The Effects of Auditory Stimulus Level and Speech Recognition Performance on fNIRS Measured Cortical Activation in Adults with Normal Hearing and Adults with Cochlear Implants

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LIST OF ABBREVIATIONS

ANOVA ....Analysis of variance

BOLD...Blood oxygenation level dependent

CAEP ....Cortical auditory evoked potential

CI...Cochlear implant

CNC ....Consonant nucleus consonant

DL-PFC...Dorsolateral prefrontal cortex

EEG..Electroencephalography

fNIRS ....Functional near-infrared spectroscopy

fMRI ....Functional magnetic resonance imaging

HbO ....Oxygenated hemoglobin

HbR ....Deoxygenated hemoglobin

IFG ....Inferior frontal gyrus

MEG...Magnetic encephalography

NH..Normal hearing

PET ....Positron emission tomography

ROI...Region of interest

SCN..Signal correlated noise

SD ....Standard deviation

SEM ....Standard error of the mean

SNR...Signal-to-noise ratio

SNR50..SNR at which 50% recognition is achieved

SNR75..SNR at which 75% recognition is achieved

CHAPTER I

INTRODUCTION

Since the initial approval of multi-channel cochlear implants (CIs) in 1985, FDA labeled

indications for cochlear implantation have expanded considerably, allowing individuals with

more residual hearing to receive a CI. In 2010, Dorman and Gifford reported that up to 60% of

adults pursuing cochlear implantation have some residual hearing—mostly low frequency—in

one or both ears (Dorman & Gifford, 2010). The prevalence of residual low-frequency hearing in

children with CIs is currently unknown; however, with expected expansions in pediatric FDA

labeled indications for cochlear implantation (Carlson et al., 2015), the prevalence of residual

low-frequency hearing in children with CIs is expected to increase. Given the preoperative

bilateral acoustic hearing available to a large proportion of current CI candidates, two viable

treatment plans have become available to unilateral CI recipients: 1) pursuit of a second CI, or 2)

continued use of a hearing aid in the non-implanted ear. Speech recognition performance

improves with the addition of either a hearing aid or a CI in a second ear (e.g. R. Gifford,

Dorman, McKarns, & Spahr, 2007; R. H. Gifford, Dorman, Sheffield, Teece, & Olund, 2014;

Litovsky, Johnstone, & Godar, 2006; Mok, Galvin, Dowell, & McKay, 2010; Schafer, Amlani,

Paiva, Nozari, & Verret, 2011). The difficult decision of which treatment plan to pursue is

complicated by the lack of established diagnostic criteria for determining bilateral implant

candidacy. Specifically, there are no data-driven recommendations for determining when the

benefit to be gained from a second CI will exceed that of a hearing aid used in a bimodal hearing

configuration.

The decision to pursue a second CI is particularly time sensitive in children due to critical

periods of auditory, speech, and language development (Colletti, Mandala, & Colletti, 2012;

Houston & Miyamoto, 2010; Niparko et al., 2010; Sharma, Gilley, Dorman, & Baldwin, 2007). Evidence suggests that binaural hearing as well as speech and language outcomes decrease with increased time between CI surgeries, suggesting a sensitive period for obtaining a second CI (K. Gordon, Wong, & Papsin, 2013; K. A. Gordon, Jiwani, & Papsin, 2011; K. A. Gordon & Papsin, 2009; K. A. Gordon, Valero, van Hoesel, & Papsin, 2008; Lammers, Venekamp, Grolman, & van der Heijden, 2014; Maria & Oghalai, 2013; Polonenko, Papsin, & Gordon, 2015). Unfortunately, it is difficult to obtain a behavioral measurement of the benefit young children gain from a hearing aid in the non-implanted ear. Thus, pursuit of a second CI might be delayed and result in poorer outcomes without data-driven recommendations. This is an example of a clinical scenario in which an objective measure, not requiring a behavioral response, could be beneficial. Inclusion of an objective measure of the benefit of the second ear would be invaluable in determining criteria for second CI candidacy in young children.

Neuroimaging can provide an objective measure of changes in cortical activation with the addition of the second ear. Ample research has shown that auditory cortical activity increases with improving speech recognition in adults with both normal hearing (NH) and CIs (Coez et al., 2008; Obleser, Eisner, & Kotz, 2008; Obleser, Wise, Alex Dresner, & Scott, 2007; S. K. Scott, Blank, Rosen, & Wise, 2000; Sophie K. Scott, Rosen, Lang, & Wise, 2006; Strelnikov, Massida, Rouger, Belin, & Barone, 2011; Kuzma Strelnikov et al., 2011). The addition of a hearing aid or a CI increases speech recognition in adults and children with unilateral CIs (e.g. Carroll, Tiaden, & Zeng, 2011; Ching, Incerti, Hill, & van Wanrooy, 2006; R. Gifford et al., 2007; Litovsky et al., 2006; Mok et al., 2010; Nittrouer & Chapman, 2009; Sheffield & Gifford, 2014; R. van Hoesel, Ramsden, & O'Driscoll, 2002; R. J. van Hoesel, 2004, 2012). Thus, a measure of auditory cortical activity has potential as an objective measure of the speech recognition benefit

obtained from the addition of a hearing aid or CI in the second ear of pediatric CI recipients. However, neuroimaging is notoriously difficult in the CI patient population. For example, functional magnetic resonance imaging (fMRI) techniques are contraindicated in most CI recipients due to the magnet in the CI.

Tange and colleagues (Tange, Grolman, & Dreschler, 2009) recommended cortical auditory evoked potentials (CAEPs) be included in pediatric assessments for second CI candidacy as an objective measure of second-ear hearing aid benefit. However, CAEPs have limited spatial resolution and require artifact rejection of the electrical activity from the CI. Additionally, CAEPs are typically measured using short stimuli with limited language content, such as consonant-vowel syllables. Thus, even though CAEPs and EEG are available as a potential measure in CI listeners, it has significant disadvantages.

Functional near-infrared spectroscopy (fNIRS) can be used in CI listeners and it does not have some of the disadvantages EEG does. fNIRS is a safe, non-invasive neuroimaging technique that utilizes light emitting diode sources and flexible fiber optics to carry the NIR light to (source) and from (detector) tissues (Ferrari & Quaresima, 2012; Quaresima, Bisconti, & Ferrari, 2012). fNIRS is not a direct measure of neural activity, but it measures changes in concentration of oxygenated (HbO) and deoxygenated hemoglobin (HbR). The measure is similar to the "blood oxygenation level dependent" (BOLD) fMRI. In contrast to fMRI, fNIRS is more portable, less expensive, has better temporal resolution, and tolerates greater patient movement. The spatial resolution of fNIRS is 1-2 cm, however, is much poorer than fMRI (Quaresima et al., 2012). fNIRS is specifically advantageous for this line of research, because it is a viable imaging technique for CI recipients. Further, fNIRS is most often used in pediatric

populations and thus holds potential as an approach to obtain objective measures of second-ear benefit for children with unilateral CIs.

The long-term goal of this research is to determine the potential of fNIRS as an objective measure of speech recognition performance in individuals with CIs, particularly young children. This dissertation will begin by examining fNIRS in groups of adults with NH and CIs. The following review of the literature and our recent pilot data will include fNIRS, fMRI, and PET results in adults with NH and adults with CIs to demonstrate the potential of fNIRS and provide evidence for our hypotheses.

CHAPTER II

LITERATURE REVIEW AND PILOT DATA

Potential of fNIRS

The use of fNIRS to study functional brain activation in infants is rapidly increasing (Cristia et al., 2013; Lloyd-Fox et al., 2014) and, since the first publication in 1998, the number of published infant studies using fNIRS is now close to 100. fNIRS has been used to address many developmental topics including communication, language, and auditory processing (Arimitsu et al., 2011; Grossmann, Oberecker, Koch, & Friederici, 2010; Homae, Watanabe, Nakano, & Taga, 2012; Kotilahti et al., 2010; Plichta et al., 2011; Quaresima et al., 2012; Telkemeyer et al., 2011; Wallois, Mahmoudzadeh, Patil, & Grebe, 2012). Auditory studies have used both block and event-related paradigms. Activation in the auditory cortex as measured by fNIRS has been shown to be sensitive to semantic, prosodic, and phonemic cues in speech (Arimitsu et al., 2011; Horovitz & Gore, 2004). Emotion of speech stimuli has also been shown to have an effect on fNIRS measured activation (Plichta et al., 2011). Perhaps most importantly for the current dissertation, activation in Wernicke's area and the superior temporal gyrus (STG) and superior temporal sulcus (STS) as measured by fNIRS has been shown to be more sensitive to speech or vocal sounds than other stimuli in NH and CI listeners (Grossmann et al., 2010; Olds et al., 2015; Pollonini et al., 2014).

Not only has fNIRS shown potential to detect changes in brain activation for various auditory stimuli, it has done so without any specified task or overt behavior. In fact, some of the studies in infants were completed during natural sleep (e.g. Grossmann et al., 2010; Plichta et al., 2011). Thus, there is some evidence that fNIRS has potential to detect the effects of speech

recognition performance and auditory stimulus level on brain activation. Research in individuals with CIs, however, is very limited.

Two studies have used fNIRS in CI recipients (Olds et al., 2015; Sevy et al., 2010). Sevy et al (2010) found activation in response to speech in the auditory cortex of young children with CIs. They also found similar activation patterns using fNIRS and fMRI in NH adults. Other studies have also found significant correlation between fNIRS and fMRI activation patterns when accounting for poorer spatial resolution (Cui, Bray, Bryant, Glover, & Reiss, 2011; Kennan, Kim, Maki, Koizumi, & Constable, 2002; Strangman, Culver, Thompson, & Boas, 2002). Olds et al (2015) found greater activation to unprocessed speech than other types of stimuli, such as vocoded speech and environmental stimuli in adults with NH and adults with CIs. Further research is needed using fNIRS in individuals with CIs to determine the potential and limitations in this group. Additionally, comparisons to control groups of individuals with NH using fNIRS or fMRI might be reasonable because the two measures are correlated.

Unlike fMRI, fNIRS allows calculation of both HbO and HbR. HbO is predicted to increase with neural activation while HbR should decrease. Figure 2.1 shows the predicted hemodynamic response for both HbO and HbR following an auditory stimulus. The peak response occurs roughly five seconds after the stimulus onset. The absolute magnitude of the change in HbO is usually larger than that of HbR. Research within and outside the auditory field has shown differences in the sensitivity of the two types of hemoglobin, with both types being more sensitive to contrasts in individual studies (Hoshi, Kobayashi, & Tamura, 2001; Pollonini et al., 2014; Sevy et al., 2010). Thus, both HbO and HbR data will be analyzed in this dissertation.
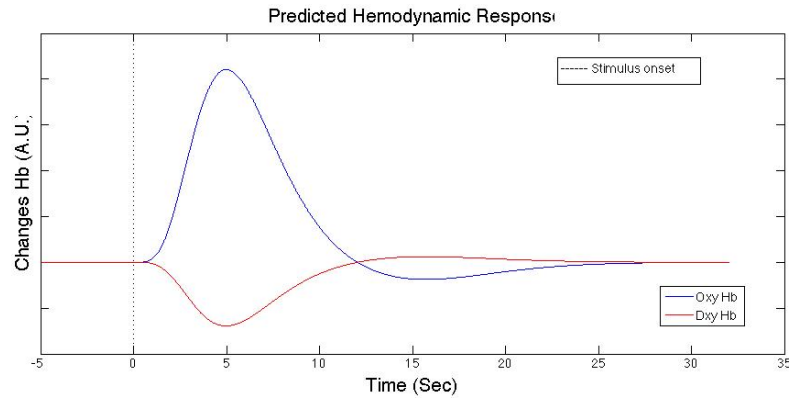
Figure 2.1: Predicted hemodynamic response measured by fNIRS for HbO and HbR in response to a transient auditory stimulus.

In summary, to determine the potential of fNIRS as an objective measure of speech recognition for CI users, basic characteristics of fNIRS responses to different auditory stimuli need to be examined. For example, we must first quantify the effects of changes in stimulus level and speech recognition performance in quiet and in noise on fNIRS responses. Additionally, these effects must be examined in individuals with CIs and with NH. The following sections will review the literature on the effects of stimulus level and speech recognition performance on auditory cortical activity.

Stimulus level effects

Stimulus level: literature review

Previous research has shown an effect of auditory stimulus level on auditory cortical activation using fMRI and EEG. Stimuli have included tones, broadband noise, and consonant-vowel syllables. Stimulus levels have varied between 10 and 100 dB SPL. In general, all studies have found a fairly linear increase in activation, strength and/or area of activation, with increases in stimulus level (Hall et al., 2001; L Jäncke, Shah, Posse, Grosse-Ryuken, & Müller-Gärtner, 1998; Langers, van Dijk, Schoenmaker, & Backes, 2007; Mulert et al., 2005; Sigalovsky &

Melcher, 2006). Significant differences in activation have been found for stimulus level differences as small as 10 dB for both speech and tones (Hall et al., 2001; L Jäncke et al., 1998).

The previous research on the effect of auditory stimulus level on cortical activation has included many different tasks, including passive. A passive task is most probable for the long-term goal of this research because it involves infants and young children. Additionally, attention is known to influence auditory cortical activity (Lutz Jäncke, Mirzazade, & Joni Shah, 1999). Thus, studies using no task were further examined. Two studies have examined the effect of stimulus level with no task other than to "attend" to the stimuli. Sigalovsky and Melcher (2006) used a broadband noise presented at 30, 50, 70 dB SL (50-99 dB SPL) and Mulert et al. (2005) used amplitude modulated tones presented at 60, 80 and 100 dB SPL. Both of these studies found significant increases in activation with increases in stimulus level. Level differences of 20 dB, the smallest tested, were significant.

In summary, previous research has shown that auditory cortical activity increases linearly with increasing stimulus level. Furthermore, the increases can be found without the listener completing a specific task. Thus, we predict that fNIRS will show increases in auditory cortical activation for higher stimulus levels.

Stimulus level: pilot data

Pilot work to examine the effect of stimulus level with fNIRS was completed. Three NH adults were tested using signal-correlated noise (SCN). The SCN stimuli were a speech-shaped noise multiplied by the amplitude envelope of four different sentences. Thus, the modulation was speech-like in nature, but without intelligibility. Both aspects are important. First, it is important that the stimulus be speech-like because the long-term goal of this research is to examine speech recognition in individuals with CIs using fNIRS. Second, it is important that the stimuli not be

intelligible because speech recognition performance changes as level increases in individuals with CIs (Skinner, Holden, Holden, Demorest, & Fourakis, 1997) and to some extent even for individuals with NH (Dubno, Horwitz, & Ahlstrom, 2005; French & Steinberg, 1947; Studebaker, Sherbecoe, McDaniel, & Gwaltney, 1999) as well as those with various degrees of sensory hearing loss (Studebaker et al., 1999). Thus, the only change in the SCN stimuli was overall sound pressure level.

The following levels were used to approximate typical speech levels ranging from soft to loud speech: 45, 55, 65, and 75 dB SPL (Olsen, 1998). Figure 2.2 shows participants' activation patterns in the left hemisphere for the linear effect of stimulus intensity level. The color scale indicates t value in each location and the participant number is in the top left of each figure. All three participants showed increasing activation with level in the STG/STS area. The activation was more anterior in P2 and P3 and covered the entire STG/STS in P1. These results support the potential of fNIRS detecting effects of stimulus intensity on auditory cortical activation.
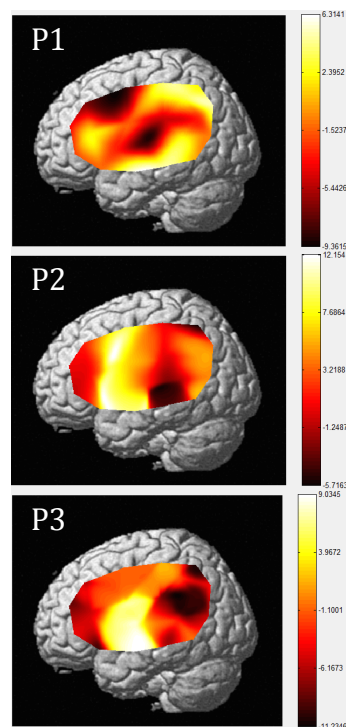
Figure 2.2: Topographical heat t-statistic maps for the linear effect of stimulus intensity level for the three pilot participants. The color map represents t-values. The brighter the color the greater the effect of stimulus intensity level.

In summary, pilot results suggest that fNIRS can detect changes in auditory cortical activation with changes in stimulus level. The linear increase in strength of activation in the auditory cortex (STG and STS) with stimulus level is consistent with previous research using fMRI (Hall et al., 2001; L Jäncke et al., 1998; Langers et al., 2007; Mulert et al., 2005; Sigalovsky & Melcher, 2006).

Speech recognition performance effects

Speech recognition performance: literature review

As previously mentioned, ample research has shown an effect of speech recognition performance on cortical activation in NH and CI listeners using fMRI and PET (Coez et al., 2008; Coez et al., 2011; Green, Julyan, Hastings, & Ramsden, 2005; Green, Ramsden, Julyan, & Hastings, 2008; Narain, 2003; Obleser et al., 2008; Obleser et al., 2007; S. K. Scott et al., 2000; Sophie K. Scott et al., 2006; K. Strelnikov et al., 2011; Kuzma Strelnikov et al., 2011). This section will focus on the limited fNIRS research on speech recognition effects on cortical activation. Oghalai and colleagues recently examined the effect of auditory stimulus type on fNIRS measured activation in bilateral STG/STS in adults with NH and adults with CIs (Olds et al., 2015; Pollonini et al., 2014). These studies are relevant as their stimuli types differed in speech intelligibility. They found a significant effect of stimulus type with unprocessed speech producing a greater area of activation than simulations of a CI, vocoded speech with reduced spectral resolution, and environmental stimuli. The unprocessed speech was more intelligible than the simulations of a CI, creating differences in speech recognition performance for the stimuli. They used two different types of vocoded speech and did not measure speech

recognition performance but noted that one type, the "scrambled speech", was generally unintelligible (0% recognition) while the "channelized speech" representing a typical CI was mostly intelligible. The two studies showed a greater area of activation for unprocessed speech than "scrambled speech" in both NH adults and adults with good speech recognition. A group of adults with CIs with poor speech recognition showed no difference between intelligible and unintelligible stimuli. The NH group also showed a greater area of activation for unprocessed speech than "channelized speech" and greater activation than the CI group for all stimuli. Although these studies showed evidence of stimulus type and group effects on cortical activation, a few limitations should be noted.

First, 30 of the 32 CI participants in the Olds et al (2015) study had only a unilateral CI. Unilateral auditory presentation is known to produce different cortical activation patterns than bilateral presentation in both NH and CI groups (Coez et al., 2011; Green, Julyan, Hastings, & Ramsden, 2011; L. Jäncke, Wuestenberg, Schulze, & Heinze, 2002; Kuzma Strelnikov et al., 2011). It is possible that a bilateral CI group would have produced results more similar to the NH group as has been shown in previous research. Second, the differences in activation between unprocessed speech and the CI simulations might have been due to "clarity" or spectral resolution or speech intelligibility. Additionally, the difference in intelligibility between the stimuli used in the studies was large, i.e. mostly intelligible to unintelligible. More research is needed to determine if fNIRS can detect effects of smaller changes in intelligibility. Third, speech recognition performance for unprocessed and vocoded speech was not matched between the groups, possibly influencing the differences between the groups. Lastly, all stimuli in the two studies were presented in quiet. Thus, no fNIRS research has examined speech recognition in noise in CI listeners. In summary, these study provides some evidence that fNIRS can detect

differences in auditory cortical activations to speech stimuli varying spectral resolution and/or speech intelligibility/recognition performance, but further research is needed to isolate the effect of speech recognition performance in quiet and in noise.

Speech recognition performance: pilot data

We also examined the effects of stimulus type on fNIRS responses in NH adults and three adults with CIs in pilot work. For speech recognition performance, we examined differences between unprocessed speech and a 15-channel CI simulation (vocoder) in ten NH adults. Speech recognition performance for unprocessed speech was greater than for the CI simulation (means of 100% and 84.1%, respectively).

An individual's single channel response to the two stimuli is shown in Figure 2.3 and group beta coefficients for the difference between the two stimuli in an average of the five most sound-activated channels in each hemisphere are shown in Figure 2.4. Group results showed stronger activation (HbO) in both the left and right hemispheres to unprocessed speech ($p < 0.05$).
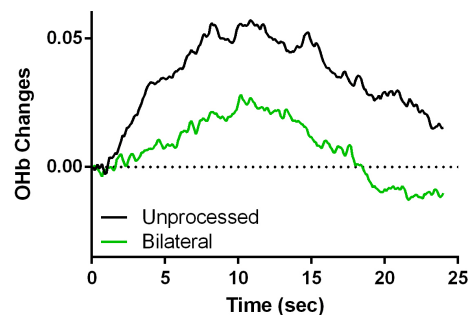
Figure 2.3: Individual's single channel response to unprocessed speech in both ears and a bilateral CI simulation.
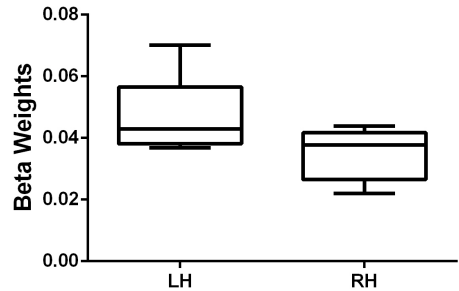
Figure 2.4: Beta coefficients (weights) averaged across five channels for the difference in activation between the unprocessed speech and bilateral CI simulation conditions (Unpr > Bi CI). LH = left hemisphere, RH = right hemisphere. Both were significantly greater than 0 at $p < 0.05$.

fNIRS responses were also collected in three listening configurations in three adults with bilateral CIs: left ear, right ear, and both ears. The five channels with the strongest activation to sound were used to compare beta weights across listening configurations. One adult with bilateral CIs had artifact in nearly all channels in all configurations for unknown reasons and was thus excluded. The results for the other two participants are shown in Figure 2.5.
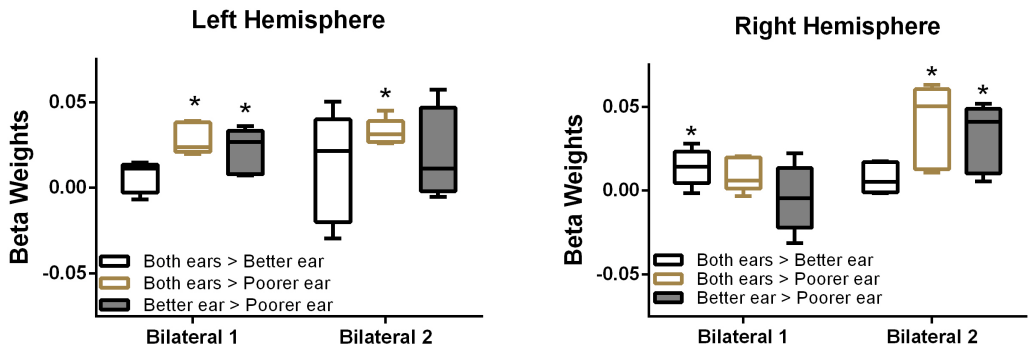
Figure 2.5: Beta coefficients (weights) averaged across five channels for each bilateral CI participant for three contrasts. The left hemisphere is on the left and the right hemisphere in the graph on the right. * $p < 0.05$.

Significant differences between listening configurations were found in the beta coefficients for HbO changes in each of the three participants ($p<0.05$). In short, the listening condition with greatest performance (bilateral CIs) resulted in significantly greater activation in the left hemisphere than that of the poorer ear alone (worst listening condition) in the two

bilateral CI participants. It is possible that this increase in activation in the bilateral CI condition is due to the increase in speech recognition performance. It is impossible, however, to rule out the effects of changes in loudness perception and binaural summation/integration on the results. Thus, further research is needed to isolate the effect of speech recognition performance.

In summary, preliminary results suggest that fNIRS can detect changes in auditory cortical activation with changes in stimulus type (unprocessed > vocoded speech) and unilateral and bilateral conditions with different speech recognition performances. Although these preliminary results are encouraging, they are difficult to interpret due to confounding variables. The variables of presentation condition (unilateral or bilateral) and stimulus level or perceived loudness, among others, could have influenced the preliminary results. Thus a controlled study of these variables using fNIRS is needed.

Additionally, a controlled comparison of the effect of these variables in individuals with NH and individuals with CIs matched for performance is needed to determine any effects of deafness and CI stimulation. Many previous studies that examined speech recognition performance effects on cortical activation in listeners with NH, however, have used CI simulations. Presenting CI simulated (vocoded) speech to individuals with CIs is not ecologically valid. Thus, a different method of speech recognition performance adjustment is needed to better compare the two hearing groups.

Auditory signal to noise ratio (SNR) can be used to adjust and match speech recognition performance in both individuals with CIs and individuals with NH. Two studies used SNR to examine the effects of speech recognition performance on cortical activation. Similar to work with CI simulations (vocoders), left anterior STG activation was found to increase with increasing i) speech recognition performance or ii) SNR using PET imaging (Sophie K. Scott,

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Rosen, Wickham, & Wise, 2004). They also found that left posterior STG activation (Wernicke's area) was greater for speech then SCN. Another group that used fMRI found that the level of activation in bilateral STG and STS changes with SNR even in the absence of speech recognition changes (Wong, Uppunda, Parrish, & Dhar, 2008). They also found that activation in the left posterior STG was greater at a poorer SNR and suggested it might be due to increased effort for speech understanding. Thus, the individual effects of SNR and speech recognition performance need to be accounted for separately. Thus, this study investigated the effect of speech recognition performance and SNR independently using intelligible and unintelligible stimuli.

Aims and hypotheses

The aims of this dissertation were to determine:

1) the effect of speech level on auditory cortical activation and

2) the effect of speech recognition performance using changes in SNR on auditory cortical activation.

We tested the following hypotheses:

1) auditory cortical activation (STG/STS) would increase with increasing level and

2) auditory cortical activation (anterior STG/STS and posterior STG/STS or Wernicke's area) would increase with increasing speech recognition performance. An alternative hypothesis, based on Wong and colleagues, was that posterior STG/STS activity would increase with decreasing SNR (decreasing speech recognition performance) due to the increased effort expended for speech recognition in noise (Wong et al., 2008).

The effect of stimulus level on fNIRS responses will be discussed in Experiment I, and presented in Chapter III. The effect of speech recognition performance will be discussed in

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Experiment II and presented in Chapter IV. A general discussion will be presented in Chapter V

and conclusion and future directions in chapter VI.

CHAPTER III

EXPERIMENT I: STIMULUS LEVEL

Introduction

Research has shown that auditory cortical activity increases linearly with increasing stimulus level as mentioned in Chapter II. Research in individuals with CIs using fNIRS might contain stimuli of different levels or perceived loudness. For example, unilateral and bilateral stimuli might be compared to determine the benefit of a second ear or a single ear might be tested with and without residual acoustic hearing. Additionally, changes in activation with level might be used as a loudness growth measure in young children. Thus, the first experiment of this dissertation was to examine the effect of stimulus level on cortical activation using fNIRS.

Because fNIRS is relatively new to the field of auditory research, no previous study has examined the effect of stimulus level on auditory cortical activation using fNIRS in NH individuals. Thus, this experiment included a group of adults with CIs and a group of age matched NH adults. Loudness growth is known to vary between NH and hearing impaired groups (Hellman & Meiselman, 1993). Further it is likely that individuals with CIs who are known to have an extremely limited dynamic range coupled with amplitude compression imposed by the sound processor(s), may not exhibit the expected level-dependent increases in cortical activation with increasing stimulus level. Perceived loudness can also vary between unilateral and bilateral stimulus presentation conditions. Therefore, the adults with CIs were required to have bilateral CIs with equivalent compression across processors to ensure fairly equal loudness between the ears.

Studies of the effect of stimulus level on cortical activation have included vastly different levels of presentation. Because this dissertation is focused on the potential of fNIRS for speech

perception applications in individuals with CIs, the levels in this experiment were based on speech. Specifically, four levels between soft (45 dBA) and loud (75 dBA) speech were used (Olsen, 1998). Additionally, the stimulus for the experiment was designed to be speech-like, similar temporal characteristics, with no intelligibility.

Pilot results using the exact paradigm described below suggested that fNIRS could detect the effect of stimulus level on auditory cortical activation as described in Chapter II. The increases in strength of activation with stimulus level were seen in the STG and STS, particularly the anterior portion in all three pilot participants. The following sections describe the methods and results for Experiment 1 and compare those to the literature.

Methods

Participants

Twenty-nine adults (16 with NH and 13 with bilateral CIs) participated in this study. See the *Power Analysis* section in Chapter IV for justification on sample sizes. The bilateral CI group had no usable residual acoustic hearing, defined as no air-conduction thresholds better than 85 dB HL between 125-8000 Hz in either ear. They made full-time use of both CIs and had at least six-months experience with each CI. CI participants were recruited through the Vanderbilt Bill Wilkerson Center in the Vanderbilt University Medical Center. The NH participants had pure-tone thresholds ≤ 20 dB HL at audiometric frequencies between 250-6000 Hz. They also had no history of ear surgeries. The NH group (40-64 years, mean = 50.1) was matched for average age to the bilateral-CI group (23-67 years, mean = 49.1). A two-sample t-test revealed no significant difference in age between the two groups (p>0.79). The NH group was dominated by female participants (14 female, 2 male) while the CI group was balanced for gender (7 female, 6 male).

Female participants likely dominated the NH group due to the fact that hearing loss is more prevalent in males in that age range (Agrawal, Platz, & Niparko, 2008).

The demographic and device information of the participants with CIs is shown in Table 3.1. Eleven of the participants had a postlingual onset of deafness and two had a prelingual onset of deafness. CI10 had a progressive loss from birth using listening and spoken language to communicate. She received her first CI as an adult. CI11 had a bilateral profound hearing loss at birth and was implanted at age two. She received her second implant as an adult and has always used listening and spoken language to communicate.

CI Participant	Age	Gender	CI Man	Processors	Months of CI use 1st/2nd	Deafness onset
1	44	Female	Cochlear	Bi CP910	Bi 6	Postlingual
2	55	Male	Cochlear	Bi CP810	L 85, R 47	Postlingual
3	48	Male	Cochlear	L Freedom, R CP810	L 193, R 82	Postlingual
4	40	Male	Cochlear	Bi CP810	Bi 82	Postlingual
5	52	Female	AB	Bi Naida Q70	L 192, R 91	Postlingual
6	62	Female	Cochlear	L CP810, R Freedom	L 34, R 76	Postlingual
7	67	Male	MED-EL	Bi Rondo	L 8, R 25	Postlingual
8	59	Female	Cochlear	Bi CP810	L 132, R 68	Postlingual
9	66	Female	MED-EL	Bi Opus 2	L 6, R 19	Postlingual
10	34	Female	MED-EL	Bi Sonnet	L 109, R 117	Prelingual
11	23	Female	Cochlear	R Freedom, L CP810	L 40, R 252	Prelingual
12	54	Male	MED-EL	Opus 2	L 139, R 33	Postlingual
13	34	Male	AB	Bi Harmony	Bi 145	Postlingual
Mean	**49.1**				**L 90.1, R 80.2**	
SD	**13.5**				**L 67.8, R 65.2**	

Table 3.1: Demographic and clinical data for the CI participants. CI Man = CI manufacturer.

Not surprisingly, the CI group had poorer hearing sensitivity than the NH group. Mean audiograms are shown in Figure 3.1. Despite the difference in hearing sensitivity between the groups, both groups had essentially symmetrical hearing between the ears. Thus, audibility was matched between ears for all testing, limiting laterality effects. The average monosyllabic word recognition was also matched between ears for the CI group as shown in Figure 4.4 in Chapter IV. It should be noted however, that some individual CI participants had differences in speech recognition between the two ears. The average difference in word recognition between the ears

was 22.3-percentage points (SD = 27.3) with seven participants demonstrating differences less than 10-percentage points, four participants with moderate differences between 14- and 34-percentage points, and two with extreme differences in performance between the ears (CI2 = 64 and CI11 = 92).

Figure 3.1: Pure-tone and warble tone thresholds for NH and CI participants, respectively. RE = right ear, LE = left ear, NH = normal hearing, CI = cochlear implant. Error bars represent SD.

Procedures

The procedures for the NH and CI groups were exactly the same except when noted.

Stimuli: Because speech recognition performance increases with increasing presentation level, particularly in individuals with CIs (Skinner et al., 1997), special care was taken to design stimuli to separate stimulus level from speech recognition performance. Thus, SCN was used. SCN was chosen because it can be constructed to have the same average spectral content and amplitude modulations as corresponding speech stimuli. A matched SCN stimulus was created for four female-spoken AzBio sentences using a speech-shaped noise with a spectrum matching

the average of the 330 female spoken AzBio sentences and the envelope modulations of the matched sentences. The overall amplitude envelope modulations were multiplied by the speech shaped noise to create one-channel SCN stimuli (Festen & Plomp, 1990; N. Stoppelman, Harpaz, & Ben-Shachar, 2013). The female-spoken AzBio sentences were used for consistency with Experiment 2.

Presentation: Stimuli for Experiment 1 were presented from a personal computer through a GSI 61 audiometer to an external speaker. The speaker was placed at 0° azimuth at head height. Calibration of stimuli was completed using a Larson-Davis LxT sound level meter with a half-inch microphone using the substitution method of calibration (microphone placed at the approximate head position of the participant). All testing was completed with both CI processors set to the participants' daily listening program and volume and sensitivity settings. All testing for the NH group was completed with both ears. Listeners were instructed not to vary volume nor sensitivity settings during testing.

Behavioral Procedures: Loudness judgments of the level stimuli were also obtained using E-prime software separate from the fNIRS testing. Participants rated the perceived loudness of stimuli using the loudness discomfort level (LDL) scale (Cox, Alexander, Taylor, & Gray, 1997). The LDL scale is shown in Figure 3.2. Loudness judgments were obtained for two reasons. First, loudness perception has been shown to differ between individuals with NH and individuals with hearing loss (Hellman & Meiselman, 1993). Second, auditory cortical activity is more strongly correlated with loudness ratings than sound intensity (Langers et al., 2007). Thus, if loudness judgments and growth for the stimuli differ between the groups we might expect the effect of stimulus level on auditory cortical activation to differ between the groups.

Loudness Categories

7. Uncomfortably loud

6. Loud, but o.k.

5. Comfortable, but slightly loud

4. Comfortable

3. Comfortable, but slightly soft

2. Soft

1. Very soft

Figure 3.2: Loudness discomfort scale the participants used to rate the loudness of the stimuli.

fNIRS Procedures: The purpose of Experiment I was to examine stimulus level effects on fNIRS responses in the auditory cortex. As previously mentioned, speech recognition is affected by stimulus level in individuals with CIs. Therefore, to examine level effects separate from speech recognition performance, SCN stimuli were presented at four different levels (45, 55, 65, and 75 dB A) in an event-related paradigm. The levels were chosen to be equidistant between soft and loud speech (Olsen, 1998). The design was optimized for maximum power and limited predictability of stimulus timing (Liu, 2004). Stimulus trials were three seconds long with 20 trials of each level and 20 trials of quiet for a total of 300 seconds per run. A sample run is shown in Figure 3.3. Each participant completed four runs with varied stimulus order.
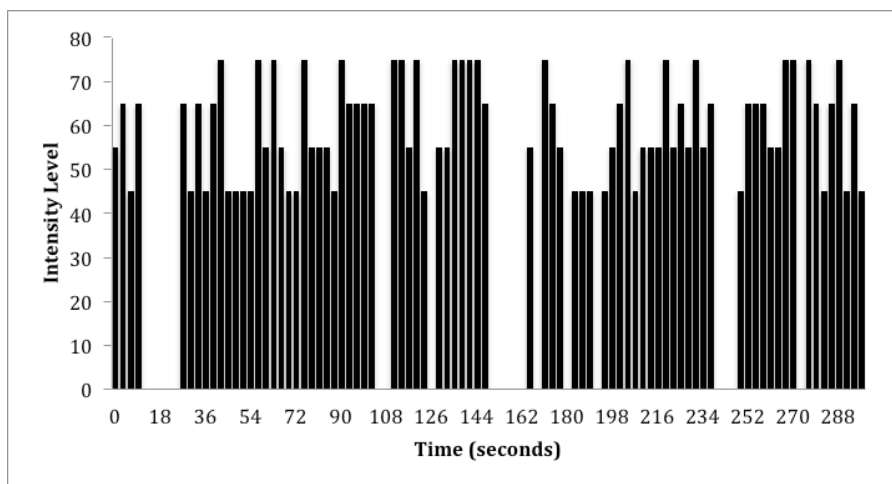
Figure 3.3: Example stimulus order and timing for an individual run.

Participants sat in a comfortable chair with optodes placed as described below. Participants were asked to sit quietly and attend to the stimuli. No active task was performed to limit somatosensory.

fNIRS acquisition: fNIRS measurements were conducted with the ETG-4000 Optical Topography System using a 22-channel optode array covering the left fronto-temporal areas of the head, to best measure auditory cortical activation (12x6 cm; inter-optode Distance = 30 mm, sampling rate = 10 Hz). Optode #14, the center of the array, was centered over C5 of the 10-20 system in an attempt to cover Broca's and Wernicke's areas as well as the left STG/STS with the entire array. A figure showing the approximate location of recording channels on an average structural MRI is shown in Figure 3.4. The spatial registration details are included in the fNIRS analysis section below. We removed optodes, as needed to accommodate the presence of the CI coil and cable but attempted to match probe placement across all participants.
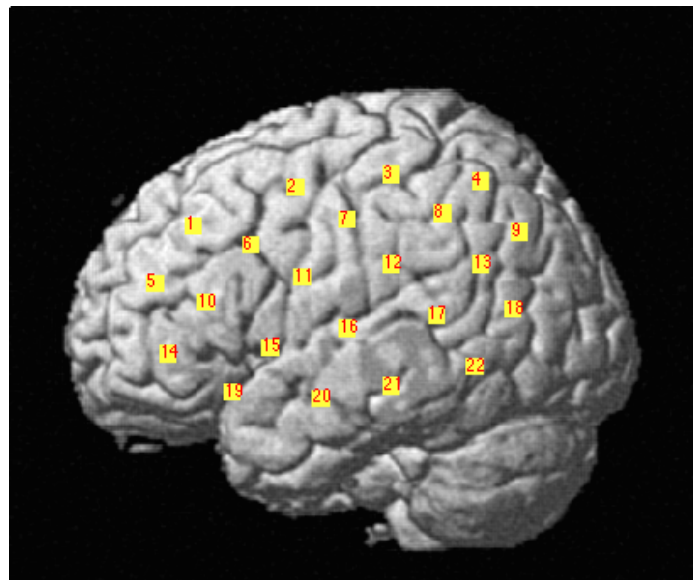
Figure 3.4: Representation of the location of each fNIRS channel displayed on a representative structural MRI. These locations are based on average 10-20 system locations being spatially registered to MNI coordinates.

fNIRS analysis: Data were analyzed in NIRS-SPM (Ye, Tak, Jang, Jung, & Jang, 2009), an SPM5 (http://www.fil.ion.ucl.ac.uk/spm/) and MATLAB (The MathWorks, Inc) -based

software for the analysis of fNIRS data. Both HbO and HbR data were analyzed, as studies have found differences in their sensitivity to activation (Hoshi et al., 2001; Pollonini et al., 2014; Sevy et al., 2010). Data were converted from comma-separated values to MATLAB files using NIRS-SPM.

A. Preprocessing: The channels were then analyzed and transformed according to their wavelength and location using the Beer-Lambert equation. Data were motion corrected with the wavelet analysis function included in the Homer2 fNIRS processing package: hmrMotionCorrect_Wavelet (Molavi & Dumont, 2012). Following the wavelet analysis no low-pass filtering was used but a high-pass filter with a cutoff frequency of 0.005 Hz was used for detrending.

B. Spatial Registration: Targeted placement of the fNIRS optodes were F7, F5, FC5, F3, FC3, FT7, T7, C5, C3, TP7, CP5, CP3, P7, P5, and P3 on the 10-20 system. fNIRS optodes and points were spatially registered in NIRS-SPM using the MNI data for these points collected by Okatomo's group in 2004 (Okamoto et al., 2004). It is important to not that there is considerable variability in the positioning of optodes relative to the cortex. As such, it is important to get an idea of how variable optode positions might be relative to the brain locations of interest. Specifically, different individuals may have very different head shapes and sizes, resulting in varying MNI coordinates for a given 10-20 point. Additionally, although we centered an optode array about one particular 10-20 point, the positions of individual optodes in the array may not have corresponded exactly to the 10-20 system positions. Optodes are 3 cm apart on the arrays provided for the Hitachi ETG 4000. Considering the curvature of the head, we predicted the optodes were 2.5 cm apart when placed on the scalp. In Figure 3.5 we mapped MNI data

corresponding to some of our 10-20 system locations of interest from 17 different subjects (Okatomo et al, 2004).
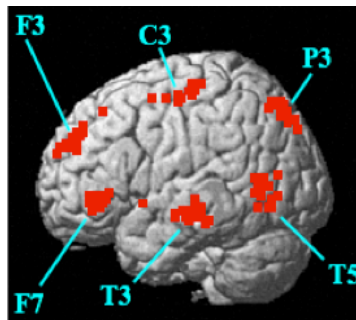
Figure 3.5: The red squares represent 17 different participant's 10-20 system locations in MNI coordinates on a representative structural MRI.

C. Artifact management: Only one (#5) of the 13 participants with CIs had a coil that did not interfere with the optode array. It was posterior and inferior to the array. The other 12 participants had coils in the posterior inferior portion of the array, interfering with the channels measuring the posterior STS and STG as well as inferior Wernicke's area. The specific channels that were affected based on visually examining the placement of the coils relative to the array were channels 9, 13, 18, and 22. These channels were confirmed to have poor skin contact by the ETG-4000 system's channel integrity check as well as visual examination of the HbO and HbR responses over time.

A measure of signal integrity used by Pollonini et al. (2014) was used. This measure calculates a scalp-coupling index (SCI) based on the correlation of the cardiac signal of the two light sources for each recording channel. They suggested a criterion of 0.75 for a sufficient SCI. They removed any channels with a SCI below 0.75 from their analysis. There is no good method for removing individual channels from the analysis in NIRS-SPM. Rather than remove the participants or runs from analyses, the channels with poor skin contact were interpolated using the data from all adjacent channels. We used a criterion of more than six channels with poor

SCIs, outside of the coil-affected channels (which was a maximum of three channels), to remove an individual run from the analysis.

These criteria resulted in two CI participants (CI1 and CI2) and two NH participants (NH3 and NH14) being removed from the analysis. Thus, the fNIRS analysis included 11 CI participants and 14 NH participants. Examples of the SCI values for an excluded participant and a retained participant are shown in Figure 3.6. A time series plot of the HbO data of a channel with good contact and a channel with poor contact due to the CI coil are also shown in Figure 3.7. Note the scales of the y-axes in the time series figures. The channel with poor contact has gross artifact through the entire run.
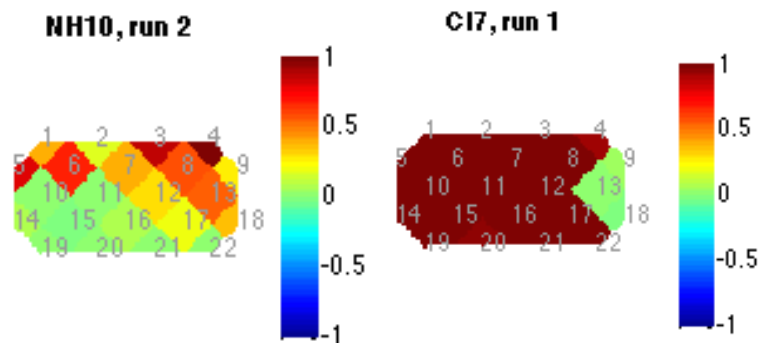
Figure 3.6: Scalp coupling index for two participants, NH10 and CI7 for each channel. NH10 had viriually all bad contact channels while CI7 had all good contact channels > 0.75 except for 9,13, and 18 which were affected by the CI coil. The color scale represent the scalp coupling index with dark red values near 1.0 indicating good scalp contact.
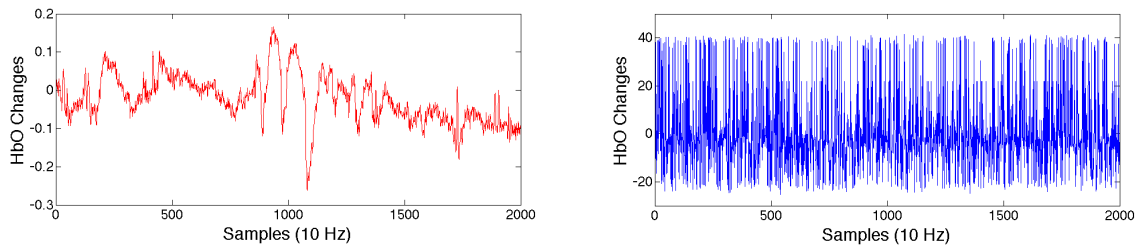
Figure 3.7: Time series data for HbO changes over the first 20 seconds of a run in CI2. The left panel displays a channel with good contact and the right with poor contact due to a CI coil.

D. fNIRS Analysis: Analysis of fNIRS data collected in Experiment I included the *dependent variables of* HbO and HbR in each recording channel. The *independent variable* was stimulus level. A general linear model was created based on predicted hemodynamic responses

that did not include time or dispersion derivatives. The recorded data in each channel was then correlated with the general linear models predicted responses. This produced beta coefficients for each stimulus condition, parameter, which can be multiplied by contrasts to produce statistical comparisons. An example of a design matrix is shown in Figure 3.8. Silence events the same length as the stimuli were used as an explicit baseline. The same predicted response was used for all parameters including silence. The design matrix is for HbO and the shading of gray to white indicate a positive response or increase in HbO for that parameter. A design matrix for HbR would show the reverse with dark shading indicating a decrease in HbR for that parameter. A multiple regression contrast to test where increases in HbO are greater for a 75-dB signal than a 45-dB signal while ignoring other parameters would be [0 -1 0 0 1 0][1]. These contrast values were multiplied by the beta coefficients to produce statistical maps.
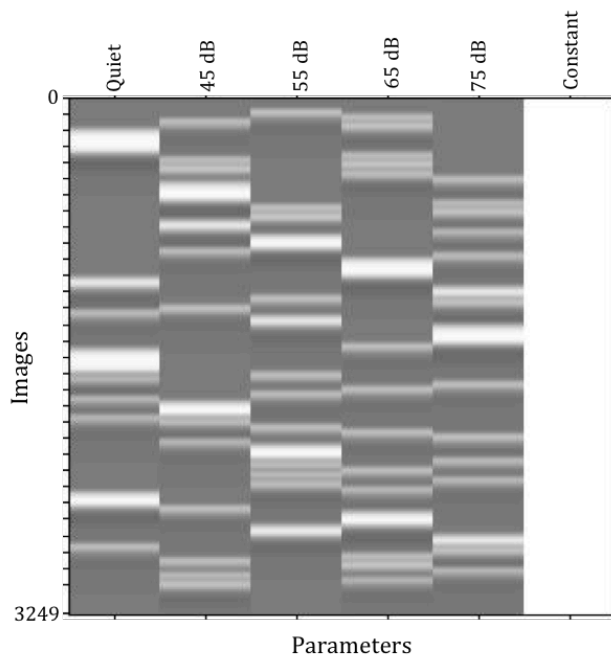
Figure 3.8: Example general linear model figure for a single run. The lighter areas represent predicted changes in HbO based on the timing of each stimulus. The same response is predicted for all conditions, including quiet/silence, to compare conditions with contrasts.

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[1] Multiple regression matrix for contrast coding with 1 and -1 for independent variables 75

The multiple regression contrasts used were for the main effects of sound > silence and the linear effect of level: $[-1\ .25\ .25\ .25\ .25\ 0]^2$ and $[0\ -.75\ -.25\ .25\ .75\ 0]^3$ for the parameter order of [Quiet 45dB 55dB 65dB 75dB Constant], respectively. The results were qualitatively compared across groups to determine any difference between participants with CIs and participants with NH. The sound > silence contrast was also performed on all participants to determine the channels with significant activation in the entire group. The hemodynamic responses to each stimulus level in these channels were then compared between the CI and NH groups using an analysis of variance (ANOVA). Specifically, a mixed ANOVA with hearing group as the between groups factor and fNIRS channel as the repeated-measure factor was completed. The same ANOVA was completed for the channels with activation for the linear effect of stimulus level contrast. All of these analyses were completed for both HbO and HbR. A threshold of $p < 0.05$, uncorrected for multiple comparisons, was used for all statistical comparisons to maximum power because this is innovative pilot work to direct future studies.

Results

Behavioral Results

Subjective loudness judgment results are shown in Figure 3.9. As expected, loudness judgments increased with stimulus level. Both the CI and NH groups used almost the entire range of the LDL scale for the 45-75 dBA stimuli. Overall results were fairly similar between the groups, particularly at 45 and 75 dBA. The CI group, however, rated the 55 and 65 dBA stimuli as slightly louder than the NH group. Statistical analyses confirmed that the CI group rated the 55 and 65 dB A SCN stimuli as louder than the NH group did ($t = 3.372$, $p < 0.006$; $t = 2.77$, $p <$

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[2] Multiple regression matrix using contrast coding (summing to 1 and -1) for the average of all stimulus levels compared to the explicit silent baseline.

[3] Multiple regression matrix using contrast coding (summing to 1 and -1) for the linear effect of stimulus level excluding the silent baseline.

0.017; respectively). The overall trend in both groups, however, was a fairly linear increase in perceived loudness with level. Thus, we concluded that use of a linear contrast would account for both loudness and stimulus level effects in the fNIRS data and preliminary analyses confirmed this.
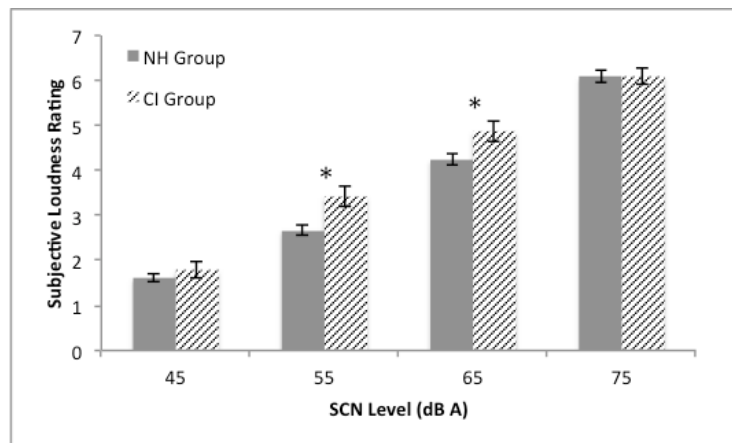
Figure 3.9: Average perceived loudness ratings for each group on the LDL scale with a maximum of seven and a minimum of one. Asterisks indicate a significant difference between the groups.

fNIRS results

The fNIRS data were analyzed for all participants together as well as for the NH and CI groups separately. First, we will describe the results for the sound > silence contrast. There was considerable variability in all contrasts across participants making it difficult to interpret individual data. As an example, Figure 3.10 shows the sound > silence contrast for HbR in all NH participants and Figure 3.11 shows the same in all CI participants. The topographical maps are t-statistic maps with a threshold of $p < 0.001$, uncorrected for multiple comparisons. Note that each individual participant has a different scale. Because of the large variability in t-value ranges, standardizing the scales made it difficult to visualize differences between individuals.

Note that all participants in both groups had at least one area of positive activation to sound and all but one participant (NH23) had at least one area of negative activation to sound.

Thus, no participants were excluded from analyses due to lack of a measured response to sound.

Because the large degree of variability across the participants makes it difficult to interpret

individual data, only group data will be presented in the remainder of the chapter.
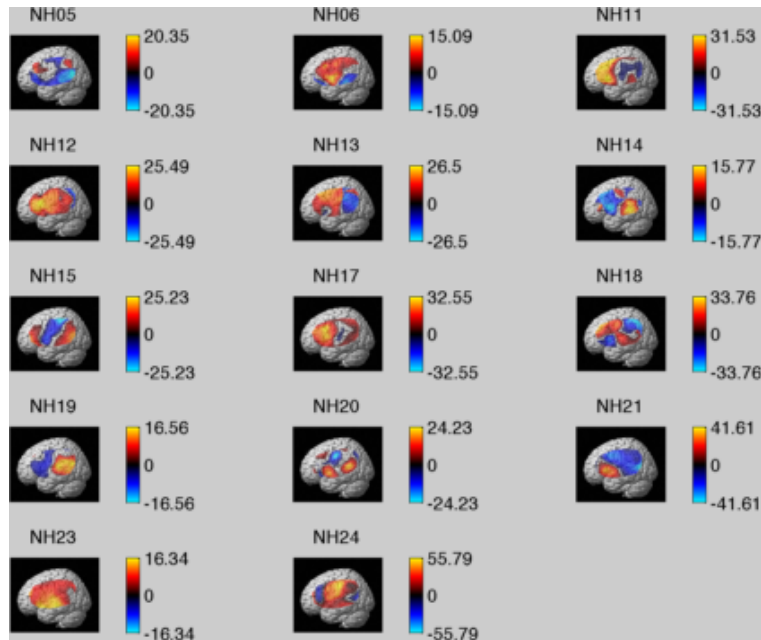
Figure 3.10: Individual t-statistical maps for the sound > silence contrast with a threshold of p < 0.001 for HbR in all included NH participants. The color maps represent t-values. A large t-value indicates greater activation for sound than the silent baseline.
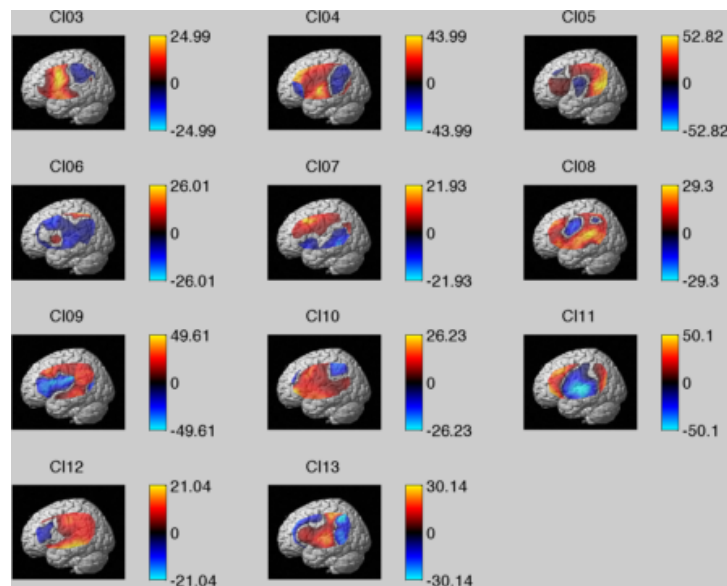
Figure 3.11: Individual t-statistical maps for the sound > silence contrast with a threshold of p < 0.001 for HbR in all included CI participants. The color maps represent t-values. A large t-value indicates greater activation for sound than the silent baseline.

Figure 3.12 shows group t-statistic maps for the sound > silence contrast in all participants, as well as in the NH and CI groups. Examination of the maps shows a positive area of activation in the anterior portion of the array in both groups as well as a posterior superior area of positive activation in only the NH group. The NH group seems to have a separate more posterior area of activation not seen in the CI group.

Figure 3.13 further demonstrates this qualitative difference between the groups. It shows significant areas of activation with a threshold of $p < 0.05$, uncorrected for multiple comparisons. The activation map for all participants shows two areas of significant activation in the anterior superior and inferior portions of the array. The NH and CI group's areas of significant activation are also represented on the map of activation in all participants as translucent green and purple shading, respectively. Both of these areas are also significant in the NH group but only the anterior superior area is significant in the CI group. The NH group also shows a significant area of activation in the posterior region mentioned above, which is not present in the CI group.
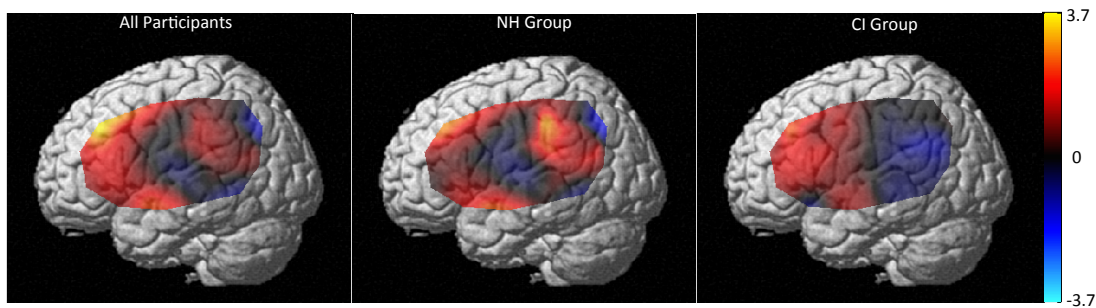
Figure 3.12: HbO t-statistical maps for the sound > silence contrast. The color map represents t-value with a high t-value (yellow) indicating greater activation to sound.
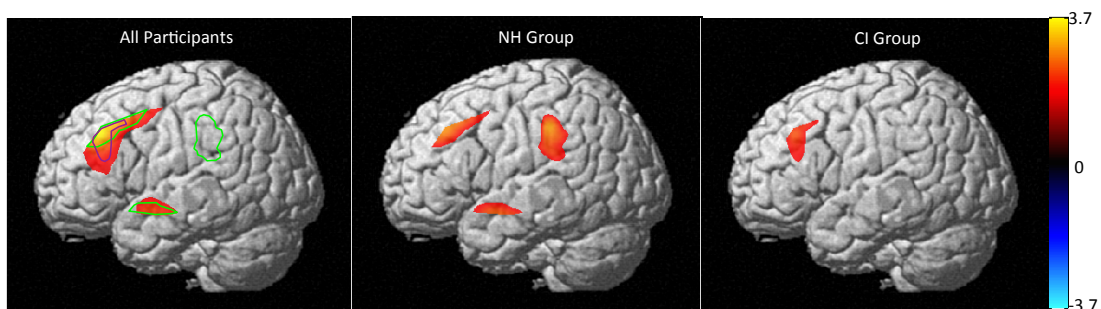
Figure 3.13: HbO t-statistical maps for the sound > silence contrast with a threshold of p < 0.05, uncorrected for multiple comparisons. The color map represents t-value with a high t-value (yellow) indicating greater activation to sound. The NH and CI group areas of activation are outlined in green and purple on the map for all participants, respectively.

The same contrast was completed with HbR and the t-statistic maps are shown in Figure 3.14. Both groups show a large area of positive activation that is represented in the map for all participants as well. The NH group appears to have stronger overall activation compared to the CI group. That difference is demonstrated again in the activation t-threshold maps in Figure 3.15. In Figure 3.15 the NH group appears to have a much larger area of significant activation, although the areas overlap as seen in the map for all participants.
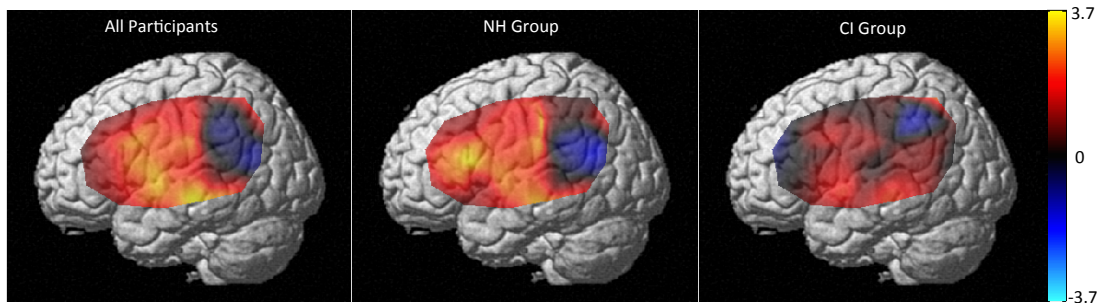
Figure 3.14: HbR t-statistical maps for the sound > silence contrast. The color map represents t-value with a high t-value (yellow) indicating greater activation to sound.
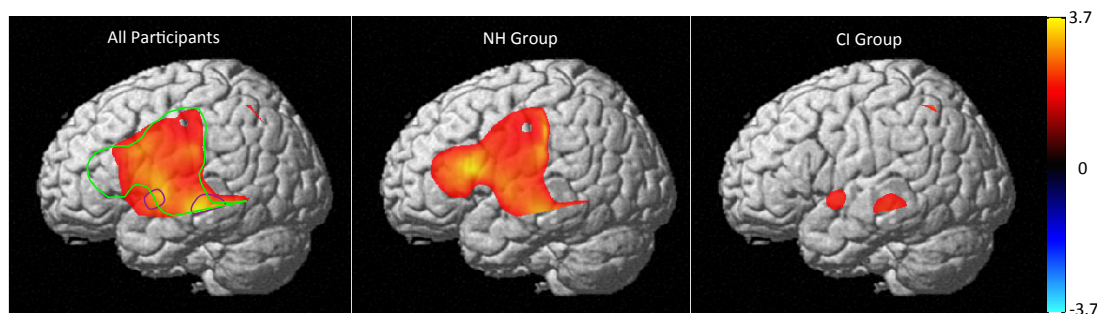
Figure 3.15: HbR t-statistical maps for the sound > silence contrast with a threshold of p < 0.05, uncorrected for multiple comparisons. The color map represents t-value with a high t-value (yellow) indicating greater activation to sound. The NH and CI group areas of activation are outlined in green and purple on the map for all participants, respectively.

When comparing the HbO and HbR results, both the maps of all participants show significant activation in the anterior half of the array, although in different anatomical areas (channels). There were only two channels (6 and 20) that showed significant changes in both

HbR and HbO for the sound > silence contrast. There were, however, some other adjacent

channels that were active in HbR and HbO such as channels 10 and 11.

To examine differences in activation to sound between the groups, two mixed ANOVAs

were completed for the sound > silence contrast beta coefficients, one for each of the hemoglobin

types including all the significantly active channels with all participants included. The two types

of hemoglobin were examined separately because the channels with significant activation were

different for each type. The beta coefficients for the contrast are in Tables 3.2 and 3.3 for HbO

and HbR, respectively. The tables include average beta coefficients for each group as well as the

average of all participants. For the ANOVAs, regions of interest were created based on the

significantly active channels when including all participants. The average beta coefficients for

each stimulus level in those regions of interests (HbO = 1, 2, 5, 6, 10, and 20; HbR = 6, 7, 11, 15,

16, 20, 21, and 22) for each hearing group are shown in Figures 3.16 and 3.17 for HbO and HbR,

respectively. The between-groups factor was hearing group (NH vs. CI) and the within-subjects

factor was fNIRS recording channel.

Group & Contrast	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11
All Sound > Silence	0.77*	0.74*	0.19	-0.06	0.51*	0.45*	0.03	0.09	-0.44	0.83*	-0.02
NH Sound > Silence	0.95*	0.94	0.38	-0.13	0.45	0.47	-0.02	0.19	-0.89	0.31	-0.31
CI Sound > Silence	0.54*	0.48	-0.03	0.02	0.60	0.41	0.10	-0.03	0.05	1.46	0.37
All Linear Level	0.22	-0.11	-0.19	-0.42	0.48	0.04	0.01	0.11	-0.15	0.69	0.10
NH Linear Level	0.07	-0.35	-0.76*	-1.09*	0.13	-0.23	-0.45	-0.15	-0.50	0.14	-0.19
CI Linear Level	0.41	0.21	0.49	0.40	0.97	0.43	0.60	0.45	0.24	1.36	0.50
Group & Contrast	CH12	CH13	CH14	CH15	CH16	CH17	CH18	CH19	CH20	CH21	CH22
All Sound > Silence	0.34	0.17	0.60	0.41	-0.18	0.16	0.22	0.41	1.09*	-0.04	-0.39
NH Sound > Silence	0.90*	0.64	0.09	0.44	-0.39	0.45	0.45	1.05	1.11*	0.09	-0.53
CI Sound > Silence	-0.17	-0.43	1.25	0.37	0.08	-0.21	-0.23	-0.42	1.06	-0.21	-0.16
All Linear Level	0.19	-0.06	-0.34	0.03	-0.08	-0.53	0.12	-0.25	-0.28	-0.41	-0.78
NH Linear Level	0.46	-0.22	-0.18	0.58	-0.15	-0.76	0.31	-0.14	0.11	-0.51	-1.00
CI Linear Level	-0.05	0.15	-0.55	-0.67	-0.00	-0.24	-0.27	-0.40	-0.79	-0.27	-0.45

Table 3.2: Average HbO beta coefficients for the sound > silence and linear level effect contrasts
for each group as well as all participants combined. * = p < 0.05, uncorrected for multiple
comparisons.

Group & Contrast	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11
All Sound > Silence	0.27	0.30	0.18	0.28	0.06	0.51*	0.56*	-0.07	0.26	0.44	0.80*
NH Sound > Silence	0.54	0.51	0.17	0.03	0.31	0.51	0.91	0.09	0.35	0.77*	1.07
CI Sound > Silence	-0.09	0.01	0.19	0.60*	-0.30	0.51	0.10	-0.28	0.16	0.03	0.43
All Linear Level	-0.32	-0.17	0.07	0.10	-0.50	-0.24	0.00	-0.01	0.04	-0.59	-0.10
NH Linear Level	-0.32	-0.18	0.27	0.13	-0.03	-0.34	0.35	-0.08	0.25	-0.35	0.10
CI Linear Level	-0.33	-0.15	-0.16	0.05	-1.15	-0.10	-0.46	0.09	-0.19	-0.88	-0.37
Contrast	CH12	CH13	CH14	CH15	CH16	CH17	CH18	CH19	CH20	CH21	CH22
All Sound > Silence	0.10	-0.10	0.21	0.61*	0.61*	0.03	-0.23	0.26	0.58*	0.53*	0.39*
NH Sound > Silence	0.18	-0.32	0.43	0.44	1.03*	-0.15	-0.33	0.13	0.56	0.48*	0.46
CI Sound > Silence	0.03	0.19	-0.06	0.82	0.08	0.25	-0.03	0.42	*0.61	0.59	0.28
All Linear Level	-0.00	0.18	0.13	-0.21	0.21	0.57*	-0.42	-0.51	0.18	0.46*	0.30
NH Linear Level	-0.19	0.23	0.13	-0.43	0.24	0.66	-0.54	-0.24	0.13	0.69*	0.50
CI Linear Level	0.17	0.11	0.14	0.07	0.16	0.46	-0.19	-0.86	0.23	0.17	-0.01

Table 3.3: Average HbR beta coefficients for the sound > silence and linear level effect contrasts for each group as well as all participants combined. * = p < 0.05, uncorrected for multiple comparisons.
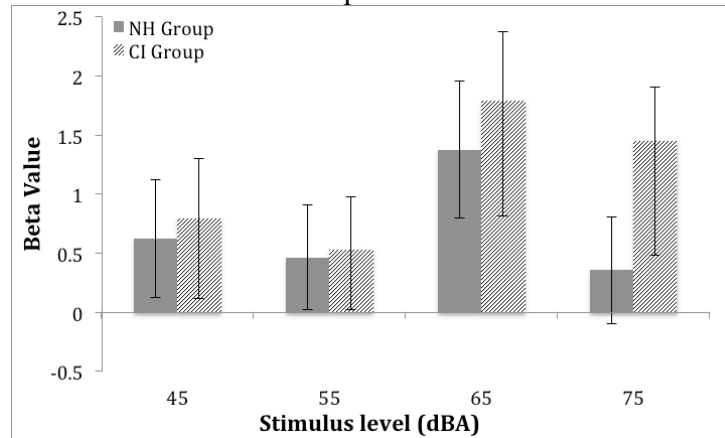
Figure 3.16: Average HbO beta coefficients for the sound > silence contrast for fNIRS channels 1, 2, 5, 6, 10, and 20. This ROI includes sound activated channels with all participants included in the analysis. Error bars represent ±1 standard error of the mean (SEM).
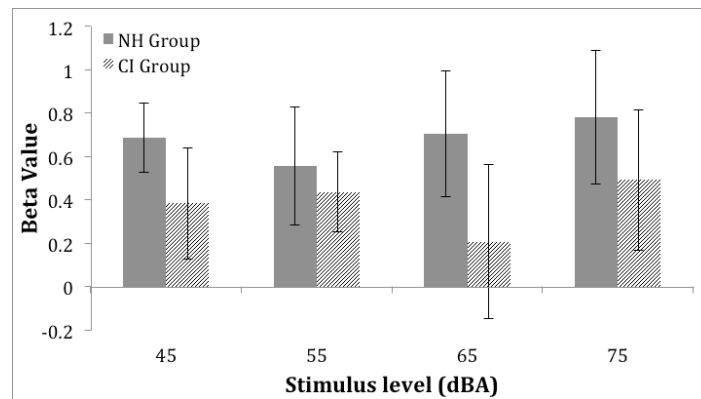
Figure 3.17: Average HbR beta coefficients for the sound > silence contrast for fNIRS channels 6, 7, 11, 15, 16, 20, 21, and 22. This ROI includes sound activated channels with all participants included in the analysis. Error bars represent ±1 SEM.

The first two ANOVAs included hearing group as the between-subjects factor (NH vs. CI) and fNIRS channel as the within-subjects factor. The results for HbO revealed no significant effects for hearing group, fNIRS channel, or an interaction (all p values > 0.2). The results for HbR also revealed no significant effects of hearing group, fNIRS channel, or an interaction. The interaction was only near significant [$F(1,1) = 3.28$, $p < 0.072$], but provides some statistical support to the apparent visual difference in area of activation: the CI group has a smaller area of significant activation overlapping the inferior area of activation in the NH group.

After determining that there was a significant response to stimuli in reference to quiet, the second and more relevant contrast for the linear effect of stimulus level was examined. The t-statistic and significant activation maps for HbO are shown below in Figures 3.18 and 3.19, respectively. There is no activation map for the CI group because there were no areas of significant activation for this contrast. Both groups show a positive linear effect of level in red spanning from the posterior portion of the array to the anterior. This area of positive linear level effect appears more superior in the CI group, however. Additionally, the NH group also shows a couple of areas with a strong negative linear level effect (blue) that are not present, at least to the same degree, in the CI group. These areas are significant as shown in Figure 3.19.
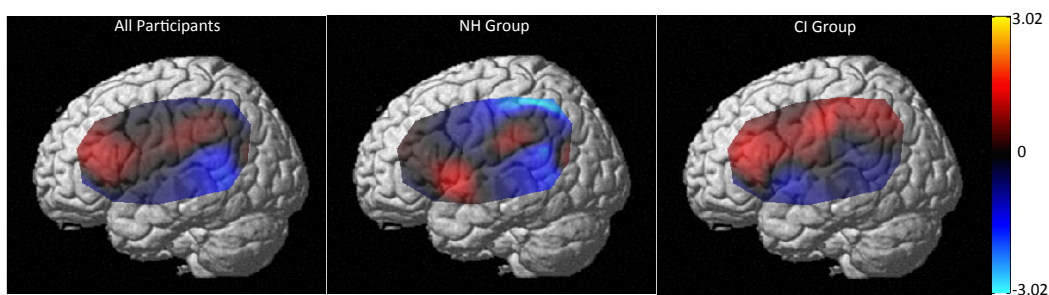
Figure 3.18: HbO t-statistical maps for the linear stimulus level contrast. The color map represents t-value with a high t-value (yellow) indicating greater activation for higher-level stimuli.
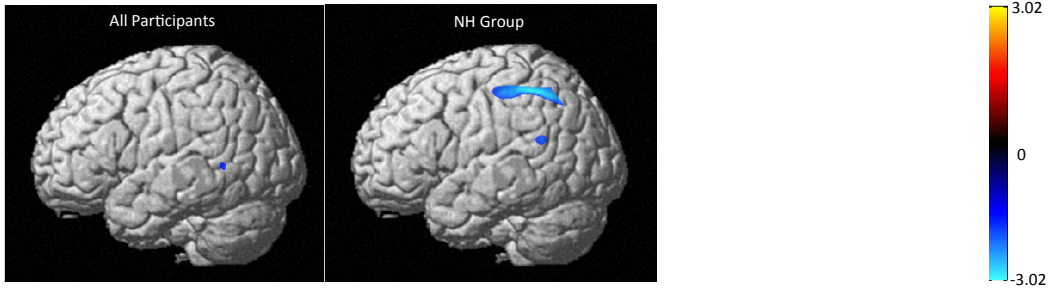
Figure 3.19: HbO t-statistical maps for the linear stimulus level contrast with a threshold of p < 0.05, uncorrected for multiple comparisons. The color map represents t-value with a high t-value (yellow) indicating greater activation for higher-level stimuli.

The t-statistic and significant activation maps for the same linear effect of stimulus level in HbR are shown in Figures 3.20 and 3.21, respectively. Both groups have a significant area with a positive correlation with stimulus level in the posterior inferior portion of the array. Both groups also have an area with a significant negative correlation with stimulus level in the anterior pole of the array. The positively correlated areas of the two groups overlap as shown in the all participants map in the green and purple shaded areas. The area that is significantly positively correlated with stimulus level appears larger again for the NH group compared to the CI group. The negatively correlated areas of the two groups do not overlap but are near each other and factor into a larger area of negatively correlated activation for the average of all participants.
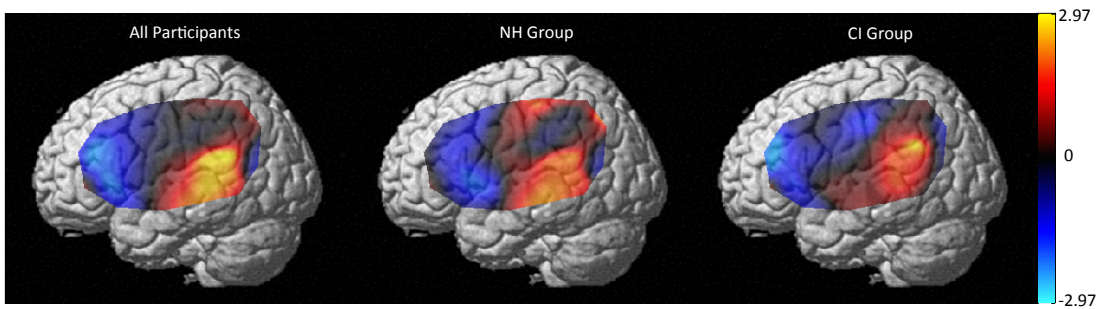
Figure 3.20: HbR t-statistical maps for the linear stimulus level contrast. The color map represents t-value with a high t-value (yellow) indicating greater activation for higher-level stimuli.
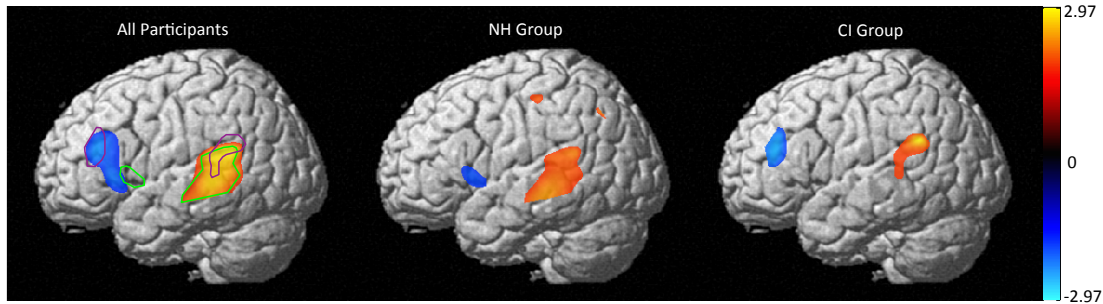
Figure 3.21: HbR t-statistical maps for the linear stimulus level contrast with a threshold of p < 0.05, uncorrected for multiple comparisons. The color map represents t-value with a high t-value (yellow) indicating greater activation for higher-level stimuli. The NH and CI group areas of activation are outlined in green and purple on the map for all participants, respectively.

When comparing the HbO and HbR results for the linear effect of stimulus level, HbR showed areas of positively and negatively correlated areas of activation in both groups while HbO showed no significant activation in the CI group and only two small areas of negatively correlated areas of activation in the NH group. There were again no channels that showed significant changes in both HbR and HbO for the linear effect of stimulus level contrast.

To further examine differences in the linear effect of level between the groups, a mixed ANOVA was completed for the linear effect of stimulus level contrast beta coefficients for HbR. No ANOVA was completed for HbO data because there were no channels with significant activation in all participants for this contrast. The beta coefficients for the linear intensity level contrast for HbO and HbR, including the average of each group as well as the average of all participants, are included in Tables 3.2 and 3.3, respectively. The HbR region of interest or channels with significant activation for the contrast when including all participants included channels 17, 21 and 22. The average beta coefficients in these channels for each group are shown in Figure 3.22.
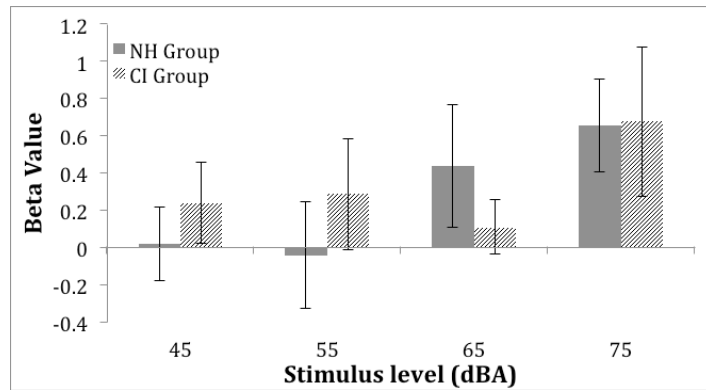
Figure 3.22: Average HbR beta coefficients for the linear intensity level contrast for fNIRS channels 17, 21, and 22. This ROI includes channels showing a significant effect of stimulus level with all participants included in the analysis. Error bars represent ±1 SEM.

The between-groups factor for the ANOVA was hearing group (NH vs. CI) and the within-subjects factor was fNIRS recording channel (17, 21, 22). The results revealed no significant effect of hearing group, fNIRS recording channel, or their interaction. Thus, despite the apparent CI group's smaller area of significant positive correlation with the linear effect of level activation, there was no statistical difference between the groups.

Discussion

The results of the stimulus level experiment provide evidence that fNIRS is sensitive to differences in auditory stimulus level at the group level in both individuals with NH and those with CIs. Though the areas of significant activation for a contrast of the linear effect of stimulus level appeared smaller in the CI group, we found no statistical evidence of a difference between the groups. When further examining the difference in group activation maps between individual stimulus levels (e.g. 75 > 65 dBA), however, the NH group had a significant area of activation for each 10 dB increase in stimulus level while the CI group only showed significant differences in activation with level differences of 20 dB or greater. It is possible that the smaller sample size of the CI group (11 vs. 14 NH participants) influenced the statistical analyses. Thus, we can say that fNIRS shows a linear increase to SCN stimulus level in both NH and CI groups.

Furthermore, fNIRS can detect differences in SCN stimulus level as little as 10 dB in a NH group and as little as 20 dB in a CI group.

It is very possible that fNIRS can detect differences in cortical activation for smaller changes in stimulus level in both populations. The smallest level difference included in this experiment was 10 dB. Thus, we could not examine the sensitivity of fNIRS to smaller level differences. Additionally, it is very possible that with more participants or testing time to increase power we could have detected activation differences to 10 dB level differences in the CI group. On the other hand, it is likely that individuals with CIs may not exhibit the expected level-dependent increases in cortical activation with increasing stimulus level, particularly at low and high levels due to their limited dynamic range and the amplitude compression of the sound processor(s). Future research is needed to determine the smallest stimulus level differences fNIRS can detect and if there are any true differences between the two hearing populations.

HbR results showed both negative and positive areas of activation for the linear effect of stimulus level in both the NH and CI groups. The areas that increased in strength of activation with increasing level were with in the posterior inferior corner of our optode array. Based on our spatial registration to average MNI coordinates, these cortical areas included the mid and posterior portions of the superior temporal gyrus, the middle temporal gyrus, and the supramarginal gyrus portion of Wernicke's area. In contrast, the areas that decreased in strength of activation with increasing level were in the anterior pole of our optode array. Based on our spatial registration these cortical areas included the inferior frontal gyrus, the dorsolateral prefrontal cortex (DL-PFC), and Broca's area.

The effect of stimulus level was very different for HbO and HbR results. The NH group had only a couple of small areas of significant activation for the effect of level and the CI group

had no significant activation for the effect of stimulus level. The NH group showed only a decrease in activation with increasing level in the postcentral gyrus, the supramarginal gyrus, and the angular gyrus, which are parts of the primary somatosensory cortex and Wernicke's area.

The increase in activation with increasing stimulus level in the HbR results in the superior temporal gyrus, the middle temporal gyrus, and the supramarginal gyrus portion of Wernicke's area is consistent with fMRI and EEG results in the literature (Hall et al., 2001; L Jäncke et al., 1998; Langers et al., 2007; Mulert et al., 2005; Sigalovsky & Melcher, 2006). These studies used pure-tone, noise, and speech stimuli (consonant-vowel syllables). None of them used SCN but the effect of level in these regions seems to be consistent across many types of stimuli as Langers et al. (2007) showed with verbal and non-verbal stimuli. Thus, it appears that at a group level fNIRS can detect stimulus-level dependent activation in the auditory cortex and surrounding areas for at least HbR.

The areas of decreased activity with increasing stimulus level in both HbR and HbO are more difficult to interpret. We are not aware of any research showing an effect of auditory intensity level in Broca's area and the DL-PFC or in the primary somatosensory cortex. All of the studies previously mentioned describe using a region of interest analysis and it is possible that the effect of intensity level was not confined to auditory areas. It is also possible that these negative effects are noise in the data, but that seems unlikely for the HbR results in the frontal cortex because they were present in both the NH and CI groups. It is possible that these changes in activation with stimulus level could be specific to temporally modulated stimuli, similar to speech and SCN used in this study. It is also possible that the task of passively listening to the stimuli contributed to this decrease in activation with increasing intensity level. Activation in the DL-PFC has been shown to correlate with task difficulty or perceived effort (e.g. Wild et al.,

2012). Thus, it is possible that participants were putting more effort into attending to the stimuli at lower presentation levels. Further research with an active task and different auditory stimuli is needed to repeat and determine the meaning of the decreases in activation with increasing intensity level.

It is important to note that ideally we would like to find similar results in both HbO and HbR for all contrasts. Theoretically, HbO and HbR results should be strongly, although not perfectly, negatively correlated as shown in the predicted hemodymanic response function (Cui, Bray, & Reiss, 2010). Thus, when using negatively correlated general linear models for HbO and HbR we would expect to find similar results for each hemoglobin type. As described in the results, HbO and HbR results were not very similar and in some cases they appear to be opposite to each other. This would indicate that in some cases our HbO and HbR results were positively correlated. Cui et al (2010) suggested that a positive correlation between the two types of hemoglobin suggests movement artifact in the data. We used wavelet analysis in an attempt to reduce movement artifact in the data but it is possible some noise remained in the data and is causing the differences between HbO and HbR results. We also completed analyses using spline correction in the Homer2 software package and the wavelet analysis algorithm in the NIRS-SPM software (Jang et al., 2009; Scholkmann, Spichtig, Muehlemann, & Wolf, 2010). Both of these noise management methods revealed similar results to the wavelet analysis used in this experiment. There is no consensus in the literature regarding a single best noise management strategy for fNIRS. It is possible that a different noise management strategy would have better dealt with the noise in these data.

To examine the effect the positively correlated data in HbO and HbR had on our results we also completed the noise management strategy suggested by Cui et al (2010). This strategy

assumes that HbO and HbR data are perfectly negatively correlated, which is not completely

correct, and removes positively correlated energy from the data. The results of this analysis were

similar to that found for HbR with the wavelet analysis. There was significantly more activation

for sound than silence in the anterior portion of the optode array and there were similar areas of

activation, although not quiet significant, positively and negatively correlated with stimulus

level. The t-statistic for the average of all participants are shown in Figure 3.23 for both the

sound > silence and linear stimulus level effect contrasts. Thus, this analysis provides some

additional evidence to the validity of at least the HbR results above.
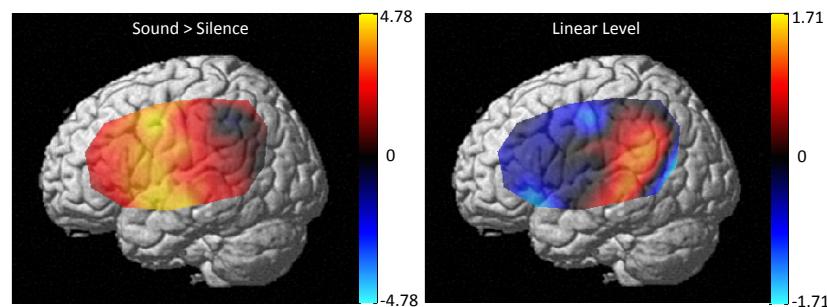
Figure 3.23: HbO t-statistical maps for the sound > silence contrast and the linear stimulus level contrast in the left and right panels, respectively. The color maps represents t-value with a high t-value (yellow) indicating greater activation for sound and for higher-level stimuli in the left and right panels, respectively.

Previous research found a stronger correlation between activation and perceived loudness

than stimulus intensity level (Langers et al., 2007). That is why we measured perceived loudness

of the SCN stimuli for this experiment and were planning to complete both loudness and

stimulus level effect contrasts. The loudness perception data collected for the SCN stimuli,

however, were essentially linear with little difference between the groups. Thus, only a linear

level contrast was used to examine the effect of level and loudness. Because loudness and

intensity level were so closely related in this experiment their effects could not be separated.

Future research should examine the effects of perceived loudness independent of intensity level

on fNIRS results. Although this might be difficult, some acoustic effects alter loudness with

altering overall intensity, such as acoustic bandwidth and reverberation (Warren, 1977). This will be important for experiments examining stimuli that might change in loudness as well as other things such as intelligibility.

The results of this experiment revealed large variability in the individual data of both the NH and CI groups. This inhibits the potential use of fNIRS for clinical use in individual patients because an expected typical response template cannot be developed. This study did not, however, examine the repeatability of fNIRS results within an individual over time. It is possible that despite the variability across individuals, fNIRS data are reliable across time within individuals. If so fNIRS could be used to examine auditory development in children with CIs, progress over time, and changes in processing between listening conditions. A recent study examined the repeatability of fNIRS in infants using audio-visual stimuli (Blasi, Lloyd-Fox, Johnson, & Elwell, 2014). They showed fair reliability for area of activation at the individual level ($r > 0.5$) and good reliability at the group level ($r > .9$). Their study was limited, however, as it examined the repeatability of the response to sound only. Further research on the repeatability of fNIRS, particularly within an individual and for differences between auditory stimuli such as intensity level, is needed.

Part of the purpose of this dissertation was to compare NH and CI groups using fNIRS. Both groups showed significant activation to SCN stimuli and both showed areas of cortical activation significantly correlated with stimulus intensity level. Although the CI group appeared to have lower strength of activation and smaller areas of significant activation, we found little statistical evidence of group differences. There was a near significant interaction between group and fNIRS channel factors for the HbR data in the sound > silence contrast. This seemed to be driven by the NH group's greater activation in the superior and anterior portions of the optode

area. Specifically, the channels with greatest differences covered the DL-PFC, Broca's area, and the middle of the superior temporal gyrus near the primary auditory cortex. No other statistical comparisons, however, reached significance. Thus, although there appeared to be some differences between the groups, there was evidence that both groups have significant cortical activation to SCN stimuli and have similar changes in activation with changes in stimulus intensity level.

In conclusion, based on the results of Experiment I both NH and CI groups show significant changes in activation with changes in stimulus intensity level. Specifically, activation increased with increasing stimulus level and loudness in the left posterior STG/STS (Wernicke's area) and the middle temporal gyrus (MTG) and decreased with increasing stimulus level in the left DL-PFC and Broca's area. All of these changes were significant for HbR, which was more sensitive than HbO. Thus, any future auditory studies using fNIRS should control for stimulus intensity level when it is not a variable of interest. Future studies need to examine the differential effects of intensity level and loudness and the reliability of fNIRS over time, particularly at the individual level.

CHAPTER IV

EXPERIMENT II: SPEECH RECOGNITION PERFORMANCE

Introduction

The results from Experiment I demonstrated that fNIRS has potential as an objective

measure of the changes in auditory cortical activation with changes in auditory stimulus intensity

level. An objective measure of auditory stimulus level and associated loudness effects has some

clinical potential such as examining loudness growth with a CI. This chapter examines a much

more important stimulus or subject characteristic that has much greater clinical implications:

speech recognition performance or stimulus intelligibility.

As previously mentioned, fMRI and PET imaging have shown some potential as

objective measures of speech recognition performance in both adults and children with NH

(Narain, 2003; Obleser et al., 2008; Obleser et al., 2007; S. K. Scott et al., 2000; Sophie K. Scott

et al., 2006; Sophie K. Scott et al., 2004; K. Strelnikov et al., 2011; Wong et al., 2008) and adults

with CIs (Coez et al., 2008; Coez et al., 2011; Fujiki et al., 1998; Naito et al., 2000; Kuzma

Strelnikov et al., 2011; Tange et al., 2009). More recent work using fNIRS in NH adults found

greater activation to natural speech than non-vocal sounds and vocoded speech, which is

spectrally degraded and hence less intelligible (Pollonini et al., 2014). Thus, fNIRS might have

the same potential as the other neuroimaging measures as an objective measure of speech

recognition performance.

If fNIRS can detect changes in auditory cortical activation with changes in speech

recognition performance, it could be used to detect speech recognition benefit with changes in

device configuration, progress over time, changing in programming, etc. This would be

particularly beneficial in individuals who have difficulty completing speech recognition tasks,

such as young children. Further research is needed, however, to determine the potential of fNIRS for such a purpose.

No published study has examined the effect of speech recognition performance on fNIRS recorded cortical activation in participants with CIs. Pollonini et al (2014) used vocoding to show a difference between natural speech and vocoded speech in NH adults. Although this finding supports the potential of fNIRS detecting speech recognition performance differences, natural and vocoded speech differ both in 1) speech intelligibility, related to speech recognition performance, and 2) spectral resolution, which affects sound quality. Thus, it is important that we examine the independent effects of speech recognition performance in both individuals with NH as well as those with CIs.

Experiment II will examine speech recognition performance effects on cortical activation using fNIRS in adults with CIs and adults with NH. We are starting with adults to better control participant movement and using SNR to vary speech recognition performance. The aim of Experiment II was to determine the effect of speech recognition performance using changes in SNR on auditory cortical activation. We tested the following hypothesis auditory cortical activation (anterior STG/STS and posterior STG/STS or Wernicke's area) would increase with increasing speech recognition performance. An alternative hypothesis, based on Wong and colleagues, was that posterior STG/STS activity would increase with decreasing SNR (decreasing speech recognition performance) due to the increased effort expended for speech recognition in noise (Wong et al., 2008).

Methods

Participants

The same participants described in Chapter III participated in this experiment: twenty-nine adults including 16 with NH and 13 with bilateral CIs. See the *Power Analysis* section for justification on sample sizes. The bilateral CI group had no usable residual acoustic hearing, defined as no air-conduction thresholds better than 85 dB HL between 125-8000 Hz in either ear. They made full-time use of both CIs and had at least six-months experience with each CI. CI participants were recruited through the Vanderbilt Bill Wilkerson Center in the Vanderbilt University Medical Center. The NH participants had pure-tone thresholds $\leq$ 20 dB HL at audiometric frequencies between 250-6000 Hz and no history of ear surgery. The NH group (40-64 years, mean = 50.1) was matched for average age to the bilateral-CI group (23-67 years, mean = 49.1). A two-sample t-test revealed no significant difference in age between the two groups (p>0.79). The NH group included mostly female participants (14 female, 2 male), however, while the CI group was balanced for gender (7 female, 6 male). One reason female participants dominated the NH group is that hearing loss is more prevalent in males in the studied age range (Agrawal et al., 2008).

The demographic and device information of the participants with CIs is shown in Table 3.1. Eleven of the participants had a postlingual onset of deafness and two had a prelingual onset of deafness. CI10 had a progressive loss from birth using spoken language to communicate. She received her first CI as an adult. CI11 had a bilateral profound hearing loss at birth and was implanted at age two. She received her second implant as an adult and has always used spoken language to communicate.

Not surprisingly, the CI group had poorer hearing sensitivity than the NH group. Mean audiograms are shown in Figure 3.1. Despite the difference in hearing sensitivity between the groups, both groups had essentially symmetrical hearing between the ears. Thus, audibility was matched between ears for all testing, limiting laterality effects. The average monosyllabic word recognition was also matched between ears for the CI group as shown in Figure 4.4 in chapter IV. It should be noted however, that some individual CI participants had differences in speech recognition between the two ears. The average difference in word recognition between the ears was 22.3-percentage points (SD = 27.3) with seven participants demonstrating differences less than 10-percentage points, four participants with moderate differences between 14- and 34-percentage points, and two with extreme differences in performance between the ears (CI2 = 64 and CI11 = 92). All participants also had no evidence of cognitive impairment based on the Mini-Mental State Examination (score > 24) (Folstein, Folstein, & McHugh, 1975).

Power Analysis

A power analysis was conducted based on the fNIRS data obtained with the NH adults with CI simulations. Specifically, the power analysis was based on the difference between the unprocessed speech and bilateral CI simulation conditions in the left auditory hemisphere. This comparison was chosen for the power analysis for two reasons: 1) it included the largest sample size in the pilot data and 2) it represents a contrast of two conditions that differed in speech recognition performance, although they also differed in spectral resolution. The preliminary study using CI simulations in NH adults showed the fNIRS responses were normally distributed with a standard deviation of 0.046. If the true difference between unprocessed and bilateral CI conditions is 0.043, we needed complete data sets for 16 NH participants and 16 bilateral-CI participants to reject the null hypothesis that fNIRS cannot detect auditory cortical differences of

speech recognition performance with a probability (power) of 0.8. The Type I error probability associated with this test of the null hypothesis is 0.05. We obtained the full group of 16 NH participants but were three short for the CI participants due to the limited population and time constraints.

Procedures

Stimuli: Female talker AzBio sentences were used for testing. These sentences were chosen because they are spoken at an average conversational rate, a large number of sentences are available, and they are commonly used in clinical testing with CI recipients (Spahr et al., 2012). Only the female talker sentences were used to limit testing to one gender and because the female talker sentences are on average more intelligible than the male talker sentences in the AzBio lists. The AzBio lists contain 330 sentences spoken by two female talkers. The two talkers have similar fundamental frequencies with an average of 205 Hz across all sentences (Zhang, Dorman, & Spahr, 2010). Stimuli will be presented in a background noise of 20-talker babble, the same babble used for clinical testing with the AzBio sentences.

The purpose of this experiment was to examine the independent effect of speech recognition performance changes on fNIRS data. To separate speech recognition effects from other SNR effects, a stimulus with no intelligibility and matched to the target speech was used. SCN, the same stimulus used in Experiment II, was chosen because it can be constructed to have the same average spectral content and amplitude modulations as corresponding speech stimuli. A matched SCN stimulus was created for each AzBio sentence using a speech-shaped noise with a spectrum matching the average of the 330 female spoken AzBio sentences and the envelope modulations of the matched sentence. The overall amplitude envelope modulations were multiplied by the speech shaped noise to create one-channel SCN stimuli (Festen & Plomp,

1990; N. Stoppelman et al., 2013). Both the SCN and speech stimuli were presented in quiet and in the same levels of 20-talker babble for fNIRS testing.

Consonant nucleus consonant (CNC) word recognition was also tested in quiet in both groups (Peterson & Lehiste, 1962). These are monosyllabic words spoken by a male. They were used to determine CI simulation settings in the NH group and to document CI group participants' performance relative to the average performance of adults with CIs. CNC words were chosen as they are very commonly used in clinical CI testing.

CI simulations: All testing in the NH group was completed using CI simulations to match performance between the groups at absolute SNRs. Simulation of CI processing was completed using a MATLAB based speech vocoder that separated speech into 15 bandpass filtered frequency bands (Litvak, Spahr, Saoji, & Fridman, 2007). The amplitude envelope obtained for each analysis band was used to modulate a narrow-band noise centered in the respective analysis band, preserving the amplitude changes of each band over time. Total bandwidth was 200 to 8000 Hz. Adjusting the filter slopes created various levels of spectral smearing, simulating CI electrode channel interaction, to achieve differing levels of speech recognition performance. The filter slopes were adjusted as necessary to ensure that participants obtain CNC word recognition scores similar to average CI listeners: 50-70% correct in the bilateral CI condition (R. H. Gifford, Shallop, & Peterson, 2008). Both the speech and 20-talker babble stimuli were vocoded for all testing. The SCN were not vocoded as they already represented a single channel vocoded signal.

Presentation: Stimuli for all experiments were presented from a personal computer through a GSI 61 audiometer to an external speaker. The speaker was placed at 0° azimuth at head height. Calibration of stimuli was completed using a Larson-Davis LxT sound level meter with a half-inch microphone using the substitution method of calibration (microphone placed at the

approximate head position of the participant). All speech and SCN stimuli were presented at an average conversational speech level of 60 dBA and the 20-talker babble level was varied to control speech recognition performance. All testing was completed with the CI processor set to the participants' daily listening program and volume and sensitivity settings.

Behavioral Procedures: CNC word recognition was tested in the sound field in the binaural configuration in the NH group and in each ear separately as well as the bilateral CI configuration in the CI group. Performance was measured using both percent words and phonemes correctly repeated.

To determine the SNRs used in Experiment II and estimate speech recognition performance on the speech stimuli for fNIRS testing, female spoken AzBio sentence recognition was tested in quiet and in 20-talker babble at +10, +5, 0 and -5 dB SNRs. This testing was completed only in the bilateral condition in both participant groups to obtain a psychometric function of performance for each participant. The function was then fit with a sigmoid function and the SNRs at which each individual would recognize 75% and 50% of the words were identified for fNIRS procedures. For this sigmoid fit quiet was represented as a SNR of 30 dB. This is similar to the procedure by Friesen and colleagues (Friesen, Shannon, Baskent, & Wang, 2001).

fNIRS procedures: The purpose of Experiment II was to examine the effect of speech recognition performance on cortical activation as measured with fNIRS. Auditory SNR was used to vary speech recognition performance. We presented both speech and SCN stimuli at three SNRs (infinite/quiet, 75% correct and 50% correct SNRs). The SNRs at which each participant obtained 75 and 50% correct on female spoken AzBio sentences were used.

A block design was used based on the previously published study of speech recognition performance using fNIRS (Pollonini et al., 2014). Each stimulus block was 20 seconds with 20 seconds of silence between the blocks for a total of four minutes per run. The order of the stimulus blocks was varied across runs and the order of runs was counterbalanced across participants using a modified Latin square technique. A sample run is shown in Figure 4.1. The sentence stimuli used at each SNR was matched for length (within 100 ms) and speech recognition performance in quiet (within five percentage points). The SCN stimuli were created to match each individual sentence stimulus at each SNR for better direct comparison. During the 20-second blocks, the 20-talker babble were heard constantly with eight speech or SCN stimuli presented with inter-stimulus intervals of 200-1000 ms. Each participant completed four runs with a pseudorandom stimulus orders.
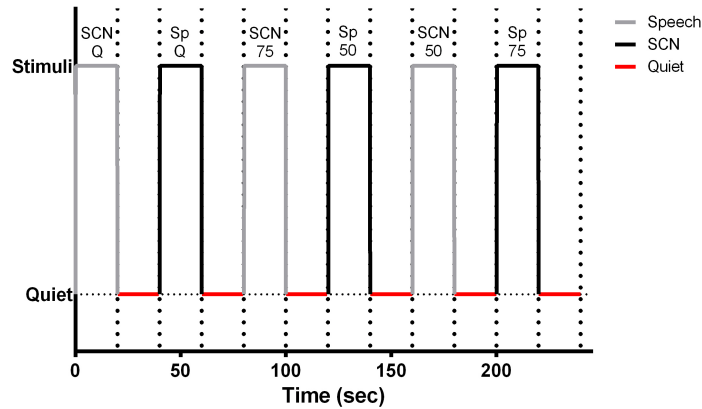
Figure 4.1: Example stimulus timing and condition order for a run for Experiment II.

Participants sat in a comfortable chair with optodes placed as previously noted. They were asked to sit quietly and attend to all stimuli. As in Experiment I no active task was performed to limit somatosensory artifact in the results.

fNIRS acquisition: The fNIRS acquisition details are exactly the same as those in Experiment I. To summarize, fNIRS measurements were conducted with the ETG-4000 Optical Topography

System using a 22-channel optode array covering the left fronto-temporal areas of the head (12x6 cm; inter-optode Distance = 30 mm, sampling rate = 10 Hz). Optode #14, the center of the array, was centered over C5 of the 10-20 system to attempt to cover Broca's and Wernicke's areas as well as the left STG/STS with the entire array. For reference, the same figure showing the approximate location of recording channels on an average structural MRI is shown again in Figure 4.2. We again removed optodes, as needed to accommodate the presence of the CI coil and cable but attempted to match probe placement across all participants.
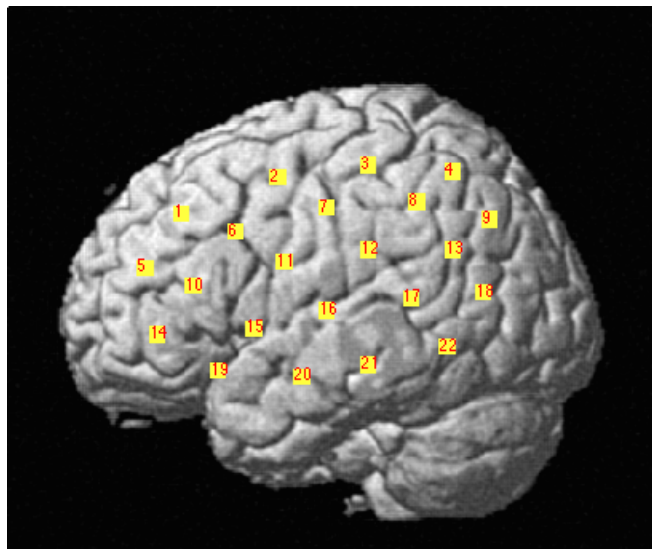
Figure 4.2: Representation of the location of each fNIRS channel displayed on a representative structural MRI. These locations are based on average 10-20 system locations being spatially registered to MNI coordinates.

fNIRS analysis: All analyses were completed using similar tools and methods as those used for Experiment I. Data were analyzed in NIRS-SPM. Both HbO and HbR data were analyzed, as studies have found differences in their sensitivity to activation (Hoshi et al., 2001; Pollonini et al., 2014; Sevy et al., 2010). Data were converted from comma-separated values to MATLAB files using NIRS-SPM.

A. Preprocessing: The channels were then analyzed and transformed according to their wavelength and location using the Beer-Lambert equation. Data were motion corrected with the

wavelet analysis function included in the Homer2 fNIRS processing package: hmrMotionCorrect_Wavelet (Molavi & Dumont, 2012). Following the wavelet analysis detrending was accomplished using a high-pass filter with a cutoff frequency of 0.005 Hz.

B. Spatial Registration: The fNIRS optodes were placed at F7, F5, FC5, F3, FC3, FT7, T7, C5, C3, TP7, CP5, CP3, P7, P5, and P3. fNIRS optodes and points were spatially registered in NIRS-SPM using the MNI data for these points collected by Okatomo's group in 2004 (Okamoto et al., 2004). Locations of 10-20 system points are plotted in MNI in Chapter III Figure 3.5.

C. Artifact management: Again, only one (#5) of the 13 participants with CIs had a coil that did not interfere with the optode array. It was posterior and inferior to the array. The other 12 participants had coils in the posterior inferior portions of the array, interfering with the channels measuring the posterior STS and STG as well as inferior Wernicke's area. The specific channels that were affected based on visually examining the placement of the coils relative to the array were channels 9, 13, 18, and 22. These channels were confirmed to have poor skin contact by the ETG-4000 system's channel integrity check as well as visual examination of the HbO and HbR responses over time.

The same measure of signal integrity used by Pollonini et al. (2014) was used. It is described in detail in Chapter III. There is no good method for removing individual channels from the analysis in NIRS-SPM. Rather than remove the participants or runs from analyses, the channels with poor skin contact were interpolated using the data from all adjacent channels. We used a criterion of more than six channels with poor SCIs, outside of the coil-affected channels (which was a maximum of three channels), to remove an individual run from the analysis.

These criteria again resulted in two CI participants (CI1 and CI2) and two NH participants (NH3 and NH14) being removed from the analysis. Thus, the fNIRS analysis included 11 CI participants and 14 NH participants. Examples of the SCI values and time series plots for channels with good and poor contact are included in Chapter III.

D. fNIRS Analysis: Analysis of fNIRS data collected in Experiment II included the *dependent variables of* HbO and HbR in each recording channel. The *independent variables* were 1) stimulus type (speech vs. SCN) and 2) SNR. A general linear model was created based on predicted hemodynamic responses that did not include time or dispersion derivatives. The recorded data in each channel was then correlated with the general linear models predicted responses. This produced beta values for each stimulus condition, parameter, which can be multiplied by contrasts to produce statistical comparisons. An example of a design matrix is shown in Figure 4.3. The design matrix is for HbO and the shading of gray to white indicate a positive response or increase in HbO for that parameter. A design matrix for HbR would show the reverse with dark shading indicating a decrease in HbR for that parameter. Thus, a multiple regression contrast to test where increases in HbO are greater for speech stimuli in quiet than SCN stimuli in quiet, while ignoring other parameters, would be $[1\ 0\ 0\ -1\ 0\ 0\ 0\ 0\ 0]^4$. These contrast values were multiplied by the beta coefficients to produce statistical maps.

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[4] Multiple regression matrix using contrast coding using 1 and -1 for the independent variables of interest, speech and SCN in quiet, ignoring other conditions.
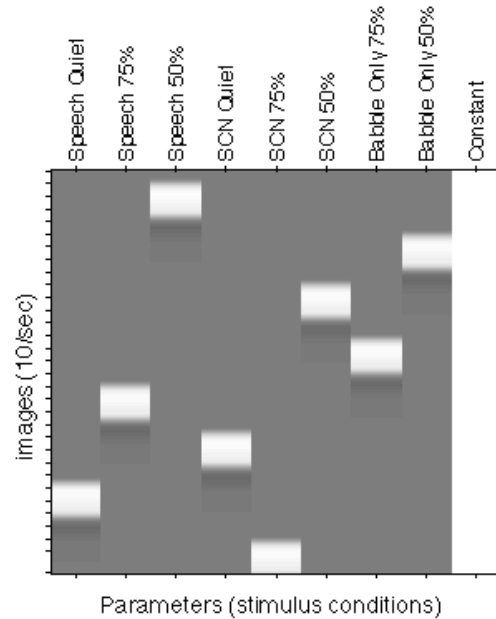
Figure 4.3: Example general linear model figure for a single run. The lighter areas represent predicted changes in HbO based on the timing of each stimulus. The same response is predicted for all conditions, including quiet/silence, to compare conditions with contrasts.

The Multiple regression contrasts used were for the main effects of stimulus type and SNR were: [.33 .33 .33 -.33 -.33 -.33 0 0 0][5] and [.5 -.125 -.375 .5 -.125 -.375 0 0 0][6] for the parameter order of [Speech Quiet, Speech 75% SNR, Speech 50% SNR, SCN Quiet, SCN 75% SNR, SCN 50% SNR, Babble Only 75% SNR, Babble Only 50% SNR, Constant], respectively. The interaction between the two variables was also examined [0.165 -0.04125 -0.12375 -0.165 0.04125 0.12375 0 0 0][7]. The variable of most interest, however, is where activation changes with SNR for speech stimuli but not for SCN stimuli, or at least not in the same way. Additionally, the speech recognition performance might be better correlated with activation then the SNR, although they are related. There is no good method for masking one contrast on another

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[5] Multiple regression matrix using contrast coding (summing to 1 and -1) for the comparison of speech and SCN averaging across SNRs.

[6] Multiple regression matrix using contrast coding (summing to 1 and -1) for the effect of SNR averaging across stimulus types (i.e. speech and SCN).

[7] Multiple regression matrix using contrast coding (summing to 1 and -1) for the interaction (product) of stimulus type and SNR.

contrast in SPM and it does not allow F-contrasts for group data. Thus, a contrast of average speech recognition performance for just speech [0.846 0.154 -1 0 0 0 0 0 0][8] was examined. The results were qualitatively compared across groups to determine any difference between participants with CIs and participants with NH.

The results were also analyzed in a region of interest (ROI) analysis for Wernicke's area, Broca's area, and the superior temporal gyrus based on previous research. The beta coefficients for each speech and SCN stimulus and SNR condition in each channel were analyzed using mixed ANOVAs for each ROI. HbO and HbR were analyzed separately. Specifically, a mixed ANOVA with hearing group as the between groups factor and stimulus type (speech vs. SCN), SNR, and fNIRS channel as the repeated-measure factors was completed for HbO and HbR in each ROI. A threshold of $p < 0.05$, uncorrected for multiple comparisons, was used for all statistical comparisons to maximum power because this is innovative pilot work to direct future studies.

Results

Behavioral Measures

Experiment II included two behavioral measures of speech recognition. The first was CNC word recognition. Figure 4.4 shows the average CNC word and phoneme recognition scores for the NH and CI groups. The CI participants were tested with each ear separately as well as in the bilateral CI condition. The NH participants were tested only in the bilateral condition. Results revealed that the NH participants performed very similarly to the bilateral CI group with each ear separately. The bilateral CI group, however, performed significantly better in the

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[8] Multiple regression matrix using contrast coding (summing to 1 and -1) for the linear effect of speech recognition performance for only speech stimuli.

bilateral condition than the NH group listening to vocoded stimuli for both phoneme and word recognition (t = 3.90, p < 0.003; t = 4.30, p < 0.002; respectively).
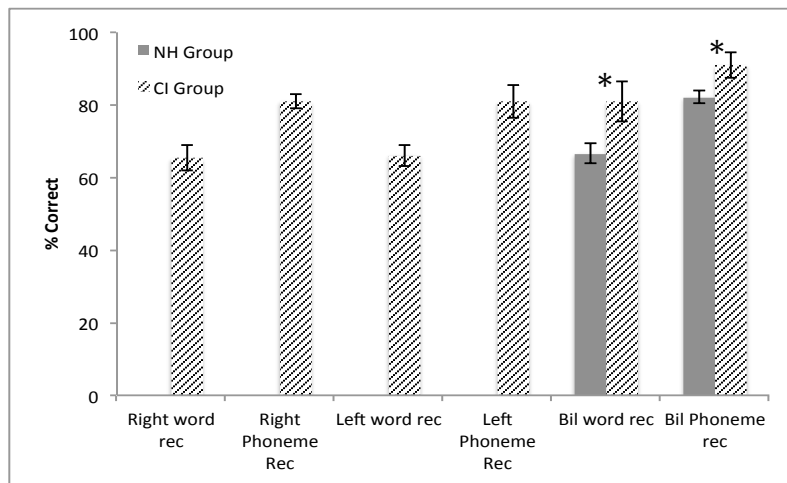
Figure 4.4: Average CNC word recognition for each group. Error bars represent ±1 SEM. Asterisks indicate a significant difference between the groups.

The bilateral CI group also performed better on recognition of the female AzBio sentences in noise. Each participant in both groups was tested in quiet and at four SNRs: +10, +5, 0, and -5 dB SNR. The average performance for both groups at each SNR is shown in Figure 4.5. The performance at -5 dB SNR was not included because all but one participant (CI10) was at floor performance (i.e. 0% correct). There was no significant difference between the groups in quiet, but the CI group performed significantly better at +10, +5 and 0 dB SNRs (t = 2.75, p < 0.018; t = 3.47, p < 0.005; t = 2.38, p < 0.035; respectively). Thus, the average SNRs for group were different as well to match performance.
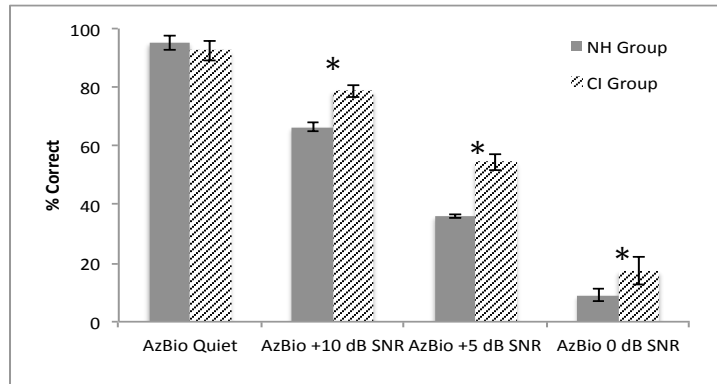
Figure 4.5: Average female spoken AzBio sentence recognition for each group. Error bars represent ±1 SEM. Asterisks indicate significant differences between the groups.

Following the AzBio sentence recognition testing, a sigmoid function was fit to each participant's data at the five SNRs, using 30 dB for quiet. An example of this for participant CI1 is shown in Figure 4.6. For this participant, the SNRs used to obtain approximately 75% and 50% correct were 13 and 7 dB, respectively. The SNRs were rounded to the nearest full number for all fNIRS procedures. The average SNRs for each group based on this procedure are shown in Figure 4.7. The SNRs were significantly worse for the NH group than the CI group for both 75% and 50% correct levels (t = 2.82, p < 0.016; t = 3.29, p < 0.007; respectively). This is not surprising as there CNC and AzBio sentence recognition scores were also worse than the CI group in the bilateral condition. It is important to note that though the absolute SNR values were different between the groups, the difference between the SNRs for 75% and 50% correct levels were similar for each group.
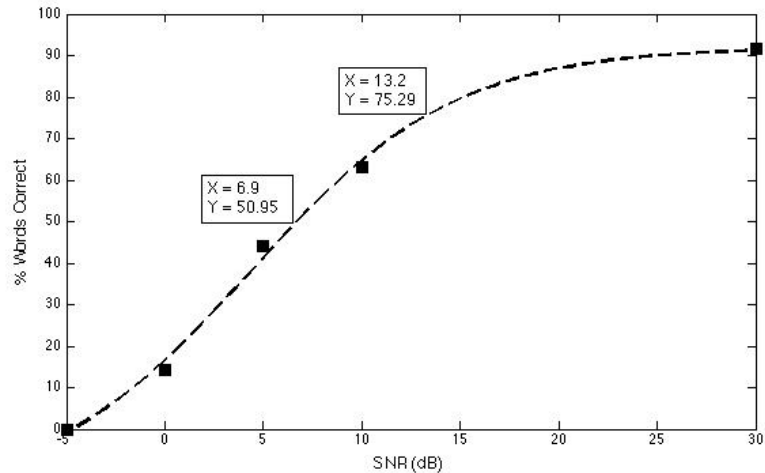
Figure 4.6: Sigmoid function fit for participant CI1 with data points marking the SNRs nearest 75% and 50% correct on female AzBio sentences. Testing in quiet was set as an SNR of 30 dB.
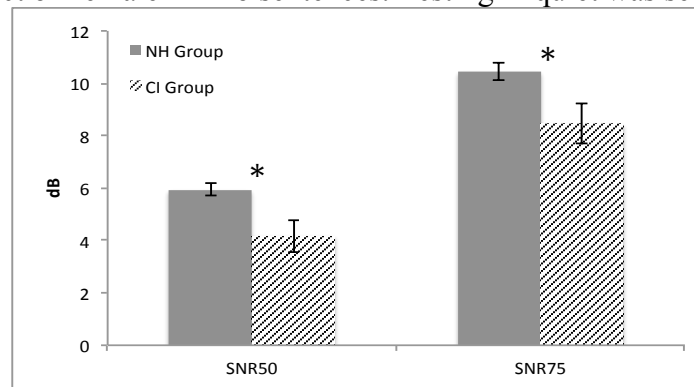
Figure 4.7: Average SNRs for 75% and 50% for each group. Error bars represent the standard error of the mean. Asterisks indicate a significant difference between the groups. SNR50 = SNR for 50% correct and SNR75 = SNR for 75% correct.

fNIRS results

The fNIRS data were analyzed for all participants together as well as for the NH and CI groups separately. First, we will describe the results for the speech > SCN, or stimulus type, contrast. There was again considerable variability across individuals for all results. Individual HbR responses to speech averaged across all three SNRs are shown in Figures 4.8 and 4.9 for NH and CI participants, respectively. All participants showed at least one area of positive activation to speech relative to the implicit baseline for either HbO or HbR. Thus, no additional participants were excluded from the analyses.
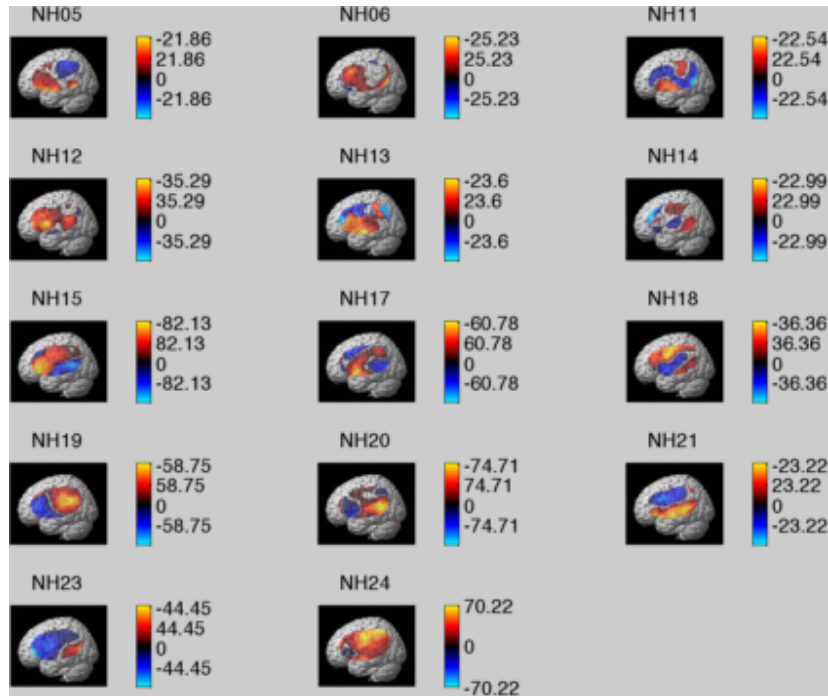
Figure 4.8: Individual t-statistical maps with a threshold of p < 0.001 for HbR in all NH participants. The color maps represent t-values. A large t-value indicates greater activation for speech (averaged across all SNRs) than the implicit baseline.
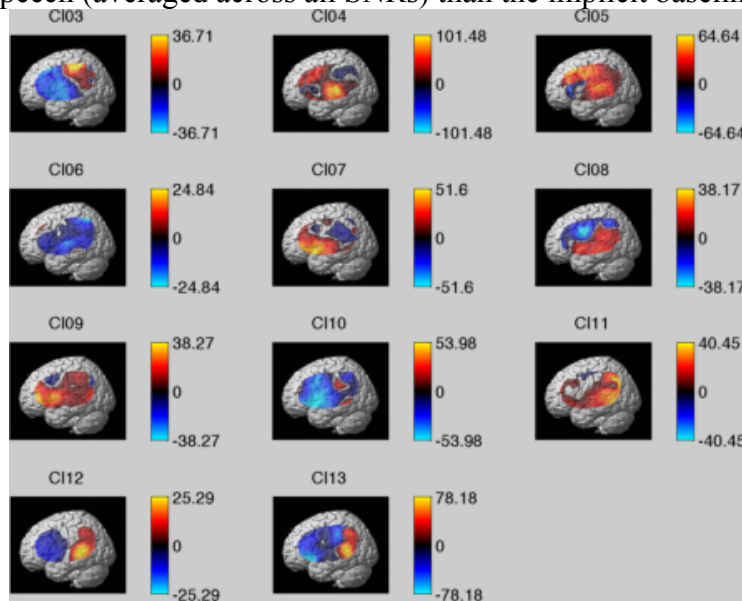
Figure 4.9: Individual t-statistical maps with a threshold of p < 0.001 for HbR in all CI participants. The color maps represent t-values. A large t-value indicates greater activation for speech (averaged across all SNRs) than the implicit baseline.

We will begin examining the group results with the stimulus type contrast (speech > SCN). Group t-statistic maps of HbO for this contrast in all participants, as well as in the NH and CI groups are shown in Figure 4.10. Figure 4.11 shows the same maps with a threshold of p <

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0.05 uncorrected for multiple comparisons. The average beta coefficients for each fNIRS channel for all participants as well as both groups as also shown in Tables 4.1 and 4.2 for HbO and HbR, respectively. The tables include beta coefficients for the stimulus type (speech > SCN), SNR, and their interaction contrasts. The results indicate significantly greater activation to speech than SCN stimuli in channel 12 in the NH group only. This channel is located over the primary auditory cortex and Wernicke's area. There are also two are of greater activation to SCN than speech in both the NH group and when all participants were included, represented in blue. These areas include the motor cortex and the posterior superior and middle temporal gyri. No significant differences were found in the CI group. Additionally, the CI group appeared to have no area of greater activation to speech than SCN that was present in the NH group.
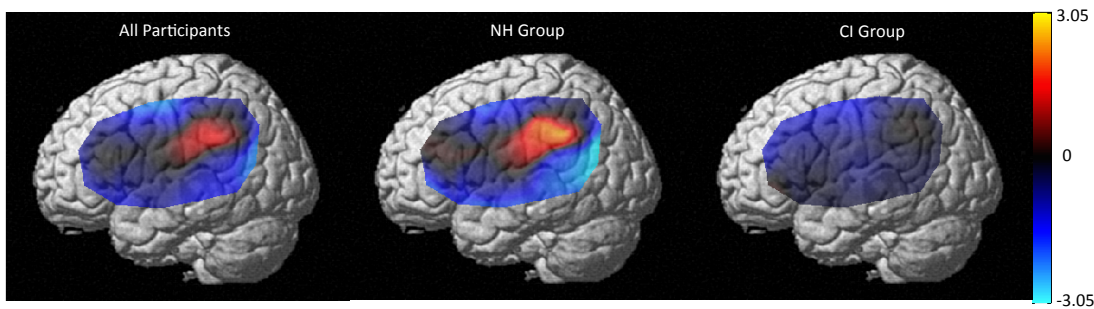
Figure 4.10: HbO t-statistical maps for the speech > SCN contrast. The color map represents t-values with a high t-value (yellow) indicating greater activation for speech than SCN stimuli.

Figure 4.11: HbO t-statistical maps for the speech > SCN contrast with a threshold of $p < 0.05$, uncorrected for multiple comparisons. The color map represents t-values with a high t-value (yellow) indicating greater activation for speech than SCN stimuli.

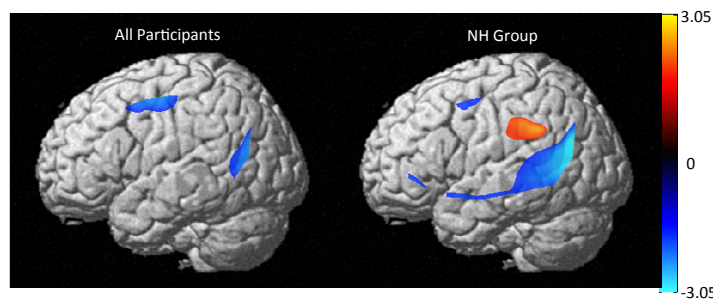| Group /Contrast	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11
All Type	-0.02	-0.04*	-0.03	-0.01	-0.03	-0.02	-0.02	0.00	-0.03	-0.00	-0.00
NH Type	-0.01	-0.04*	-0.03	-0.01	0.00	-0.02	-0.02	0.00	-0.04*	0.01	0.00
CI Type	-0.04	-0.05	-0.02	-0.02	-0.07	-0.02	-0.03	0.00	-0.01	-0.01	-0.01
All SNR	-0.02	-0.02	0.01	-0.00	-0.00	0.00	-0.01	0.01	0.00	-0.01	0.01
NH SNR	-0.03	-0.03	0.00	-0.02	0.01	0.00	-0.01	0.02	-0.02	0.02	0.00
CI SNR	-0.00	-0.00	0.01	0.01	-0.02	0.00	-0.00	0.01	0.03	-0.04	0.01
All Interaction	0.00	-0.01	-0.01	-0.00	-0.00	-0.01	-0.01	0.00	-0.00	-0.02*	-0.02
NH Interaction	0.01	-0.00	-0.01	-0.00	-0.00	-0.00	0.00	0.01	-0.01	-0.00	-0.00
CI Interaction	-0.01	-0.01*	-0.01	-0.01	-0.01	-0.03	-0.02*	-0.01	-0.00	-0.04*	-0.04*
Group /Contrast	CH12	CH13	CH14	CH15	CH16	CH17	CH18	CH19	CH20	CH21	CH22
All Type	0.02	0.00	-0.03	-0.02	-0.00	-0.03	-0.06*	-0.04	-0.03	-0.03	-0.03
NH Type	0.05*	-0.00	-0.07*	-0.04	0.00	-0.05*	-0.09*	-0.07	-0.05*	-0.05*	-0.05*
CI Type	-0.00	0.01	0.02	0.00	-0.01	-0.00	-0.01	-0.01	-0.01	-0.01	0.00
All SNR	0.01	0.01	0.00	0.04	0.01	-0.01	-0.01	-0.00	0.00	0.02*	0.02
NH SNR	0.02*	0.01	0.03	0.09	0.01	-0.02	-0.00	0.02	0.02	0.04	0.01
CI SNR	-0.00	0.01	-0.02	-0.03	0.01	0.01	-0.03	-0.03	-0.02	0.01	0.02
All Interaction	0.01	0.01	-0.00	-0.01	0.00	-0.00	0.00	-0.01	-0.00	-0.00	0.00
NH Interaction	0.03	0.02	0.00	0.01	0.01	0.00	0.00	-0.01	0.00	-0.00	-0.00
CI Interaction	-0.01*	-0.01*	-0.01	-0.02	-0.00	-0.00	0.01	-0.01	-0.01	-0.00	0.01

Table 4.1: Average HbO beta coefficients for the speech > SCN, SNR, and their interaction contrasts for each group as well as all participants combined. * = p < 0.05, uncorrected for multiple comparisons.

Group/Contrast	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11
All Type	-0.04*	-0.03	0.01	-0.01	-0.01	-0.02	-0.01	0.02	-0.02	0.03	-0.01
NH Type	-0.06*	-0.03	0.01	-0.00	-0.04	-0.04	-0.01	0.02	-0.02	0.07	-0.03
CI Type	-0.01	-0.03	0.01	-0.03	0.03	0.00	-0.01	0.01	-0.01	-0.01	0.01
All SNR	0.05*	0.03	0.01	0.01	0.02	0.02	0.02	0.01	0.01	-0.04	0.00
NH SNR	0.10*	0.07	0.01	0.00	0.05*	0.06	0.03	0.00	0.02	-0.05	0.01
CI SNR	-0.01	-0.01	-0.00	0.01	-0.03*	-0.04	-0.00	0.01	-0.00	-0.03	-0.02
All Interaction	0.25*	0.03	0.07	-0.10	0.03	0.14	0.09	0.01	-0.04	0.10	-0.09
NH Interaction	0.28*	0.11	0.03	-0.02	0.06	0.14	0.08	-0.12	-0.01	0.29*	-0.13
CI Interaction	0.20	-0.07	0.11	-0.21	-0.01	0.14	0.10	0.18	-0.09	-0.12	-0.02
Group/Contrast	CH12	CH13	CH14	CH15	CH16	CH17	CH18	CH19	CH20	CH21	CH22
All Type	0.01	0.00	-0.00	0.02	0.00	0.01	0.01	-0.02	0.02	0.02*	0.01
NH Type	0.01	-0.00	0.00	0.02	-0.00	0.02	0.01	-0.00	0.02	0.02	-0.01
CI Type	0.00	0.01	-0.01	0.01	0.01	0.01	0.01	-0.04	0.02	0.03	0.03
All SNR	-0.00	0.00	-0.01	-0.02	0.01	0.01	0.01	0.02	0.02	-0.00	-0.02*
NH SNR	-0.01	-0.00	-0.00	-0.04	0.02*	0.01	0.01	0.02	0.02	-0.00	-0.00
CI SNR	0.00	0.01*	-0.03	-0.00	0.01	-0.00	0.00	0.01	0.02	0.00	-0.04*
All Interaction	-0.05	-0.08	-0.18*	-0.12	0.03	0.08	-0.01	-0.02	0.19*	0.09	0.02
NH Interaction	-0.16	0.08	-0.06	-0.10	0.06	0.15	-0.07	-0.02	0.29*	0.08	0.04
CI Interaction	0.04	-0.28*	-0.32*	-0.15	-0.00	-0.01	0.11	-0.03	0.06	0.09	-0.01

Table 4.2: Average HbR beta coefficients for the speech > SCN, SNR, and their interaction contrasts for each group as well as all participants combined. * = p < 0.05, uncorrected for multiple comparisons.

HbR group t-statistic maps for this same contrast in all participants, as well as in the NH and CI groups are shown in Figure 4.12. Figure 4.13 shows the same maps with a threshold of p

< 0.05 uncorrected for multiple comparisons. In contrast to the HbO results, the HbR results in

Figure 4.12 appear somewhat similar in both the NH and CI groups. When using a threshold of p

< 0.05, however, the CI group showed an area of greater activation to speech than SCN in the

posterior middle temporal gyrus (channel 21) while the NH group showed an area of greater

activation to SCN than speech in the dorsolateral prefrontal cortex (channel 1). Both of these

areas of significant activation also are represented in the analysis of all participants. In summary,

both HbO and HbR showed evidence of an effect of stimulus type in the NH group while only

HbR showed evidence of such an effect in the CI group. Additionally, HbO results appear to

show some evidence of a difference between the groups for stimulus type.

Figure 4.12: HbR t-statistical maps for the speech > SCN contrast. The color map represents t-values with a high t-value (yellow) indicating greater activation for speech than SCN stimuli.

Figure 4.13: HbR t-statistical maps for the speech > SCN contrast with a threshold of p < 0.05, uncorrected for multiple comparisons. The color map represents t-values with a high t-value (yellow) indicating greater activation for speech than SCN stimuli.

The other main effect we examined was SNR. Though the average SNRs for 75 and 50%

performance were different between the two groups, we used the same SNR contrast for all

participants for comparison purposes. The values for SNR used were 30, 10 and 6 dB for quiet,

75 and 50% correct, respectively resulting in contrast weights of [.5 -.125 -.375 .5 -.125 -.375 0 0 0]. Group t-statistic maps of HbO for the SNR contrast in all participants, as well as in the NH and CI groups are shown in Figure 4.14. Figure 4.15 shows the same map for the NH group with a threshold of p < 0.05 uncorrected for multiple comparisons. The CI group and all participants together showed no area with a significant SNR effect. The NH group showed greater activation for better SNRs in three distinct areas, near channels 12, 15 and 21. These channels correspond to the primary auditory cortex and Wernicke's area, Broca's area, and the middle temporal gyrus, respectively. The activation pattern appeared different between the groups, particularly in the anterior inferior portion of the array near Broca's area.

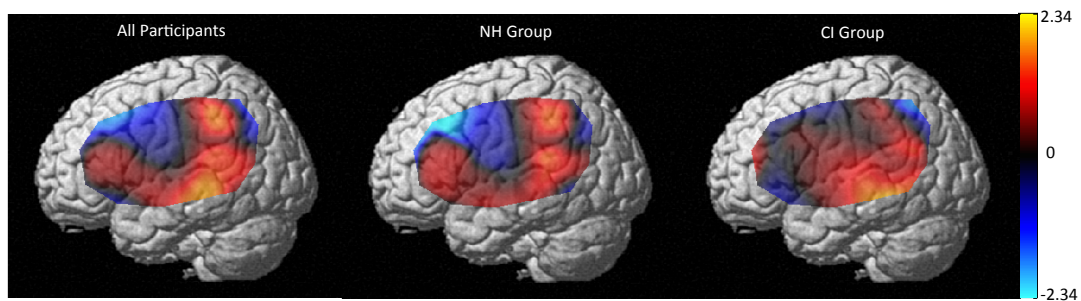Figure 4.14: HbO t-statistical maps for the SNR contrast. The color map represents t-values with a high t-value (yellow) indicating greater activation for better SNRs or performance.

Figure 4.15: HbO t-statistical maps for the SNR contrast with a threshold of p < 0.05, uncorrected for multiple comparisons. The color map represents t-values with a high t-value (yellow) indicating greater activation for better SNRs or performance.

The results for the SNR contrast also appeared more similar between groups in the HbR data. The HbR group t-statistic maps for the SNR contrast in all participants, as well as in the NH and CI groups are shown in Figure 4.16. Figure 4.17 shows the same map for the NH group with

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a threshold of p < 0.05 uncorrected for multiple comparisons. Although there are apparent

differences between the activation patterns of the groups, they both show an area of greater

activation for better SNRs in the inferior portion of the area around the STG. Statistically, both

groups showed areas with a significant SNR effect. The NH group had greater activation for

better SNRs in the inferior portion of the array near the middle STG and in the anterior superior

portion of the array near Broca's area and the dorsolateral prefrontal cortex. In contrast, the CI

group had greater activation for better SNRs in the posterior portion of the array near Wernicke's

area and less activation for better SNRs in the posterior inferior portion of the array, the posterior

STG. The map for all participants showed a similar area to the NH group of greater activation for

better SNRs in the middle STG. It also showed an area of greater activation for better SNRs in

the superior portion of the array near the motor cortex. In summary, just as for the effect of

stimulus type both HbO and HbR showed evidence of an SNR effect in the NH group while only

HbR showed evidence of such an effect in the CI group. Additionally, HbO results appear to

show some evidence of a difference between the groups for SNR effects, specifically in the

anterior inferior portion of the array near Broca's area and the temporal pole.
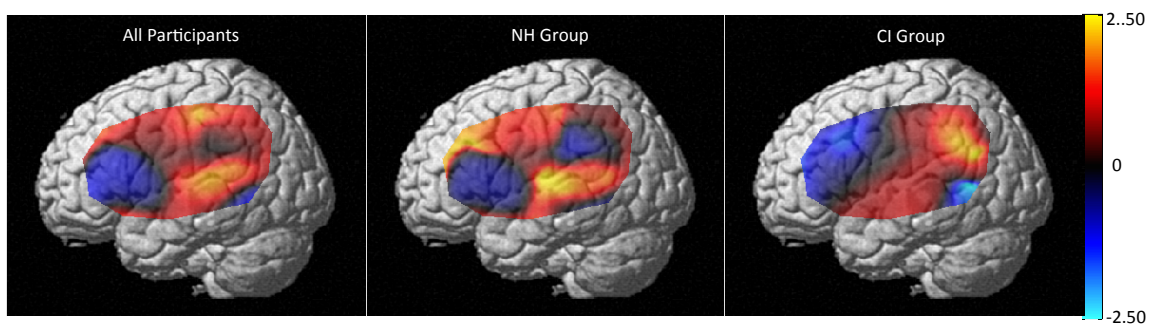
Figure 4.16: HbR t-statistical maps for the SNR contrast. The color map represents t-values with
a high t-value (yellow) indicating greater activation for better SNRs or performance.
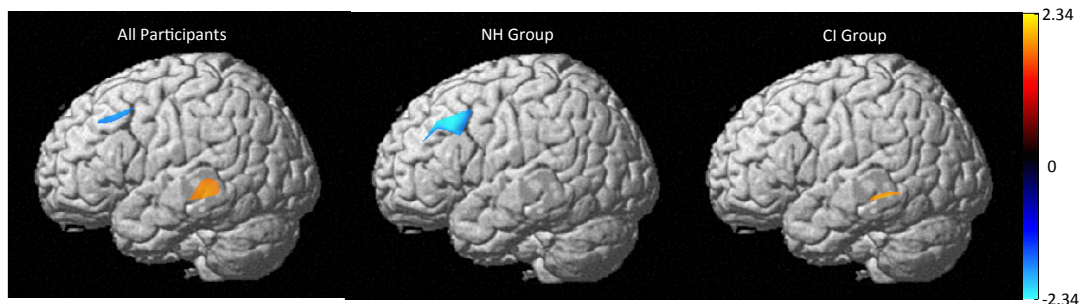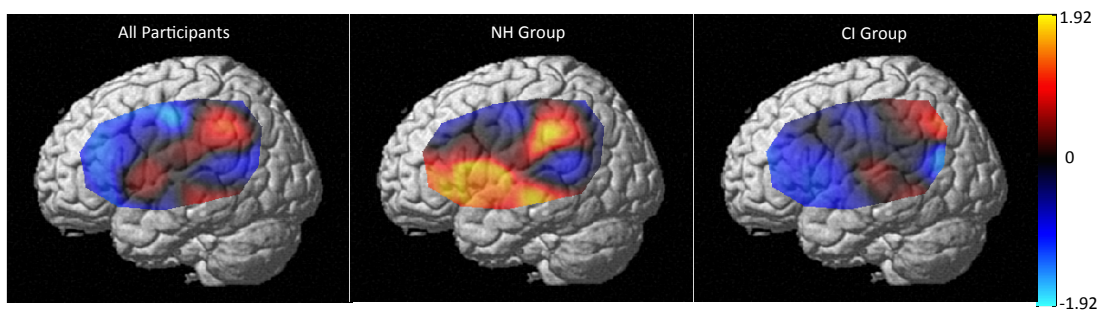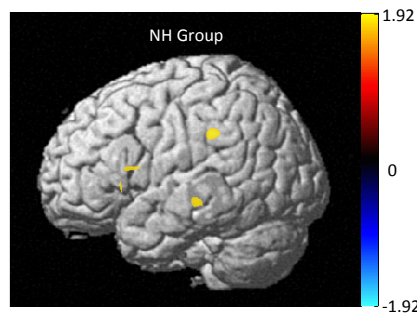
Figure 4.17: HbR t-statistical maps for the SNR contrast with a threshold of $p < 0.05$, uncorrected for multiple comparisons. The color map represents t-values with a high t-value (yellow) indicating greater activation for better SNRs or performance.

The main effects of stimulus type and SNR are of interest for fNIRS sensitivity but the main effect of interest in this study is the effect of speech recognition performance on cortical activation measured with fNIRS. The interaction of stimulus type and SNR begins to examine this effect. We examined the interaction effect or product of the contrast weights for stimulus type and SNR: [0.165 -0.04125 -0.12375 -0.165 0.04125 0.12375 0 0 0]. Thus, this contrast indicates areas with activation that increase with SNR for speech but decrease with SNR for SCN stimuli. The HbO group t-statistic maps for the interaction of stimulus type and SNR in all participants, as well as in the NH and CI groups are shown in Figure 4.18. Figure 4.19 shows the same maps for the CI group and all participants with a threshold of $p < 0.05$, uncorrected for multiple comparisons. The t-statistic maps appear different for the two groups with the NH group showing a positive interaction effect in the posterior portion and projecting forward to the anterior inferior portion of the array. In contrast, the CI group showed a general negative interaction effect in the entire array, particularly in the superior portion. There was no significant interaction effect in the NH group, however. The CI group, in contrast, had a negative interaction effect in the superior middle to anterior portion of the array including Broca's area. This indicates that activation in this area *decreased with improving SNR* for speech stimuli and increased with improving SNR for SCN stimuli. A smaller but similar area showed the same

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result for all participants. Thus, these results again suggest differences between the groups but

with a significant effect in only the CI group.

Figure 4.18: HbO t-statistical maps for the interaction of stimulus type and SNR. The color map represents t-values with a high t-value (yellow) indicating greater activation for better SNRs with speech and less activation for better SNRs with SCN stimuli.

Figure 4.19: HbO t-statistical maps for the interaction of stimulus type and SNR with a threshold of $p < 0.05$, uncorrected for multiple comparisons. The color map represents t-values with a high t-value (yel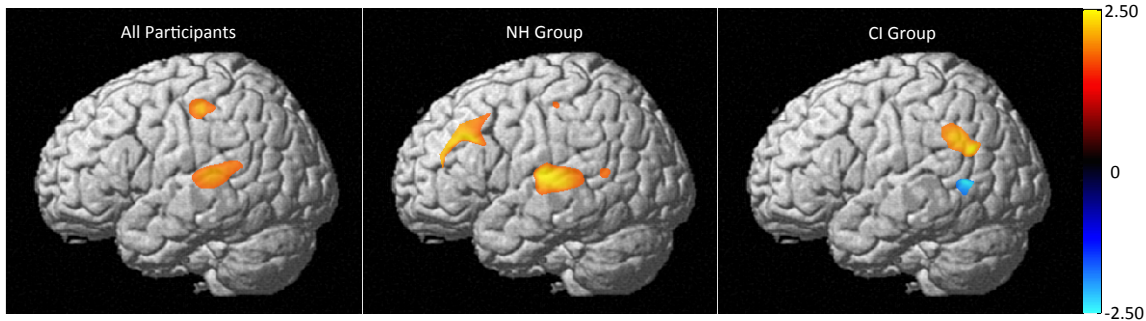low) indicating greater activation for better SNRs with speech and less activation for better SNRs with SCN stimuli. There was no significant effect in the NH group.

The interaction effect was also examined for HbR changes. The HbR group t-statistic

maps for the interaction of stimulus type and SNR in all participants, as well as in the NH and CI

groups are shown in Figure 4.20. Figure 4.21 shows the same maps with a threshold of $p < 0.05$,

uncorrected for multiple comparisons. Similar to the HbO results, the maps appear different for

the two groups, particularly in the anterior inferior of the array. The NH group had a positive

interaction effect in the anterior-inferior portion of the array, the anterior STG shown in Figure

4.19. In contrast, the CI group had a positive interaction effect in the posterior-superior portion

of the array, part of Wernicke's area and the somatosensory cortex. When including all

participants, there was also a positive interaction effect in a similar area to that found in the CI group. These results indicate that activation in these areas increased with improving SNR for speech stimuli and decreased with improving SNR for SCN stimuli. In summary, the HbO and HbR results indicated a significant interaction of stimulus type and SNR effects in the CI group while only HbR results indicated a significant interaction in the NH group.
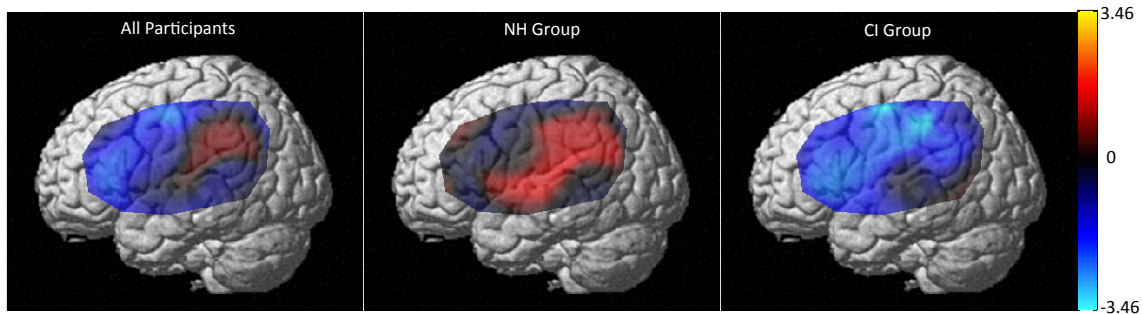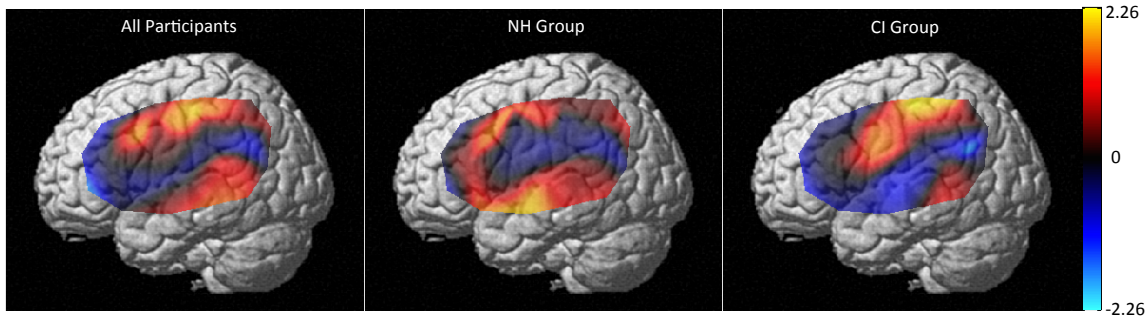

Figure 4.20: HbR t-statistical maps for the interaction of stimulus type and SNR. The color map represents t-values with a high t-value (yellow) indicating greater activation for better SNRs with speech and less activation for better SNRs with SCN stimuli.
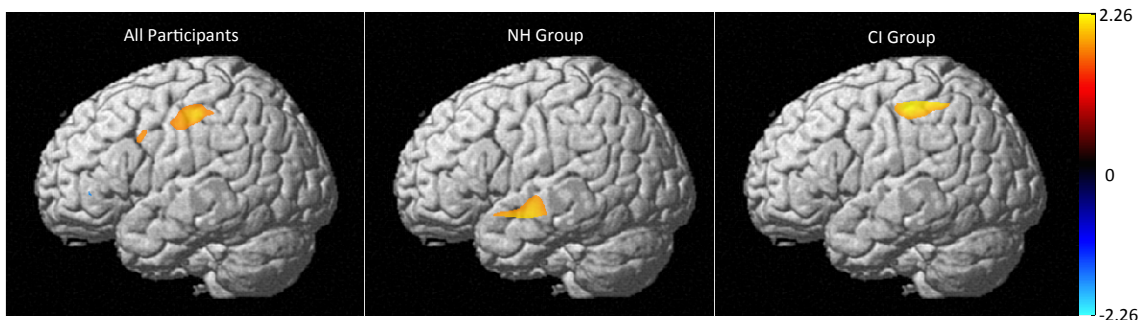
Figure 4.21: HbR t-statistical maps for the interaction of stimulus type and SNR with a threshold of p < 0.05, uncorrected for multiple comparisons. The color map represents t-values with a high t-value (yellow) indicating greater activation for better SNRs with speech and less activation for better SNRs with SCN stimuli.

To further examine the effect of speech recognition performance on cortical activation, we used a contrast of speech recognition performance for the speech stimuli at each SNR. We used the average speech recognition performance in quiet in all participants (93.9%) and 75 and 50% to create a speech recognition performance contrast of [0.846 0.154 -1 0 0 0 0 0 0]. The HbO group t-statistic maps for the effect of speech recognition performance in all participants, as

well as in the NH and CI groups are shown in Figure 4.22. Figure 4.23 shows the same maps

with a threshold of p < 0.05, uncorrected for multiple comparisons. Figures 4.22 and 4.23 appear

to show the greatest difference between the two groups of any of the examined contrasts. Figure

4.21 shows the significant activation areas in the NH group on the same brain as the CI group.

The NH group areas are represented in green. The NH group had three areas of increasing

activation with increasing speech recognition performance in the posterior superior and the

anterior inferior portions of the array, near Wernicke's and Broca's areas, respectively. In

contrast, the CI group showed an opposite significant effect of speech recognition performance

in the anterior-inferior and the posterior portions of the array. The posterior area in the CI group

is inferior to the posterior area in the NH group. The areas in the anterior-inferior portion of the

array, near Broca's area, in both groups overlap. Thus, these results indicate an opposite effect of

speech recognition performance between the groups in similar anatomical areas.

Figure 4.22: HbO t-statistical maps for the effect of speech recognition performance. The color map represents t-values with a high t-value (yellow) indicating greater activation for better greater speech recognition conditions.

Figure 4.23: HbO t-statistical maps for the effect of speech recognition performance with a threshold of p < 0.05, uncorrected for multiple comparisons. The color map represents t-values with a high t-value (yellow) indicating greater activation for better greater speech recognition conditions. The areas of activation in the NH group are represented on the CI group map in green.

The HbR results also showed significant effects of speech recognition performance, although with not as stark a group difference. The HbR group t-statistic maps for the effect of speech recognition performance in all participants, as well as in the NH and CI groups are shown in Figure 4.24. Figure 4.25 shows the same maps with a threshold of $p < 0.05$, uncorrected for multiple comparisons. The biggest apparent difference between the groups in HbR data for the speech recognition performance contrast is in the anterior-superior portion of the array (Dorsolateral prefrontal cortex and Broca's area). The NH group had a significant increase in activation with increasing speech recognition in this area while the CI group had a non-significant decrease in activation. Both groups had significant areas of activation that increased with increasing speech recognition, however. The CI group's area was in the posterior-superior portion of the array near Wernicke's area and the somatosensory cortex. The NH group had two areas in addition to the one in the anterior-superior portion of the array, one near the anterior STG and superior temporal sulcus and one near the posterior STG. When including all participants the only area with a significant increase in activation with speech recognition performance was in the posterior-superior portion of the array similar to the CI group. The analysis of all participants also revealed a small area of decreasing activation with increasing speech recognition performance in the anterior inferior corner of the array near Broca's area. In summary, the speech recognition performance contrast revealed significant effects of speech recognition on cortical activation in both groups for HbO and HbR. There appeared to be group

differences, however, particularly in the HbO data with speech recognition performance showing the opposite effects on cortical activation between the groups.
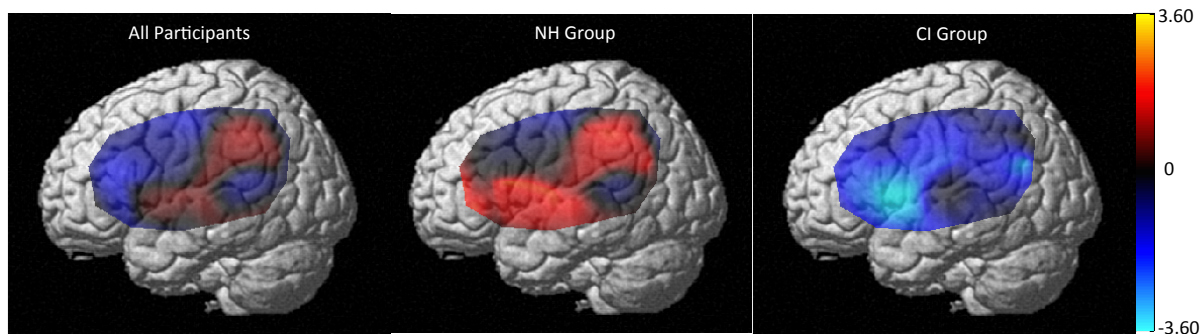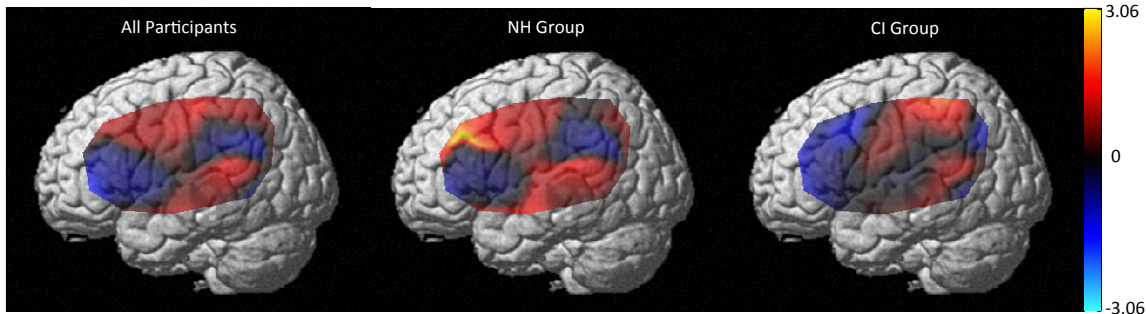

Figure 4.24: HbR t-statistical maps for the effect of speech recognition performance. The color map represent t-value with a high t-value (yellow) indicating greater activation for better greater speech recognition conditions.
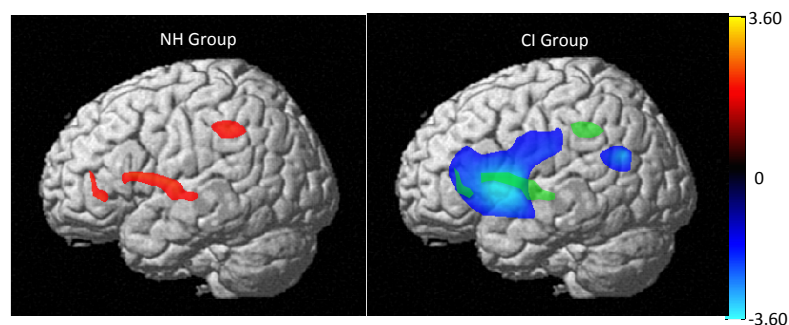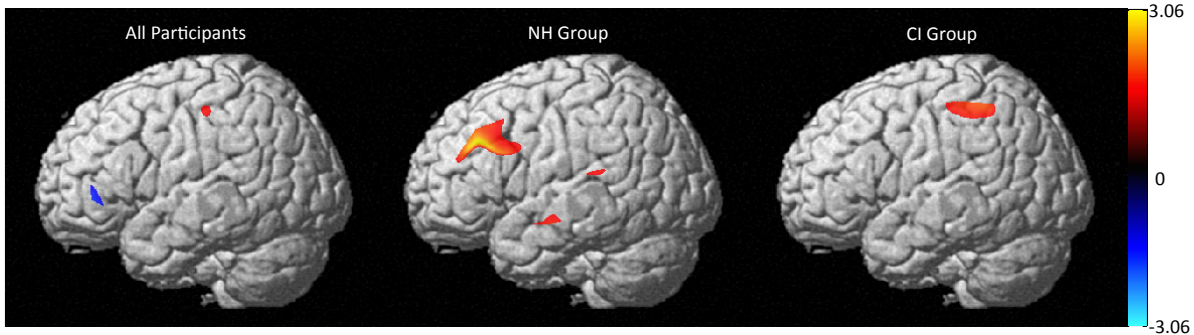

Figure 4.25: HbR t-statistical maps for the effect of speech recognition performance with a threshold of p < 0.05, uncorrected for multiple comparisons. The color map represent t-value with a high t-value (yellow) indicating greater activation for better greater speech recognition conditions.

Region of interest (ROI) analyses: Many of the contrasts revealed apparent differences between the NH and CI groups. Therefore, we examined differences between the groups further using mixed ANOVAs in three regions of interest: Wernicke's area, Broca's area, and the left STG/STS. Based on the 10-20 system locations of the fNIRS channels projected to MNI space, the channels included in each ROI analysis were 3, 4, 8, 9, 12, 13 and 18 for Wernicke's area; 1, 5, 6, 10, and 14 for Broca's area; and 15, 16, 17, 19, 20, 21, and 22 for STG/STS. Thus, the only channels that were not included in an ROI were 2, 7 and 11, which were located over the motor and somatosensory cortices. For each ANOVA the HbO or HbR beta coefficients for speech and

SCN stimuli at each of the three SNRs were included as the dependent variable. The independent factors were the same for each ANOVA. The between-subjects factor was participant group and the within-subjects factors were fNIRS channel, stimulus type (speech vs. SCN), and SNR.

We will first examine HbO data in Wernicke's area. The NH group had significantly greater HbO activation for speech than SCN in channels 12 and 13 in Wernicke's area as described above (Figure 4.11). In contrast, the CI group showed no such difference. The NH group also had a significant effect of SNR in HbO data that was not present in the CI group in Wernicke's area (Figure 4.15). There also appeared to be an interaction with channel and SNR as the CI group had an area of increasing activation with SNR in the posterior portion of Wernicke's area while the peak in the NH group was more anterior (Figure 4.14). These differences were supported by the ANOVA results. Significant main effects of stimulus type and fNIRS channel were found [$F(1,24) = 4.2$, $F(6,144) = 5.6$; $p < 0.041$, $p < 0.019$; respectively] as well as near significant effects of the interaction between stimulus type and SNR [$F(2,48) = 2.9$, $p < 0.091$] and a three-way interaction between group, stimulus type, and SNR [$F(2,96) = 3.6$, $p < 0.059$]. No other main and interaction effects were significant ($p > 0.1$). The three-way interaction between group, stimulus type, and SNR can be better visualized in Figure 4.26. This figure shows the beta coefficients averaged across channels 12 and 13, which were the significant channels for stimulus type in the NH group. The NH group shows a decrease in activation with SNR for speech but an increase in activation with SNR for SCN. In contrast, the CI group trends toward the opposite interaction between stimulus type and SNR. Thus, the HbO data support a difference in type and SNR effects between the groups in Wernicke's area. It is important to note that channels 13 and 18 were the channels with the most signal coupling issues

in both groups and particularly in the CI group due to the coils. This issue will be further discussed below.
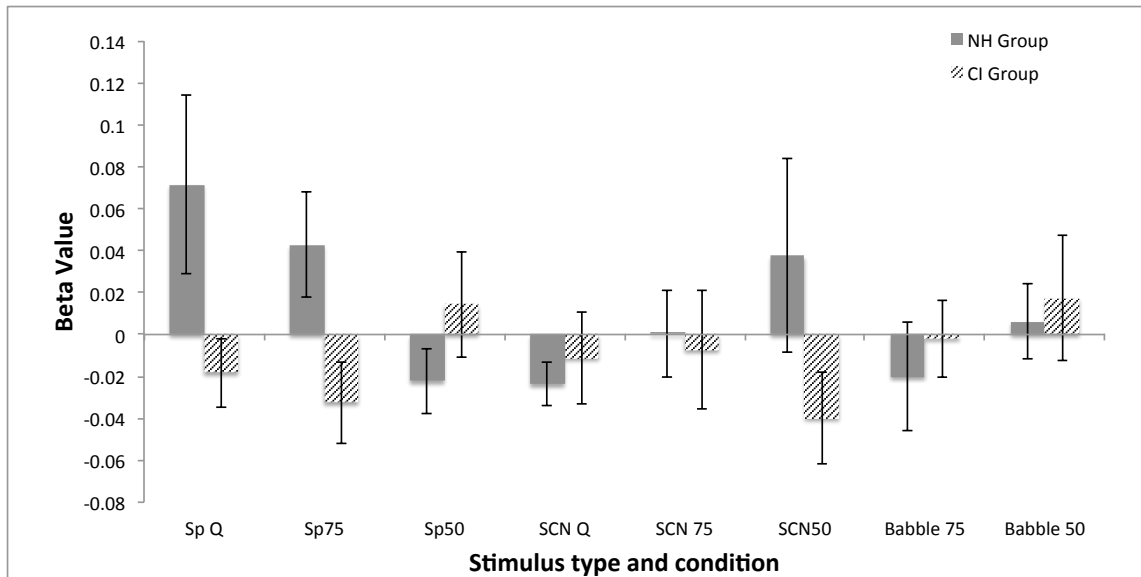
Figure 4.26: Average beta coefficients for each group for channels 12 and 13 in Wernicke's area. Error bars represent the ±1 SEM. SP = Speech, Q = quiet, and 75 and 50 are the SNRs at which 75% and 50% speech recognition was obtained. Babble = only the 20-talker babble with no target was presented.

The HbR data in Wernicke's area also revealed a difference between the groups. The mixed ANOVA revealed a main effect of group [$F(1,46) = 12.7$, $p < 0.001$] and a near significant interaction between group and stimulus type [$F(1,46) = 3.751$, $p < 0.054$]. All other main and interaction comparisons were non-significant ($p > 0.1$). The main effect was driven by greater activation in the NH group than the CI group and the interaction showed greater activation for speech than SCN stimuli in the NH group but greater activation for SCN than speech stimuli in the CI group (Figure 4.13). In summary, these data along with the t-statistical maps provide evidence of a difference between the NH and CI groups for stimulus type and SNR effects on cortical activation near Wernicke's area.

The next ROI we will examine is Broca's area, located in the anterior pole of the array. HbO maps of the effects of stimulus type, SNR and their interaction revealed significant effects

of SNR and stimulus type in the inferior portion of this ROI in the NH group and an interaction effect in the CI group (Figures 4.11, 4.15, 4.19). There appeared to be a difference in the interaction effect between the groups, particularly in the inferior portion of Broca's area. Despite these apparent differences there were no significant main or interaction effects in the HbO data in Broca's area ($p > 0.1$). The discrepancy might be due to the difference across channels in this ROI analysis. The effects nearest significance were the interactions of group and channel as well as group and stimulus type ($p < 0.15$). HbR results did, however, reveal some significant effects.

HbR maps showed significant effects of stimulus type and SNR in the superior portion of Broca's ROI in the NH group but not in the CI group (Figures 4.13, 4.17). There was no significant interaction effect in this region. The ANOVA revealed a main effect of SNR [$F(2,72) = 4.5, p < 0.034$], consistent with that seen in the NH group as well as significant interactions between fNIRS channel and type [$F(5,120) = 6.6, p < 0.011$] as well as channel and SNR [$F(10,240) = 7.9, p < 0.005$]. All other main and interaction comparisons were non-significant. The significant SNR effect was probably caused by the same effect seen in the NH group map, and the interactions caused by the SNR and stimulus type effects being restricted to the upper portion of the ROI. In summary, the ANOVA analyses produced some evidence of SNR and stimulus type effects in Broca's area but little evidence of a difference between the NH and CI groups.

The last ROI is the left STG/STS. This region covered the inferior portion of the array. The HbO maps revealed a significant effect of stimulus type in the NH group with greater activation to SCN stimuli than speech stimuli (Figure 4.11). There was no effect of stimulus type in the CI group. There was also a small area with a significant effect of SNR in the NH group in the middle STG (Figure 4.15). No significant interaction, however, was found in either group in

this ROI analysis. The ANOVA of the HbO results revealed a very significant effect of stimulus type [$F(1,24) = 13.3$, $p < 0.001$], likely caused by the greater activation to SCN than speech in the NH group. No other main or interaction comparisons were significant ($p > 0.1$).

HbR results were more sensitive to differences between the groups. The HbR maps above showed significant effects of SNR and the interaction between SNR and stimulus type in the NH group (Figures 4.15, 4.19). There was also a small area with greater activation to speech than SCN in the CI group and an area in the posterior STG that showed decreasing activation with improving SNR in the CI group (Figure 4.11, 4.15). This SNR effect was opposite to that seen in the NH group in a more anterior portion of the STG. The ANOVA revealed a significant interaction between stimulus type and SNR as well as a three-way interaction between group, stimulus type, and SNR. These results support the apparent differences in interaction effects between the groups seen in the t-statistical maps above. In summary, HbO results showed no evidence of group differences but HbR results supported the apparent difference between the groups in the interaction of stimulus type and SNR.

Discussion

The results for Experiment II support the potential for fNIRS as an objective measure of speech recognition at a group level. The variability across individuals, however, might limit the potential of individual data. Although the main purpose of this experiment was to examine the effect of speech recognition performance on cortical activation using fNIRS, the design allowed the examination of stimulus type and SNR effects. Thus, we will first discuss the main effects of stimulus type and SNR. Then we will discuss the effect of speech recognition performance. We will finish the discussion by contrasting HbO and HbR data, comparing the NH and CI groups,

and summarizing the potential of fNIRS as an objective measure of speech recognition performance based on the results.

Stimulus Type

The HbR activation was somewhat similar between groups overall, but the specific areas of significant stimulus type effects were different. Specifically, the NH group showed greater activation to the SCN stimuli than speech in the anterior superior corner of the array, near Broca's area. On the other hand, the CI group showed a small area of greater activation to speech than SCN stimuli in the middle temporal gyrus or STG/STS. In contrast, the HbO activation maps show a significantly greater activation to speech than SCN stimuli in the primary auditory cortex and Wernicke's area in the NH group. This effect is absent, not just non-significant, in the CI group. This group difference was supported by the ANOVA analysis as well. HbO maps also showed greater activation to SCN stimuli than speech in the NH group and in all participants in the STG/STS, particularly in the posterior portion, and in the superior portion of the array near the somatosensory cortex. These differences were not significant in the CI group. *Thus, these data provide evidence that fNIRS is sensitive to auditory stimulus characteristics, such as the differences in speech and SCN stimuli in both Wernicke's area and the STG/STS.*

It is important to note that the coils in the CI group possibly influenced the group difference in Wernicke's area. As previously noted, only one participant with a CI had a coil placement that was outside the fNIRS optode array. All of the other CI participants had a coil in the posterior portion of the array and channels 13 and 18 were the channels that were most affected. Both channels fell in the Wernicke's area ROI and channel 13 was one of the channels with significantly greater activation to speech than SCN stimuli in the NH group. This is likely to be an issue in any CI population because, although coil placement varies, many are near the area

overlying Wernicke's area. Further research is needed to determine the exact brain areas that might be obstructed by coil placement in a CI population.

The NH group showed a trend to greater activation to speech than SCN stimuli in the STG/STS that was not significant as in the CI group for HbR data. The NH group also had greater activation to SCN stimuli than speech in the same area for HbO data that was not present in the CI group. It is possible that these group differences were influenced by the difference in stimuli between the groups. The NH group listened to vocoded speech to equate performance on speech recognition with the CI group while the CI group listened to unprocessed "natural" speech. It is possible that this difference influenced the effect of stimulus type in our results. Indeed, Pollonini et al. (2014) found that fNIRS detected differences in cortical activation between unprocessed and vocoded speech for HbR data but found no difference between intelligible and unintelligible vocoded speech. Although their unintelligible vocoded speech stimuli were scrambled frequency channels rather than a single channel vocoder like our SCN stimuli, the comparison of intelligible and unintelligible speech might be more similar to our comparison of vocoded speech to SCN than unprocessed speech to vocoded speech. That might be why we did not see a significant effect of stimulus type in the NH group for HbR data.

The greater activation to SCN stimuli than speech in the HbO data in the NH group and when all participants were included might also have been influenced by the effect of vocoding on speech. This difference was found in the STG/STS, particularly the posterior portion, as well as in a portion of Broca's area and the somatosensory cortex. Stoppelman et al. (2013) used SCN and speech stimuli to locate functional areas of speech processing. They found greater activation to speech than SCN stimuli in the posterior STG/STS similar to our area in HbO data near Wernicke's area. It is opposite to our finding of greater activation to SCN stimuli in the area

inferior to Wernicke's area, part of the posterior STG/STS. They also found greater activation to speech than SCN in the anterior STG/STS and the inferior frontal gyrus. We again found the opposite effect for HbO data, but a non-significant trend to the same effect in HbR data. Further research is needed to determine the effect of vocoding on cortical activation and the difference between unprocessed speech and SCN using fNIRS in NH individuals.

Previous research in fMRI has used vocoding to examine the effects of speech recognition/intelligibility. These studies varied the number of vocoder channels to control speech recognition and examine its effect of cortical activation. In general these studies found increasing activation with increasing speech recognition/vocoder channels in the anterior STG/STS, Broca's area, and Wernicke's area (Obleser et al., 2008; Obleser et al., 2007; S. K. Scott et al., 2000; Sophie K. Scott et al., 2006). Our current HbO results in Wernicke's area in the NH group and HbR results in the STG/STS in the CI group and the same trend in the NH group are consistent with this research. In contrast, again the HbO results in the NH group in the STG/STS and in Broca's area showed the opposite effect with greater activation for unintelligible SCN stimuli. Other than the image modality difference, another difference between the current experiment and the previous research is most of those studies had a task even if it was simply rating how well they could understand the stimuli. We used no task to limit the movement of the participants and in anticipation of future work in children who might have difficulty completing a task. Active tasks and increased attention have been shown to increase activation in auditory experiments (Lutz Jäncke et al., 1999). Processing vocoded (degraded) speech requires attention (Wild et al., 2012). Thus, using an active task to increase attention might have changed our results. Again, further research is needed to determine if the cause of this effect, whether it be vocoded speech compared to SCN stimuli, an effect of task, or artifact in the data.

SNR

 The main effect of SNR is closer to the purpose of the experiment: to determine the effect of speech recognition performance on cortical activation using fNIRS. This main effect, however, examines changes in cortical activation with SNR for both speech and SCN. Of course the intelligibility or speech recognition performance for SCN stimuli does not change with SNR, as it is always zero percent. We did find main effects of SNR found in both groups in this experiment. The NH group had a significant effect of SNR for both HbO and HbR activations. For HbO activation, the NH group showed increasing activation with improving SNR in the middle STG/STS and the posterior STG/STS as well as in the dorsolateral prefrontal cortex near Broca's area. For HbR activation, the NH group showed increasing activation with improving SNR again in Broca's area, in the middle temporal gyrus/STS and in a small area near the primary auditory cortex and Wernicke's area. In contrast, the CI group only had a significant effect of SNR in HbO activation. The CI group had increasing activation with improving SNR in a part of Wernicke's area and decreasing activation with improving SNR in the posterior STG/STS.

 Previous research has examined the effect of SNR on cortical activation using fMRI for speech recognition (Jeffrey R Binder, Liebenthal, Possing, Medler, & Ward, 2004; Wong et al., 2008). Wong and colleagues also used three SNRs in their experiment: quiet, +20, and -5 dB. Participants were asked to identify the presented word as one of three pictures presented visually. They found an increase in activation at poorer SNRs in many areas, which we did not find, other than in the CI group in the posterior STG/STS. This finding in the CI group is consistent with their results for both speech recognition in noise compared to quiet as well as speech recognition at a -5 dB SNR compared to the better +20 dB SNR. Wong and colleagues did not report an

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analysis of areas with greater activation for speech in quiet than speech in noise. They did, however, report greater activation for the +20 dB SNR than the -5 dB SNR in the anterior left STS/STG and the left fusiform gyrus. These results are consistent with our findings of increasing activation in the STS/STG and near the fusiform gyrus of the NH group for both HbO and HbR data. Binder et al. (2004) used a simpler task of syllable discrimination in white noise and found a general increase in activation in bilateral STG/STS region with increasing performance and a correlation with response time in the inferior frontal gyrus. Because response time decreased with improving SNR, this would indicate that activation decreased with improving SNR in the inferior frontal gyrus. Our data showed the same increase in activation with improving SNR in the STG/STS, other than the small region in the CI group, in both groups. We found no evidence of activation decreasing with improving SNR in Broca's area, however. Because our main effect of SNR included both speech and SCN, the comparison to previous studies might be difficult. Therefore, we will briefly examine the effect of SNR on speech stimuli only to compare to the previous studies.

The group t-statistic maps for the effect of SNR on speech [1 -.25 -.75 0 0 0 0 0 0][9] evoked activation in HbO and HbR data are shown in Figures 4.27 and 4.28, respectively. The NH group had a significant increase in activation with improving SNR in the anterior STG/STS in both HbO and HbR, consistent with the previous studies. They also had a small area near Broca's area and the prefrontal cortex with significant increase in HbO activation with improving SNR and a superior portion of the prefrontal cortex with an increase in HbR activation with improving SNR. These results are opposite to those shown in Wong et al (2008)

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[9] Multiple regression matrix using contrast coding (summing to 1 and -1) for the SNR effect of only speech stimuli.

and Binder et al (2004) studies. In contrast, the CI group had a large area in the prefrontal cortex and Broca's area expanding in to the motor cortex with a significant decrease in HbO activation with improving SNR. They also had an area in the posterior superior portion of the array near the somatosensory cortex and Wernicke's area with an increase in HbR activation with improving SNR. The result in the prefrontal cortex and Broca's area in the CI group is consistent with both the previous studies of SNR on speech recognition (Jeffrey R Binder et al., 2004; Wong et al., 2008).
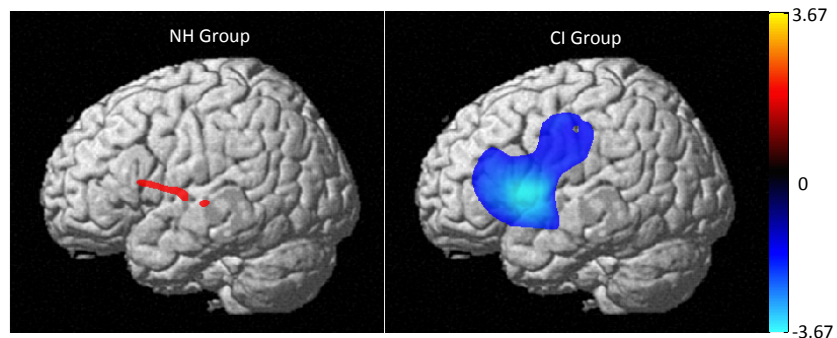
Figure 4.27: HbO t-statistical maps for the effect of SNR on speech stimuli evoked activation with a threshold of $p < 0.05$, uncorrected for multiple comparisons. The color map represents t-value with a high t-values (yellow) indicating greater activation for better SNRs.
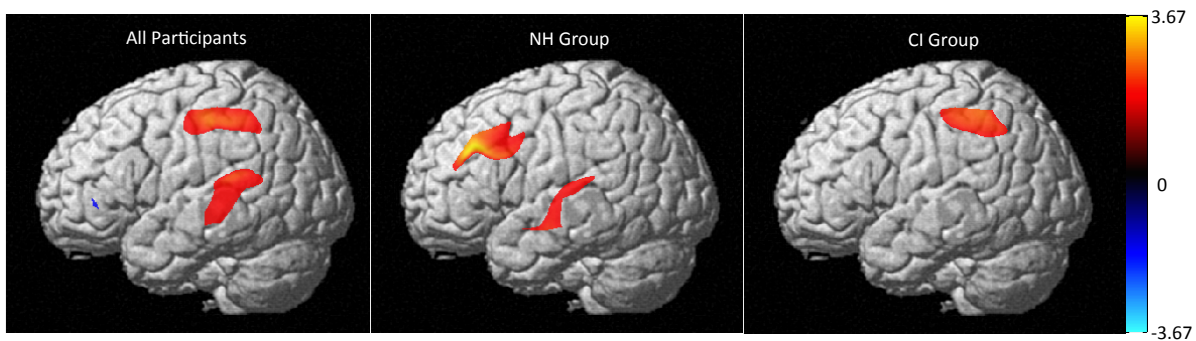
Figure 4.28: HbR t-statistical maps for the effect of SNR on speech stimuli evoked activation with a threshold of $p < 0.05$, uncorrected for multiple comparisons. The color map represents t-values with a high t-value (yellow) indicating greater activation for better SNRs.

In summary, the results of SNR analyses were in some cases consistent with previous literature but also some discrepancies were found. Additionally, there appeared to be a large

difference between the groups for SNR effects in the prefrontal cortex and the anterior STG/STS. The difference in the anterior STG/STS was supported with ANOVA analyses as well. Wong et al (2008) suggested that the differences between their results and those of the Binder et al (2004) study might be based on task. Our study contained only a passive listening task, and it is possible that this caused no only the differences between our results and the previous literature but also the difference between the groups. It is also possible that the vocoding of the speech for the NH group again influenced the results. Future research is needed with a better-controlled task and vocoded and unprocessed speech in NH participants. In spite of those weaknesses, the results support and a main effect of SNR, even when only speech stimuli are considered in both groups.

Interaction and Speech Recognition Performance

Now we will discuss the main purpose of this experiment, the effect of speech recognition performance on cortical activation measured by fNIRS. We examined this question with two contrasts, one to examine the interaction between stimulus type and SNR and the other to examine the effect of speech recognition performance on only speech stimuli. The interaction sought areas where the activation increased with improving SNR for speech but not for SCN. Thus, it is an effect of intelligibility, not just SNR. Both of these effect contrasts revealed similar results to the SNR effect for only speech stimuli in Figures 4.27 and 4.28.

The interaction effect revealed a trend in the NH group for HbO activation in the same areas that had significant type and SNR effects, Wernicke's area and the STG/STS. The interaction effect, however, was not significant. In contrast, the CI group showed an opposite interaction effect spanning the superior portion of the array from Wernicke's area to Broca's area. Again, this is consistent with the SNR effect for only speech stimuli showing a decrease in activation with improving SNR in this group.

The interaction effect for HbR activation was not as different between the groups but still showed different areas of significance. The NH group had a significant interaction effect in the anterior STG/STS near the same area they had a significant SNR effect for both speech and all stimuli. In contrast, the CI group had a significant interaction effect, this time in the same direction with increasing activation with improving SNR for speech, in the posterior-superior corner of the array near the somatosensory cortex and Wernicke's area. This is the same area that showed a significant effect of SNR for only speech stimuli in the CI group.

As previously stated, the speech recognition performance contrast of only speech stimuli revealed perhaps the largest apparent group difference in HbO activation. The NH group had three areas of increasing activation with improving speech recognition that included an area in Wernicke's area near the significant effect of stimulus type, and areas in the anterior STG/STS and in Broca's area. The last two areas are similar to those found in the SNR effects for HbO activation in the NH group. The CI group, on the other hand, had a large area of decreasing activation with improving speech recognition similar to that seen in the SNR contrast for only speech stimuli and the interaction contrast, as well as another area of decreasing activation with improving SNR in Wernicke's area inferior to the area in the NH group. These can be seen again in Figure 4.23. In HbR activation on the other hand, the results are almost identical to those of the SNR effect for only speech stimuli in Figure 4.28.

The effects of speech recognition performance in the NH group are similar to those shown in the literature. Specifically, activation increases with improving speech recognition in the anterior STG/STS, in Broca's area or the inferior frontal gyrus, and in Wernicke's area or the posterior STG/STS (Jeffrey R Binder et al., 2004; Obleser et al., 2008; Obleser et al., 2007; S. K. Scott et al., 2000; Sophie K. Scott et al., 2006; K. Strelnikov et al., 2011; Wong et al., 2008).

These areas continued to be significant when we examined the difference between activation for speech at 75% and 50% performances with greater activation for the 75% condition. Thus, fNIRS appears to be able to detect differences as small as 25-percentage points in speech recognition performance at a group level based on SNR. The CI group, on the other hand, was not as consistent with the literature but still had significant effects of speech recognition performance.

There is understandably not as much neuroimaging literature in the CI population as there is in the NH population. The limited research in the CI population using PET does support similar activation patterns in the two groups with bilateral CIs (Coez et al., 2008; Coez et al., 2011; Green et al., 2005, 2011; Green et al., 2008; Kuzma Strelnikov et al., 2011). Strelnikov et al (2011) found that participants using bilateral CIs had more similar activation to NH controls than when they used either CI alone. They found that activation patterns between the two groups were similar, with small areas of greater activation in the NH group in the right STS, which was not included in the optode array for this experiment. Coez et al (2011) also reported no difference between the PET results of CI participants with bilateral CIs and NH controls during a passive listening task to voice and non-voice sounds. In an earlier study, however, Coez et al (2008) found that only good performing CI participants had no difference in PET results to speech stimuli. The participants in this study were at or above average performance for CNC word recognition, as compared to the mean outcomes in the literature. Finally, Green et al (2005, 2008, 2011) found that cortical activation in participants with CIs changes with CI experience up to at least one year. All the participants in this study, with the exception of CI1 who was not included in fNIRS analyses, had more than one year CI listening experience. Thus, we predicted

that we would see similar activation effects in the two groups, as long as the CI coils did not influence results.

The CI coils were in the region of Wernicke's area and might have impacted results in this region. In contrast, there were no coils near the anterior STG/STS or Broca's area. In these regions we saw either no significant effect in the CI group or the opposite effect to that of the NH group, decreasing activation with increasing speech recognition performance. Thus, if we expect to see the same activation patterns in both CI and NH groups, the group differences could be due to differences in the task they were performing or attention they gave to the stimuli, the difference in the vocoded compared to unprocessed speech, differences in the group sizes, as well as differences in processing between the groups. These factors will be further discussed below.

NH Group vs. CI Group

Experiment II provided substantial evidence of differences in fNIRS responses between the NH and CI groups. The evidence included differences in the effects of stimulus type, SNR, and their interaction. ANOVA analyses supported the evidence of group differences for Wernicke's area and the STG/STS. Perhaps the greatest piece of evidence for a difference in results between the groups was the comparison of the speech recognition performance contrast of HbO activation. This contrast showed opposite effect between groups with activation increasing with speech recognition performance in the NH group and decreasing in the CI group. We have noted a few possible causes of the group differences and will elaborate on those causes here.

The first possible cause only applies to the posterior portion of the array, particularly Wernicke's area. As previously mentioned, the coils for the CIs for all but one participant obstructed fNIRS channels in the posterior option of the array. Specifically, channels 13 and 18

were most affected. Both of these channels were included in the Wernicke's area ROI. It is

possible that the CI group results would be different if all CI coils were outside of the optode

array. Coil placement, however, is likely to be an issue in all CI populations if using an optode

placement to include the primary auditory cortex and Wernicke's area. Thus, this is a limitation

of fNIRS in this population, but it should be limited to a restricted anatomical area. It is

important to note that this issue is not limited to fNIRS. Coils and the internal CI also obstruct

the placement of electrodes for EEG and create artifact in fMRI and magnetic encephalography

(MEG) when these are approve with the CI. Future research is needed to determine the range of

coil placements in the CI population and their effect on the use of fNIRS in this population.

Another possible cause of differences between the groups is the size of the groups. A

limitation of this study is that the CI group is smaller than the NH group (11 and 14 participants,

respectively). It is possible that a larger CI group would have altered the results. Additionally,

there were a couple of participants who were prelingually deafened while the remaining nine

participants were postlingually deafened. This highlights the diversity in the clinical population

that might have influenced results. Previous research has found differences between activation

patterns based on duration of deafness, CI listening experience, and first and second CIs (Green

et al., 2005, 2011; Green et al., 2008). There was substantial variability in individual data making

it difficult to interpret differences between individuals. Thus, we do not know whether there was

a difference between the prelingually deafened and postlingually deafened CI participants. The

two prelingually deafened participants had always used spoken language to communicate and

both performed similar to the rest of the CI group on speech recognition tasks. The two had very

different histories of hearing loss and CI use than the rest of the group. We examined the results

without the two prelingual participants, however, and found very little difference in the outcomes, indicating they had little effect on the results.

There were also some individual CI participants with large asymmetries in performance between their ears. Specifically, four participants had moderate differences in CNC word recognition between the ears (14- to 34-percentage points), and two had extreme differences in performance between the ears (CI2 and CI11 exhibited interaural differences of 64- and 92-percentage points, respectively). It is possible that these asymmetric participants would have had different activation patterns for each ear, similar to the differences between first and seconds CI Green and colleagues found with PET (Green et al., 2011). As a reminder, however, all fNIRS procedures were completed in the bilateral CI condition, hopefully limiting ear-specific effects. The interaction of ears could still have influenced cortical activation results as has been shown in both adults with NH and CIs (Green et al., 2011; L. Jäncke et al., 2002). Thus, we examined the effects of stimulus type and SNR in the CI participants with minimal asymmetry between ears (<10 percentage points) and with some asymmetry to examine the effect of asymmetry on the results.

Figure 4.29 shows the HbO activation maps using the speech recognition performance contrasts for the full CI group as well as the participants with near symmetrical performance between the ears and the participants with an asymmetry in performance. All three maps have thresholds of $p < 0.05$, uncorrected for multiple comparisons. The maps show an apparent difference between the asymmetric and symmetric groups. Particularly there is an area in the middle STS that shows an increase in activation with improving speech recognition in the symmetrical CI group and a decrease in activation in the same area in the asymmetrical CI group. This area in the symmetrical CI group is near the area in the NH group in the anterior

STS/STG that shows the same speech recognition effect. Thus, it appears that asymmetric performance between the ears might affect activation patters, even for bilateral conditions and it should be controlled for in future studies. Even when only including the symmetric CI group, however, the activation pattern is different from that in the NH group. In fact the area of decreasing activation with improving speech recognition that is opposite of the effect seen in the NH group increased in strength compared to the entire CI group. Thus, though the asymmetry in some CI participants might have influenced results it is unlikely that it caused all group differences between the NH and CI groups.
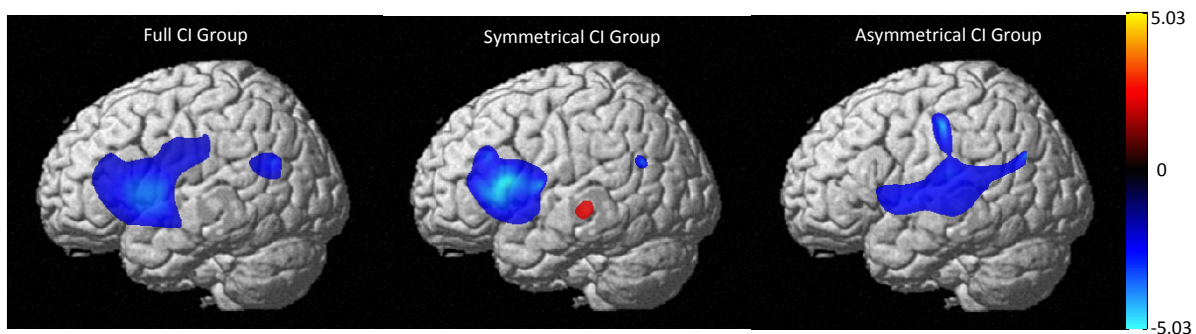
Figure 4.29: HbO t-statistical maps for the effect of speech recognition performance with a threshold of $p < 0.05$, uncorrected for multiple comparisons. The color map represents t-values with a high t-value (yellow) indicating greater activation for improving speech recognition.

Another reason for differences between the groups could be the vocoding used in the NH group for speech stimuli to equate performance between the groups at similar SNRs. It is possible that the comparison of vocoded speech to SCN had different effects on cortical activation than the comparison of unprocessed speech to SCN, even with performance matched between vocoding and SCN. There is evidence that the effect of speech recognition or intelligibility is present with or without vocoding. Narain et al (2003) found that both unprocessed and vocoded speech evoked greater activation in Wernicke's area and the middle and anterior STS compared to reversed speech. It is still possible that the comparison to SCN

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would reveal different results. Therefore, future research is needed to determine the effect of vocoding, without changes in performance, on cortical activation.

Another possible reason for differences between the groups is a difference in attention to the stimuli. We used a passive listening task to limit movement and in looking forward to future work with young children. It is possible that the two groups differed in the attention and effort they put into listening and understanding the stimuli. It is especially possible that the CI group attended more closely to the stimuli, as they are typically very invested in auditory research and speech understanding. Previous research has found an effect of attention of cortical activation in auditory research (Choi, Wang, Bharadwaj, & Shinn-Cunningham, 2014; Lutz Jäncke et al., 1999). Most of our results showed greater activation in the NH group, however, which would indicate greater attention in the NH group than the CI group.

Another possible reason for the differences between the groups is a difference in task performed by the two groups. The passive listening task we used was fairly undefined. It is possible that the two groups performed different tasks. There is also auditory research in fMRI showing an effect of task on cortical activation (J. R. Binder, Swanson, Hammeke, & Sabsevitz, 2008). Generally, the more active the task, the greater the activation. Even though introducing a task risks more motion artifact, a more controlled active task should be used in future research to compare these two groups.

One last possible reason is that cortical processing for speech recognition differed between the two groups. Although there is little evidence of different cortical activation patterns in a CI group compared to a NH group, there is ample evidence of changes in activation with auditory deprivation (Butler & Lomber, 2013; Doucet, Bergeron, Lassonde, Ferron, & Lepore, 2006; Fine, Finney, Boynton, & CDobkins, 2005; A Kral, Hartmann, Tillein, Heid, & Klinke,

2002; Andrej Kral & Tillein, 2006; A. Kral, Tillein, Heid, Hartmann, & Klinke, 2005). Most of this research has been shown in children with congenital deafness or at least a prelingual onset of deafness. Most of the CI participants in this study had a postlingual onset of deafness. There is some evidence of changes with auditory deprivation in adulthood and differences between the cortical activation patterns of NH control and CI groups during speech processing (Giraud et al., 2000; Musiek & Daniels, 2010; Rouger et al., 2012). Research with experienced CI listeners with two CIs similar to our participants, has always found the groups' activation patterns to be similar. Further research is needed to determine if any differences exist between the two groups in cortical processing when completing the same task.

HbO vs. HbR

Just as we noted in Chapter III, HbO and HbR results should be strongly, although not perfectly, negatively correlated as shown in the predicted hemodynamic response function (Cui et al., 2010). Thus, when using negatively correlated general linear models for HbO and HbR we would expect to find similar results for each hemoglobin type. Just as in Chapter III, HbO and HbR results were not very similar and in some cases they appear to be opposite to each other. Cui et al (2010) suggested that such a finding suggests movement artifact in the data. We imposed a wavelet analysis in an attempt to reduce movement artifact in the data but it is possible some noise remained in the data and is causing the differences between HbO and HbR results. As stated in Chapter III, we also completed analyses using spline correction in the Homer2 software package and the wavelet analysis algorithm in the NIRS-SPM software (Jang et al., 2009; Scholkmann et al., 2010). Both of these noise management methods revealed similar results to the wavelet analysis used in this experiment. There is no consensus in the literature of a best noise management strategy for fNIRS and many have been suggested. As we did with

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Experiment I, we also completed the noise management strategy suggested by Cui et al (2010). This strategy assumes that HbO and HbR data are perfectly negatively correlated, which is not completely correct, and removes positively correlated energy from the data. The results are briefly described below. Because the HbO and HbR data are assumed to be perfectly correlated, only the HbO data are shown.

The activation patterns remain very different between the two groups as shown in Figures 4.30 and 4.31. The NH group continues to have an area of increasing activation with improving speech recognition in the anterior portion of the left STG/STS. This is consistent with the HbO and HbR results reported above as well as the literature. There is also an area of increasing activation with improving speech recognition in the superior dorsolateral prefrontal cortex near Broca's area that was present in the HbR results reported above. The area that showed a significant increase in activation with improving speech recognition in Wernicke's area for the HbO data reported above, however, was not present in this result. In contrast, the CI group showed similar results to those in the HbO data reported above but with only a small area of significance in the posterior portion of the array, the posterior STG. Again, the results in the anterior portion of the array near Broca's area and the anterior STG/STS suggest a difference in the speech recognition effects between the NH and CI groups.
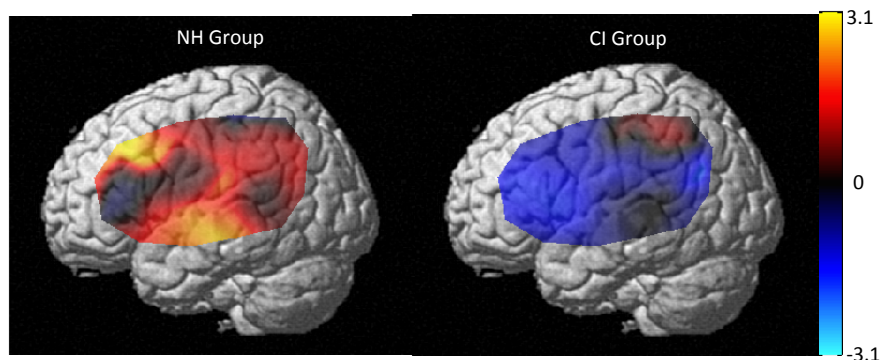
Figure 4.30: HbO t-statistical maps for the effect of speech recognition performance on speech stimuli only. The color map represents t-values with a high t-value (yellow) indicating greater activation for better performance.
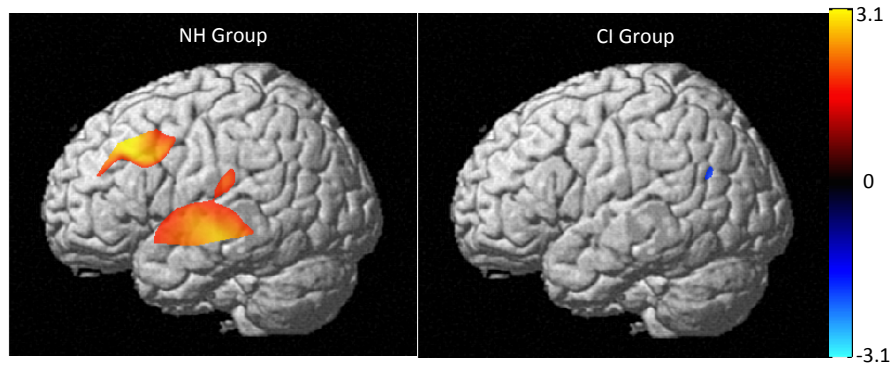
Figure 4.31: HbO t-statistical maps for the effect of speech recognition performance on speech stimuli only with a threshold of p < 0.05, uncorrected for multiple comparisons. The color map represents t-values with a high t-value (yellow) indicating greater activation for better performance.

Potential of fNIRS as Objective Measure of Speech Recognition

As previously mentioned, the results of this experiment revealed large variability in the individual data of both the NH and CI groups. Similar substantial variability was found in Experiment I. As noted in Chapter III, this inhibits the potential use of fNIRS for clinical use in individual patients because an expected typical response template cannot be developed at this time. If fNIRS is reliable within an individual over time, however, it could be used to examine auditory development in children with CIs, progress in speech recognition over time, and changes in processing between listening conditions. Blasi et al (2014) showed fair reliability for the area of activation for sound compared to a quiet baseline at the individual level (r > 0.5) and good reliability at the group level (r > .9). Further research on the repeatability of fNIRS, particularly within an individual and for differences between auditory stimuli such as degrees of speech recognition, is needed to determine the potential of fNIRS as an objective measure of speech recognition within an individual.

The current experiment supports the potential of fNIRS as an objective measure of speech recognition at a group level. The results indicate that in both NH and CI groups' activation changed with speech recognition changes. It is important to note that the minimum speech recognition difference between conditions in this experiment was roughly 20- to 25-percentage points. Thus, it is possible that detection of a smaller difference in speech perception within or between groups might be difficult or impossible, especially within a reasonable time frame for testing. Further research is needed to determine if smaller differences in speech recognition can be detected.

This experiment allowed examination of speech recognition effects on auditory cortical activation independent of SNR. Thus, we predict that any variable that systematically varies speech recognition performance should show these results, in addition to others that might be specific to that variable, such as spectral resolution. It is important in any design, however, that other variables that interact with speech recognition be controlled just as SNR was in this experiment. For example, when examining the change in speech recognition performance with the addition of a hearing aid in the same ear as a CI for electroacoustic hearing, carefully controlling perceptual loudness levels might be very important as suggested in Chapter III. The interaction between stimulus level and speech intelligibility as well as other factors and their influence on the potential of fNIRS in the CI population will be discussed further in Chapter V.

Conclusions

In conclusion, this experiment provides evidence for the potential of fNIRS as an objective measure of speech recognition performance in a group of NH individuals or individuals with CIs. Both HbO and HbR results showed significant a significant effect of speech recognition in both the NH and CI groups, albeit in different areas for each group. The results

also suggest possible limited potential for the used of fNIRS as a measure of speech recognition in an individual due to the substantial variability across participants. Further research is needed on the reliability of speech recognition effects within an individual over time to further examine fNIRS's potential for this purpose. Finally, the results suggest differences in activation patterns between the NH and CI groups. The reason for these differences is unknown and further research is needed to determine if there are differences in the effect of speech recognition on cortical activation for the two groups.

CHAPTER V

GENERAL DISCUSSION

The long-term goal of this research was to determine the potential of fNIRS as an objective measure (i.e. not requiring a response) of speech recognition in individuals with CIs. An objective measure of speech recognition in young children who have difficulty with behavioral testing could direct recommendations for rehabilitation such as programming adjustments, changes in therapy recommendations, and additional device recommendations such as a second CI or use of remote microphone technology such as an FM system. For example, if an objective measure of speech recognition showed limited or no benefit from a hearing aid in the contralateral ear of a young child with a unilateral CI, a second CI in the non-implanted ear could be recommended.

Neuroimaging methods including fMRI, PET, and EEG have shown potential as objective measures of speech recognition in NH individuals as well as those with CIs (Coez et al., 2008; Coez et al., 2011; Fujiki et al., 1998; Giraud et al., 2000; Green et al., 2005, 2011; Green et al., 2008; Narain, 2003; Obleser et al., 2008; Obleser et al., 2007; Pantev, Dinnesen, Ross, Wollbrink, & Knief, 2006; Sophie K. Scott et al., 2006; K. Strelnikov et al., 2011; Kuzma Strelnikov et al., 2011). PET and fMRI are contraindicated with CIs or in children and are generally expensive. They also are very sensitive to any participant movement. Even if cleared for fMRI, the implanted magnet obstructs visibility of cortical activity up to several cm surrounding the magnet. EEG is less expensive and tolerates more movement, but methods must include the rejection of electrical artifact from the CI, limiting its potential. Additionally, as

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previously mentioned its spatial resolution is relatively poor. For these reasons, this dissertation and future work will examine the potential of fNIRS in the CI population, adults and children.

fNIRS is relatively inexpensive and might have slightly better spatial resolution than EEG. Additionally, because it uses near-infrared light there is no electrical artifact from the CI in the recorded responses. For these reasons research has begun to examine the potential of fNIRS in CI populations. Previous research has found that fNIRS can detect auditory cortical responses in adults and children with CIs and that it can detect differences between unprocessed speech and vocoded speech in adults with NH and with CIs (Olds et al., 2015; Pollonini et al., 2014; Sevy et al., 2010). Other research has also shown that fNIRS can detect differences in auditory cortical activity in NH children and adults based on stimulus characteristics, such as phonemes or emotional content (Ehlis et al., 2009; Homae et al., 2012; Kotilahti et al., 2010; Plichta et al., 2011; Telkemeyer et al., 2011). This dissertation expanded on previous research by examining the sensitivity of fNIRS to speech recognition performance in quiet and in noise and stimulus intensity level differences in NH adults and adults with CIs. Future work will expand the testing to children, where the potential of fNIRS has the greatest clinical implications.

Stimulus level and speech recognition performance

The main effect of interest in this dissertation is the effect of speech recognition performance on auditory cortical activation. The effect of stimulus intensity level was also examined because it is known to affect auditory cortical activation measured with fMRI and EEG (Hall et al., 2001; L Jäncke et al., 1998; Langers et al., 2007; Mulert et al., 2005; Sigalovsky & Melcher, 2006) as well as behavioral speech recognition performance, particularly in CI listeners (Firszt et al., 2004; Skinner et al., 1997). The effect of stimulus level is important

to examine relative to speech recognition effects, because some variables that change speech recognition involve changes in stimulus level or perceived loudness, such as the addition of a hearing aid in the same or contralateral ear to a unilateral CI. The effects of stimulus level examined in Experiment I were described in Chapter III and the effects of speech recognition examined in Experiment II were described in Chapter IV. We will briefly summarize the results again here and then compare the effects and different areas of activation for the two variables.

Both NH and CI groups showed significant changes in activation with changes in stimulus intensity level in Experiment I. Specifically, activation increased for higher stimulus levels and perceived loudness in the left middle to posterior STG/STS and MTG and decreased with increasing stimulus level in the left DL-PFC and Broca's area. All of these changes were significant for HbR, which was more sensitive than HbO.

In Experiment II, both HbO and HbR results showed a significant effect of speech recognition in both the NH and CI groups, albeit in different areas for each group. The results suggest differences in activation patterns between the NH and CI groups. The NH group showed increased activation with higher levels of speech recognition in the middle to anterior STG/STS, in the DL-PFC and Broca's area, and in a portion of the supramarginal gyrus of Wernicke's area. In contrast, the CI group showed decreased activation with better speech recognition in similar areas: the middle to anterior STG/STS, the dorsolateral prefrontal cortex and Broca's area, and the angular gyrus of Wernicke's area. They also had an area of increasing activation with increasing speech recognition in the superior portion of the supramarginal gyrus of Wernicke's area.

To compare the effects of stimulus level and speech recognition performance on activation, we first examined HbR results because they showed significant effects of both

variables in the NH group. The results for both variables are represented in Figures 5.1 and 5.2. Ignoring statistical significance, activation in the middle and posterior STG/STS increased with speech recognition performance and increased with higher stimulus levels in both groups. Both groups also had decreased activation in the inferior DL-PFC and Broca's area with higher levels of speech recognition and higher stimulus levels. Additionally, HbO results for both groups showed similar trends for both variables (Figures 3.18 and 4.22). Thus, speech recognition and stimulus level had similar effects in the posterior STG/STS and Broca's area in both groups.
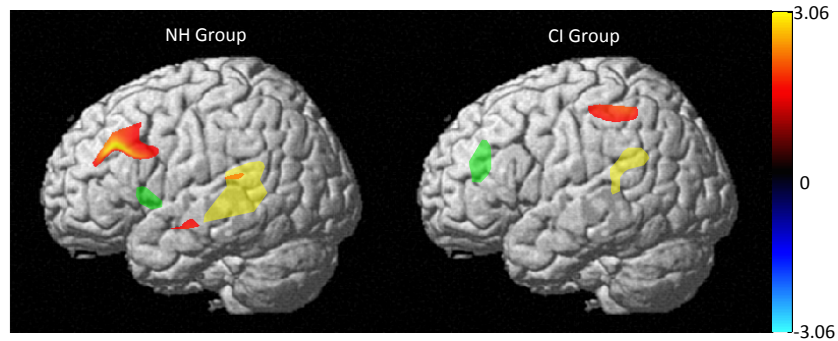
Figure 5.1: HbR t-statistical maps for the effect of speech recognition performance and stimulus level with a threshold of p < 0.05, uncorrected for multiple comparisons. The color map represents t-values with a high t-value (yellow) indicating greater activation for higher performance. The areas with a significant effect of stimulus level are represented in yellow and green shaded regions for positive and negative effects of level, respectively.
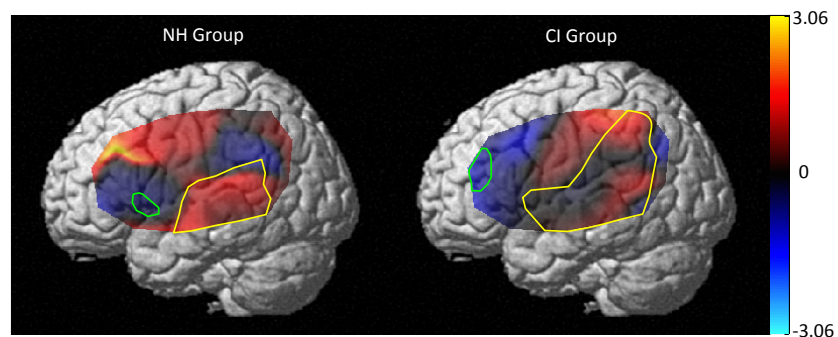

Figure 5.2: HbR t-statistical maps for the effect of speech recognition performance and stimulus level. The color map represents t-values with a high t-value (yellow) indicating greater activation for better speech recognition performance. The areas representing an effect of stimulus level are outlined in yellow and green for positive and negative effects of level, respectively.

The NH group did show a difference between the two variables in the anterior STS and the superior DL-PFC. They had increases in activation with better speech recognition performance in these areas, but a non-significant decrease in activation for higher stimulus levels. The NH group also had a significant area of interaction between stimulus type and SNR, indicating an effect of speech recognition performance in the anterior STS (Figure 4.21).

In summary, the middle and posterior STG/STS increased in activation with increases in speech recognition performance and stimulus level. Although significance varied, this trend was present in both NH and CI groups for HbR results. These results are consistent with previous literature showing increases in activation with speech recognition performance and stimulus level in similar areas (Coez et al., 2008; Coez et al., 2011; Green et al., 2005; Green et al., 2008; Hall et al., 2001; L Jäncke et al., 1998; Langers et al., 2007; Mulert et al., 2005; Narain, 2003; Obleser et al., 2008; Obleser et al., 2007; Sigalovsky & Melcher, 2006; K. Strelnikov et al., 2011; Kuzma Strelnikov et al., 2011). In contrast, NH group activation in the anterior STG/STS and superior DLPFC increased with speech recognition with no evidence of an effect of stimulus level. The increase in activation with speech recognition in the NH group was present in both HbR and HbO results and is consistent with the literature (Narain, 2003; Nadav Stoppelman, Harpaz, & Ben-Shachar, 2013). The results in the DL-PFC and Broca's area varied across groups and HbR and HbO data. Parts of this region showed effects of speech recognition and stimulus level while others showed effects of only one of the variables. The data in the literature has varied somewhat as well and might vary based on speech recognition in quiet or in noise (e.g. S. K. Scott et al., 2000; Sophie K. Scott et al., 2006; Wong et al., 2008). Therefore, any research examining cortical activation in the middle to posterior STG/STS or in the region of the DL-PFC and Broca's area should carefully control for either of these variables when varying the other.

Additionally, the anterior STG/STS might be more specific to speech recognition processing than general auditory processing as has been suggested by previous research.

NH group vs. CI group

Experiments I and II revealed similarities and differences between speech recognition and stimulus level effects as well as between the NH and CI groups. Experiment I revealed similar results in both groups with an increase in activation with stimulus level in the posterior STG/STS. The CI group appeared to have a smaller area of significant activation but an ANOVA revealed no significant difference between the groups. In contrast, Experiment II revealed significant differences between the groups in both the STG/STS and Wernicke's area. Previous research has been inconsistent when comparing NH and CI groups. Some studies have shown differences between the groups, including less activation in the CI group and additional cortical areas activated in the CI group for speech recognition tasks (Coez et al., 2008; Giraud et al., 2000; Naito et al., 2000; Olds et al., 2015). Other research has shown that differences between controls and CI participants were larger or only present in poor performers or newly implanted participants (Coez et al., 2008; Green et al., 2005; Green et al., 2008). In fact, the limited research including only participants with bilateral CIs and good performance has found little to no difference between NH and CI groups (Coez et al., 2011; Kuzma Strelnikov et al., 2011). Thus, we only included CI participants with bilateral CIs and more than six months experience with each CI to limit differences between the groups. There are still differences between the groups, however, that might have influenced our results. A number of possible reasons for the differences between the groups are discussed in Chapter IV. Possible reasons for the differences in the group comparisons between the two experiments will be summarized here.

One reason that was mentioned in Chapter IV and must again be mentioned again is the presence of the CI coil in the CI group. This reason is mostly relevant to Wernicke's area but does depend on the surgical placement of the CI. Neither group had significant activation in most of Wernicke's area for the SCN stimuli in Experiment I. Thus, perhaps the CI coils had little influence on the activation in Experiment I. In contrast, particularly for HbO results the NH group had significant activation in Wernicke's area while the CI group did not. The CI coil might have limited the activation in the CI group in Wernicke's area for Experiment II and caused the group difference.

Another possible reason that the group effect was only present in Experiment II is a difference in higher-level processing between the groups. Experiment I included only SCN stimuli with no intelligibility and the task only involved listening to stimuli of varied intensity level. In contrast, Experiment II included speech stimuli at difference SNRs. Although the tasks were both to passively listening to the stimuli, participants were instructed to attempt to understand what they could. Thus, it could be that there are differences between the groups in speech recognition processing that are not present in processing of unintelligible stimuli.

Much of the previous research showing differences in cortical activation between NH and CI groups with PET or fNIRS has been limited by differences between the groups, such as unilateral compared to bilateral hearing and performance differences (Coez et al., 2008; Naito et al., 2000; Olds et al., 2015). In contrast, this study matched speech recognition performance between the groups and only included individuals with bilateral CIs yet still showed differences in the speech recognition effects on activation between the groups. It is possible that this study revealed differences between the groups that have not been shown before because it included speech recognition in noise.

As far as we are aware this is the first study to examine cortical activation in CI participants for speech recognition in noise. Most previous studies have examined speech recognition in quiet or the differences in cortical activation for types of stimuli such as unprocessed speech, vocoded speech, and environmental stimuli. Previous research in NH individuals has found some differences in cortical activation for speech recognition in quiet compared to speech recognition in noise (Wong et al., 2008). CI listeners are known to have significant difficulty understanding speech in noise. It is possible that cortical activation patterns are different in NH and CI groups for understanding speech in noise. It is also difficult to conclude, however, that there is a difference in cortical processing between the groups for speech recognition because Experiment II included no active task. Future research is needed to further examine cortical activation in NH and CI groups for speech recognition in noise, particularly with active tasks to control attention and measure performance.

It is important to note that although we tried to match the NH and CI groups for age, speech recognition performance, and bilateral hearing, there were characteristics of the CI group in this study that could have influenced the current results. These characteristics include asymmetrical performance between ears in four participants and two participants with a prelingual onset of deafness. There was also some evidence that the effect of speech recognition performance was different between the participants with symmetric and asymmetric performance between their ears. Further research is needed to determine the impact of asymmetrical hearing between the ears on cortical activation.

The main purpose of the current study was not to compare the NH and CI groups. The sample sizes are relatively small and the CI group is diverse. Despite these limitations, the results

support differences between NH and CI groups for the effect of speech recognition on cortical activation. Future research is needed to determine the cause of the difference between the groups.

Potential of fNIRS in the CI population

The potential of fNIRS as an objective measure of speech recognition was discussed in Chapter IV. In summary, the results of Experiment II support the potential of fNIRS as an objective measure of speech perception at the group level. Variability across individuals might limit its potential within individuals. Further research is needed to determine the reliability of fNIRS within individuals across time. Although Experiment II found differences between the NH and CI groups, both groups had a significant effect of speech recognition on cortical activation. Thus, the data support the potential of fNIRS as a measure of speech recognition in both groups, possibly with different expectations for each group.

fNIRS might also have potential for other uses in a CI population. Some examples are a measure of loudness growth or changes with stimulus level, a measure of changes in activation with duration of deafness or CI stimulation, the development of speech processing in young children with CIs, as well as differences in cortical processing between sub-populations of CI listeners. The results of Experiment I support the potential of fNIRS as a measure of loudness growth or changes in cortical activity with stimulus level in groups with CIs. There are also observations and results from this study relevant to other potential uses of fNIRS in the CI population.

The first and probably most relevant finding was the complication of the CI coil near Wernicke's area. As previously mentioned, coil placement varies across individuals and a study of the variability in coil placement might be beneficial. In the participants in this study, 12 of the 13 CI participants had coils in the region of Wernicke's area. Thus, if this is representative of the

CI population fNIRS research might be limited in Wernicke's area for this population. The results found significant effects for both stimulus level and speech recognition in the left STG/STS and Broca's area supporting its potential outside the area of the coil.

Another finding in this study was that asymmetry in performance between the ears might influence cortical activation patterns, at least for speech stimuli. In Chapter IV, we examined the speech recognition performance effects in subgroups of the CI group with symmetrical and asymmetrical speech recognition between their ears. There appeared to be differences between the groups. No statistical comparison of the two subgroups was made and differences must be cautiously interpreted due to the small sample sizes. Any future research in groups with bilateral CIs should control for or examine any effects of asymmetry between the ears.

fNIRS is beginning to be used in the CI population by a number of research groups throughout the world. With fMRI, PET, and MEG being expensive and sometimes contraindicated in individuals with CIs or children fNIRS present a viable option for neuroimaging. The most important comparison for advantages and disadvantages, perhaps, is EEG. Some advantages and disadvantages of the two have been mentioned but more research is needed to determine when EEG, fNIRS, or both can best answer a research question in the CI population.

CHAPTER VI

CONCLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH

This dissertation examined the potential of fNIRS as such an objective measure, particularly of speech recognition in quiet and in noise, in adults with NH and adults with CIs. The specific aims were to determine

1) the effect of speech intensity level on auditory cortical activation and

2) the effect of speech recognition performance using changes in SNR on auditory cortical activation.

Experiment I revealed increased activation for higher stimulus levels and perceived loudness levels in the middle to posterior STG/STS in both adults with NH and adults with CIs, consistent with our hypothesis. Thus, any research examining cortical activation with fNIRS in these areas should carefully control for the stimulus level and perceived loudness of all presented stimuli.

Experiment II revealed increased activation with better speech recognition performance in the middle to anterior STG/STS as well as Broca's and Wernicke's area in the NH group, again consistent with our hypothesis. The anterior STG/STS showed more sensitivity to speech recognition performance than stimulus level effects consistent with previous literature. In contrast, the CI group had decreased activation in Broca's area, the DL-PFC, Wernicke's area, and the anterior STG/STS with better speech recognition performance, contrary to our hypothesis. Studies using an active task to control attention and measure performance for speech recognition in quiet and in noise should be undertaken to further examine differences between cortical activation in adults with CIs and adults with NH. Despite the differences between

groups, Experiment II supports the potential of fNIRS as an objective measure of changes in speech recognition performance in both NH and CI groups.

The results of this study regarding the potential of fNIRS were promising at the group level but limited at the individual level due to the variability across individuals. Studies should examine the reliability of fNIRS measured speech recognition effects over time to determine its potential within an individual.

Finally, an objective measure of speech recognition and other auditory processing in the CI population has the greatest potential in groups that are difficult to test behaviorally, such as young children. Because this study found evidence of the potential of fNIRS as an objective measure of speech recognition, studies should expand this research to young children with CIs.

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