both random and fixed effects to take into account. In this case, a model was created for the attend condition accuracy data in which participant and sentence were assigned as random effects, and group, block order, and trial number (position in list) were assigned as fixed effects. Appendix 6 lists the data tables for the model, which found a significant effect of block order (i.e. whether the first target was the NS or NNS), with an estimated $p = 0.02$. This suggests that, across both groups, accuracy was different depending on whether the NS or NNS block was administered first. In addition, a significant interaction was found between trial number and target speaker, with an estimated $p = 0.0001$. This interaction is shown in Figure 17, in which responses to the NS target across both groups increase in accuracy over the course of the experiment while responses to the NNS target slightly decline. Like the regression analysis, linear mixed-effects modeling is limited in that each trial had only five possible keywords to repeat, which reduced the possible variation in scores.

Overall, these analyses do not support the hypothesis that the TBI group would accommodate more slowly than the control group, but there may be effects depending on which target was presented first during the experiment. The differing results found by the two methods suggest that further research is needed to explore the question of accommodation in more detail.

Standardized test measures and repetition accuracy.

Participants in Experiment 2 completed a battery of standardized tests, partly as demographic measures in order to be able to compare the abilities of the two groups, and also in order to be able to examine connections between cognitive and auditory processing abilities and performance on the experimental sentence repetition task. Results of the standardized tests of cognition and communication were discussed in the methods section, and the full dataset of scores for each participant can be found in Appendix 2. In addition, participants completed three tests of auditory processing in order to establish if and how these tests are related to performance on the experimental sentence repetition task. The results of those tests are presented here, along with a set of exploratory correlation matrices designed to explore the relationship between test scores and sentence repetition accuracy.

Central auditory processing.

Three tests of central auditory processing were included in the standardized test battery for participants in Experiment 2. Table 19 lists the means and standard deviations for these tests for each group of participants.

For the SCAN-A, univariate ANOVAs showed no group differences for any of the three subtests: filtered words $F(1, 24) = 2.24$, $p = 0.15$; figure-ground $F(1, 24) = 0.088$, $p = 0.77$; and dichotic listening $F(1, 24) = 0.52$, $p = 0.48$.

The MLD test showed group differences, in which the TBI group had a lower masking level difference than the healthy control group, $F(1, 24) = 4.29$, $p = 0.05$ ($\eta_p^2 = 0.15$, observed power = 0.51). This difference may be partly explained by one outlier: the only participant in either group who scored below the cutoff for “failing” the test was #5 in the TBI group, who had an MLD of 2. When this datapoint is excluded, the group difference merely trends toward significance, $F(1, 24) = 3.41$, $p = 0.08$, with the TBI group mean rising from 31.54 (SD 10.3) to 34.0 (SD 5.46).

Like the SCAN-A, the GIN test showed no significant difference in either the accuracy of the two groups on this task, $F(1, 24) = 0.05$, $p = 0.83$, or the number of false positives, $F(1, 24) = 1.39$, $p = 0.25$.

Overall, the lack of group differences for the standardized tests of auditory processing supports the hypothesis that these tests are not sensitive to the type of speech processing difficulties reported by participants with TBI.

Correlations between standardized tests and sentence repetition accuracy.

Tables 20 and 21 show exploratory correlation matrices for key cognitive and demographic measures along with accuracy and effort on the sentence repetition task. Table 20 is for the TBI group only and Table 21 shows the control group only. The groups were separated because of the significant differences between them on multiple measures.

When the TBI group was considered alone, the positive correlation between NNS and NS accuracy scores in the alone condition was significant, but the correlations between targets in the attend condition and between conditions for both the NNS and NS targets all merely showed trends toward significance. Effort scores for the TBI group were positively correlated for the two speakers within each condition; effort scores were also positively correlated between the NS target in the attend condition and the NNS target in the alone condition. As for correlations between accuracy and other measures, only age significantly correlated with accuracy: in both blocks of the attend condition, higher age was correlated with poorer accuracy. Age was also positively correlated with years since injury, not surprisingly. There were additional trends toward significance for a positive correlation between Listening Span and accuracy repeating the NNS target in the alone condition, and for a negative correlation between Decision Speed accuracy and accuracy repeating the NNS target in the attend condition. These trends suggest that there may be relationships among good linguistic working memory, fast processing speed, and success with complex speech processing in adults with TBI, but further study is needed to explore these relationships.

In the case of the control group, all participants scored 100% for sentence repetition in the alone NS block, so no correlations were possible with this factor. Within the attend condition, however, NS and NNS accuracies were significantly positively correlated, and effort was also positively correlated between the two targets within the alone condition but not the attend condition. Moreover, in the attend condition, accuracy in the NNS block was significantly correlated with effort in both the NNS and NS blocks. The correlation between age and accuracy observed in the TBI group was not present in the control group, although, interestingly, Decision Speed was correlated with MLD score.

These preliminary correlational findings support the hypothesis that no one standardized test of cognition or auditory processing would be able to explain performance on the single-talker interference task. The fact that the standardized test scores were not all intercorrelated with each other supports the assumption that they were testing somewhat independent factors. However, these results are merely exploratory, in that they do not take into account any corrections for reducing Type I error. The small *n* involved in this study means that such corrections would eliminate most of the significant results in the correlation analysis.

Semi-structured interviews.

Both qualitative and mixed-methods approaches were used to analyze data from the semi-structured interview. These methods were used to explore whether there were group differences in how participants subjectively described their speech perception, and how those subjective experiences were related to the quantitative measures in the experiment. There has been very little prior research in this area. Bergemalm and Borg (2001) included the Gothenberg Hearing Questionnaire and a questionnaire about quality of life in their study of long-term audiological consequences of TBI; however, the responses relating to possible informational masking or experiences in different environments are not analyzed or discussed in the article.

Appendix 7 lists the 45 thematic codes that emerged from the semi-structured interview transcriptions, along with example quotes representing each theme. The total number of quotes culled from the TBI group was 325 (*M* 19.85, *SD* 7.99), compared to 219 (*M* 13.08, *SD* 2.33) from the control group. A univariate ANOVA demonstrated that this was a significant difference, $F(1, 14) = 4.26$, $p = 0.01$. Given that the structure of each interview was the same (see Appendix 5), this difference shows that participants with TBI had more to say on the topic of complex speech processing than did healthy controls.

One way to examine the interviews' thematic data is to look at the number of participants who mentioned various themes. This is relevant because some people repeatedly mentioned the same theme several times, and it is illustrative to remove the effect of multiple mentions. Table 22 lists each theme and the difference between the number of participants in each group who mentioned that theme. Positive difference scores represent themes that were mentioned more frequently by the TBI group, and negative difference scores represent themes that were mentioned by more control participants.

Table 22 demonstrates a number of interesting results. First, there was similar discussion of strategies in the interviews for each group: 92% people in the TBI group mentioned strategies, as did 100% in the control group, giving that theme a difference score of -1. This is not surprising, given that part of the interview specifically asked about strategies, so each participant responded by mentioning that theme. In addition, the strategy theme is particularly prevalent because it is not subdivided into the different types of strategies discussed.

In contrast, nearly 40% of the TBI group specifically mentioned lacking a strategy in some context (the “no strategy” theme), while none of the control participants stated that they lacked strategies, leading to a difference score of 5. The same difference occurred with the “can’t process” theme, in which participants with TBI explicitly reported difficulty processing complex speech information. Likewise, the “overload” and “stressful” themes, referring to feeling overwhelmed, overloaded, or stressed by complex speech processing situations, were mentioned by 32% of TBI participants but no healthy controls, resulting in difference scores of 4 for each theme.

Other notable contrasts between the groups included the “change” themes, in which improvement in speech processing over time (change + theme) and no noticeable change over time (change =) were overwhelmingly reported by control participants (difference scores of -4 and -3, respectively) whereas the TBI group was much more likely to report their speech processing getting worse (change- theme; difference score = 7). Interestingly, particular strengths in speech processing contexts were mentioned by 69% of TBI participants versus 39% of healthy controls (strength theme; difference score = 4).

Next, in order to address the primary research question of whether people with TBI report more subjective difficulty with complex speech processing, interview quotes were evaluated based only on specifically negative reports. In other words, positive and neutral quotes were eliminated and the remaining quotes were compared across groups. Table 23 shows the results of that comparison.

As with the total quotes overall, the number of negative quotes was significantly greater for the TBI group than the control group, as shown by a *t*-test assuming unequal variances, $t(50)=2.95$, $p = 0.002$, with a mean number of quotes per theme of 7.2 (SD 6.0) for the TBI group and 2.8 (SD 5.0) for the control group.

A correlation matrix was also created to compare sentence repetition accuracy, total number of interview quotes, and number of negative themes mentioned by each participant. There was a highly significant correlation between the number of quotes coded per participant and the number of negative themes appearing in the participant's interview, $r(24) = 0.88$, $p < 0.001$. This is not surprising, but does support the assumption that participants who had a lot to say in their interviews were actually discussing a range of themes and not simply giving repetitive comments on a small number of topics. No other correlations in the matrix were significant.

In the next analysis, plots were created showing the number of negative quotes and total quotes for each participant versus their overall attend condition accuracy, in order to show whether interview reports directly corresponded with sentence repetition accuracy. Figures 18 and 19 show these relationships; none of these regressions were significant. For number of negative themes only, the TBI group regression was R^2 = 0.004, $F(1, 11) = 0.04$, $p = 0.84$, $\beta = -1.67$, and the control group regression was R^2 = 0.005, $F(1, 12) = 0.05$, $p = 0.83$, $\beta = -1.05$. For the total quotes overall, the TBI group regression was $R^2 = 0.002$, $F(1, 11) = 0.02$, $p = 0.88$, $\beta = -2.05$, and the control group regression was $R^2 = 0.11$, $F(1, 11) = 1.31$, $p = 0.28$, $\beta = -6.28$.

Finally, the relationship between interview reports and sentence repetition accuracy was examined by relating the number of negative themes reported by each participant to above- and below-average sentence repetition accuracy groupings. The themes of particular negative affect reported by each participant were counted: distracted, focus, stressful, focus, can't process, filter, frustrated, change-, anxiety, and overload. The number of these themes mentioned by each person is shown in Figure 20, presented by high- and low-accuracy groups (above and below the mean for the TBI and control groups).

Although it is clear again that participants with TBI reported more negative experiences with complex speech processing, there is little apparent difference in these reports between those who performed well on the single-talker interference task and those who performed relatively poorly. The only notable pattern is that four out of the seven control participants who had below-average accuracy cited *none* of the negative-affect categories in their interviews. Overall, the mixed-method findings suggest that, within groups, there is little or no direct relationship between subjective report of difficulty with speech processing and how each participant performed on the experimental sentence-repetition task.

Experiment 1 and Experiment 2

The primary purpose of Experiment 1 was to determine whether any speech processing effects observed in participants with TBI were similar to peripheral hearing effects. To determine this, the TBI group results from Experiment 2 were compared to those of the filtered group from Experiment 1. Unlike the groups within each experiment, these two groups were not matched demographically. Two-sample *t*-tests showed that they were significantly different in age, $t(12) = -4.66$, $p = 0.0003$, where the mean age for the TBI group was 39 compared to 21 for the filtered group; and in estimated verbal IQ, $t(22) = -1.76$, $p = 0.05$, where the TBI group mean was 113 and the filtered group mean was 108. Table 24 shows the overall comparison of sentence repetition accuracy for all the participant groups across both studies.

As with Experiments 1 and 2, a three-way repeated-measures ANOVA was used to compare the filtered group to the TBI group, in which group (filtered vs. TBI) was a within-subjects factor while target (NS vs. NNS) and condition (alone vs. attend) were repeatable between-subjects factors. As with the analysis for Experiment 2, block order was initially included as a nested factor within group, was demonstrated to have no significant effect, and was eliminated from further analysis. Three covariates were also tested: a model with age, education, and verbal IQ as covariates showed that, whereas age was a significant factor, IQ and education were not and were eliminated from the final model. Age was kept as a covariate. Statistics for this analysis are shown in Table 25.

As shown in Table 25, there were significant main effects of group, condition, and target, such that the TBI group was more accurate than the filtered group, the alone condition was more accurate than the attend condition, and the NS was more accurate than the NNS target. There were also two-way interactions between condition and age, condition and group, and target and group; and a three-way interaction between condition, target, and group. Figure 21 illustrates the three-way interaction.

Pairwise comparisons for the components of the three-way interaction using two-sample *t*-tests assuming unequal variances showed numerous significant differences. Within the alone condition, the TBI group was significantly more accurate than the filtered group for both speakers, $t(16) = 7.59$, $p = 5.48\text{x}10^{-7}$ for NS; $t(25) = 20.37$, $p = 2.18\text{x}10^{-17}$ for NNS, and this difference was larger for the NNS target. The difference between the NS and NNS targets in the alone block was significant within each group, $t(16) = 2.43$, $p = 0.01$ for TBI and $t(27) = 11.13$, $p = 6.82\text{x}10^{-12}$ for filtered, but much more distinct for the filtered group. Within the attend condition, the TBI group was again more accurate than the filtered group for both targets, $t(14) = 7.68$, $p = 1.1\text{x}10^{-6}$ for NS and $t(12) = 5.78$, $p = 4.35\text{x}10^{-5}$ for NNS. The filtered group was significantly more accurate for the NS target than the NNS target in the attend block, $t(22) = 5.21$, $p = 1.6\text{x}10^{-5}$, whereas this difference was only a trend toward significance for the TBI group $t(23) = 1.58$, $p = 0.06$. Finally, both groups were significantly more accurate in the alone than the attend condition for both targets: for the TBI group the comparison was $t(12) = 9.23$, $p = 4.23\text{x}10^{-7}$ for the NS target and $t(13) = 8.84$, $p = 3.68\text{x}10^{-7}$ for the NNS; for the filtered group the comparisons were $t(22) = 24.92$, $p = 6.44\text{x}10^{-18}$ for the NS target and $t(18) = 20.07$, $p = 4.54\text{x}10^{-14}$ for the NNS.

Overall, the results of the comparison between Experiment 1 and Experiment 2 support the hypothesis that the pattern of performance for adults with TBI on the single-talker interference sentence repetition task is different from the performance of healthy adults with simulated peripheral hearing loss. The filtered group in Experiment 1 had consistently poorer accuracies in each listening condition compared to the TBI group from Experiment 2; moreover, the pattern of accuracies was different for the two groups, with the filtered group showing strong reductions in performance between the NS and NNS target in both conditions, whereas the TBI group had a much smaller (although still significant) decrease in accuracy between the NS and NNS targets in the alone condition compared to the attend condition. The fact that age remained a significant factor in this last comparison even after being covaried out in the analysis suggests that age needs to be considered in more detail in future studies.

Discussion

People who have experienced TBI often report lingering difficulties with processing speech in challenging situations. Even those who have returned to work or school, and perform well on many standardized assessments of language and cognition, may experience problems when faced with conversation in noisy backgrounds, with multiple talkers, with unfamiliar accents, or in other challenging circumstances. In this study a group of adults with TBI demonstrated reduced accuracy on a single-talker interference task compared to healthy controls. In interviews, the TBI group also reported more negative subjective experiences with speech processing compared to the control group, including experiences of frustration, feeling overwhelmed, and changes for the worse over time.

Previous research has demonstrated impairment-level deficits following TBI in multiple areas potentially relevant to complex speech processing. These include central auditory processing (e.g. Bergemalm & Borg, 2001), processing speed (e.g. Madigan et al., 2000), short-term memory (e.g. Rios et al., 2004), and regulation of attention (e.g. Rueda et al., 2004). The combination of these factors is behind the prediction that the TBI group in this study would exhibit greater informational masking effects than the healthy control group, while showing equivalent energetic masking effects. Most prior research has focused on measurements of basic function in individuals with TBI in order to study impairments following brain injury. Using a mixed-methods design, this dissertation compared performance across standardized tests measuring body-function level, an experimental single-talker interference task intended to approximate activity-level ability, and semi-structured interviews designed to assess participation-level experiences. The goal of combining these measures was to provide a more complete picture of complex speech processing after brain injury.

An additional goal of the project was to compare the performance of adults with TBI on the experimental sentence repetition task with the performance of a group of healthy adults with simulated peripheral hearing loss. This peripheral effect was explored in Experiment 1, which compared young adults in filtered and unfiltered groups completing the sentence repetition task. Experiment 2 comprised a healthy control and TBI group performing the same task with only unfiltered stimuli, as well as a battery of standardized assessments of cognition and auditory processing, and semi-structured interviews about participants' subjective experiences with complex speech processing. The results of each experiment are discussed in the following section.

Experiment 1

The purpose of Experiment 1 was to examine purely peripheral effects on sentence repetition with single-talker interference. Healthy control participants repeated sentences spoken by native- and non-native-accented speakers, in alone and attend conditions (speakers heard individually vs. simultaneously). One group heard the stimuli without filtering, and the other heard them with 1400 Hz low-pass filtering. The research questions for Experiment 1 were:

- Is the filtered group less accurate than the control group on the sentence repetition task?
- Are participants less accurate in the NNS than the NS condition?

- Is there an interaction between group and target (i.e. is the filtered group more susceptible to target effect than the control group)?

The work of Nelson et al. (2003, 2004) and Cullington and Zeng (2008) suggests that people with peripheral hearing loss are more susceptible to masking effects, and less able to achieve release from energetic masking, than healthy controls. The results of Experiment 1 in this dissertation support these conclusions, in that listeners in the filtered group did much more poorly than those in the unfiltered group. A simulated peripheral hearing loss, as predicted, reduced accuracy and increased effort in the sentence repetition task.

In addition to the main effects of group (unfiltered > filtered), condition (alone > attend) and target speaker (NS > NNS) on accuracy in Experiment 1, there was a three-way condition x target x group interaction. One component of this interaction was that the filtered group but not the unfiltered group was significantly less accurate for the NNS target than the NS target in the alone condition. In other words, in an ideal listening situation, the unfiltered group's accuracy was at ceiling regardless of speaker, but the filtered group was less accurate with the non-native target. This is consistent with research such as that of Wilson and Spaulding (2010) showing that non-native speech intelligibility is more affected by energetic masking effects than native speech. In the attend condition, the same pattern was observed, in that the unfiltered group performed the same for both targets while the filtered group did significantly worse with the NNS than the NS target.

These results suggest that much of the main effect of target in Experiment 1 was driven by differences in the filtered group. These differences are consistent with the theory that NNS speech has less redundancy in the signal than NS speech. This idea was based on previous research by Oxenham and Simonson (2009), who discussed redundancy regarding filtered speech, and Cooke et al. (2008), who examined it from the perspective of non-native listeners. Any reduction in access to acoustic information, such as band-pass filtering, would be easier to overcome in a target with more redundant information available, such as the NS. Moreover, what little information is available in the filtered condition would be further limited by single-talker interference. The decrease in attend-condition accuracy for the NS target from 68% in the unfiltered group to 15% in the filtered group illustrates the impact of reduced access to peripheral auditory information.

The results of Experiment 1 also suggest that energetic effects were dominant over informational masking effects in that experiment. Block 3 and Block 4 of the experiment were the same except for the attention factor: the stimuli throughout both blocks comprised sentences from the NS and NNS presented simultaneously, and the only difference was which speaker the participant was instructed to repeat. This was intended to measure informational masking effects, because the acoustic signal between the two blocks did not change. In contrast, the 1400 Hz low-pass filtering experienced by the filtered group was intended to gauge energetic masking effects. The contrasting patterns of performance between the two groups suggests that the energetic effects of the filtered condition was more influential than the informational masking involved in the attend condition. The fact that the filtered group did so much worse with the NNS in the alone condition, when there was no informational masking at all, while the unfiltered group showed no difference between the two talkers in either condition, demonstrates that the peripheral effects overwhelmed informational effects in this experiment.

In addition to accuracy, Experiment 1 also looked at effects of subjective effort ratings. Significant main effects for group, condition, and target showed that the filtered group reported greater effort overall than the unfiltered group; the attend condition required greater effort than the alone condition, and the NNS target was more effortful to repeat than the NS. A two-way interaction between condition and target showed that, across groups, effort was uniformly high for both target speakers in the attend condition but significantly higher for the NNS target in the alone condition. This shows that the difficulty of the single-talker interference task was high enough to overcome the more subtle effects of target speaker that were apparent in the alone condition. There was also a two-way interaction between condition and group: both the filtered and unfiltered groups had high effort in the attend condition, but the filtered group reported significantly greater effort than the unfiltered group in both conditions. This difference was more pronounced in the alone condition, possibly an artifact of ceiling effects for the filtered group. As shown in Figure 8, that group's mean effort ratings went from 6.2 in the alone condition to 9.3 out of 10 in the attend condition, whereas the unfiltered group showed more range, going from mean effort ratings of 2.3 to 8.1. It is possible that the slopes of these changes might have been more parallel, reducing the interaction effect, if the rating scale had allowed the filtered group to increase their ratings further in the attend condition.

These findings are consistent with studies such as Sarampalis et al.(2009) that have studied the high effort associated with peripheral hearing loss; Krause et al. (2009) also found increased effort in a sentence repetition task involving energetic masking. The uniformly high effort reported in the attend condition of Experiment 1 may indicate ceiling effects. This possibility is discussed further in the context of Experiment 2.

The goal of Experiment 1 was to provide information about the effects of a purely peripheral auditory deficit on the sentence-repetition task. Results demonstrated that peripheral effects, as modeled by a low-pass filter, have a significant impact on both the accuracy and effort involved in the experimental sentence-repetition task. Moreover, the effect of speaker accent is more pronounced for the alone condition, whereas in the attend condition the filtered group's accuracy was near floor for both speakers. Results suggest that the energetic masking effects of the low-pass filtering dominated the informational masking effects of the single-talker interference task.

The comparison of the filtered group from Experiment 1 with the TBI group from Experiment 2 will be discussed further below.

Experiment 2

Experiment 2 had several primary goals. The first goal was to explore any differences between adults with and without TBI on the experimental sentence-repetition task. The second goal was to describe relationships between the sentence-repetition results and standardized tests of cognition and auditory processing. The third goal was to provide a qualitative description of participants' subjective reports on their experiences of complex speech processing. Finally, the fourth goal was to offer a mixed-methods analysis combining data gleaned from interviews with those of the sentence-repetition task.

Sentence repetition task.

The primary quantitative research questions for Experiment 2 included the following:

- Was the TBI group less accurate than the control group with the sentence repetition task? Did the TBI group report more effort**?**
- Were participants less accurate, or did they report more effort, in the NNS than the NS condition?
- Was there an interaction between group and target (i.e. was the TBI group more susceptible to target effect than the control group?) for either accuracy or effort?

Similar to Experiment 1, in the alone condition of Experiment 2 the accuracy for both groups was essentially at ceiling for across target speakers. There was a small but significant difference in accuracy between the NS and NNS target across groups, with the NNS being slightly less accurate. This significant difference between targets indicates that, despite pilot testing that showed both speakers' intelligibility to be at ceiling, the goal of finding two speakers who were equally intelligible in quiet listening conditions was not quite met. Ideally, both the NS and NNS would have been 100% intelligible in the alone condition. However, the difference was small: 100% versus 99% for the control group, and 99% versus 97% for the TBI group.

In the attend condition, in contrast, the significant main effect of target reflected larger differences between the two speakers: 64% versus 57% for the control group, and 54% versus 42% for the TBI group. There were also main effects for group, such that the TBI group was less accurate than controls, but there were no interactions between group and the other factors. Although the hypothesis that participants with TBI would be differentially affected by target accent was not supported, Experiment 2 does offer clear evidence that people who have had a TBI are more likely than controls to have difficulty with single-talker interference such as the experimental sentence-repetition task.

The high variability in accuracy among participants in both groups is also noteworthy, particularly in the attend condition. This is consistent with the findings of Freyman, Helfer, and Balakrishnan (2007), who showed high variability among healthy controls in a two-talker interference task. Whether there are different patterns of variability between TBI and healthy control groups may be worth further examination in the future.

Another analysis of repetition accuracy centered on the frequency with which participants repeated the interfering speaker rather than the target speaker in the attend condition, asking “Was the TBI group more likely than the control group to repeat interfering words?” Difference scores were calculated between words repeated from the target and interfering sentences. Although there was not a significant group effect, there was a trend ($p = 0.09$) in the direction of smaller differences for the TBI group than the control group. There was a significant effect of target, such that when the NS was the target, the difference between target and interfering word repetitions was greater than when the NNS was the target. In other words, when the NNS was the target, participants across groups were more likely to repeat interfering words than they were when the target speaker was the NS.

Research on attention such as Rueda et al. (2004), Telling et al. (2010), and Schmitter-Edgcombe and Nissley (2000) has demonstrated that adults with TBI can show greater distractibility than healthy controls, particularly in situations requiring conscious control of attention. This led to the prediction that participants with TBI would have greater difficulty than healthy controls ignoring the distracter voice in Experiment 2. This prediction was not supported by the current analysis, although there was a statistical trend in the predicted direction. Across groups, participants showed the predicted effect of speaker familiarity, in that the NS distracter intruded more on the NNS target than the other way around. Some participants had much greater difficulty filtering out the interfering speaker than others across both groups, and some were more accurate with the NNS target. It is possible that some participants were more susceptible than others to the odd-distracter salience effect described by Brungart et al. (2001), in which a single odd-sex distracter voice combined with several same-sex distracters was more intrusive than an equal number of distracters that were all the same sex as the target. In the current experiment, this effect could explain the few participants who had significantly greater accuracy in the NNS target condition than the NS target. This phenomenon warrants further study; it is not clear to what extent differences among listeners were related to listener characteristics, the target speaker, the order of presentation, some combination of these, or other factors entirely.

Patterns of reported effort were also analyzed in Experiment 2. Prior research such as Kennedy et al. (2008, 2011) and Krause et al. (2009), in which participants with TBI reported increased effort following their injuries, led to the prediction that participants with TBI would report greater effort than controls in the current project. Analysis of results did not support this prediction of a group effect; however, there were main effects of condition and target, as well as an interaction between condition and target. The attend condition was significantly more effortful than the alone condition overall, and the NNS target was significantly more effortful than the NS target. The interaction showed that effort increased more between the NS and NNS target in the alone condition than in the attend condition.

The interaction illustrates one drawback to the effort measure used here. Ratings were uniformly high in the attend condition regardless of target, and it is possible that ratings were not sensitive to subtle differences between stimulus blocks, particularly in the attend condition. Participants may have been reacting mostly to the contrast in effort between the alone and attend condition, rather than offering a nuanced evaluation of any difference in effort between blocks within the attend condition. Finally, it is also possible that the long delay between effort ratings (30 trials in the attend condition, compared to only 10 in the alone condition) made it difficult for participants to accurately calibrate their ratings. This delay was instituted in order to minimize “breaks” and maximize fatigue effects within the repetition task, but it may have undermined the sensitivity of the effort ratings.

Despite these shortcomings, regressions of effort versus accuracy (Figure 15) did show significant correspondence in the attend condition between higher reported effort and lower repetition accuracy. This suggests that participants perceived poorer performance as more effortful, as opposed to low accuracy occurring when listeners were not trying hard. Further study is needed to determine details about the relationship between effort and accuracy, but the current data suggests that the increased effort reported in the attend condition is tied to the specific difficulty of the task for individual participants. In other words, participants did not arbitrarily rate each attend block as highly effortful, but did calibrate their ratings somewhat in relation to their ability to complete the task. This is consistent with the findings of Fraser et al. (2010), who found a similar negative correlation between effort rating and accuracy in the audio-visual condition of their speech recognition task.

Another research question important to understanding how participants performed on the sentence repetition task was, “Did the control group accommodate faster than the TBI group?” Previous research has studied the phenomenon of accommodation to unfamiliar speech stimuli such as vocoded speech (Davis et al., 2005) and non-native speech (Clarke & Garrett, 2004), which can occur with very brief exposure; and that this process of accommodation can be disrupted by peripheral effects such as background noise (e.g. Clopper & Bradlow, 2008). These findings led to the prediction that participants would increase their accuracy over the course of the single-talker interference task when the NNS was the target. Moreover, due to the difficulty with regulation of attention experienced by people with TBI (e.g. Rueda et al., 2004), it was predicted that the selective attention required in the single-talker interference task would lead to slower accommodation for the TBI group in this experiment than for healthy controls.

In contrast to these predictions, simple regressions did not reveal any increase in accuracy over the course of the NNS block for either participant group. However, with only five keywords per trial, this type of regression analysis may not have been sufficiently sensitive to detect accommodation effects.

A more complex picture emerged from linear mixed-effects modeling of order effects, which suggest that the order of presentation (which speaker was targeted first and which second) interacted with target speaker and group to affect accuracy. This interaction suggests that, rather than accommodating to the unfamiliar accent over time as predicted, participants may have been accommodating to the single-talker interference task in the NS target condition, and were less able to do so in the NNS condition. The practice block was intended to limit this type of effect, but it was conducted only with an NS target. The lack of interaction with group in this model suggests that this effect was not significantly stronger for the TBI group than it was for controls, although further analysis is warranted to explore this phenomenon further.

Block order (whether the NS or NNS target was presented first) was considered as a factor nested within groups in the repeated-measures ANOVAs of accuracy and effort for both Experiment 1 and 2. These analyses showed that block order was not significant, and it was excluded from further consideration. The findings of the linear mixed-effects model do not undermine these results; rather, they suggest a possible avenue for future study. In particular, clinical research could benefit from a more detailed understanding of the patterns of learning and accommodation for people with and without TBI.

Standardized test measures and repetition accuracy.

Along with the sentence repetition task, a battery of standardized tests of cognition and auditory processing was administered to each participant in Experiment 2, both for the purposes of demographic comparison between groups and as a way to assess the features, such as processing speed and attention, predicted to affect speech processing. The group differences that were found were in the expected direction, such that the TBI group in this study showed significantly lower overall scores on the RBANS, higher self-reported attention difficulties on the APT-II questionnaire, and lower recall scores on the Listening Span task. There were no group differences on two tests of basic executive function, digits backwards and the D-KEFS trails switching subtest when motor speed was accounted for, or on the BADS-Dex questionnaire. This demonstrates that the participants with TBI in this study comprised individuals who have achieved strong recovery after their brain injuries.

Another research question related to standardized testing in Experiment 2 was, “Are there correlations between standardized tests or demographic factors and sentence repetition accuracy?” In order to address this question, exploratory correlation matrices were created between measures of repetition accuracy and standardized tests of cognition and central auditory processing that could influence complex speech processing.

For the TBI group, accuracies were significantly positively correlated for the two speakers in the alone condition, and showed trends toward significance positively in the attend condition. This is not surprising given that variability was much higher in the attend condition. Correlations among effort ratings showed that, within each condition, participants rated both speakers similarly, and that effort ratings for the NNS target in the alone condition were significantly positively associated with reported effort on the NS target of the attend condition. In other words, people who found the NNS effortful even in the alone condition were also likely to report high effort for the NS target in the attend condition. As for the significant correlations with age found in the TBI group, it is difficult to offer any confident interpretations due to the fact that, in this group, age is also strongly correlated with time since injury. Future research could be designed to specifically address the relationships among age, time since injury, and speech processing.

Both decision speed and listening span showed nonsignificant trends toward correlation with sentence repetition measures for the TBI group: better listening span was associated with better accuracy for the NNS target in the alone condition, while less decision speed accuracy (i.e. slower speed) was associated with better NNS target accuracy in the attend condition. The possible association between sentence repetition and verbal working memory seems fairly straightforward: in functional situations where single-talker interference occurs, working memory demands similar to those of the experimental task may occur. The listener may need to maintain the first part of an utterance in working memory long enough to reinterpret based on information gleaned from the latter part of the utterance. Indeed, several participants reported attempting this strategy during the sentence repetition task. The negative association between processing speed and sentence repetition accuracy is more difficult to explain. One possibility is that low decision speed scores reflected greater deliberation by some participants, who then demonstrated the same care in completing the sentence repetition task. Clearly, further research would be needed to learn to what extent these cognitive factors are associated with performance on sentence repetition tasks.

None of the measures of central auditory processing showed significant group differences, with the exception of the MLD test, which approached significance with lower scores for the TBI group after an outlier was removed. Little prior research exists describing how this type of measure is affected by TBI. Olsen, Noffsinger, and Carhart (1976) found that MLD scores were normally distributed among a healthy control group of 50 adults, and based their pass-fail criterion on the 5^{th} percentile of that population. They also tested disordered populations, including a group of 20 participants with cortical lesions (e.g. stroke or hemispherectomy, but not TBI). In results similar to the current study, all but one of the participants in Olsen et al.'s disordered group had normal spondee MLDs, but the authors do not comment on whether the cortical lesion group's mean MLD was any lower than that of the healthy control group.

In addition to the lack of group mean differences for auditory processing tests in Experiment 2, there were also no significant correlations found between auditory processing scores and accuracy on the experimental sentence repetition task. These findings suggest that, while these tests are designed to measure central as opposed to peripheral auditory processing, they are not sensitive to the type of central processing required for the experimental sentence repetition task. This is not entirely surprising, given the range of neurological functions that may be considered "central." Nevertheless, it is important to highlight the point that if individuals with a history of TBI complain of speech processing difficulty, some standard central auditory processing assessments may not be ecologically valid measures of their abilities. This is consistent with the Schneider et al.'s (2007), discussion of informational masking, in which they observe that "at present there are no tools in the audiologist's toolbox to assess a person's ability to use the available auditory cues to parse the auditory scene and suppress the processing of irrelevant information" (p. 590).

Semi-structured interviews.

The primary qualitative research question relating to data from the semi-structured interviews in Experiment 2 was, "Is there a difference in how the two groups describe their speech processing subjectively?" Overall, results from the semi-structured interviews support the hypothesis that people with TBI would report greater difficulty than controls with everyday experiences of complex speech processing. Participants in the TBI group spoke more extensively during their interviews, using a wider range of topics and reporting negative experiences more often than healthy controls.

Some specific results from the semi-structured interviews warrant closer examination. At first glance, it seems contrary to expectations that the control group should endorse difficulties with speech processing more frequently than the TBI group (19% of quotes versus 8%), while the TBI group spent 5.7% of their responses denying difficulty (the “not a problem” theme). However, these contrasts may be artifacts of coding: the “endorse” code was used whenever a participant simply agreed with an interview question about whether one scenario was more difficult than another for speech processing (e.g. “Is there any difference for you in how easy it is to understand someone in a crowded restaurant versus eating at home?”) If the respondent simply said “Yes,” or “a busy street would be harder,” that was coded as “endorsing” the difficulty. However, if the participant went on to give specific examples, there were additional, more specific codes. For example, in response to the same question, participant #3 in the TBI group stated, “Yeah, it’s just the noise is a big deal, and you know it’s stuff that you never really want to pay attention to. It took me years to figure that out.” This quote was coded as fitting the “background noise” and “filter” themes as well as the “endorse” theme. Thus, the prevalence of the “endorse” code in the control group represents the tendency of participants in that group to simply agree that some situations are more difficult than others without elaborating or sharing any personal experience. Similarly, the “not a problem” code represents a non-specific comment that something is not particularly difficult; this theme represented 5.7% of quotes for the TBI group, not much higher than the 3.9% for the control group.

Another interesting group difference in the interviews occurred with the "strength" code. Participants with TBI referred to strengths in their speech processing more frequently than controls. This may reflect a greater awareness of strengths and weaknesses on the part of people with TBI, or a propensity to mention strengths in contrast to the weaknesses under discussion. However, it is worth noting that only participants in the control group specifically cited processing in the presence of background noise as a strength. For example, participant #16 in the control group stated, "In fact I tend to work better when there's actually a lot of noise around;" and participant #18 in the control group said, "I kind of like white noise, I mean I, things going on in the background." None of the participants with TBI reported a tolerance, much less a preference, for noisy backgrounds.

One purpose of the mixed-methods analyses was to help explain the quantitative findings. An exploratory correlation matrix and regressions were used to assess whether there were direct relationships between interview results and quantitative measures. Neither the correlation matrix nor the regressions of interview measures against sentence repetition scores found any direct relationship between the total number of quotes or number of negative themes in interviews and performance on the sentence-repetition task. This could be because self-perceptions of speech processing are idiosyncratic and reflective of social and autobiographical factors more than actual ability. In addition, the interviews were deliberately not conducted during the same session as the sentence-repetition task, in order to reflect broader experience outside the experiment.

TBI versus filtered results.

The purpose of comparing accuracy results between the filtered group from Experiment 1 and the TBI group from Experiment 2 was to evaluate whether the pattern of performance of participants with TBI could be explained by peripheral auditory effects. As predicted, the patterns of performance on the experimental task were significantly different between the filtered and TBI groups. While the simulated peripheral hearing loss of band-pass filtering significantly decreased accuracy even in the alone condition, participants with TBI showed little decrement in accuracy until the single-talker interference portion of the task. And whereas the TBI group was less accurate than the control group in the attend condition, they remained more accurate than the filtered group.

Further support for the idea that peripheral auditory effects on the sentence repetition task are different from the effects of TBI is provided by the example of two participants who were disqualified from analysis in the TBI group due to hearing loss. Participants A and B both stated during the initial screening that their hearing was adequate but, once they were on site to participate in the study, the preliminary hearing screening revealed that they did have hearing loss. Table 26 shows the screening results for these two participants.

Obviously, data from only two participants are not sufficient to make any broad statements, but it is interesting that these two examples of people with both TBI and hearing loss had accuracies generally in between the mean performance of the TBI group with normal hearing and the healthy controls with simulated hearing loss. The fact that participant B, who arguably had more significant hearing loss, was more accurate than participant A, adds further support to the idea that far more factors than peripheral hearing play into the ability to perform the task. Because of their disqualification, these two participants did not complete the standardized testing and interview parts of the study, so further comparison with the other experimental groups is not possible. The question of compounded effects of hearing loss and TBI on speech processing is relevant for future research, however, particularly in light of the frequent comorbidity of hearing loss with TBI (e.g. Scott, Bauch, & Olsen, 1999).

Finally, the comparison between the TBI and filtered groups raised the issue of age as a significant factor in sentence repetition accuracy. The groups compared within Experiment 1 and Experiment 2 were deliberately matched for age, so age was not covaried in the ANOVAs. However, the fact that age differed between the TBI and filtered groups even after being covaried out suggests that it may play an important role in sentence repetition accuracy. One possible explanation for this is that there was relatively little variation in age for the filtered group (18 to 26 years old) compared to the TBI group (20 to 58 years old). Therefore, it is possible that the significant effect of age in the TBI versus filtered group comparison was partly an artifact of the strong difference in accuracy between the two groups. In other words, the model may have been showing that younger people (i.e. the filtered group) were less accurate than older people (i.e. the TBI group). Another possibility is that increasing age is genuinely associated with better – or worse – speech processing abilities. This was not evaluated in Experiments 1 and 2 because of the matching of mean age between groups, as well as the confound between age and time since injury for the TBI group, which was discussed previously. Further study is needed to explore the effects of age on complex speech processing abilities, a topic that has particular clinical applications for elderly adults with communication needs in health care and other settings that may pose speech processing challenges.

Limitations

The present study has a number of limitations. Some are related to the small number of participants, which restricted the statistical power of many analyses, particularly given the high within-group variability. Other weaknesses in the project were inherent in the design or arose as the experiment progressed, partly because this was the first time the experimental method had been used; some drawbacks were discovered only after data collection was underway. For example, one procedural challenge occurred with the process of adjusting loudness in the sentence repetition task. Because the experimenter had to step outside of the sound booth to adjust the loudness, some participants may have been hesitant to request a change. Ideally, in future studies, a system should be devised so that participants can adjust the loudness themselves. The compensation scheme used for this study was also cumbersome without necessarily adding the hoped-for motivational boost for participants. When they were told how much compensation they had earned, several participants commented that they had forgotten about the incentive scheme; others explicitly stated that it did not make any difference in their motivation during the task. This suggests that future studies using this methodology may be able to simplify the compensation system without concern about participants' motivation levels affecting performance.

One limitation inherent in the design of the study was the fact that, for most participants, accuracy was at ceiling for the NS target in the alone condition. Because the scores were at ceiling for the unfiltered group in Experiment 1 and for both groups in Experiment 2, all condition by group or condition by target interactions must be called into question. The choice to include stimuli that were 100% intelligible was deliberate, based on the drive for clinical and ecological validity: it was important to demonstrate whether each speaker could be understood in ideal circumstances (the alone condition) in order to establish the effects of the single-talker interference (attend) condition. Nevertheless, these ceiling effects – deliberate or not – may have confounded some of the statistical findings. One possible way to address this limitation would have been to calculate RAU scores for all alone condition accuracies using the same method that was applied to the attend condition of Experiment 1, in which the filtered group scores were near zero. Future studies using this methodology could also incorporate techniques to bring the alone condition performance off ceiling, such as increasing demands of speed or adding a dual-task component or small amounts of noise masking.

Another possible limitation in the study is that the repetition task did not explicitly establish listeners' ability to distinguish between the two speakers in the attend condition, though this is unlikely because almost all participants did consistently repeat the target speaker, suggesting that they were able to tell the two speakers apart. The experiment also could have done more to distinguish between energetic and informational masking effects (e.g. by having the NNS speak Mandarin for some interfering sentences and English for others, and/or using speech-shaped noise as interference). On the other hand, the task did provide its own control in that energetic masking would be equal for the two attend blocks: the acoustic signal is the same, the only difference being in the instructions about which voice to attend to.

Future Directions

The current study sets the stage for numerous possible follow-ups and extensions. Further analyses of the existing dataset related to accuracy, error patterns, response times, effort ratings, and interview responses could be used in the future to expand on the findings already presented. Future studies can also be designed to follow up and continue the line of inquiry begun with the current study, including increasing the number of participants, expanding to studies of treatment or effects in elderly rather than TBI populations, focusing within the TBI population on mild TBI or course of recovery, or possibly developing standardized assessments for complex speech processing.

Several areas of further analysis would be possible with the data already collected for this dissertation. As mentioned in the discussion, there may be more to learn from different patterns of repetition accuracies within groups, such as whether individual participants scored higher on the NNS or the NS target in the attend condition. These patterns could be examined in conjunction with demographic variables, cognitive variables, and order effects. The order effects themselves should also be explored further, possibly using nonparametric statistical tools and/or with a larger n for increased power.

Error analyses of the sentence repetition data could also be illuminating. The only error analysis of the sentence repetition data that has been done so far is the comparison of number and percentage of interfering words repeated. Further error analysis could examine which sentences were more or less likely to be repeated correctly or incorrectly, as well as the phonemic and semantic errors produced by participants. For example, were participants more likely to provide incorrect words that were phonetically related to the target (i.e. based on available acoustic information, using a bottom-up process) or semantically related to the rest of their repetition (i.e. based on available content information, a more top-down process)? Any group differences – or lack thereof – in such error patterns could further illuminate the effects of brain injury on speech processing.

Another potential avenue for analysis is reaction or recovery time data for the sentence repetition task. Data measuring the duration between the presentation of the "press the space bar when you are ready to continue" instruction and when the participant pressed the space bar to advance to the next trial were collected automatically using E-prime software. This is not strictly the time it took to respond to each stimulus, so a better description might be "recovery time" or simply "trial time." Similar analyses could be done with these data as were done for accuracy and effort, although the data are extremely variable for participants in both groups; a trial-by-trial evaluation along with the audio recordings of the relevant sessions would be necessary in order to eliminate data points that included conversation or questions as well as simple statistical outliers.

Effort ratings are another avenue for additional analysis. As discussed briefly above, the method of assessing effort was potentially problematic, particularly in the attend condition, in which effort ratings were made only after each 30-sentence block was completed. This may have made it difficult for participants to be precise in comparing the two blocks. Future studies could ask for a preliminary effort rating after only 5–10 sentences before proceeding with the rest of the block; further analysis is also possible with the data that were already collected. In addition to the numerical effort ratings made after each block in the sentence repetition task, participants were asked to elaborate on their ratings once the entire task was completed. These follow-up questions are listed in Appendix 4. Further analysis could be useful in that these qualitative data could offset some of the limitations of the numerical effort ratings. They could also be analyzed for correlations with accuracy using a similar method to that applied already to the semi-structured interview data: it is possible that subjective commentary that is more directly related to the experimental task would reveal stronger correlations with task performance.

Further analyses of the interview transcriptions would be another potentially fruitful avenue of research. For example, closer examination and development of subthemes for utterances coded within the catchall category of “strategy” could address several research questions. What were the types and specificities of strategies mentioned by participants in each group? Did control participants differ from participants with TBI in the quantity or quality of the strategies they described? Given that the TBI group mentioned their strengths more often than controls during the interviews, are they correspondingly more prone to discuss strategies for successful speech processing?

Finally, along with further examination of the “strategy” and “strength” codes (and other relatively broad codes such as “not a problem” and “accent”), a conversational analysis of the interviews could be used to address some questions about the effects of TBI on conversation. For example, are word choices and syntactic patterns different in the interview statements of participants with and without TBI? Are there differences in fluency or patterns of word choice?

Along with further analyses of data already collected, the current work suggests several possible avenues of future research on this topic. For example, as mentioned above, future studies could repeat a very similar methodology with a greater number of participants in order to (a) re-assess effort using methods designed to increase validity and (b) analyze the effects of presentation order with increased statistical power.

Research into therapy or remediation is another promising direction for future research. While documenting deficits after brain injury such as those found in the current study does serve a purpose in the greater scheme of TBI research, it is of questionable value unless followed up with investigations into how to remediate those deficits. Future intervention studies could target the subjective perception of effort in the task as well as improvement of sentence repetition accuracy. For example, the experimenter noted that, in the current study, the single-talker interference task seemed subjectively easier when participants in the unfiltered condition were run immediately after participants in the filtered condition: it would be interesting to explore whether training in the filtered condition would reduce effort and/or improve accuracy on a subsequent unfiltered condition. Reduced effort alone could be a worthwhile goal for this type of intervention, given the prevalence of feelings such as frustration, stress, and anxiety reported in interviews among individuals with brain injury regarding complex speech processing. Metacognitive training could also be explored as a means to improve both subjective experience and objective accuracy. Both Kennedy and Coelho (2005) and Chen, Abrams, and D’Esposito (2006) emphasize the importance of metacognitive strategy instruction that is both explicitly goal-oriented and individualized to the client. In addition, Chen et al. recommend multi-modal treatments to activate across multiple components of the prefrontal cortical network for executive functioning.

A third avenue for future research to build on the present study would be to pursue issues of processing non-native-accented speech in elderly adults as opposed to adults with TBI. As discussed above, age was a significant factor in some of the analyses in the current study. Aging adults are faced with the potential for mild cognitive impairment, reduced processing speed, and dementia, not to mention peripheral hearing loss even in those with completely intact cognitive abilities. As the baby boomer population in the United States ages, increasing numbers of people are entering assisted living and skilled nursing facilities and staff at such facilities often include non-native-accented speakers of English. Therefore, quality of life for residence and job satisfaction and effectiveness for staff have the potential to be affected by issues of complex speech processing such as those addressed in the present line of research.

Targeted research into speech processing after mild TBI is another potential direction that this line of research could explore. The current study population comprised mostly individuals who had experienced moderate to severe brain injury. Additional research is needed to determine whether comparable difficulties with speech processing occur following specifically mild (or, more likely, mild-complicated) TBI. This is an area of growing public interest, with increasing media discussion of sports-related concussion and the prevalence of mild (or worse) TBI among military service members.

Both civilian and military populations would also benefit from better research on the long-term effects of TBI. All participants in the present study were in the post-acute stage, ranging from two to 22 years after injury. Several participants mentioned in their interviews that, although their speech processing had worsened relative to their premorbid abilities, it had improved over the course of their recovery. Further research would be useful in order to establish whether there is a common time-course for improvement of speech processing deficits after TBI; in addition, this could be combined with treatment studies to determine if there are differential treatment effects at different stages of recovery.

Finally, the current project may be used as a jumping-off point for future development of a standardized assessment of complex speech processing. At this time, no such assessments are available, though the subjective reports of participants in this study suggest that they might be of considerable benefit to people with TBI. The assessments could be useful in the acute stage after TBI, in order to alert clinicians and clients to difficulties that may occur outside the environment of acute care; they could also, in conjunction with treatment research, help clinicians and clients in post-acute stages to select and apply appropriate interventions.

Conclusions

This dissertation has examined several facets of complex speech processing, specifically in a single-talker interference task with native- and non-native-accented speakers. Experiment 1 showed that a simulated peripheral hearing loss led to significantly lower accuracy for repeating the non-native speaker than the native speaker target, particularly in the alone condition. The results of Experiment 2 demonstrated that adults with TBI were less accurate than healthy controls at the sentence repetition task, particularly in the attend condition. The TBI group also reported greater difficulty with complex speech processing in everyday situations. Although there was no direct correspondence found between subjective reports and repetition accuracy, within the interviews participants reported experiences of distraction, reduced attention and difficulty filtering that led to experiences of frustration, stress, and anxiety as well as reduced comprehension. Exploratory correlations with standardized testing of cognition and auditory processing showed that, for the TBI group, listening span (a measure of verbal working memory) and processing speed showed trends toward significant associations with the ability to repeat one speaker while ignoring another. In contrast, standardized measures of central auditory processing showed no correspondence with performance on the single-talker interference task.

People who experience TBI face many challenges as they adjust to the chronic stage of their recovery. One of the challenges common among TBI survivors is difficulty with complex speech processing; the present study has shown that this difficulty can be demonstrated quantitatively as well as qualitatively, and offers numerous avenues for future investigation.

Tables

Table 1

Explanations of Different Types of Masking

Type of masking	Reference and definition
Energetic Masking	Schneider & Daneman (2007) “the signal-to-noise ratio (SNR) is often so low in such environments that the energy in the competing sound sources simply overwhelms (masks) the energy in the signal (energetic masking).” Stickney et al. (2004) “Energetic masking is thought to be a peripheral masking phenomenon that occurs when energy from two or more sounds overlaps both spectrally and temporally, thereby reducing signal detection.”
Informational Masking	Oxenham et al. (2003) “thought to reflect central, rather than peripheral, limitations on the processing of sound” Schneider & Daneman (2007) “information from the competing talkers intrudes into the message conveyed by the target talker either because the listener cannot perceptually separate the two streams of information, or because attention switches back and forth between the target talker and one or more of the competing talkers. In other words, listeners might experience difficulties in such situations because they are unable to parse the auditory scene into its different component sources so that they may attend to one source and ignore the others. Hence a failure to perceptually segregate sound sources can contribute to the masking of speech by competing sounds.” OR “competing sound sources may initiate phonetic, semantic, and/or linguistic activity that interferes with the processing of the speech target… the activation elicited by the competing speech could interfere with the processing of information in the target speech at a cognitive level.”
Gated Masking	Noise masking fluctuates periodically; noise cuts in and out at a certain frequency

Table 2

Healthy Control Participants, Stimulus Conditions, and Experiment(s) Using Data

ID	Sex	Age	Stimulus condition	Experiment(s)
1	F	21	Unfiltered	1 and 2
2	F	18	Unfiltered	1
3	F	20	Unfiltered	1
4	F	19	Unfiltered	1 and 2
5	F	21	Unfiltered	1 and 2
6	F	21	Unfiltered	1
8	F	19	Unfiltered	1
9	F	20	Unfiltered	1
10	F	23	Unfiltered	1
11	M	21	Unfiltered	1 and 2
12	M	38	Unfiltered	2
13	F	23	Unfiltered	1 and 2
14	M	21	Unfiltered	1
15	M	20	Unfiltered	1
17	M	20	Unfiltered	1 and 2
18	M	42	Unfiltered	2
19	M	19	Unfiltered	1
21	M	55	Unfiltered	2
22	F	59	Unfiltered	2
23	F	59	Unfiltered	2
24	M	31	Unfiltered	2
25	F	28	Unfiltered	2

Table continued on next page

Table 2

Continued from Previous Page

ID	Sex	Age	Stimulus condition	Experiment(s)
1	F	21	Filtered	1
2	F	21	Filtered	1
3	M	19	Filtered	1
4	F	20	Filtered	1
5	F	22	Filtered	1
6	F	18	Filtered	1
7	F	20	Filtered	1
8	F	26	Filtered	1
9	F	18	Filtered	1
10	M	19	Filtered	1
11	F	22	Filtered	1
12	F	22	Filtered	1
13	F	22	Filtered	1
14	F	22	Filtered	1
15	F	20	Filtered	1

Note: The “Experiment(s)” column indicates whether each participant’s data were used for analysis in Experiment 1, Experiment 2, or both.

Table 3

Experiment 1 Participant Demographics (Healthy Adults Without TBI)

	Unfiltered group					Filtered group			
ID	Sex (M/F)	Age	Education (yrs)	Est. verbal IQ	ID	Sex (M/F)	Age	Education (yrs)	Est. verbal IQ
1	F	21	15	111	1	F	21	15	103
2	F	18	12	113	2	F	21	15	102
3	F	20	13	107	3	M	19	13	113
4	F	19	13	103	4	F	20	14	110
5	F	21	15	107	5	F	22	15	105
6	F	21	15	99	6	F	18	12	109
7	F	19	12	100	7	F	20	14	115
8	F	20	15	108	8	F	26	17	98
9	F	23	16	123	9	F	18	12	99
10	M	21	14	95	10	M	19	12	108
12	F	23	15	106	11	F	22	16	114
13	M	21	15	106	12	F	22	15	115
14	M	20	14	110	13	F	22	15	110
15	M	20	14	110	14	F	22	15	108
17	M	19	13	109	15	F	20	14	113
M	5/10	20.4	14.07	107.13		2/13	20.8	14.27	108.13
SD		1.4	1.22	6.58			2.0	1.49	5.63

Table 4

Experiment 2 Participant Demographics (Adults With and Without TBI)

Control group					TBI group				
ID	Sex (M/F)	Age	Education (yrs)	Est. verbal IQ	ID	Sex (M/F)	Age	Education (yrs)	Est. verbal IQ
1	F	21	15	111	1	M	55	13	113
4	F	19	13	103	2	F	30	16	113
5	F	21	15	107	3	F	48	12	110
10	M	21	14	95	4	M	21	13	100
11	M	38	16	121	5	F	23	17	103
12	F	23	15	106	6	M	42	12	111
15	M	20	14	110	7	M	47	11	125
16	M	42	18	119	8	F	58	16	119
18	M	55	16	119	9	M	22	14	113
19	F	59	14	116	10	F	20	13	112
20	F	59	16	123	11	F	55	18	105
21	M	31	16	115	12	F	47	22	124
22	F	28	16	118	13	M	43	14	115
M	6/7	33.62	15.23	112.5		6/7	39.21	14.64	112.1
SD		15.45	1.30	8.13			13.64	2.93	7.22

Table 5

TBI Participant Injury Information

ID	Time post injury (yrs)	Severity of injury*	Type & description of injury
1	6	N/A	CSF deficit; no LOC but severe pain & functional impairments
2	3	Mild complicated	2 falls in 2 mos; 5-15 min LOC each time
3	9	Severe	MVA; 17 days coma
4	2	Severe	Fall; 6 wks coma (induced)
5	4	Severe	MVA; 9 days LOC
6	21	Severe	MVA; 10 days coma
7	22	Severe	MVA; 10 days coma
8	40	Severe	MVA; 6 days coma
9	2	Severe	MVA; 4 days coma
10	2	Severe	MVA; 1 month LOC
11	15	Moderate	Bike accident; 30 min LOC
12	5	Mild complicated	Bike accident; 5-10 min LOC
13	16	Severe	MVA; 1-2 wks PTA
M	11.31		
SD	11.26		

Note: CSF = cerebrospinal fluid; LOC = loss of consciousness; MVA = motor vehicle accident
*Severity of injury estimated based on hospital records and/or length of coma or post-traumatic amnesia (Lezak, 1995)

Table 6

Summary List of Standardized Tests Administered in Experiment 2

Test name	Acronym	Process measured
National Adult Reading Test	NART	Estimated verbal IQ
Repeatable Battery for the Assessment of Neuropsychological Status	RBANS	Subtests for immediate memory, delayed memory, verbal, visuospatial, attention
Tompkins Listening Span test	Listening Span	Working memory
Woodcock-Johnson Test of Cognition, decision speed subtest	Decision Speed	Processing speed
Attention Process Training – II questionnaire	APT-II questionnaire	Attention
Behavioral Assessment of Dysexecutive Syndrome Dex questionnaire	BADS questionnaire	Executive function
Delis-Kaplan Executive Function System, trail-making subtest	D-KEFS Trails	Executive function (switching)
Western Aphasia Battery	WAB	Screen for aphasia
Weschler Memory Scale – III, digits backwards subtest	WMS-III digits backward	Working memory
SCAN for adolescents and adults	SCAN-A	Central auditory processing (CAP): subtests for filtered words, words in noise, dichotic listening
Masking Level Difference test	MLD	CAP: brainstem
Gaps in Noise test	GIN	CAP: temporal auditory processing
Hearing screening		Peripheral hearing loss

Table 7

Mean Performance on Standardized Tests of Cognition for Participants in Experiment 2

		TBI	Control
Test	Subtest/outcome	Mean (stdev)	Mean (stdev)
RBANS	Immediate memory (%ile)	40.31 (31.44)	53.08 (23.69)
	Visuospatial (%ile)	71.69 (22.96)	80.69 (18.03)
	Language (%ile) *	28.85 (18.92)	47.54 (20.14)
	Attention (%ile) *	43.69 (27.83)	68.69 (30.31)
	Delayed memory (%ile)	46.85 (24.92)	62.38 (20.52)
	Total (%ile) *	42.85 (25.53)	68.54 (22.49)
NART	Predicted verbal IQ	113.15 (6.50)	112.85 (8.46)
Listening Span	Listening Span (raw) **	32.85 (5.11)	37.77 (2.28)
WMS-III	Digits backwards	7.54 (2.37)	7.92 (2.22)
APT-II	APT questionnaire *	19.67 (14.30)	9.31 (7.03)
BADS	Dex questionnaire	19.08 (14.49)	15.92 (5.87)
WJ-III	Decision Speed: time (sec)	178.62 (4.99)	172.00 (15.20)
	Decision Speed: accuracy (raw) ***	35.00 (3.19)	38.54 (1.27)
D-KEFS	Trails: non-switching (letters+numbers) (SS) *	11.38 (3.23)	13.54 (1.76)
	Trails: switching (SS) *	10.92 (1.89)	12.23 (1.30)
	Trails: motor speed (SS)	12.15 (3.39)	12.15 (1.14)
	Trails: switching/non-switching diff (SS)	8.92 (2.47)	8.46 (3.02)
	Trails: switching/motor diff (SS)	9.77 (2.0)	9.77 (1.7)

Note:%ile = percentile; raw = raw score; SS = standard score

Significant group differences: * $p \leq 0.05$ ** $p \leq 0.01$ *** $p \leq 0.001$

Table 8

Sequence of presentation for experimental blocks in sentence-repetition task

Experimental block	Sequence I	Sequence II	Sequence III	Sequence IV
1	NNS alone	NS alone	NNS alone	NS alone
2	NS alone	NNS alone	NS alone	NNS alone
3	NNS target	NNS target	NS target	NS target
4	NS target	NS target	NNS target	NNS target

Note: "Target" indicates which speaker was the target in each block of the attend condition.

Table 9

Mean Proportion Correct by Group and Target Speaker for Experiment 1

	Alone condition		Attend condition	
Group	NNS	NS	NNS	NS
Filtered Group (mean, SD)	0.48 (0.07)	0.82 (0.09)	0.08 (0.03)	0.16 (0.05)
Unfiltered Group (mean, SD)	0.99 (0.02)	1.00 (0.01)	0.65 (0.10)	0.68 (0.12)

Note: Attend condition values are RAU adjusted; scores for the NNS target in the alone condition were calculated out of 49 words to exclude one that was missed by most participants.

Table 10

Statistics Table for Experiment 1 Accuracy

Comparison	Mean Square	df	F	Sig.	η_p^2	Observed Power
Group	(6.22)	1	753.42	2.23×10^{-33}	0.96	1.00
Error (Group)	(0.01)	28				
Condition	(5.93)	1	664.31	4.77×10^{-21}	0.96	1.00
Condition x Group	(0.37)	1	41.94	514×10^{-7}	0.60	1.00
Error (Condition)	(0.01)	28				
Target	(0.43)	1	198.84	3.03×10^{-14}	0.88	1.00
Target x Group	(0.31)	1	144.60	1.42×10^{-12}	0.84	1.00
Error (Target)	(0.002)	28				
Condition x Target	(0.07)	1	22.48	5.63×10^{-5}	0.45	1.00
Condition x Target x Group	(0.11)	1	33.55	3.20×10^{-6}	0.55	1.00
Error (Condition x Target)	(0.003)	28				

Note: p values significant at the $p < 0.05$ level.

Table 11

Mean Effort ratings by Group and Target Speaker for Experiment 1

	Alone condition		Attend condition	
Group	NNS	NS	NNS	NS
Filtered Group (mean, SD)	7.43 (1.21)	5.03 (1.61)	9.37 (0.72)	9.17 (0.62)
Unfiltered Group (mean, SD)	3.67 (1.89)	0.93 (1.02)	8.23 (1.39)	7.87 (1.06)

Table 12

Statistics Table for Experiment 1 Effort

Comparison	df	Mean Square	F	Sig.	η_p^2	Observed Power
Group	1	(117.51)	18.62	1.79×10^{-4}	0.40	0.99
Error (Group)	28	(6.31)				
Condition	1	(463.06)	100.70	8.91×10^{-11}	0.78	1.00
Condition x Group	1	(18.21)	4.21	0.05	0.13	0.51
Error (Condition)	28	(4.33)				
Target	1	(50.38)	58.28	2.57×10^{-8}	0.68	1.00
Target x Group	1	(0.001)	0.001	0.98	0.00	0.05
Error (Target)	28	(0.86)				
Condition x Target	1	(29.75)	49.18	1.26×10^{-7}	0.64	1.00
Condition x Target x Group	1	(0.33)	0.54	0.47	0.02	0.11
Error (Condition x Target)	28	(0.61)				

Note: p values significant at the $p < 0.05$ level.

Table 13

Mean Accuracies by Group and Target Speaker for Experiment 2

	Alone condition		Attend condition	
Group	NNS	NS	NNS	NS
TBI (mean, SD)	0.97 (0.05)	0.99 (0.02)	0.42 (0.21)	0.54 (0.17)
Control (mean, SD)	0.99 (0.01)	1.0 (0.0)	0.57 (0.12)	0.64 (0.14)

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Table 14

Statistics Table for Experiment 2 Accuracy

Comparison	Df	Mean Square	F	Sig.	η_p^2	Observed Power
Group	1	0.12	4.58	0.04	0.16	0.54
Error(Group)	24	0.03				
Condition	1	5.13	248.45	3.67×10^{-14}	0.91	1.00
Condition x Group	1	0.08	3.69	0.07	0.13	0.45
Error (Condition)	24	0.02				
Target	1	0.08	18.30	2.61×10^{-4}	0.43	0.98
Target x Group	1	0.01	1.75	0.20	0.07	0.25
Error (Target)	24	0.004				
Condition x Target	1	0.04	10.21	0.004	0.30	0.87
Condition x Target x Group	1	0.002	0.62	0.44	0.03	0.12
Error (Condition x Target)	24	0.004				

Note: p values significant at the $p < 0.05$ level.

Table 15

Mean Effort (on a 0-to-10 scale) by Group,Target Speaker, and Condition for Experiment 2

	Alone condition		Attend condition	
Group	NNS	NS	NNS	NS
TBI (mean, SD)	4.10 (2.38)	1.67 (1.68)	8.23 (2.28)	7.42 (2.56)
Control (mean, SD)	3.62 (1.91)	0.81 (1.22)	8.65 (1.11)	7.96 (1.32)

Table 16

Statistics Table for Experiment 2 Effort

Comparison	df	Mean Square	F	Sig.	η_p^2	Observed Power
Group	1	(0.24)	0.03	0.87	0.001	0.05
Error (Group)	24	(8.89)				
Condition	1	(792.01)	263.57	1.92×10^{-14}	0.92	1.00
Condition x Group	1	(8.65)	2.88	0.10	0.11	0.37
Error (Condition)	24	(3.01)				
Target	1	(73.62)	67.03	2.09×10^{-8}	0.74	1.00
Target x Group	1	(0.12)	0.11	0.75	0.004	0.06
Error (Target)	24	(1.10)				
Condition x Target	1	(22.62)	19.25	1.97×10^{-4}	0.45	0.99
Condition x Target x Group	1	(0.41)	0.35	0.56	0.01	0.09
Error (Condition x Target)	24	(1.18)				

Note: *p* values significant at the $p < 0.05$ level.

Table 17

Target-Interfering Repetition Differences in Experiment 2, Reported in Proportions

	Proportion difference between target and interfering words	
Group	NNS	NS
TBI (mean, SD)	0.32 (0.31)	0.44 (0.25)
Control (mean, SD)	0.50 (0.15)	0.55 (0.20)

Table 18

Statistics Table for Experiment 2: Differences Between Target and Interfering Word Repetitions

Comparison	df	Mean Square	F	Sig.	η_p^2	Observed Power
Group	1	0.28	3.10	0.09	0.11	0.39
Error (Group)	24	0.09				
Target	1	0.11	5.46	0.03	0.19	0.61
Target x Group	1	0.02	0.78	0.39	0.03	0.14
Error (Target)	24	0.02				

Note: *p* values significant at the $p < 0.05$ level.

Table 19

Test Scores for Assessments of Central Auditory Processing

	Assessment	TBI group Mean (SD)	Control group Mean (SD)
i	SCANA filtered words (SS)	9.15 (2.27)	10.46 (2.18)
	SCANA figure-ground (SS)	10.00 (2.73)	10.23 (2.65)
	SCANA dichotic listening (SS)	9.85 (2.44)	10.54 (2.47)
ii	Masking Level Difference *	31.54 (10.30)	38.77 (7.24)
iii	Gaps In Noise (% accuracy)	0.66 (0.10)	0.67 (0.14)
	Gaps In Noise (number of false positives)	1.77 (2.83)	0.77 (1.17)

* $p < 0.05$

Table 20

Correlation Matrix: Pearson Correlations Among Cognitive Test Scores and Sentence Repetition Accuracies for the TBI Group

	Age	APT	Dcsn Speed Acc	Listen Span	MLD	Alone NNS: acc	Attend NNS: acc	Alone NNS: eff	Attend NNS eff	Alone NS: acc	Attend NS:acc	Alone NS:eff	Attend NS: eff	yrs. since injury
Age	1.00	0.07	0.33	-0.45	-0.33	-0.27	-0.63*	0.37	0.35	0.16	-0.61*	0.26	0.48	0.67*
APT		1.00	0.10	-0.02	0.51	0.03	-0.47	0.09	0.01	0.08	-0.43	-0.01	0.24	-0.18
DcsnSpdAcc			1.00	0.19	-0.28	-0.03	-0.54 ~	0.36	0.26	-0.06	0.01	-0.31	-0.05	0.37
ListnSpan				1.00	0.13	0.55 ~	0.45	-0.07	0.03	0.34	0.59	-0.12	-0.21	-0.09
MLD					1.00	0.36	0.07	-0.55 ~	-0.45	0.34	-0.04	-0.09	-0.37	-0.49
AloneNNS:acc						1.00	0.55 ~	-0.16	-0.27	0.79**	0.51	0.10	-0.39	-0.04
AttendNNS:acc							1.00	-0.32	-0.45	0.25	0.58 ~	0.08	-0.48	-0.16
AloneNNS:eff								1.00	0.46	-0.24	-0.31	0.63*	0.60*	0.02
Attend NNS:eff									1.00	-0.24	0.10	0.05	0.80**	0.15
Alone NS:acc										1.00	0.16	0.19	-0.19	0.20
Attend NS:acc											1.00	-0.37	-0.30	-0.17
Alone NS:eff												1.00	0.46	-0.24
Attend NS:eff													1.00	0.02
yrs.since.injury														1.00

Note: N= 11 Acc = accuracy; Eff = effort ~ $p \leq 0.1$ * $p \leq 0.05$ ** $p \leq 0.01$

Table 21

Correlation Matrix: Pearson Correlations Among Cognitive Test Scores and Sentence Repetition Accuracies for the Control Group

	Age	APT	Dcsn SpdAcc	Listen Span	MLD	Alone NNS: acc	Attend NNS: acc	Alone NNS: eff	Attend NNS eff	Alone NS: acc	Attend NS:acc	Alone NS:eff	Attend NS: eff
Age	1.00	-0.31	0.03	-0.34	-0.20	0.06	0.08	0.02	-0.47	NA	-0.21	-0.24	0.22
APT		1.00	0.12	0.03	0.33	-0.16	-0.28	-0.41	0.12	NA	0.02	-0.02	-0.02
DcsnSpdAcc			1.00	0.22	0.66*	-0.20	-0.42	0.20	0.14	NA	0.00	-0.04	0.14
ListnSpan				1.00	0.46	0.31	0.12	-0.03	0.15	NA	0.41	0.07	-0.37
MLD					1.00	-0.13	-0.45	0.02	0.31	NA	0.11	0.07	0.26
AloneNNS:acc						1.00	0.51 ~	0.07	-0.11	NA	0.31	-0.06	0.02
AttendNNS:acc							1.00	-0.08	-0.72**	NA	0.78**	0.25	-0.58*
AloneNNS:eff								1.00	0.33	NA	-0.04	0.62*	0.43
Attend NNS:eff									1.00	NA	-0.54	0.07	0.53
Alone NS:acc										1	NA	NA	NA
Attend NS:acc											1.00	0.43	-0.53 ~
Alone NS:eff												1.00	-0.06
Attend NS:eff													1.00

Note: N = 13 Acc = accuracy; Eff = effort The Alone NS:acc factor lists "NA" because all participants were 100% accurate. ~ $p \leq 0.1$ * $p \leq 0.05$ ** $p \leq 0.01$

Table 22

Interview Themes (number reporting from TBI group minus control group)

Theme	Group Difference
change -	7
can't process	5
focus	5
frustrated	5
no strategy	5
accommodation	4
distraction	4
less social	4
overload	4
strength	4
stressful	4
extra effort	3
fatigue	3
filter	3
multiple talkers	3
speaking	3
alcohol	2
conversation partners	2
impulsivity	2
slow	2
anxiety	1
difficult	1
headache	1
simple	1
think	1
tinnitus	1
topic	1

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Table 22

Continued from previous page.

Theme	Group Difference
accent	0
familiarity	0
mumble	0
nonverbal	0
Not a problem	0
visual	0
camouflage	-1
depends	-1
fluency	-1
monotone	-1
phone	-1
strategy	-1
text	-2
background noise	-3
change =	-3
endorse	-3
change +	-4

Table 23

Counts (and Percentages) of Only Negative Interview Themes

Count (%)	TBI group	Control group	Count (%)
20 (10.3)	Distraction	background noise	22 (29.3)
16 (8.2)	Accent	accent	14 (18.7)
16 (8.2)	Multiple talkers	distracted	7 (9.3)
16 (8.2)	Filter	multiple talkers	7 (9.3)
16 (8.2)	Focus	filter	5 (6.7)
15 (7.7)	Background noise	focus	5 (6.7)
14 (7.2)	Change -	change-	3 (4.0)
11 (5.6)	Can't process	topic	3 (4.0)
10 (5.1)	Frustration	slow	2 (2.7)
7 (3.6)	Fatigue	mumble	2 (2.7)
7 (3.6)	Less social	familiar	2 (2.7)
6 (3.1)	Speaking	anxiety	1 (1.3)
5 (2.6)	Slow	fluency	1 (1.3)
5 (2.6)	Extra effort	think	1 (1.3)
5 (2.6)	No strategy	frustrated	0 (0)
4 (2.1)	Topic	fatigue	0 (0)
4 (2.1)	Overload	less social	0 (0)
4 (2.1)	Stressful	speaking	0 (0)
3 (1.5)	Anxiety	extra effort	0 (0)
2 (1.0)	Think	no strategy	0 (0)
2 (1.0)	Mumble	overload	0 (0)

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Table 23

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Count (%)	TBI group	Control group	Count (%)
2 (1.0)	Impulsivity	Can't process	0 (0)
2 (1.0)	Simple	impulsivity	0 (0)
1 (0.5)	Familiar	simple	0 (0)
1 (0.5)	Difficult	stressful	0 (0)
1 (0.5)	Headache	difficult	0 (0)
0 (0)	Fluency	headache	0 (0)
195	*Total count*	*Total count*	*75*

Note: Excluded neutral/positive themes: strategy, endorse, strength, deny, depends, visual, phone, change=, change+, camouflage, accommodation, text, nonverbal, alcohol, conversation partner, tinnitus, and monotone.

Table 24

Proportion of Repetition Accuracy, mean (SD), for All Groups in Experiment 1 and Experiment 2

	Alone		Attend	
Group	NNS	NS	NNS	NS
Experiment 1 Control	0.97 (0.02)	1.00 (0.01)	0.65 (0.10)	0.68 (0.12)
Experiment 2 Control	0.99 (0.01)	1.0 (0.0)	0.57 (0.12)	0.64 (0.14)
Filtered	0.48 (0.07)	0.82 (0.09)	0.08 (0.03)	0.16 (0.05)
TBI	0.97 (0.05)	0.99 (0.02)	0.42 (0.21)	0.54 (0.17)

Table 25

Statistics Table for Accuracy Comparing the Filtered Group from Experiment 1 and the TBI Group from Experiment 2

Comparison	df	Mean Square	F	Sig.	η_p^2	Observed Power
Age	1	0.19	13.04	0.001	0.34	0.93
Group	1	2.79	191.20	$3.25x10^{-13}$	0.88	1.00
Error(Group)	25	0.02				
Condition	1	0.21	17.32	$3.26x10^{-4}$	0.41	0.98
Condition x Age	1	0.16	13.12	0.001	0.34	0.94
Condition x Group	1	0.14	12.02	0.002	0.33	0.92
Error (Condition)	25	0.01				
Target	1	0.03	8.62	0.007	0.26	0.81
Target x Age	1	0.003	0.68	0.42	0.03	0.12
Target x Group	1	0.11	26.88	$2.32x10^{-5}$	0.52	1.00
Error (Target)	25	0.004				
Condition x Target	1	0.004	0.86	0.36	0.03	0.15
Condition x Target x Age	1	$2.36x10^{-4}$	0.05	0.83	0.002	0.06
Condition x Target x Group	1	0.09	18.01	$2.64x10^{-4}$	0.42	0.98
Error (Condition x Target)	25	0.005				

Table 26

Hearing Thresholds for Disqualified Participants A and B in the TBI Group

	500 Hz	1000 Hz	2000 Hz	4000 Hz
	Screening Threshold (R / L)			
A	25 dB / 20 dB	30 dB / 20 dB	50 dB / 35 dB	40 dB / 35 dB
B	60 dB / 25 dB	Unable / 30 dB	Unable / 30 dB	Unable / 50 dB

Table 27

Sentence Repetition Accuracy (Proportion Correct) for Disqualified Participants A and B with TBI and Hearing Loss

	Alone		Attend	
	NS	NNS	NS	NNS
A	0.94	0.38	0.21	0
B	0.98	0.96	0.36	0.09

Figures

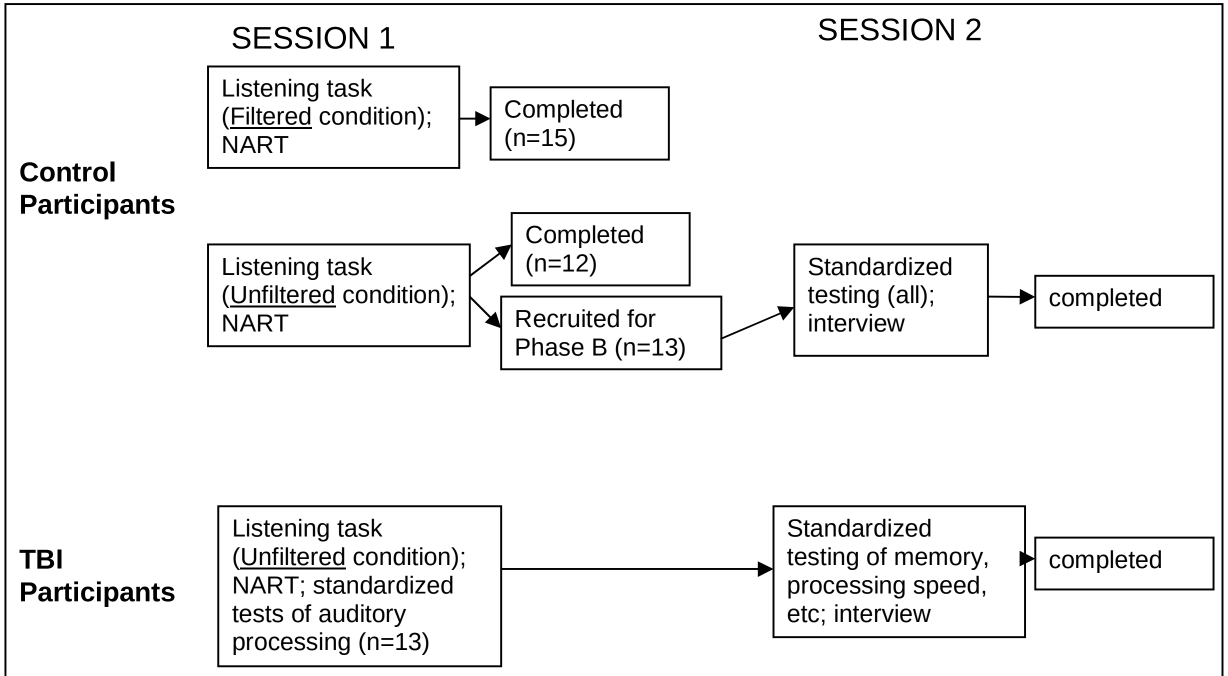

Figure 1. Overall study design.

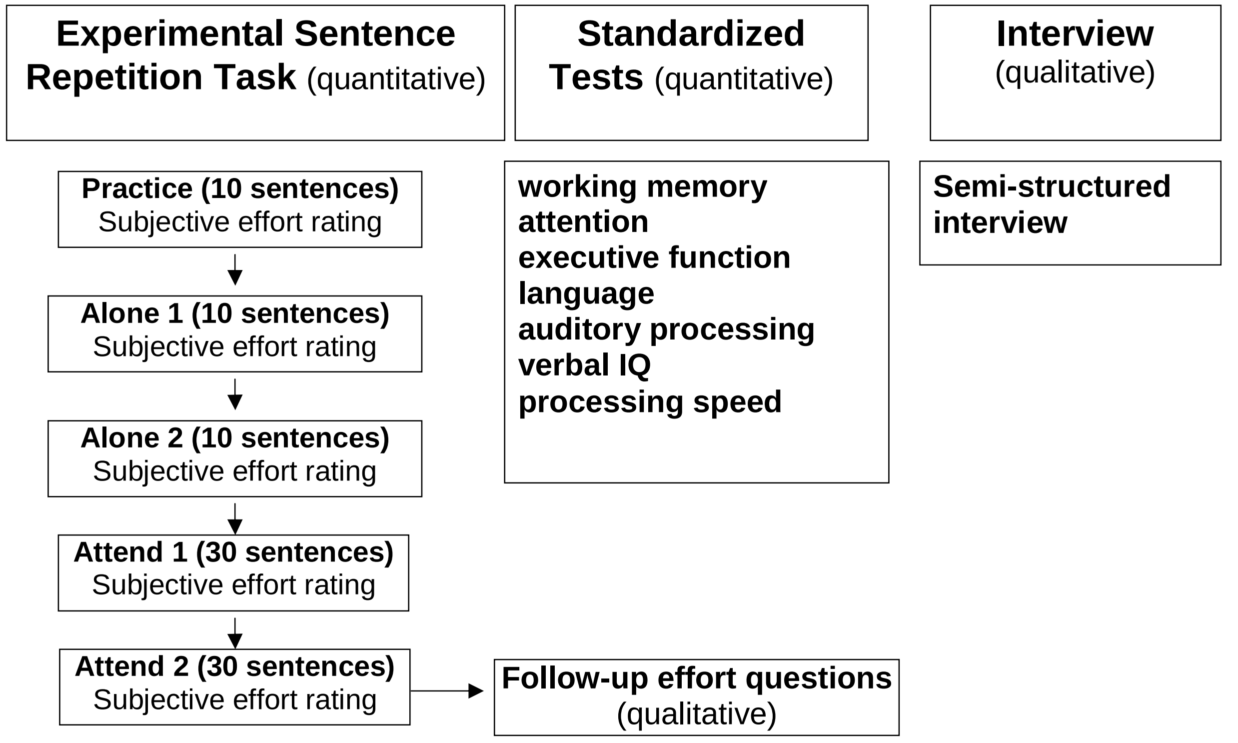

Figure 2. Experimental procedure for Experiment 2, including the experimental sentence repetition task, standardized tests, and semi-structured interview.

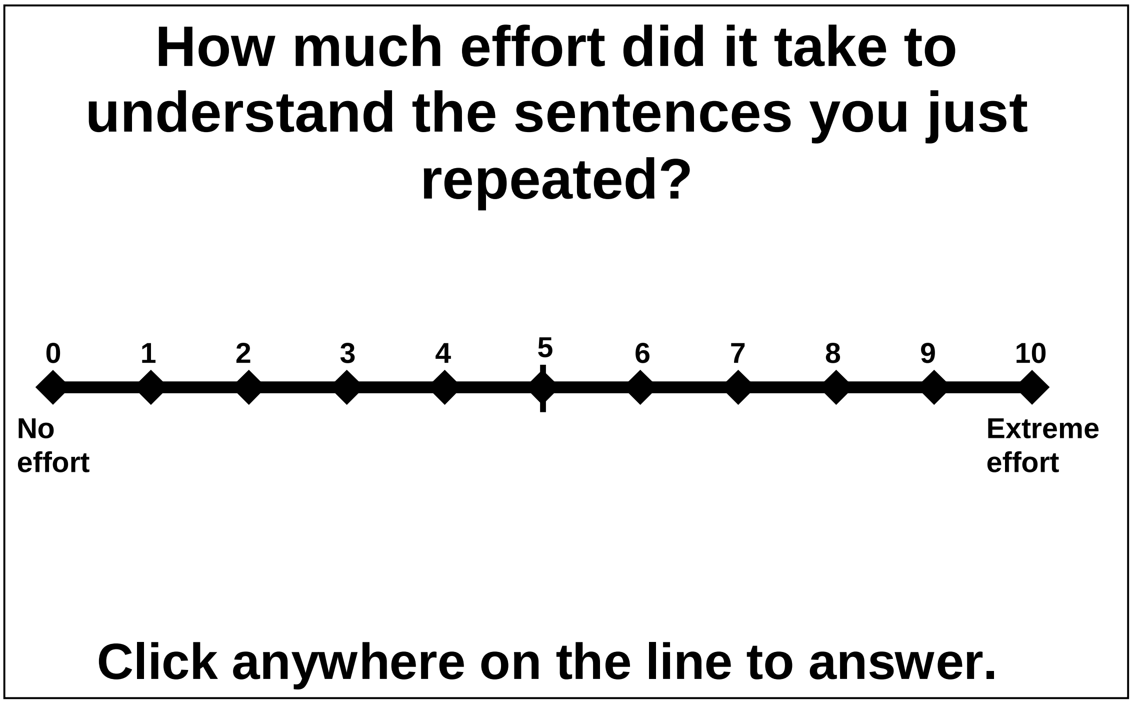

Figure 3. Effort rating screen from E-Prime

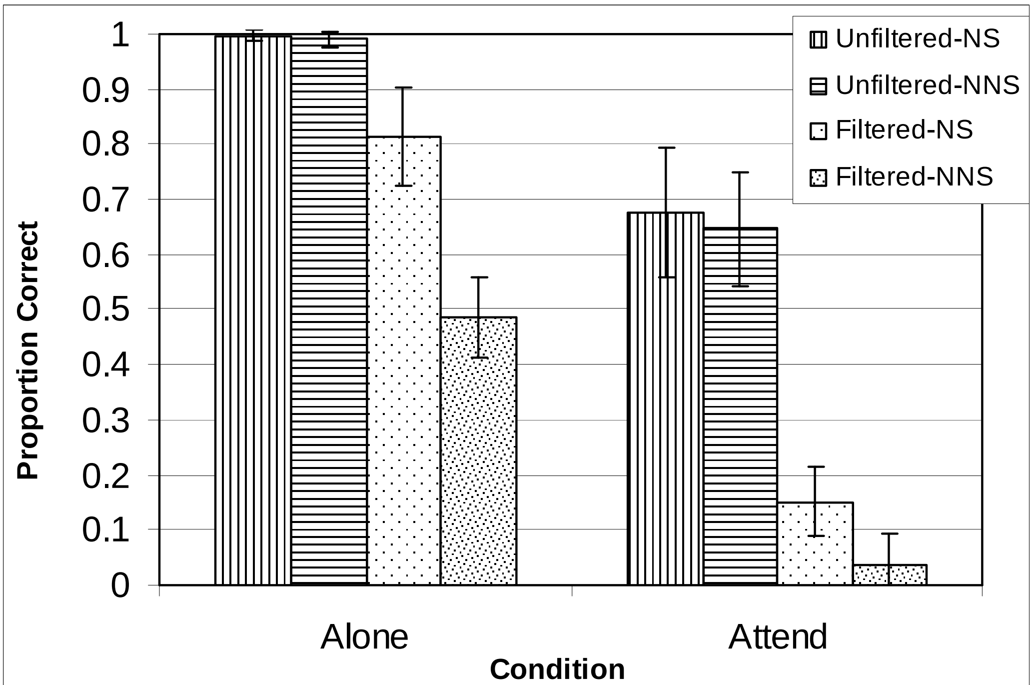

Figure 4. Sentence repetition accuracy for Experiment 1.

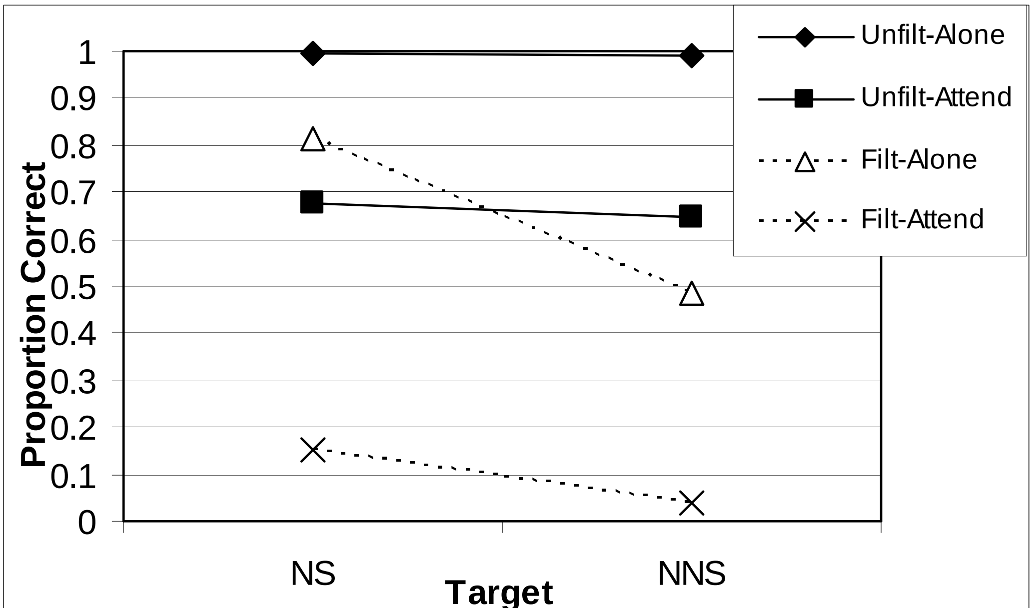

Figure 5. Three-way interaction of accuracy for condition x target x group in Experiment 1.

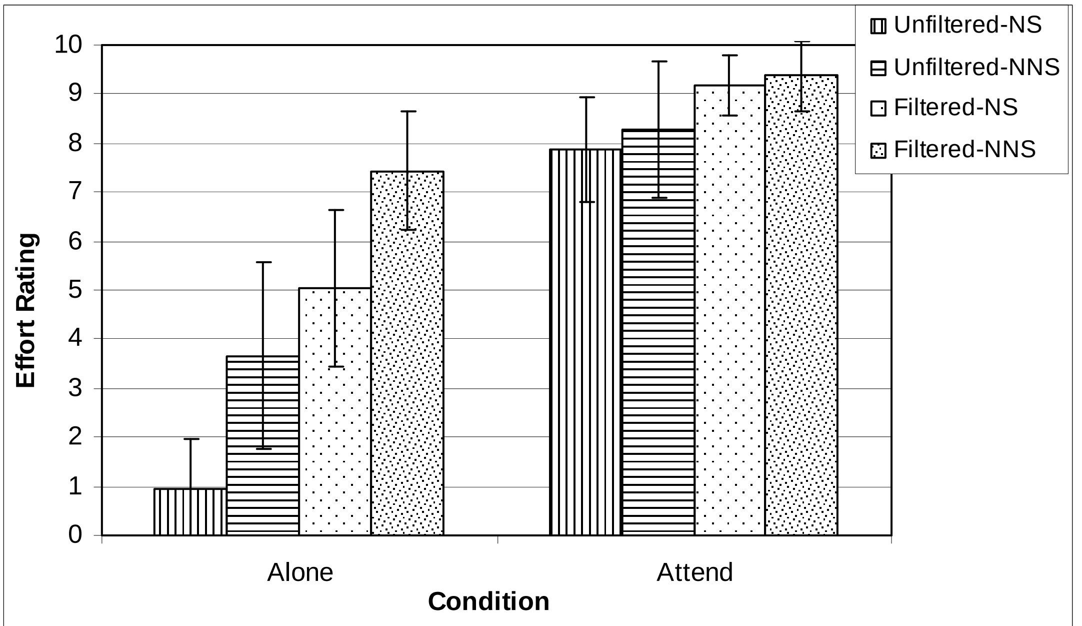

Figure 6. Sentence repetition effort ratings for Experiment 1.

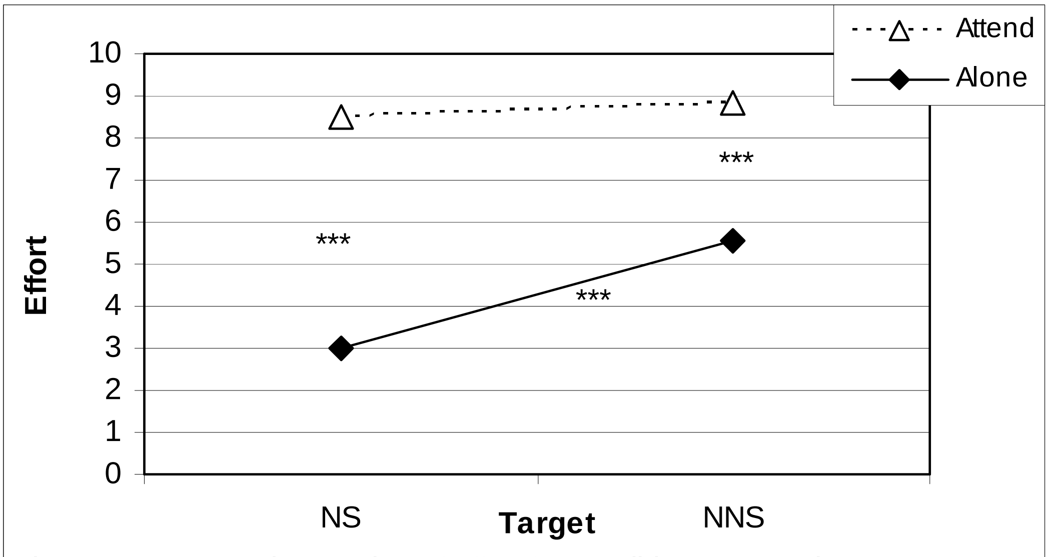

Figure 7. Two-way interaction of effort for condition x target in Experiment 1. *** $p < 0.001$

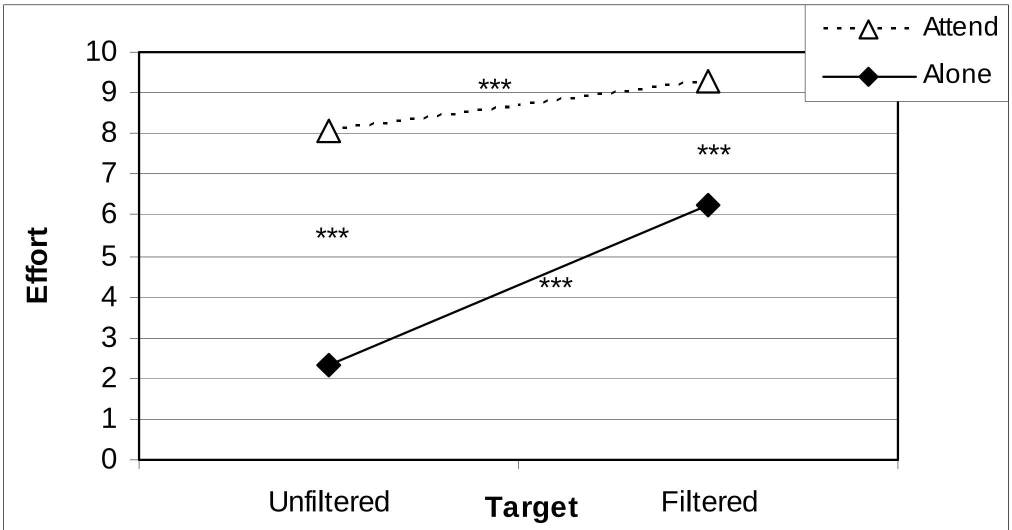

Figure 8. Two-way interaction of effort for condition x group in Experiment 1. *** p <0.001

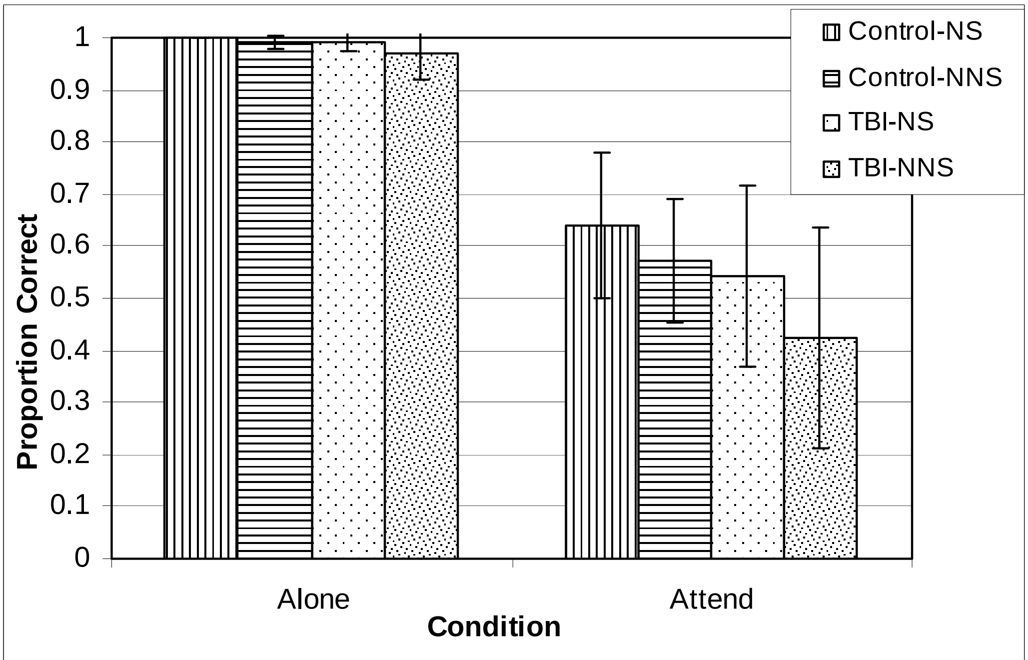

Figure 9. Sentence repetition accuracy for Experiment 2.

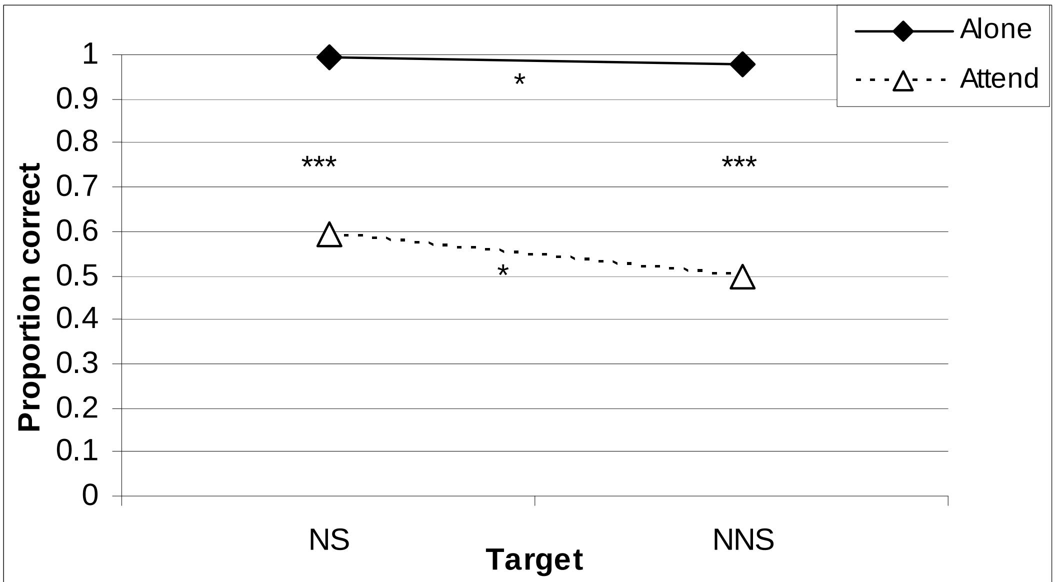

Figure 10. Two-way interaction of accuracy for condition x target, collapsed across groups, in Experiment 2. * p<0.05 ***p<0.001

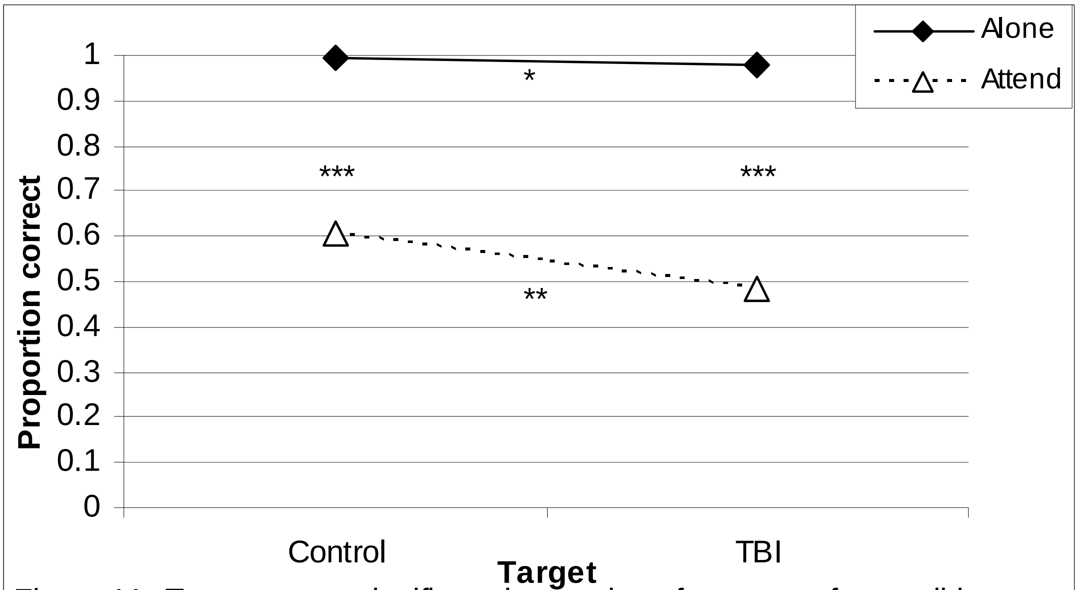

Figure 11. Two-way non-significant interaction of accuracy for condition x group collapsed across targets, in Experiment 2.
* *p*<0.05 ** *p*<0.01 ****p*<0.001

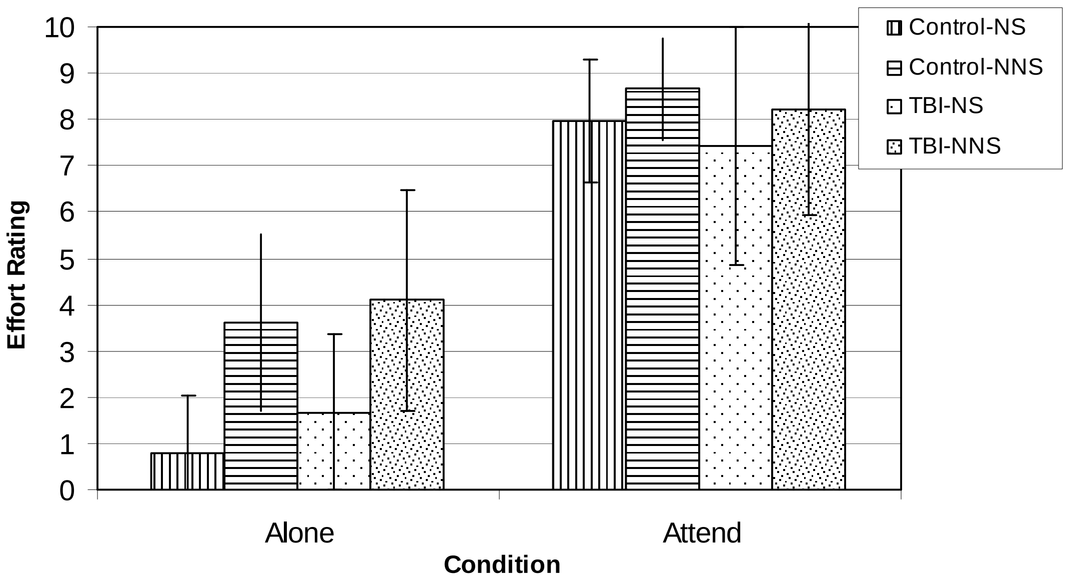

Figure 12. Sentence repetition effort for Experiment 2.

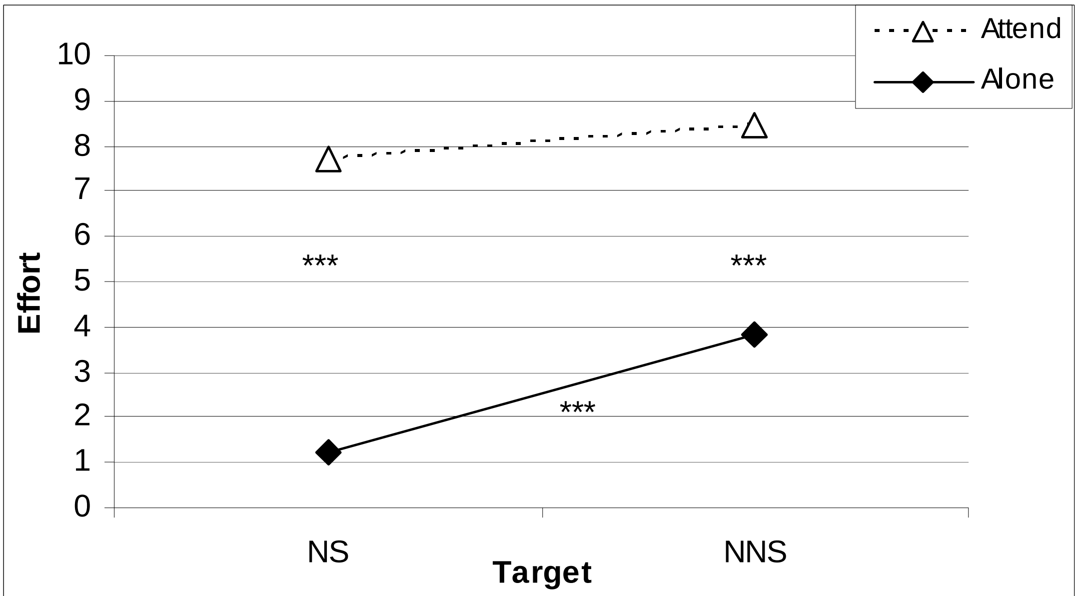

Figure 13. Two-way interaction of effort for condition x target, collapsed across groups, in Experiment 2. ***p<0.001

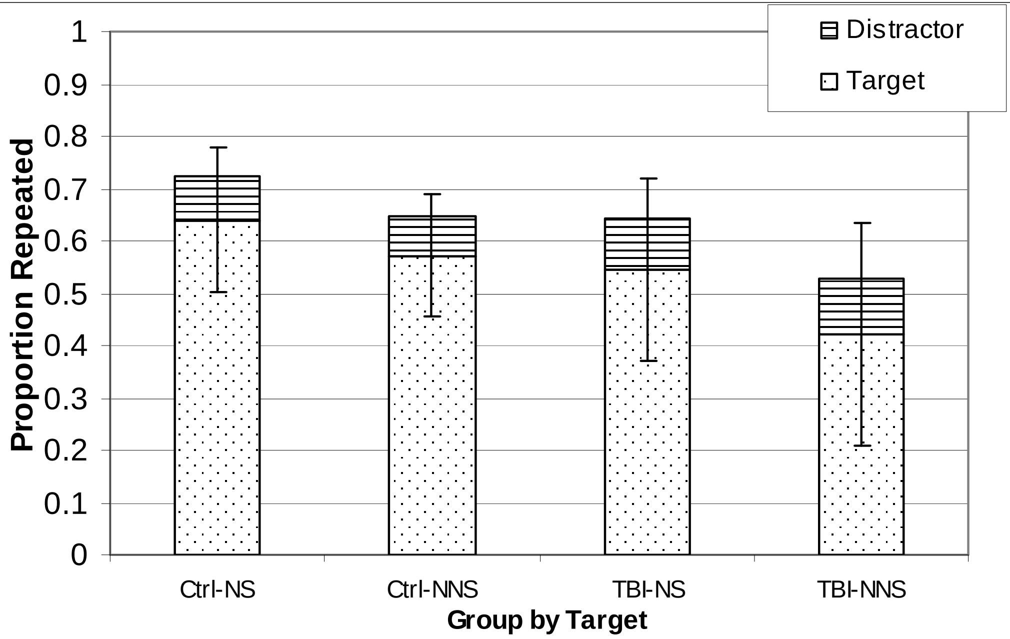

Figure 14. Repetition of target and distractor words in Experiment 2

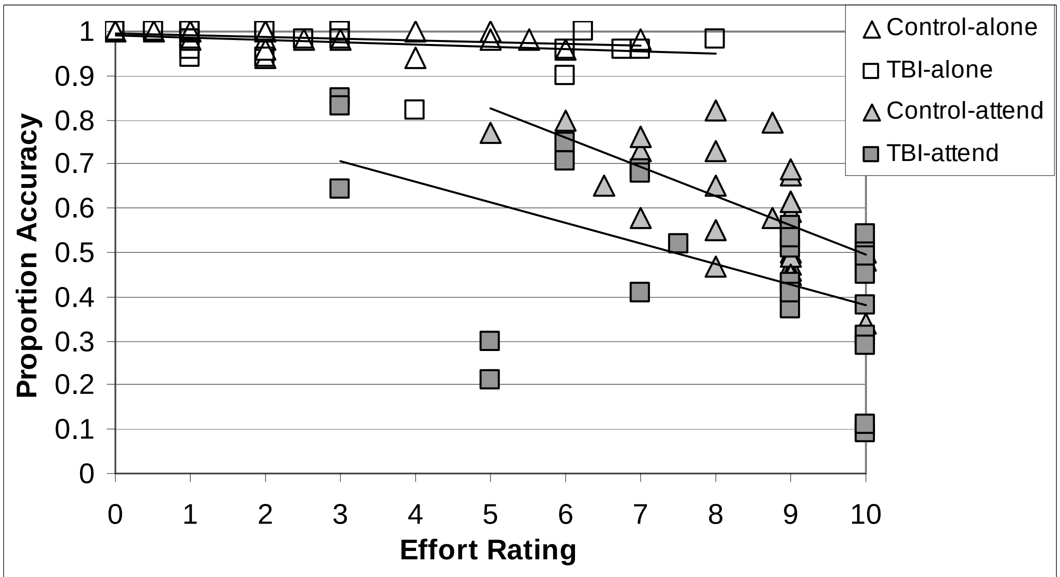

Figure 15. Effort ratings regressed against repetition accuracy

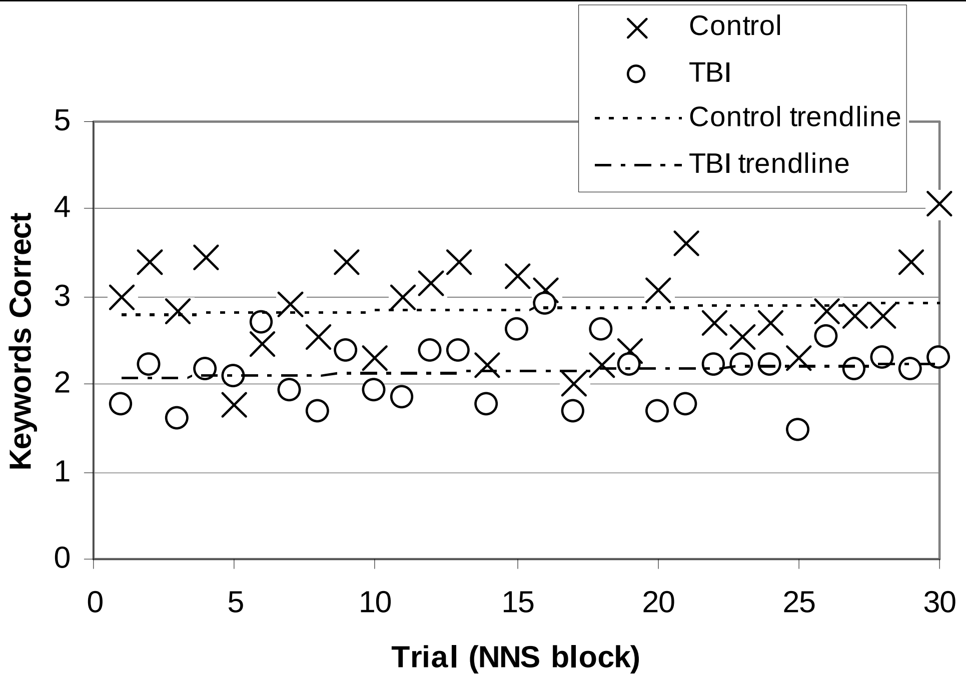

Figure 16. Average keywords correct by trial in the NNS block of the attend condition.

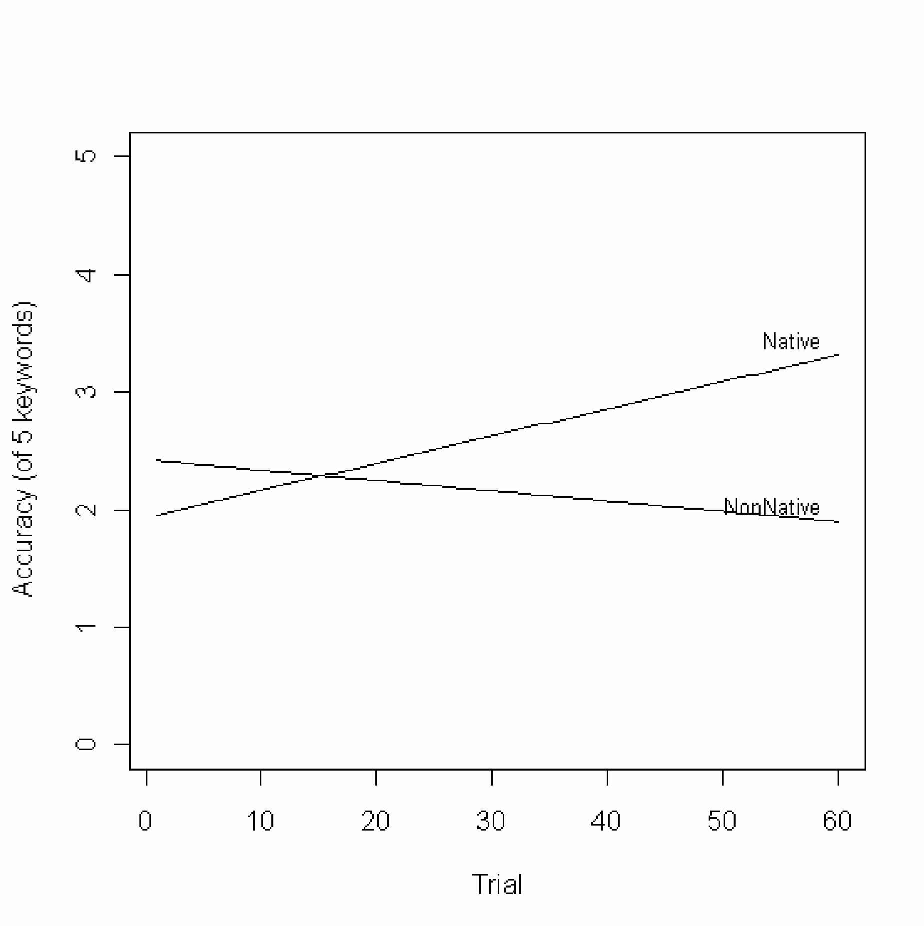

Figure 17. Interaction between trial number (position in list) and target speaker in the attend condition, based on linear mixed-effects modeling.

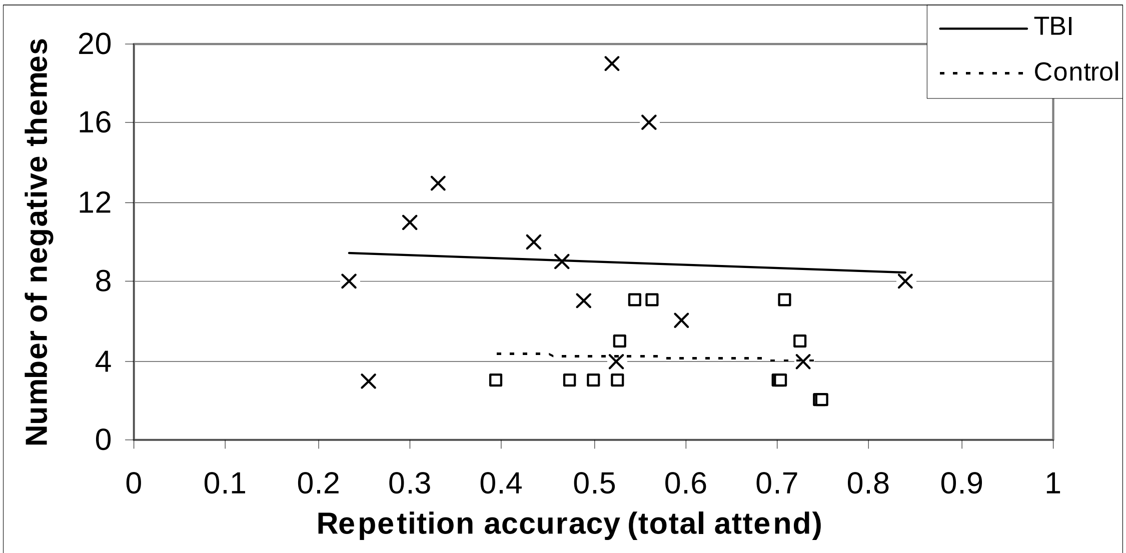

Figure 18. Negative quotes from interviews plotted against attend condition repetition accuracy

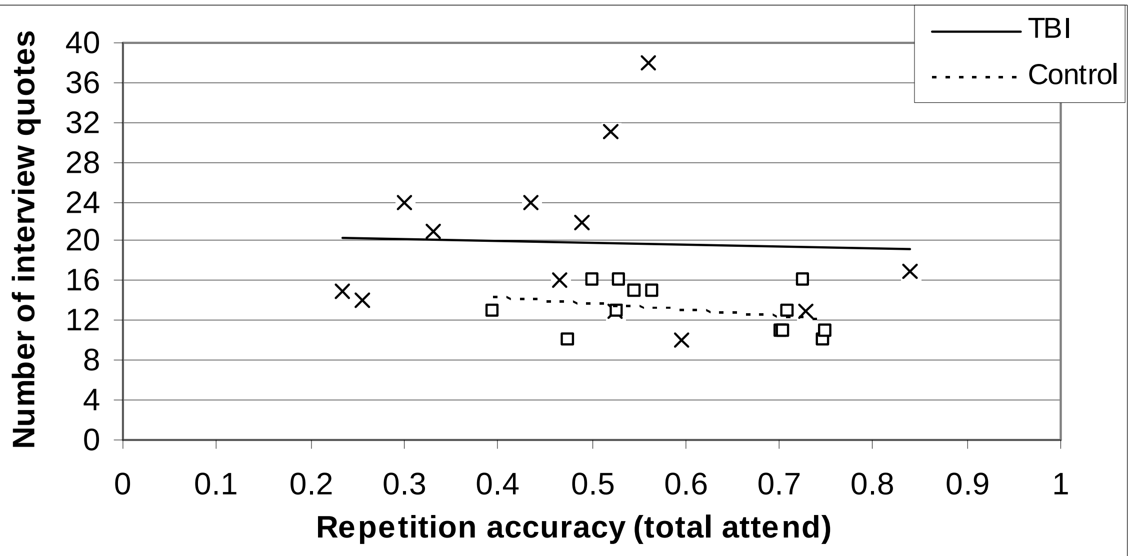

Figure 19. Total quotes from interviews plotted against attend condition repetition accuracy

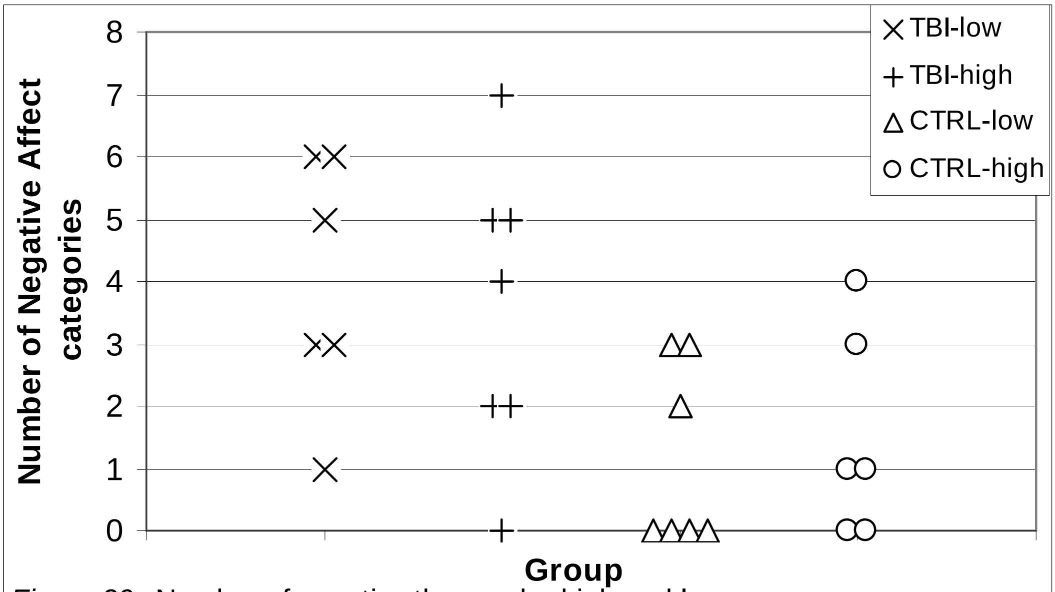

Figure 20. Number of negative themes by high and low accuracy groups

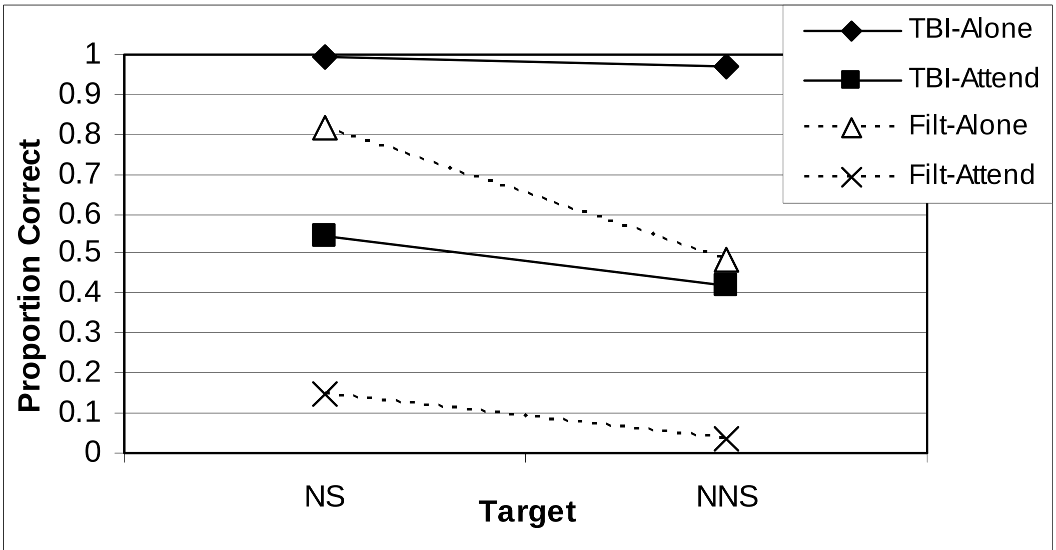

Figure 21. Three-way interaction of accuracy for condition x target x group in comparing filtered (Experiment 1) and TBI (Experiment 2) groups.

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Appendices

Appendix 1: Preliminary Screening Form

The effects of brain injury and talker characteristics on speech perception in a single-talker interference task

Initial Screening – Email Version

Introduction:

Thanks for expressing an interest in my study! The purpose of this form is to tell you more about the study and to find out if you fit the demographics we need and are eligible to participate.

Brief description of the study:

This study is designed to learn about how people who have survived a brain injury understand speech in a challenging listening situation. You would be participating in the study as either an Experimental participant (if you have had a brain injury) or a Control participant (if you have never had a brain injury).

If you decide to participate in this study, we would ask you to do several different things. First, you would take several types of standardized assessments that are designed to evaluate things like vocabulary, thinking speed, and short-term memory. Second, the main part of the experiment involves listening to sentences and repeating back what you hear based on how much you understand. These sentences will be played with a second voice speaking that you have to ignore, which may make them harder to understand. In addition to repeating the sentences, you will be asked to evaluate how much effort it takes to understand the sentences.

Participation in the study takes two to three hours, spread over two days about a week apart. Each day will include several breaks. You will receive $30 to compensate you for participating.

If you are still interested in participating, please fill out the rest of this form (it should take 5 to 10 minutes). You are free to decline to answer any of the questions that you don't want to answer. Some questions have to do with your prior experiences in school, and others are more personal, like, "When you were in school, did you ever have difficulty learning how to read or write?" and "Have you ever experienced an extended period of alcohol abuse?" and so on.

If you would prefer to complete this questionnaire by phone, or if you have any questions, please contact me at krau0067@umn.edu or 612-625-3327.

Screening Questions:

- Are you a high school graduate? ☐Yes☐No
- What is the last grade or year of school you completed?
- How old are you? What is your birthdate?
- Is English your first language? ☐Yes ☐No
- If NO: when did you learn English?
- Do you speak or understand any languages other than English? ☐Yes ☐No
- If YES: which language(s)?
- How many semesters/years have you studied/spoken these other languages?

Do you consider yourself fluent in any language other than English? ☐Yes ☐No

- When you were in school, did you have any difficulty learning to read or write?

☐Yes ☐No * If YES, please explain:

- Did you ever receive speech therapy or remedial help for anything in school?

☐Yes ☐No. * If YES, please explain:

- Were you ever told that you had a learning disability? ☐Yes ☐No
- Did you ever participate in classes for gifted students, or skip a grade? ☐Yes ☐No

* If YES, please explain:

- To the best of your knowledge, are your hearing AND vision adequate?

☐Yes ☐No * If NO, please explain:

11. Do you sing or play a musical instrument? ☐Yes ☐No

* If YES, did you ever take lessons? ☐Yes ☐No If YES, for how long?

* How would you rate your musical ability and involvement?

☐ expert/professional ☐ active amateur ☐ casual ☐ minimal

12. What type of work do you do?

13. Have you ever had an acquired brain injury (ABI)? ☐Yes ☐No

IF YOU ANSWERED "NO" TO QUESTION 13, PLEASE SKIP TO QUESTION 19.

14. What type of injury did you have?

When was it? Date:

15. Were you unconscious after your injury? ☐Yes ☐No

*If YES, for how long?

*What is the first thing you remember after the injury?

15. Did you receive any therapy after your injury? ☐Yes ☐No

*If YES, what type?

16. Do you have any problems walking or moving that would keep you from coming to the University to participate in this study? ☐Yes ☐No

*If YES, please explain:

17. Do you require any assistance in any of your activities of daily living? ☐Yes ☐No

*If YES, please explain:

18. Do you sign legal documents yourself, or do you have a co-signer?

☐sign myself ☐co-signer or guardian

ALL PARTICIPANTS PLEASE CONTINUE HERE:

19. Have you ever experienced any of the following?

* neurological disease	☐Yes ☐No
* extended alcohol abuse	☐Yes ☐No
* drug abuse	☐Yes ☐No
* hospitalization for psychological difficulty	☐Yes ☐No
* periods of unconsciousness	☐Yes ☐No
* previous head or brain injury	☐Yes ☐No

If YES to any of the above, please explain:

Thank you very much for your time!
I will contact you shortly to let you know whether or not you are eligible for this study. At that time, if you are eligible and still interested in participating, we will schedule times for your two sessions. When you come for your first appointment we will go over the details of the study and will ask you to sign your consent to participate in the study. Even after that, at any time you are free to withdraw from the study. I will send you confirmation of the date, time, and place for our appointment, including a map of how to get here.

Please contact me if you have any questions.

Thank you again!

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Appendix 2: Standardized Test Scores

TBI group scores.

Participants	RBANS						Working memory		Questionnaires	
TBI	Immed memory	Visuospatial	Language	Attention	Delayed memory	Total	Listening Span	WMS-III Digits Bkwd	APT	BADS
1	58	86	34	50	53	58	27	6	18	15
2	19	63	39	8	27	19	40	11	24	24
3	34	96	58	95	58	82	36	11		
4	13	73	4	16	34	16	33	7	8	6
5	25	79	39	27	42	37	37	8	7	15
6	90	92	50	50	58	58	31	6	1	8
7	42	86	19	58	58	53	27	9	35	24
8	87	23	55	79	90	75	38	8	9	16
9	19	63	16	21	42	23	32	5	24	12
10	7	50	4	42	6	9	38	10	14	8
11	91	39	25	27	70	50	23	3	10	9
12	34	96	27	79	68	68	35	8	43	36
13	5	86	5	16	3	9	30	6	43	56
M	40.31	71.69	28.85	43.69	46.85	42.85	32.85	7.54	19.67	19.08
SD	31.44	22.96	18.92	27.83	24.92	25.53	5.11	2.37	14.30	14.49

Note: Questionnaire data for participant #3 is missing because she did not complete them during the in-person session due to lack of time, and did not submit them later even after several requests. *Continued on next page.*

TBI group scores *continued*

Participants	WJ-III Decision Speed		DKEFS-Trails (standard scores)				
TBI	Time (seconds)	Accuracy	NoSwitch	Switch	Motor Speed	NoSwitch-switch difference	Motor-switch difference
1	180	31	14	13	11	9	12
2	180	34	14	12	23	8	10
3	180	40	8	12	11	11	11
4	180	30	12	7	11	5	6
5	180	34	12	12	11	10	11
6	180	39	11	9	11	8	8
7	180	33	14	12	12	8	10
8	180	37	13	12	9	9	13
9	180	35	9	12	13	13	9
10	180	33	11	13	11	8	12
11	180	35	15	10	12	5	8
12	162	40	12	9	12	9	9
13	180	34	3	9	11	13	8
M	178.62	35.00	11.38	10.92	12.15	8.92	9.77
SD	4.99	3.19	3.23	1.89	3.39	2.47	2.01

Appendix 2: Continued

Control group scores.

Participants	RBANS						Working memory		Questionnaires	
Control	Immed memory	Visuo-spatial	Language	Attention	Delayed memory	Total	Listening Span	WMS-III Digits Bkwd	APT	BADS
1	42	92	61	50	92	79	37	6	11	15
4	50	92	23	34	53	50	34	6	17	19
5	50	63	39	99	63	77	40	8	14	26
10	16	92	23	79	47	53	38	9	3	4
11	13	92	30	73	42	50	36	6	0	9
12	42	55	53	21	42	37	39	7	23	17
15	82	79	61	79	34	73	41	7	5	12
16	50	96	42	95	93	91	37	10	2	12
18	58	92	34	95	53	79	39	9	11	21
19	87	92	63	88	70	91	37	7	7	21
20	79	73	73	88	96	93	34	10	6	13
21	42	39	30	8	63	27	38	5	18	19
22	79	92	86	84	63	91	41	13	4	19
M	53.08	80.69	47.54	68.69	62.38	68.54	37.77	7.92	9.31	15.92
SD	23.69	18.03	20.14	30.31	20.52	22.49	2.28	2.22	7.03	5.87

Continued on next page.

Control group scores *continued*

Participants	WJ-III Decision Speed		DKEFS-Trails (standard scores)				
	Time				Motor	NoSwitch-switch	Motor-switch
Control	(seconds)	Accuracy	NoSwitch	Switch	Speed	difference	difference
1	142	39	14	13	13	9	10
4	180	37	14	13	11	9	12
5	161	40	15	12	12	7	10
10	180	39	16	11	13	5	8
11	168	40	14	13	13	9	10
12	190	38	11	15	13	14	8
15	180	38	11	11	12	10	9
16	180	37	14	13	12	9	11
18	141	40	15	13	11	8	12
19	180	39	12	12	11	10	11
20	180	37	12	11	10	9	11
21	174	40	16	10	14	1	6
22	180	37	12	12	13	10	9
M	172.00	38.54	13.54	12.23	12.15	8.46	9.77
SD	15.20	1.27	1.76	1.30	1.14	3.02	1.74

Appendix 3: Sentence Repetition Task Stimuli

PRACTICE BLOCK

Pair	Speaker	Sentence (keywords capitalized)								
a	NNS	The	CLEAT	SANK	DEEPLY	into	the	SOFT	TURF.	
a	NS	The	RAMP	LED	UP	to	the	WIDE	HIGHWAY.	
b	NNS	The	KITE	FLEW	WILDLY	in	the	HIGH	WIND.	
b	NS	The	DUSTY	BENCH	STOOD	by	the	STONE	WALL.	
c	NNS	The	CURTAIN	ROSE	and	the	SHOW	WAS	ON.	
c	NS	The	FIRST	PART	of	the	PLAN	NEEDS	CHANGING.	
d	NNS	The	BIG	RED	APPLE	FELL	to	the	GROUND.	
d	NS	The	YOUNG	PRINCE	BECAME	HEIR	to	the	THRONE.	
e	NNS	The	HORN	of	the	CAR	WOKE	the	SLEEPING	COP.
e	NS	The	NOZZLE	of	the	FIRE	HOSE	was	BRIGHT	BRASS.

PRACTICE BLOCK *continued*

Pair	Speaker	Sentence (keywords capitalized)								
f	NNS	The	PEARL	was	WORN	in	a	THIN	SILVER	RING.
f	NS	The	RISE	to	FAME	of	a	PERSON	TAKES	LUCK.
g	NNS	The	PIRATES	SEIZED	the	CREW	of	the	LOST	SHIP.
g	NS	The	CLUB	RENTED	the	RINK	for	the	FIFTH	NIGHT.
h	NNS	The	BEACH	is	DRY	and	SHALLOW	at	LOW	TIDE.
h	NS	The	SKY	that	MORNING	was	CLEAR	and	BRIGHT	BLUE.
i	NNS	The	ZONES	MERGE	in	the	CENTRAL	PART	of	TOWN.
i	NS	The	PETALS	FALL	with	the	NEXT	PUFF	of	WIND.
j	NNS	The	BROWN	HOUSE	was	ON	FIRE	to	the	ATTIC.
j	NS	The	MUTE	MUFFLED	the	HIGH	TONES	of	the	HORN.
k	NNS	The	LOGS	FELL	and	TUMBLED	into	the	CLEAR	STREAM.
k	NS	The	TRAIN	BROUGHT	our	HERO	to	the	BIG	TOWN.

Note: The target speaker was the NS for all practice block items. Order was randomized across participants.

Appendix 3: Continued.

ALONE CONDITION

Speaker	Sentence									
NNS	The	KITE	DIPPED	and	SWAYED,	but	STAYED	ALOFT.		
NNS	The	CHAIR	LOOKED	STRONG	but	had	NO	BOTTOM.		
NNS	The	SMELL	of	BURNED	RAGS	ITCHES	my	NOSE.		
NNS	The	CHAP	SKIPPED	INTO	the	CROWD	and	was	LOST.	
NNS	The	SOFA	CUSHION	is	RED	and	of	LIGHT	WEIGHT.	
NNS	The	SQUARE	WOODEN	CRATE	was	PACKED	to	be	SHIPPED.	
NNS	The	RUSH	for	FUNDS	REACHED	its	PEAK	TUESDAY.		
NNS	The	RIPE	TASTE	of	CHEESE	IMPROVES	with	AGE.		
NNS	The	DRY	WAX	PROTECTS	the	DEEP	SCRATCH.			
NNS	The	BUNCH	of	GRAPES	was	PRESSED	INTO	WINE.		
NS	The	OLD	PAN	was	COVERED	with	HARD	FUDGE.		

ALONE CONDITION *continued*

Speaker	Sentence									
NS	The	BEAM	DROPPED	DOWN	on	the	WORKMEN'S	HEAD.		
NS	The	SHEEP	were	LED	HOME	BY	a	DOG.		
NS	The	SMALL	PUP	GNAWED	a	HOLE	in	the	SOCK.
NS	The	FISH	TWISTED	And	TURNED	on	the	BENT	HOOK.
NS	The	DUNE	ROSE	FROM	the	EDGE	of	the	WATER.
NS	The	MEAL	was	COOKED	BEFORE	the	BELL	RANG.		
NS	The	TERM	ENDED	In	LATE	JUNE	that	YEAR.		
NS	The	LAST	SWITCH	CANNOT	be	TURNED	OFF.			
NS	The	HOUSES	are	BUILT	of	RED	CLAY	BRICKS.		

Note: There are no sentence pairs in the alone condition because each sentence was presented individually. Block order (whether NS or NNS was presented first) was counterbalanced across participants, and sentence order was randomized within each block.

Appendix 3: Continued

ATTEND CONDITION

Pair	Speaker	Sentence							
a	NNS	The	STRAW	NEST	HOUSED	FIVE	ROBINS.		
a	NS	The	FIRST	WORM	GETS	SNAPPED	EARLY.		
aa	NNS	The	BLIND	MAN	COUNTED	his	OLD	COINS.	
aa	NS	The	BRASS	TUBE	CIRCLED	the	HIGH	WALL.	
ab	NNS	The	GOLD	RING	FITS	only	a	PIERCED	EAR.
ab	NS	The	DARK	POT	HUNG	in	the	FRONT	CLOSET.
ac	NNS	The	COLD	DRIZZLE	will	HALT	the	BOND	DRIVE.
ac	NS	The	FLINT	SPUTTERED	and	LIT	a	PINE	TORCH.
af	NNS	The	HORSE	BALKED	and	THREW	the	TALL	RIDER.
af	NS	The	STORE	WALLS	were	LINED	with	COLORED	FROCKS.
ag	NNS	The	KEY	YOU	DESIGNED	will	FIT	the	LOCK.
ag	NS	The	PEACE	LEAGUE	MET	to	DISCUSS	their	PLANS.
ah	NNS	The	PLEASANT	HOURS	FLY	by	much	TOO	SOON.

ATTEND CONDITION *continued*

Pair	Speaker	Sentence								
ah	NS	The	QUICK	FOX	JUMPED	on	the	SLEEPING	CAT.	
ai	NNS	The	LEAF	DRIFTS	ALONG	with	a	SLOW	SPIN.	
ai	NS	The	COPPER	BOWL	SHONE	in	the	SUN'S	RAYS.	
aj	NNS	The	COUCH	COVER	and	HALL	DRAPES	were	BLUE.	
aj	NS	The	DIRT	PILES	were	LINED	ALONG	the	ROAD.	
ak	NNS	The	DESK	was	FIRM	ON	the	SHAKY	FLOOR.	
ak	NS	The	FUR	of	CATS	GOES	by	MANY	NAMES.	
am	NNS	The	ROOM	was	CROWDED	WITH	a	WILD	MOB.	
am	NS	The	DESK	and	BOTH	CHAIRS	were	PAINTED	TAN.	
an	NNS	The	GREEN	LIGHT	in	the	BROWN	BOX	FLICKERED.	
an	NS	The	CLOTHES	DRIED	on	a	THIN	WOODEN	RACK.	
ao	NNS	The	HITCH	BETWEEN	the	HORSE	and	CART	BROKE.	
ao	NS	The	YOUTH	DROVE	with	ZEST,	but	LITTLE	SKILL.	

ATTEND CONDITION *continued*

Pair	Speaker	Sentence								
ap	NNS	The	FACTS	DON'T	ALWAYS	SHOW	who	is	RIGHT.	
ap	NS	The	BANK	PRESSED	FOR	PAYMENT	of	the	DEBT.	
aq	NNS	The	MAIL	COMES	in	THREE	BATCHES	per	DAY.	
aq	NS	The	LINE	WHERE	the	EDGES	JOIN	was	CLEAN.	
ar	NNS	The	PODS	of	PEAS	FERMENT	in	BARE	FIELDS.	
ar	NS	The	KNIFE	was	HUNG	INSIDE	its	BRIGHT	SHEATH.	
at	NNS	The	FRUIT	of	a	FIG	TREE	is	APPLE	SHAPED.
at	NS	The	BEAUTY	of	the	VIEW	STUNNED	the	YOUNG	BOY.
av	NNS	The	LURE	is	USED	to	CATCH	TROUT	and	FLOUNDER.
av	NS	The	ROPE	will	BIND	the	SEVEN	BOOKS	at	ONCE.
ax	NNS	The	HARDER	he	TRIED	the	LESS	he	GOT	DONE.
ax	NS	The	FIN	was	SHARP	and	CUT	the	CLEAR	WATER.
ay	NNS	The	WHARF	COULD	be	SEEN	at	the	FARTHER	SHORE.
ay	NS	The	BOSS	RAN	the	SHOW	with	a	WATCHFUL	EYE.

ATTEND CONDITION *continued*

Pair	Speaker	Sentence									
az	NNS	The	PLAY	BEGAN	as	SOON	as	we	SAT	DOWN.
az	NS	The	CIGAR	BURNED	a	HOLE	in	the	DESK	TOP.
b	NNS	The	TIN	BOX	HELD	PRICELESS	STONES.			
b	NS	The	PENCILS	HAVE	ALL	BEEN	USED.			
ba	NNS	The	BABY	PUTS	his	RIGHT	FOOT	in	his	MOUTH.
ba	NS	The	COFFEE	STAND	is	TOO	HIGH	for	the	COUCH.
bb	NNS	The	NIGHT	SHIFT	men	RATE	EXTRA	PAY.		
bb	NS	The	EARLY	PHASE	of	LIFE	MOVES	FAST.		
bc	NNS	The	SUN	CAME	up	to	LIGHT	the	EASTERN	SKY.
bc	NS	The	WRECK	OCCURRED	by	the	BANK	on	MAIN	STREET.
bd	NNS	The	SLAB	was	HEWN	from	HEAVY	BLOCKS	of	SLATE.
bd	NS	The	SHELVES	were	BARE	of	BOTH	JAM	or	CRACKERS.
c	NNS	The	BILL	was	PAID	EVERY	THIRD	WEEK.		
c	NS	The	JUICE	of	LEMONS	MAKES	FINE	PUNCH.		

ATTEND CONDITION *continued*

Pair	Speaker	Sentence							
cc	NNS	The	POOR	BOY	MISSED	the	BOAT	AGAIN.	
cc	NS	The	RED	PAPER	BRIGHTENED	the	DIM	STAGE.	
d	NNS	The	FRIENDLY	GANG	LEFT	the	DRUG	STORE.	
d	NS	The	SOFT	CUSHION	BROKE	the	MAN'S	FALL.	
dd	NNS	The	WIDE	ROAD	SHIMMERED	in	the	HOT	SUN.
dd	NS	The	BIRCH	CANOE	SLID	on	the	SMOOTH	PLANKS.
e	NNS	The	LEASE	RAN	OUT	in	SIXTEEN	WEEKS.	
e	NS	The	YOUNG	GIRL	GAVE	no	CLEAR	RESPONSE.	
ee	NNS	The	BOY	was	THERE	WHEN	the	SUN	ROSE.
ee	NS	The	BOX	was	THROWN	BESIDE	the	PARKED	TRUCK.
f	NNS	The	SLUSH	LAY	DEEP	ALONG	the	STREET.	
f	NS	The	STRAY	CAT	GAVE	BIRTH	to	KITTENS.	
ff	NNS	The	URGE	to	WRITE	SHORT	STORIES	is	RARE.
ff	NS	The	HOGS	were	FED	CHOPPED	CORN	and	GARBAGE.

ATTEND CONDITION *continued*

Pair	Speaker	Sentence							
g	NNS	The	TINY	GIRL	TOOK	OFF	her	HAT.	
g	NS	The	FROSTY	AIR	PASSED	THROUGH	the	COAT.	
gg	NNS	The	IDEA	is	to	SEW	BOTH	EDGES	STRAIGHT.
gg	NS	The	GIRL	at	the	BOOTH	SOLD	FIFTY	BONDS.
h	NNS	The	LAWYER	TRIED	to	LOSE	HIS	CASE.	
h	NS	The	WAGON	MOVED	on	WELL	OILED	WHEELS.	
hh	NNS	The	TWO	MET	WHILE	PLAYING	on	the	SAND.
hh	NS	The	SALT	BREEZE	CAME	ACROSS	from	the	SEA.
i	NNS	The	PIPE	BEGAN	to	RUST	WHILE	NEW.	
i	NS	The	NAVY	ATTACKED	the	BIG	TASK	FORCE.	
ii	NNS	The	WALLED	TOWN	was	SEIZED	WITHOUT	a	FIGHT.
ii	NS	The	SWAN	DIVE	was	FAR	SHORT	of	PERFECT.
j	NNS	The	PLAY	SEEMS	DULL	and	QUITE	STUPID.	
j	NS	The	GRASS	CURLED	AROUND	the	FENCE	POST.	

ATTEND CONDITION *continued*

Pair	Speaker	Sentence							
jj	NNS	The	CLOCK	STRUCK	to	MARK	the	THIRD	PERIOD.
jj	NS	The	COLT	REARED	and	THREW	the	TALL	RIDER.
k	NNS	The	PENNANT	WAVED	WHEN	the	WIND	BLEW.	
k	NS	The	HOG	CRAWLED	UNDER	the	HIGH	FENCE.	
kk	NNS	The	CEMENT	had	DRIED	WHEN	he	MOVED	IT.
kk	NS	The	WRIST	was	BADLY	STRAINED	and	HUNG	LIMP.
l	NNS	The	LARGE	HOUSE	had	HOT	WATER	TAPS.	
l	NS	The	CUP	CRACKED	and	SPILLED	ITS	CONTENTS.	
m	NNS	The	DOCTOR	CURED	HIM	with	THESE	PILLS.	
m	NS	The	YOUNG	KID	JUMPED	the	RUSTY	GATE.	
mm	NNS	The	INK	STAIN	DRIED	on	the	FINISHED	PAGE.
mm	NS	The	LAZY	COW	LAY	in	the	COOL	GRASS.
n	NNS	The	CHILD	ALMOST	HURT	the	SMALL	DOG.	
n	NS	The	JUST	CLAIM	GOT	the	RIGHT	VERDICT.	

ATTEND CONDITION *continued*

Pair	Speaker	Sentence							
nn	NNS	The	THAW	CAME	EARLY	and	FREED	the	STREAM.
nn	NS	The	CROOKED	MAZE	FAILED	to	FOOL	the	MOUSE.
o	NNS	The	RUDE	LAUGH	FILLED	the	EMPTY	ROOM.	
o	NS	The	TONGS	LAY	BESIDE	the	ICE	PAIL.	
oo	NNS	The	PAPER	BOX	is	FULL	of	THUMB	TACKS.
oo	NS	The	FRUIT	PEEL	was	CUT	in	THICK	SLICES.
p	NNS	The	PLUSH	CHAIR	LEANED	AGAINST	the	WALL.	
p	NS	The	BIRCH	LOOKED	STARK	WHITE	and	LONESOME.	
pp	NNS	The	TREE	TOP	WAVED	in	a	GRACEFUL	WAY.
pp	NS	The	HEART	BEAT	STRONGLY	and	with	FIRM	STROKES.
q	NNS	The	PURPLE	TIE	was	TEN	YEARS	OLD.	
q	NS	The	PRINCE	ORDERED	his	HEAD	CHOPPED	OFF.	
qq	NNS	The	MAP	HAD	an	X	that	MEANT	NOTHING.
qq	NS	The	HAT	BRIM	was	WIDE	and	TOO	DROOPY.

ATTEND CONDITION *continued*

Pair	Speaker	Sentence							
r	NNS	The	JUNK	YARD	HAD	a	MOLDY	SMELL.	
r	NS	The	RED	TAPE	BOUND	the	SMUGGLED	FOOD.	
ss	NNS	The	NEW	GIRL	was	FIRED	TODAY	at	NOON.
ss	NS	The	SLANG	WORD	for	RAW	WHISKEY	is	BOOZE.
t	NNS	The	STALE	SMELL	of	OLD	BEER	LINGERS.	
t	NS	The	CLAN	GATHERED	on	EACH	DULL	NIGHT.	
tt	NNS	The	SHAKY	BARN	FELL	with	a	LOUD	CRASH.
tt	NS	The	EMPTY	FLASK	STOOD	on	the	TIN	TRAY.
u	NNS	The	CHILD	CRAWLED	INTO	the	DENSE	GRASS.	
u	NS	The	NEWS	STRUCK	DOUBT	into	RESTLESS	MINDS.	
uu	NNS	The	LAKE	SPARKLED	in	the	RED	HOT	SUN.
uu	NS	The	OFFICE	PAINT	was	a	DULL,	SAD	TAN.
v	NNS	The	NAG	PULLED	the	FRAIL	CART	ALONG.	
v	NS	The	BOY	OWED	his	PAL	THIRTY	CENTS.	

ATTEND CONDITION *continued*

Pair	Speaker	Sentence							
vv	NNS	The	FLY	MADE	its	WAY	ALONG	the	WALL.
vv	NS	The	HOSTESS	TAUGHT	the	NEW	MAID	to	SERVE.
w	NNS	The	MUSIC	PLAYED	ON	WHILE	they	TALKED.	
w	NS	The	WALL	PHONE	RANG	LOUD	and	OFTEN.	
ww	NNS	The	FIGHT	will	END	in	JUST	SIX	MINUTES.
ww	NS	The	DOORKNOB	was	MADE	of	BRIGHT	CLEAN	BRASS.
x	NNS	The	BLACK	TRUNK	FELL	FROM	the	LANDING.	
x	NS	The	LITTLE	TALES	THEY	TELL	are	FALSE.	
xx	NNS	The	BEETLE	DRONED	in	the	HOT	JUNE	SUN.
xx	NS	The	LAMP	SHONE	with	a	STEADY	GREEN	FLAME.
y	NNS	The	LONG	JOURNEY	HOME	TOOK	a	YEAR.	
y	NS	The	SMALL	RED	NEON	LAMP	went	OUT.	
yy	NNS	The	KITTEN	CHASED	the	DOG	DOWN	the	STREET.
yy	NS	The	ANCIENT	COIN	was	QUITE	DULL	and	WORN.

ATTEND CONDITION *continued*

Pair	Speaker	Sentence						
z	NNS	The	RAM	SCARED	the	SCHOOL	CHILDREN	OFF.
z	NS	The	FAN	WHIRLED	its	ROUND	BLADES	SOFTLY.

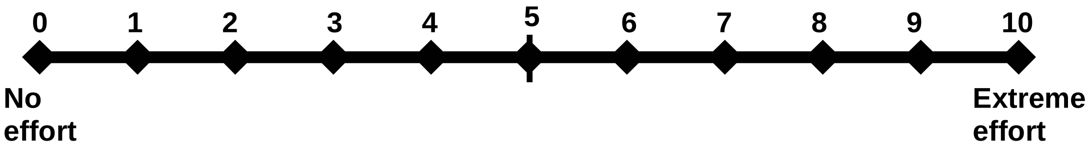
Note: Order of sentence pairs was randomized across participants. The first 30 sentence pairs were Block 1 and the second 30 sentence pairs were Block 2. Block order (whether the NS or NNS was assigned first as the target) was counterbalanced across participants.

Appendix 4: Effort Follow-Up

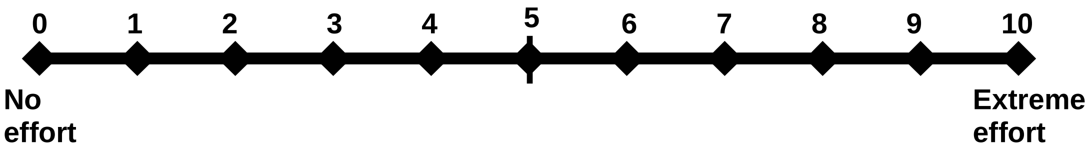
The following worksheet was used to record effort ratings, which were shown to to the participant as context for the follow-up questions.

Here are the ratings you made for how much effort it took to understand the sentences you heard:

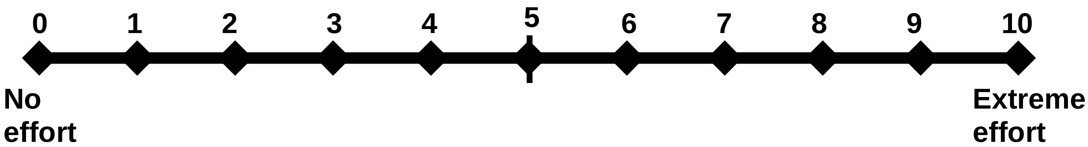
Practice Combined



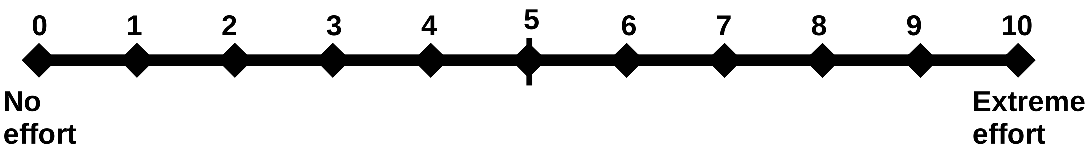
Section 1: Voice A



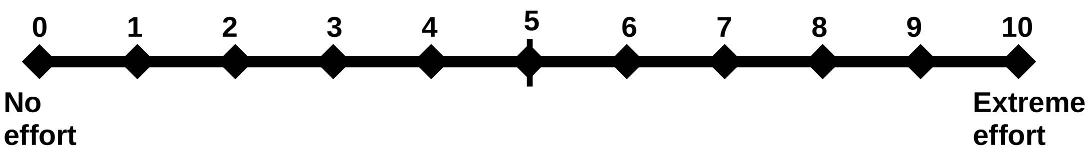
Section 2: Voice B



Section 3: Combined



Section 4: Combined



Please tell me more about why you made these ratings.
Did you use any strategies to help you repeat the sentences?
Did you ever find that your mind wandered or you lost concentration during the experiment?

Appendix 5: Semi-Structured Interview Questions

The following questions were asked of each participant in Experiment 2. Participants in the TBI group were also asked if their experiences had changed since before their injury; participants in the control group were asked if their experiences had changed over time or as they got older.

1. Are there situations that you find more difficult than others for listening to and understanding speech? If so, please describe them.
2. Ask the participant to elaborate on any specific situations mentioned in answer to question 1.
3. If not mentioned in answer to question 1, ask about each of the following situations:
    a. Is there any difference for you in how easy it is to understand someone outside compared to inside?
    b. … near a busy street compared to on a quiet street?
    c. … in a crowded restaurant compared to eating at home?
    d. … talking to someone with an accent compared to someone without an accent?
    e. … talking to someone when there is someone else nearby discussing something interesting, compared with no one nearby, or compared with people nearby who are discussing something you don't find interesting?
4. For any of the scenarios in which you notice difficulty, do you use any strategies to help you overcome that difficulty?

Appendix 6: Linear mixed effects model output

```
Linear mixed model fit by REML
Formula: Target ~ Trial + Group + Target + NativeFirst + Group * NativeFirst + +Target * Trial + Trial *
Group + (1 | Participant) + (1 | Sentence)
 Data: attend
 AIC BIC logLik deviance REMLdev
 5625 5684 -2802 5572 5603
Random effects:
 Groups Name Variance Std.Dev.
 Sentence (Intercept) 0.88002 0.93809
 Participant (Intercept) 0.59387 0.77063
 Residual 1.70871 1.30718
Number of obs: 1560, groups: Sentence, 125; Participant, 26
```

Fixed effects:

	Estimate	Std. Error	t-value	Estimate	MCMCmean	HPD95lower	HPD95upper	pMCMC	Pr(>|t|)
(Intercept)	1.934109	0.423221	4.570	1.9341	1.9469	1.1705	2.6869	0.0001	0.0000
Trial	0.023032	0.004896	4.705	0.0230	0.0227	0.0131	0.0327	0.0002	0.0000
GroupTBI	0.062320	0.492305	0.127	0.0623	0.0626	-0.7814	0.9695	0.8774	0.8993
TargetNonNative	0.489861	0.298859	1.639	0.4899	0.4991	-0.0602	1.0661	0.0842	0.1014
NativeFirst	1.118301	0.466065	2.399	1.1183	1.1020	0.2845	1.9193	0.0106	0.0165
GroupTBI:NativeFirst	-0.840455	0.628624	-1.337	-0.8405	-0.8335	-1.9209	0.2687	0.1398	0.1814
Trial:TargetNonNative	-0.031766	0.007945	-3.998	-0.0318	-0.0317	-0.0472	-0.0153	0.0001	0.0001
Trial:GroupTBI	-0.006427	0.003895	-1.650	-0.0064	-0.0065	-0.0142	0.0014	0.1020	0.0991

\>

Random effects:

	Groups	Name	Std.Dev.	MCMCmedian	MCMCmean	HPD95lower	HPD95upper
1	Sentence	(Intercept)	0.9381	0.7176	0.7198	0.6220	0.8140
2	Participant	(Intercept)	0.7706	0.6688	0.6763	0.4972	0.8632
3	Residual		1.3072	1.3416	1.3421	1.2912	1.3914

Appendix 7: Thematic Coding and Example Quotes from Interviews

Code	Key words and concepts	Example quote
Accent	accent of speaker affects comprehensibility	“You have to listen more carefully to someone with an accent”
Accommodation	improvement as they become accustomed to listening	“I’ve… like adapted to their speaking styles and, but I, I’ve learned ways to compensate for it”
Alcohol	any mention of alcohol	“drinking actually makes it a little better”
Anxiety	anxiety, anxious, worried	“I have a lot more anxiety because of the fact that I know the grasp is not as strong as it used to be”
Background noise	background noise	“I think it is a little easier outdoors probably because, um, outdoors there’s not, there’s not the concentration of the noise”
Camouflage	“nod and smile” – pretend to understand or try to wait and figure out from context	“sometimes I’d just smile and “yeah, hmhmhmh”. That kind of stuff”
Can't process	difficulty processing	“it seems like [my] deepest deficit is just processing verbal information”

Appendix 7 *Continued*

Code	Key words and concepts	Example quote
Change-	worsening over time	"I never had problems with it before my brain injury, so it's definitely worse"
Change+	getting better over time	"I feel like listening to people with accents has gotten easier just 'cause I've done it more"
Change=	no change over time	"I feel like I've been the same."
Conversation partners	effect of conversation partner (e.g. depends who I'm talking to)	"probably the most challenging thing, is just dealing with people that you need to converse with"
Depends	usually in response to a prompt	"it would just depend on how calm the environment is"
Difficult	"it's just harder"	"having a basic conversation is pretty difficult."
Distraction	distraction, pulling attention, hard to re-focus, multitasking	"every single thing outside of me is a distraction"
Endorse	agree that something is difficult in response to prompt but don't elaborate much OR state it can be difficult but is not a big deal	"Obviously a loud busy street would be difficult"

Appendix 7 *Continued*

Code	Key words and concepts	Example quote
Extra effort	hard work, effort,	“it’s just huge amounts of concentration…wears me out.”
Familiarity	better with more familiar person or accent	“the more time I spend with an individual, the easier it gets for me to be able to understand them”
Fatigue	tired, fatigue, progressively harder, worn out	“The later in the day the worse it gets”
Filter	tuning out, ignoring, filter, hearing unwanted information	“there’s so much other noise that my brain can’t tell what to listen to.”
Fluency	e.g. Less fluent = less comprehensible	“a stuttering problem … and I was really kind of panicked because I didn’t want to appear [rude]”
Focus	pay attention, focus, honing in, concentrating	“I’m not…able to differentiate some of the speech from one person to the other, unless I’m really concentrating and focusing on what they’re saying”
Frustration	frustrated, annoyed, aggravated	“I tend to get really frustrated and it’s a lot harder to pay attention to the one conversation.”

Appendix 7 *Continued*

Code	Key words and concepts	Example quote
Headache	headache	"my migraines are funny cause my brain does this like coping mechanism, like it won't get that bad during the day."
Impulsivity	communication affected by being impulsive	"I tend to interrupt people a lot because they're talking and I think of a response, and if I try to hold on to it, it's gone."
Less social	change in social behaviors, go out less, avoid situations	"I used to be a lot more social, and um, outgoing, and since the brain injury I've really become an introvert"
Monotone	less prosodic variation in speaker affects comprehension	"if they don't have a lot of fluctuation in the way they talk it's hard to listen to them."
Multiple talkers	more than one person talking; prefer one-on-one	"Like last night when two people were trying to tell me directions as I was driving. It was driving me crazy."
Mumbling	mumbling, muttering, talking too quietly	"when people are muttering or speak under their breath"

Appendix 7 *Continued*

Code	Key words and concepts	Example quote
No strategy	explicitly state lack of strategy	"I haven't come up with a really good coping mechanism for that"
Nonverbal	trying to interpret nonverbal meanings (different from visual – watching lips, gestures)	"if they seem like they're interested, or interested in you, Like, body language, eye contact, stuff like that"
Not a problem	disagree that something is difficult; opposite of endorse	"[I] wouldn't have to work any harder"
Overload	overwhelming, overloading, too much	"especially put in that kind of a crazy situation and it's, it's just overload. It's guaranteed migraine day"
Phone	mention of telephone, phone conference, speaker phone	"I don't understand sometimes over the phone, what people say if they're running their words together"
Simple	need content to be simplified to understand	"I used to say, 'Talk to me like I'm eight.' […]Because I need very simple explanations"

Appendix 7 *Continued*

Code	Key words and concepts	Example quote
Slow	slower, can't keep up, too fast, take extra time	"everything when I'm tired is magnified, slows way down and stuff"
Speaking	Interviewee's speaking affected by environment or TBI	"the more frustrated I got, probably the worse I was having trouble with coming up with the right words and just talking to anybody"
Strategy	something done to improve difficult situation	"if I really really need to get something done […] Then I will either leave, or, I very rarely get up and move,"
Strength	something people are explicitly good at, used to, never a problem, or even an advantage	"I'm pretty good with accents."
Stressful	stress, not relaxing	"it's not relaxing just to sit and have a conversation with somebody anymore"
Text	text vs. speech	"when you can see it you can visualize it in text, and you can see the sequence of things"

Appendix 7 *Continued*

Code	Key words and concepts	Example quote
Think	pause to re-play or think through what has been said	"And then replay it back in my head before I try and respond"
Tinnitus	tinnitus	"I'd say it makes it harder cause it makes the ringing in my ears louder."
Topic	depends on the topic/type of conversation , interest, preference	"something that I know about I understand more than a new topic of information."
Visual	focus on mouth, harder if can't see, watch for gestures	"And if it were face-to-face, I have so much more information, to be able to figure out what they're saying."