

EFFECTS OF MATCHED AND MISMATCHED STIMULATION RATES ON SPEECH  
PERCEPTION IN BILATERAL COCHLEAR IMPLANT USERS

by

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A dissertation submitted to the Graduate Faculty in Speech-Language-Hearing Sciences in  
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## **Abstract**

### **EFFECTS OF MATCHED AND MISMATCHED STIMULATION RATE ON SPEECH PERCEPTION IN BILATERAL COCHLEAR IMPLANT USERS**

by

**NICOLE CHRISTINE SISLIAN**

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Does matching stimulation rates in bilateral cochlear implants (CI) really matter? When bilateral CI recipients are implanted sequentially, the first implant is likely to be mapped at a relatively slow stimulation rate, while the second may be capable of faster stimulation rates, due to the technology available at implantation. Ten sequential bilateral CI recipients were used to investigate this question. Prior to the experiment, all participants used slow rates in the first CI, ranging from 720-1856 Hz. Five used slow rates (900Hz) (matched) on the second CI, and five used high rates (2400-3867Hz) (mismatched). The stimulation rate in the first implanted CI was never changed (non-modified), but all participants were given at least four weeks experience with both low and high rates on the newer implant.

Speech perception in quiet (CNC) and in noise (CRISP) with the first CI alone (non-modified), the second CI alone (modified), and bilaterally was evaluated four times during the experiment. Phase 1) Baseline testing was conducted prior to any re-programming. The second implant was re-mapped with either a slow or high rate. Phase 2) Participants were tested and re-mapped with the alternative rate after four weeks experience with the new map. Phase 3) After four weeks experience with the alternative map, participants were retested then re-mapped with the original rates. Phase 4) Participants were given one week of additional experience before

final testing. Participants were asked which mapping configuration they preferred and would like to continue using. Most (8/10) participants choose to leave with the mismatched configuration.

With bilateral stimulation, speech perception was better listening in quiet when they used a higher stimulation rate in one ear and a slow rate in the other ear than when they used slow rates in both ears, regardless of the program used before entering the study. There was no significant improvement in the CRISP (independent of noise source location) when participants were using both rate configurations with the modified CI alone, non-modified CI alone, or bilateral CIs. Clinicians programming bilateral CI patients who have internal equipment with different capabilities may find this information helpful when mapping this population.

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## Chapter 1. Introduction

Cochlear implants (CIs) are prosthetic devices, which consist of an electrode implanted in the cochlea of severely hearing impaired individuals, providing partial restoration of hearing. These devices consist of the implanted electrode array and receiver as well as an external speech processor. The internal electrode array is surgically inserted into the cochlea, near the auditory nerve. When current is sent to the electrodes, neurons near these electrodes are stimulated. Because of the tonotopic nature of the auditory nerve fibers, the user perceives an auditory signal with some of the properties of acoustic stimuli that would normally stimulate that place. Therefore, when apical (deeper) electrodes are stimulated, neurons from the apex will fire and the cochlear implant user will perceive a lower pitch and electrodes which stimulate neurons at the basal end of cochlea will evoke a higher pitch percept.

The external speech processor has various functions, including controlling the electrical stimulation sent to the internal electrodes. Individual settings are mapped into the speech processor by an audiologist using subjective input from the cochlear implant recipient to create a 'map'. A map consists of a set of rules programmed into the speech processor. The speech processor uses these rules in order to control electrode stimulation based on individual user levels. Mapping refers to setting electrical stimulation limits for individual electrodes, necessary for the user to perceive soft and comfortably loud sound corresponding to psychophysical measurements known as Threshold (T) and Comfort or Most Comfortable (C or M) Levels respectively (van Hoesel, Bohm, Battmer, Beckschebe, & Lenarz, 2005). During mapping, various parameters are also set. Map parameters are various available speech processor settings including electrode stimulation rate. Parameter settings and psychophysical measures may vary

from user to user (Zeng et al., 2002; Zeng & Galvin, 1999; Sun, Skinner, Liu, & Huang, 1999), due to anatomical differences, surgical complications or patient sound quality preferences.

The current state of the research in cochlear implantation indicates that appropriate mapping of the cochlear implant is essential for optimization of the device for each implant user (Dawson, Skok, & Clark, 1997; Fu & Shannon, 2000; Fu & Shannon, 1999; Jethanamest, Tan, Fitzgerald, & Svirsky, 2010; Skinner, Holden, Holden, & Demorest, 1999; Spahr & Dorman, 2005; van Hoesel et al., 2005; Xu & Pfungst, 2005). The way in which cochlear implant speech processor psychophysical measures and map parameters are set may influence the speech perception of the cochlear implant user (Skinner et al., 1999). Various techniques have been implemented in order to map these devices (Shalloo & Ash, 1995; Skinner, Holden, Holden, & Demorest, 1995), which may also affect speech perception. Consonant, vowel, and sentence perception in quiet and/or in noise are often used to measure the effects of varying the map (Fu & Shannon, 1998; Fu & Shannon, 1999).

One of the mapping parameters influencing speech perception in unilateral cochlear implant users is stimulation rate (Plant et al., 2007). Cochlear implant stimulation rate refers to the number of times per second the electrodes are stimulated. Theories of sound processing in cochlear implants suggest that higher rates of electrode stimulation may result in improved speech perception ability (Drullman, 1995; McLaughlin, Reilly, Zeng, 2013; Plant et al., 2007). This is based on the claim that high neural firing rates generate neural responses which are more similar to the neural responses in typically hearing auditory systems.

Slow electrode stimulation rates provide adequate information about speech envelope, but they provide much less information about fine structure than higher stimulation rates. Two important features that can affect speech perception are the temporal envelope and temporal fine

structure of the speech signal (Drullman, 1995). Temporal envelope refers to the amplitudes of the frequency bands over time in a given speech signal. Temporal fine structure refers to a higher frequency carrier signal within the temporal envelope of the speech signal, which incorporates timing cues from the signal. The higher frequency carrier stems from voicing in speech and from fundamental frequency of instruments (Chen & Zhang, 2006; Drullman, 1995; Imennov, Won, Drennan, Jaymeson, & Rubinstein, 2013; e.g., Moore, 2008). Temporal fine structure information may provide tonal information in the speech signal that may not be accessed by the envelope cues (Chen, & Zhang, 2006; Drullman, 1995; McLaughlin et al., 2013; Moore, 2008; Xu & Pfingst, 2005) and, thus, may play a role in pitch perception (Drennan & Rubinstein, 2008; Moore, 2008). Better representation of fine temporal information may enhance music and speech in noise perception (Chen & Zhang, 2006; Drennan & Rubinstein, 2008; McLaughlin et al., 2013; Moore, 2008; Xu & Pfingst, 2005).

Although the theoretical considerations suggest that high rates of electrode stimulation will result in increased speech perception scores, the literature shows mixed results for unilateral cochlear implant users. Some research show a significant effect of rate on speech perception of unilateral cochlear implant users (Chen & Zhang, 2006; Frijns, et al., 2003; Holden, Skinner, Holden, & Demorest, 2002; Imennov et al., 2013; McLaughlin et al., 2013; Plant et al., 2007; Ostrof, David, Shipp, Chen, & Nedzelski, 2003; Rubinstein & Hong, 2003; Rubinstein et al., 1999; Verschuer, 2005) and bilateral users (Dunn, Tyler, Witt, & Gantz, 2006), while other research show no significant effect (Arora, Vandali, Dowell, & Pawson, 2011; Arora, Dawson, Dowell, & Vandali, 2009; Friesen, Shannon, & Cruz, 2005; Shannon, Cruze, & Galvin, 2011; Vandali, Whitford, Plant, & Clark, 2000; Xu & Pfingst, 2005).

Another factor potentially affecting cochlear implant users' speech perception is unilateral vs. bilateral implantation. Unilateral cochlear implantation refers to patients being surgically implanted with a cochlear implant in one ear. Bilateral cochlear implantation refers to cochlear implantation in both ears.

Hearing with two ears, or binaural hearing, provides valuable binaural cues to typically hearing listeners (Sandel et al., 1955; Blonkhorst & Plomp, 1988; Blonkhorst & Plomp, 1989; Blauert, 1997; Hawley, Litovsky, & Colburn, 1999; Schleich, Hopp, & D'Hease, 2004; Schon, Fuller, & Helms, 2002; Tyler et al., 2002; van Hoesel, Ramsden, & O'Driscoll, 2002; Litovsky, Johnston, & Godar, 2006; Ihlefeld & Litovsky, 2012; Litovsky et al., 2012). Binaural cues, known as interaural time differences (ITDs) and interaural level/intensity differences (ILDs) provide information for sound localization and speech understanding in noise (Blonkhorst & Plomp, 1988; reviewed in van Hoesel et al., 2002). ITDs refer to the difference in arrival time of sound waves to the two ears. These time delays vary according to the sound source location and thus primarily provide sound localization information. ILDs refer to the difference in the intensity of the signal reaching the two ears. Localization of tones below 1500Hz is determined by ITD cues, while ILD cues determine localization for frequencies above 1500Hz (reviewed in Sandel et al., 1955). The masking level difference (MLD) effect refers to signal processing taking place in the brain in response to input from both ears, enable the brain to better separate the speech signal from the noise based on ITDs and ILDs, and therefore improve speech intelligibility (reviewed in Ihlefeld & Litovsky, 2012; Litovsky et al., 2006; reviewed in Tyler et al., 2002).

The head shadow effect, squelch effect, and binaural summation are different kinds of binaural cues which benefit speech understanding in noise. The term "head shadow" refers to

the head acting as an acoustic barrier, which attenuates the high frequencies of the ear farthest from the sound source. Hearing in the ear contralateral to the noise side improves the signal-to-noise ratio (SNR) in that ear, improving speech understanding in noise. SNR refers to the decibel level difference between the speech signal level and the decibel level of the noise (reviewed in Litovsky, Parkinson, & Arcaroli, 2009; Tyler et al., 2002). Binaural Squelch refers to the benefit resulting from the spatial separation between the signal source and the noise source (Schleich et al., 2004), due to signal processing by the brain of input from two ears. With two ears, the brain may have a better representation of the noise and speech and is better able to separate them, improving speech perception in noise (reviewed in Litovsky et al., 2009; Tyler et al., 2002). With binaural summation, a signal arriving at both ears improves the hearing threshold three decibels compared to one ear alone (reviewed in Litovsky et al., 2009; Schleich et al., 2004; Schon et al., 2002).

Hearing impaired listeners perform more poorly in noise than normal hearing listeners (reviewed in Blonkhorst & Plomp, 1989). Patients with mild-to-moderate sensorineural hearing loss, had 2.5dB poorer speech reception thresholds (SRTs - defined as the lowest level at which an individual can correctly understand spondees at least half of the time) in noise than typically hearing listeners when speech and noise were presented from the front (0° azimuth). However, overall SRTs improved when the noise was presented to the side (90° azimuth).

Advantages of binaural amplification compared to unilateral amplification include increased speech intelligibility in quiet and in noise (Day, Grownig & Gatehouse, 1988; Byrne, 1981) and more accurate sound localization (Byrne, Noble, & LePage, 1992). Severely hearing impaired patients demonstrated improved speech understanding in noise with binaural hearing aids compared with monaural aids (Day et al., 1988).

Some of the binaural cues utilized by typically hearing individuals appear to be available to bilateral cochlear implant users as well (Goupell, Kan, & Litovsky, 2013; Ihlefeld & Litovsky, 2012; Litovsky et al., 2009; Litovsky et al., 2006; van Hoesel, Tong, Hollow, & Clark, 1993; van Hoesel & Clark, 1997; van Hoesel et al., 2002; van Hoesel & Tyler, 2003). Bilateral CI recipients possess good access to ILD cues. Unfortunately, bilateral cochlear implantees demonstrate poor ability to detect ITD cues (Ihlefeld & Litovsky, 2012; van Hoesel et al., 1993; Van Hoesel & Clark, 1997; van Hoesel et al., 2002; van Hoesel & Tyler, 2003), which provide salient localization information and are potentially useful for speech understanding in noise. This may explain why sound localization and speech perception in noise continues to be challenging to bilateral CI patients.

Even so, bilateral stimulation yields both improved speech perception in the presence of background noise, as well as more accurate sound localization compared with unilateral cochlear implantation (Chadha, Papsin, Jiwani, & Gordon, 2011; Johnston, Durieux-Smith, Angus, O'Connor, & Fitzpatrick, 2009; Litovsky et al., 2009; Litovsky et al., 2006; Litovsky, Parkinson, & Arcaroli, 2004; Simon, 2005; Muller, Schon, & Helms, 2002; Nopp, Scheich, & D'Haese, 2004; Sparreboom, Snik, & Mylanus, 2011; Strelnikov et al., 2011; Tyler et al., 2002; e.g., van Hoesel & Tyler, 2002; van Hoesel et al., 2005; van Hoesel & Tyler, 2003; van Hoesel & Clark, 1997; van Hoesel et al., 1993). Bilateral cochlear implant users preferred bilateral stimulation to unilateral stimulation (Tyler, Perreau, & Ji, 2009).

Due to the described benefits of bilateral cochlear implantation, the number of sequential bilateral implantations is on the rise. Consequently, there are many bilateral recipients who have several years of unilateral experience prior to receiving a second implant. Newer technology, including higher stimulation rate capabilities, may be available in the second internal and

external devices these patients receive. This allows these patients to take advantage of this state of the art technology and possibly achieve even better speech perception results using current processing capabilities, namely higher stimulation rates.

Since unilateral cochlear implant research suggests that mapping manipulations, such as varying threshold and comfort levels, amplitude mapping, and stimulation rate, may affect the speech perception of the user (Arora et al., 2010; Arora et al., 2009; Dawson, Skok, & Clark, 1997; Friesen et al., 2005; Frijns, et al., 2003; Fu & Shannon, 2000; Fu & Shannon, 1999; Ostrof et al., 2003; Pfungst & Xu, 2005; Plant et al., 2007; Rubinstein & Hong, 2003; Rubinstein et al., 1999; Skinner et al., 1999; Spahr & Dorman, 2005; Vandali et al., 2000; van Hoesel et al., 2005; Verschuer, 2005), mapping strategies for bilateral implants may also have an impact on speech perception performance (Goupell, Kan, & Litovsky, 2013; Nardo et al., 2008; van Hoesel et al., 2005). However, methods of mapping unilateral implants and bilateral implants have not as yet been standardized (Skinner et al., 1995).

Furthermore, there is no standardized method to program the speech processors of sequential bilateral cochlear implant patients when the two devices have different capabilities such as different maximal stimulation rates. For many sequentially implanted adults, the first CI, will often have been implanted several years prior to the second CI and is mapped using parameters (e.g., stimulation rate), which were considered to be state-of-the-art at the time of implantation and activation. However, implant capabilities change over time, and newer implants can now stimulate at much higher rates. However, these higher rates are not always used by clinicians.

Mapping procedures for bilateral cochlear implants have not been widely addressed in the literature. Of particular interest is the question of whether it is advantageous to map the second

device with a higher stimulation rate or keep the rate equal to the older, first device.

Furthermore, there is no agreement that higher cochlear implant stimulation rates improve speech perception. Consequently, audiologists are using their own judgment when mapping these devices. There is a need for a more systematic approach. However, the lack of knowledge about the potential advantages and disadvantages of matching electrode stimulation rates, prevents recommendations as to the optimal fitting strategy.

The stimulation rate of the second device may be set equal to that of the first CI or at a much higher rate. In the clinic, the rates are often matched, even though a higher rate is available on the newer implant. This limits the patients' access to the newer technology. If faster is preferable for a given patient, he/she does not have the opportunity to use it.

A more systematic trial of the available technology must be explored in order to provide these patients with the best signal possible. This may not be possible if the second CIs are mapped similarly to the first CI, which may have older technology. If the first CI device is capable of high rates, they may be programmed to slow rates by the clinician. Based on the hypothesis that higher stimulation rates may produce improved speech perception performance, the goal of this dissertation was to compare matched and mismatched stimulation rates in sequential bilateral CI users, in terms of speech understanding in quiet and in noise. The hypothesis is that participants should be able to adapt to the differences in information coming from the two ears and that programming the second CI using more state of the art processing than the first CI can improve patient performance.

The goal of this dissertation was to determine whether matching the stimulation rate of the second CI to that of the first CI (matched rates), or running a higher stimulation rate on the second CI (mismatched rates) would affect speech perception in sequential bilateral cochlear

implant recipients. This was accomplished in a within subject design by programming bilateral CI devices in both matched and mismatched mapping stimulation rate configurations in all participants. Participants underwent a battery of speech perception tests before map manipulation. All participants listened with both the new configurations for four weeks, because the length of time before stabilization of mapping manipulations can range from two to 10 weeks (Holden, Skinner, Holden, & Demorest, 2002; Skinner et al., 2002; Sun & Skinner, 1999).

Inter-subject variability of cochlear implant user performance is high (reviewed in Seldran, et al., 2011; Finley & Skinner, 2009; Fu, 2002), making it difficult to perform a between subjects experimental design that has adequate statistical power. Therefore, in the present study, a within subjects experimental design was implemented, controlling the effect of previous experience and other variables which contribute to the high variability of performance in CI patients. A crossover condition was used in order to ensure that differences in performance were due to the mapping modifications rather than individual differences in experience with the different bilateral configurations.

Prediction:

Increasing the stimulation rate on the second implanted device should improve overall speech perception of bilateral CI users, both with the second device and in the bilateral condition.

Null Hypothesis:

Speech perception in quiet (CNC) and speech in noise (CRISP) were evaluated when the participants were using matched and mismatched stimulation rates, in order to determine whether we could reject the null hypothesis that there was no effect of mismatched vs. matched stimulation rates on the speech perception of these participants.

## Chapter 2. Methods

Ten sequentially implanted bilateral cochlear implant participants were recruited. Six participants were female and four were male, ranging in age from 15-73 years. Other participant demographics are listed in Table 1. They were recruited as volunteers through referral and fliers posted at cochlear implant centers and support groups in the area. The staff at these centers announced a call for participants and described the study protocol to them. If people were interested, they were given contact information for the principle investigator. The participants made the initial contact. Those who met the inclusion criteria and agreed to follow the study protocol by completing all four phases of the study and were willing to use experimental maps during the research participated in the study. This study received IRB approval from the City University of New York Graduate Center as well as New York Eye & Ear Infirmary. Informed Consent was signed by each participant prior to entering into the study. The parent of the 15 year old participant signed the Informed Consent assent form.

Patients unable to discriminate recorded CNC words were excluded from the study. Pediatric bilateral cochlear implant recipients under the age of 15 were also not included. Recipients who were recently implanted (within six months) with their first CI, simultaneously implanted, or were using a high stimulation rate on the first implanted side, were also excluded.

Half of the participants entered into the study with matched stimulation rates in the two ears and half entered with mismatched rates. During the experiment all patients had experience with both high and low rates on the second implant. We will refer to the rate configuration in which the first and second CIs were set at slow rates, as “matched”. We will refer to the configuration in which, patients were mapped with the slow stimulation rate on the first CI and a high stimulation rate on the second CI as “mismatched”. In order to distinguish between

participants entering the study with matched or mismatched rates, participants using matched rates prior to the study were placed in an “initial slow/slow” group and those entering using mismatched rates were in an “initial slow/high” group. Participants in the slow/slow group are coded as SS1-SS5. Participants in the slow/high group are coded SH1-SH5.

The participants differed in their hearing, CI history, and implant characteristics. The details of the participants’ first and second CI, implant characteristics, and rate information, can be found in Tables 1, 2 and 3 respectively. Seven participants were postlingually deafened, meaning that these participants became deaf as an adult or after developing speech. Three participants were prelingually deafened meaning that these participants became deaf at an early age, prior to speech development. Time between surgeries varied across participants ranging from four months to eight years (see Table 1). The only consistent difference between the groups entering the study with different rate configurations was that was that participants with longer time periods between surgeries were more likely to enter the study with the slow/high configuration.

Participants were implanted with either bilateral Cochlear Corporation (Nucleus) or Advanced Bionics cochlear implant devices. The internal and external equipment they were using are outlined in Table 2. Participants enrolled using the Nucleus devices used either the Freedom or Nucleus 5 sound processors, which are both capable of slow and high speed sound processing. All but one Advanced Bionics participant, SH5, was bilaterally implanted with the HiRes90K electrode. SH5 had a C1 HiFocus 1.2 device on the first side and the HiRes90K HiFocus device on the second side. The HiRes90K and Harmony devices are capable of high rate speech coding strategies such as High Resolution and Fidelity 120 processing strategies. However, the C1 is unable to produce high rate speech coding strategies (see Table 2).

Prior to the experiment, all participants used slow rates in the first CI, ranging from 720-1856 Hz. On the second CI, five participants used slow rates (900Hz) (matched) and five used high rates (2400-3867Hz) (mismatched) prior to entering the study (see Table 3). For the matched rate configuration condition, the second CIs were set at a similar rate to the first CI (slow/slow). For the mismatched rate configuration condition (slow/high), the second CI was set to the fastest rate available (i.e., a higher rate than the first CI).

All participants entering the study with slow/slow rates used a 900Hz rate on their bilateral CIs prior to entrance into the study. Rates for the slow/slow group's second CI (modified CI) ranged from 1800Hz to 3500Hz, or two to four times the rate of the first/non-modified CI depending on the capability of the second CI (see Table 3). For all participants entering the study with slow/high rates, the rates for their first CIs ranged from 720Hz to 1856Hz and for the second CI ranged from 2400Hz to 3867Hz. Stimulation rates for the slow/high group's modified CIs ranged from two to five times slower than their non-modified CIs. In some cases, the rate set for participants' modified CIs for those entering the study with slow/slow stimulation were similar to the slower rates for the slow/high participants. Therefore, the rates used in the study were considered slow or high relative to the individual participant's original stimulation rates. Each participant's rate configuration preference (the rate configuration they chose to use) upon completion of the study is also displayed in Table 3. In a matched rate condition, the rate of the modified CI is always slow and during a mismatched condition, the rate of the modified CI is always high. The rate of the non-modified CI is slow regardless of the rate condition.

In order to ensure that differences in performance with the different rate configurations were minimally influenced by experience with the possible rate configurations, the newest

implant was re-mapped with either slow or fast rates over a period of 13 weeks. The participants wore each configuration before returning to be re-mapped. There were four visits to the clinic during which a battery of tests were conducted and the CIs were re-mapped. During each visit and subsequent experience with the rate configuration (which we refer to as phases), audiometric sound field thresholds, speech perception in quiet (i.e., CNC words and phonemes) and in competing noise (i.e., CRISP test) were examined. All tests were performed with the participant listening under three conditions; with each CI independently activated (monaurally), and with both CIs activated (bilaterally).

## EXPERIMENTAL PHASES

The study protocol consisted of four visits to the clinic. Figure 1 provides an illustration of the evaluation and fitting protocols the participants experienced during the research. The first session of the study protocol (Phase 1-Baseline) provided information about participant performance at the start of the research and the initial CI mapping. Two participants, SH5 and SS5, did not undergo baseline testing, however, their mapping protocol was the same as all participants. Following baseline testing, the first CI was re-mapped if necessary with the same slow rate they were familiar with. Only the threshold and comfort levels were adjusted. The second CI was re-mapped with either a slow rate (matched) or high rate (mismatched). Participants were then given this new rate configuration to use for four weeks. The rate the participant received during this Phase was counterbalanced. Participants were not informed which stimulation rate they were given. At the end of the four weeks, participants returned for the Phase 2 session.

During Phase 2, participants were first tested utilizing the mapping configuration created at the end of the Phase 1 then, the second CI was re-mapped with the alternative rate.

Participants used this configuration for another four weeks then returned for Phase 3.

At the start of Phase 3, the same test battery was administered, then the second CI was re-mapped again, with the map used in the first experimental phase. At this point all participants had had at least four weeks experience with both rate configurations. Participants were asked to use this mapping configuration and return after one week's time for the final phase of the protocol, Phase 4. This provided speech perception information with both possible configurations within a relatively short time, but only after they had had significant experience with both configurations.

During Phase 4, participants were re-tested with the mapping from the previous visit. Participants were then asked which rate configuration they preferred over the course of the study protocol and would like to return home with. The requested configuration was then set on their speech processors (see Table 3 left most column).

## MAPPING

Participants underwent mapping during the first visit following baseline testing. Mapping permitted evaluation of the threshold and comfort levels. Programs using the experimental stimulation rates in each of the bilateral implants were created. Participants were mapped using two rate configurations, matched and mismatched. The first implanted CI was mapped in the original slow rate the participant used prior to enrollment in the study but the stimulation rate in the first implanted CI was never changed (non-modified). The second implanted CI was then randomly assigned to either a high or slow stimulation rate independent of the rate they entered the study wearing. Half the subjects were mapped at the same slow rate

as the first implanted CI. In the other subjects, the second CI was set with the highest possible rate the system would allow, depending on the capabilities of the equipment and patient comfort. It was set to a minimum of two times the original rate.

The modified rate used for the second device during baseline mapping was counterbalanced across phases. Participants entered Phase 1 with either a matched or mismatched rate configuration, regardless of the stimulation rate they were using prior to entering the study.

The stimulation rate for the first implanted CI was never changed. It remained at a slow rate because it was either never programmed with a high stimulation rate or not capable of high rates. The participants' first cochlear implant will be henceforth be referenced as the "non-modified" CI. For all participants, the rate of the second CI was changed (stimulation rates were adjusted) throughout the study. The participants' second cochlear implant will henceforth be referred to as the "modified" CI. For the participants in the slow/slow group, those entering the study with the matched rate configuration, the modification was always to change from a slow to a high rate. For the participants in the slow/high group, those entering with mismatched rates, the modified CI was always changed from a high to a slow rate.

## EVALUATION BATTERY

Every time the participant came to the clinic, all tasks were performed when participants were using the modified CI alone, non-modified CI alone, and bilateral CIs. The order of testing was counterbalanced. This evaluation included; audiometric sound field thresholds, CNC, CRISP with noise presented near the modified CI and with noise presented near the non-modified CI. The order of the CNC and CRISP tests was also counterbalanced.

All testing was carried out in a two-room audiology suite. A standard clinical setup was utilized for audiometric and speech testing, with the participant seated alone in a sound-treated room separated from the tester by a transparent glass partition. A Grason Stadler Instrument (GSI) 61 audiometer was used for audiometric threshold testing. In order to ensure that each cochlear implant device was operating appropriately, audiometric sound field thresholds, using narrow band noise for the frequencies 500, 2000, and 4000Hz, were obtained from each participant during each evaluation session prior to speech testing. Thresholds were obtained with the modified and non-modified CIs monaurally as well as with bilateral CIs.

Loudness balancing was always performed prior to testing. Loudness balancing refers to setting the volume evenly for the right and left CIs according to the patient's perception. To do this, the audiologist spoke to the participant while mapping seated directly in front of them, with bilateral CI microphones activated. Participants were asked to verbally express whether the loudness of the two devices sounded comfortable and even. If they were not even, global comfort levels were either turned up or down, depending of on the participants' report, until loudness was judged even. Loud sounds, such as clapping and elevated voice were used to determine discomfort. Adjustments were made, by lowering global comfort levels on the uncomfortable CI. When participants were not connected to the CI programming software, loudness-level balancing was performed by adjusting the volume settings on one or both CI processors, until loudness was comfortable and even for both CIs. The above techniques were used in order to determine balance and comfort (Litovsky et al., 2009).

#### SPEECH PERCEPTION IN QUIET

The House Ear Institute and Cochlear Corporation recording of the CNC (Consonant-Nucleus-Consonant) word lists were used to test word and phoneme recognition in quiet. The

CNC test contains lists of monosyllabic words consisting of a vowel surrounded by two consonants, i.e., 'cat'. Words were presented at 63dB SPL (C-Scale) through a speaker directly in front of the participant. The speech materials were played from a Compact Disc (CD) player. The output of the CD player was amplified, attenuated through a GSI 61 audiometer, and sent to a Cambridge Soundworks Center Surround IV loudspeaker.

A 25-word list was presented to each participant monaurally for the modified CI, non-modified CI, and bilaterally. A different standardized word list was presented for each condition. Word lists were never used more than once per participant. The participants were instructed to verbally repeat the words he/she heard. Responses were recorded on a score sheet. Each correct word received one point. Each correct phoneme received three points per word, one point for each correct phoneme. Total word scores and phoneme scores were then converted into percent correct. The order of testing of the ears was counterbalanced across subjects.

A phoneme is defined as a meaningful individual speech sound, i.e., /a/ or /c/ or /t/. For example, if the presented word is /cat/, and the participant's response is /cat/, he/she will receive one point for a correct word in the word category, and then receive three points for each correct phoneme from the same list of words. Therefore, the phoneme score is always related to the word score. The phoneme score is always greater than or equal to the word score as there are three phonemes per word and if only one phoneme is perceived incorrectly, it changes the perceived word. The phoneme score is a more sensitive indicator of the details of speech perception. However, the word score is an indication of how the listener may process complete words.

## SPEECH PERCEPTION IN NOISE

The CRISP (Children's Realistic Intelligibility Speech Perception) test, developed at The University of Wisconsin, was used to test speech reception thresholds (SRTs) in noise (Litovsky, 2005). The CRISP stimuli consisted of target spondee words and competing sentences. All stimuli and the software, were provided by The University of Washington and are available on a DVD. They are played back under software control during the actual evaluation. Target words consisted of 25 closed-set spondees spoken by a male talker (e.g., hotdog, ice cream, barnyard, etc.). Root mean square stimulus levels were equalized for all words. The competing noise consisted of two different sentences spoken simultaneously by two separate female talkers (i.e., two-talker babble) (Litovsky, Parkinson, & Arcaroli, 2004).

The administration of the CRISP was controlled by a Dell laptop computer. The output of the computer was amplified, attenuated through a Crown D-75A amplifier and sent to Cambridge Soundworks Center Surround IV loudspeakers. The participant was seated, five feet from one loudspeaker at 0° azimuth. The spondee target words were presented through the loudspeaker directly in front of the participant. The competing noise was fixed at a level of 60dB SPL and presented through a second loudspeaker at five feet distance from the listener located at 270 degrees azimuth from the participant for one condition (Figure 2 Left) and at 90 degrees azimuth for another condition (Figure 2 Right). Speaker calibration took place prior to each participant's session. The loudspeaker at 0° azimuth was calibrated at 75 dB SPL, while the noise stimulus loudspeaker was calibrated at 60dB SPL, according to CRISP software specifications.

An adaptive tracking procedure was used to vary the target level. A four-alternative-forced-choice discrimination procedure was implemented. In each trial, the participant heard the target stimulus spondee and was instructed to click on a word out of a list of 25 words in front of

them on the computer screen. When the participant was ready for the next word presentation, the word 'go' was selected on the computer screen and the next word was presented. A five-minute practice test took place prior to actual testing for the purpose of familiarizing the participant with the task. Correct responses resulted in a decrease in the level of the spondee words by 3dB SPL and incorrect responses in a level increase of 1dB SPL. The level of the target words was systematically decreased and increased until SRT was obtained, by estimating a speech threshold where spondees were recognized 50 percent of the time. The Signal-to-Noise Ratio (SNR), the decibel level difference between the levels of the SRT and the level of the noise of the SRT, was recorded. Only eight of the ten participants were able to complete the task. Two (one from the Slow/Slow group and one from the Slow/High group) were unable to complete the text due to poor speech perception in noise.

SRTs in noise were measured in three listening modes; modified CI alone, non-modified CI alone, and bilaterally while competing noise was presented on the side of the participants' near the modified CI and then near the non-modified CI (90 or 270 degrees azimuth). Two trials were conducted for each listening condition for a total of six listening conditions. An average of the SRTs obtained during the two trials were recorded.

The order of testing of the CIs was counterbalanced across participants. The noise stimulus side was also counterbalanced. The sequence of evaluation (CNC vs. CRISP) condition was counterbalanced across participants.

## ANALYSIS

Speech perception in quiet (CNC) and speech in noise (CRISP) were evaluated when the participants were using matched and mismatched stimulation rates, in order to determine whether we could reject the null hypothesis that there was no effect of mismatched vs. mismatched

stimulation rates on the speech perception of these participants. In order to limit the impact of variability between participants, a repeated measures design was used in which all participants had experience, and were tested, with both matched and mismatched stimulation rates. Repeated measures ANOVAs were implemented to discern whether there was a significant learning effect that might account for the pattern of results and/or the stimulation condition the participants were using before the beginning of the experiment affected performance.

In order to determine whether there was an effect of matched vs. mismatched rate configuration on the performance of the ten participants in this study a series of paired sample *t*-tests were conducted on the word and phoneme recognition scores and signal-to-noise ratios (SNRs) obtained during the final two phases of the study protocol (Phases 3 and 4). Data from this particular data set were chosen since all participants completed these phases and each phase consisted of either a mismatched or matched rate configuration. By the final two phases, participants had had time to adapt to each mapping configuration. Separate assessments were conducted when the participants were listening just to the non-modified (always at the slow rate they were using before entering the study) and modified CIs (tested at both slow and fast rates) and with the bilateral condition (when both implants were activated).

Cohen's *d* analyses were also performed in order to determine the effect size. The effect size is a measure of the strength of the relationship between two variables in a statistical population. In this case the two variables were defined as matched and mismatched rate configurations and speech recognition results. Cohen's *d* is defined as the difference between two means divided by a standard deviation for the data. This measure will determine whether speech perception scores and stimulation rate are related.

### **Chapter 3. Results**

The goal of the current research was to determine whether using a slow/high stimulation rate configuration (mismatched) compared with slow/slow rates (matched), leads to an improvement in speech perception in sequentially implanted bilateral cochlear implant patients.

#### **Speech in Quiet - CNC**

The CNC (Consonant-Nucleus-Consonant) word lists were used to test word and phoneme recognition in quiet. The participants were instructed to verbally repeat the words he/she heard. Each correct word received one point. Each correct phoneme received three points per word, one point for each correct phoneme. Total word scores and phoneme scores were then converted into percent correct. Participants were tested with the modified CI alone, non-modified CI alone, and bilateral CIs.

#### **Impact of starting condition and the order of stimulation rate configuration**

A mixed effects regression analysis was used to test whether the phase of the experiment (potential learning effects) and baseline rate configuration status (matched vs. mismatched) significantly predicted participants' CNC bilateral word and phoneme perception in quiet. The impact of the starting condition and stimulation rate configuration prior to the experiment was evaluated using a Repeated Measures ANOVA (see Table 4 (words) and Table 5 (phonemes)). The order in which the participants experienced the conditions also did not impact results. There is no systematic trend across phases or time and performance was similar for individuals using mismatched or matched stimulation rates at baseline (Figures 3 and 4). CNC percent correct for individual participants at each phase are presented in Figures 1A - 3A (Word Recognition) and Figures 4A -6A (Phoneme Recognition) of the Appendices.

## **Impact of cochlear implant rate configuration: Paired t-tests of final sessions for all ten participants**

The performance was scored both by counting either the number of words or phonemes correctly identified. Word and phoneme scores were analyzed separately and converted to percent correct. In order to test the impact of CI rate configuration on CNC word and phoneme recognition, paired t-tests were performed on of the percent correct recognition in the final two sessions (one each of matched and mismatched stimulation rates). These data include comparisons for the modified CI, non-modified CI, and bilateral conditions for the ten participants who completed the data sets in both matched and mismatched rate configurations. The results of the paired t-test analyses for percent correct word and phoneme recognition obtained from the CNC test in quiet during the last two phases of the study protocol are shown in Table 6.

### **CNC Word Recognition**

#### **Modified CI Alone**

When the CNC word test was restricted to the modified CI (the 2nd implanted ear), a paired-samples t-test indicated that word recognition was not significantly different when participants were tested with a mismatched rate configuration ( $M = 45.8$ ,  $SD = 20.62$ ) than with a matched configuration ( $M = 41.4$ ,  $SD = 17.02$ ),  $t(9) = 0.62$ ,  $p = 0.55$ .

#### **Non-Modified CI Alone**

When the CNC word test was restricted to the non-modified CI (the first implanted ear in which no programming changes were made during the research), a paired-samples t-test was employed. Although word performance fluctuated from phase to phase, results of the t-test indicated that there was no strong evidence of a significant change in speech perception for the

non-modified CI when participants were tested during the mismatched phase ( $M = 59.2$ ,  $SD = 20.00$ ) or the matched phase ( $M = 53.8$ ,  $SD = 19.05$ ),  $t(9) = 2.30$ ,  $p = 0.05$ ,  $d = 0.73$ ).

### Bilateral

Bilateral CNC word recognition was statistically significantly different when comparing the matched vs. mismatched rate configurations. The paired-samples t-test indicated that when the listeners were using both CIs, significantly more words were correctly identified when the participants were tested with the mismatched rate configuration ( $M = 70.4$ ,  $SD = 16.78$ ) than with a matched rate configuration ( $M = 60.6$ ,  $SD = 18.10$ ),  $t(9) = 2.61$ ,  $p = 0.028$ ,  $d = 0.83$ . Mean and standard error for bilateral word scores in the mismatched and matched conditions are shown in Figure 5.

The Cohen's  $d$  test suggested that in the bilateral condition, the effect size was above 0.8, indicating that CNC performance depends on whether the stimulation rates were mismatched (when one of the ears was using the faster rate) (see Table 6).

### CNC Phoneme Recognition

#### Modified CI Alone

When participants were tested with the modified ears alone, a paired-sample t-test indicated that phoneme recognition was not significantly different whether the modified CIs were programmed in a mismatched rate configuration ( $M = 67.2$ ,  $SD = 15.43$ ) or a matched rate configuration ( $M = 60.0$ ,  $SD = 13.68$ ),  $t(9) = 1.51$ ,  $p = 0.16$ ).

#### Non-Modified CI Alone

When the CNC phoneme test was restricted to the non-modified CI (the first implanted ear in which no programming changes were made during the research), a paired-samples t-test indicated that phoneme recognition was not significantly different when participants were tested

during a mismatched rate phase ( $M = 78.9$ ,  $SD = 14.66$ ) or a matched rate phase ( $M = 75.4$ ,  $SD = 12.70$ ),  $t(9) = 1.66$ ,  $p = 0.13$ .

### Bilateral

Bilateral CNC phoneme recognition was statistically significant different when comparing the matched vs. mismatched rate configuration. A paired-samples t-test indicated a significant improvement when participants were tested in the mismatched rate configuration ( $M = 85.1$ ,  $SD = 9.06$ ) than in the matched rate configuration ( $M = 78.3$ ,  $SD = 12.33$ ),  $t(9) = 2.49$ ,  $p = 0.035$ ,  $d = 0.84$ . Mean and standard error for bilateral word scores in the mismatched and matched conditions are shown in Figure 6.

Again, the Cohen's  $d$  test suggested that in the bilateral condition, there was enough effect size above 0.8 indicating that CNC performance and stimulation rate are related (see Table 6).

The CNC phoneme percent correct are higher than the percent correct for word recognition but the patterns of change are very similar and indicated a significant improvement when participants were evaluated wearing bilateral cochlear implants in the mismatched rate configuration for both CNC word and phoneme tests. Because the pattern of results for words and phonemes are very similar, the data for the words are presented in this section. Similar figures for phoneme recognition can be found in the Appendix, which is indicated by adding an A to the Figure.

Bilateral CNC word and phoneme recognition data during the final two phases of the study protocol, comparing matched vs. mismatched results are displayed in Figure 7 (words) and Figure 7A (phonemes). Non-Modified CNC word and phoneme recognition data during the final two phases of the study protocol, comparing matched vs. mismatched results are displayed in

Figure 8 (words) and Figure 8A (phonemes). Bilateral CNC Phase 3 vs. Phase 4 results for each individual participant are shown in Figures 9 (words) and Figure 9A (phonemes). Results indicate that for CNC words, more than half of the participants (six out of ten) demonstrated improved percent correct word identification with the mismatched stimulation rates than with matched rates. These participants' improvements with mismatched rates ranged from 6% to 28%. The remaining participants showed either no difference or a slight improvement with matched compared to mismatched rates. Similarly, five of the ten participants demonstrated improved percent correct identification of phonemes when wearing the mismatched rates, two performed more poorly, and three showed no change as a function of rate. Improvements with mismatched rates ranged from 13% to 20%. Ceiling effects emerged for one participant for CNC words (SS4) and for three participants for phonemes (SS4, SH4, and SH1). Overall individual bilateral percent correct phoneme identification was higher than percent correct word identification (see Figure 7 and Figure 7A).

When comparing bilateral CNC performance for Phases 3 and Phase 4, percent correct bilateral CNC word and phoneme identification varied across participants, indicating that performance was not determined by time within the experiment (see Figure 9 and Figure 9A).

Although all the participants in this study performed the CNC task, participants SS2 and SH2 were eliminated from the analysis because they were unable to perform the CRISP task. We wanted to determine whether the data from these two participants affected the outcome of the CNC analysis. These two participants are have dashed lines on Figures 7 - 9, and Figures 7A - 9A. One of these participants (SS2) was the poorest performer on the CNC. We re-analyzed the CNC data using the eight participants who were unable to score on the CRISP task.

## **Impact of cochlear implant rate configuration: Paired t-tests of final sessions for eight participants**

The results of the paired t-test analyses for percent correct word and phoneme recognition obtained from the CNC test in quiet during the last two phases of the study protocol for eight participants are shown in Table 7.

### Modified CI Alone

When the CNC word and phonemes tests, for both the eight and ten participants, were restricted to the modified CI (the 2nd implanted ear), a paired-samples t-test indicated that speech recognition was not significantly different when participants were tested with a high rate than with a slow rate.

### Non-Modified CI Alone

When the CNC word and phoneme tests, for both the eight and ten participants, were restricted to the non-modified CI (the first implanted ear in which no programming changes were made during the research), results of the t-test indicated that there was evidence of a significant change in speech perception when participants were tested during the mismatched compared with the matched phase.

### Bilateral

Bilateral CNC word recognition for both the eight and ten participants, were statistically significant different when comparing the matched vs. mismatched rate configurations. Paired-samples t-tests for the eight participants showed a significant improvement when they were tested with the mismatched rate configuration ( $M = 74.0$ ) than in the matched rate configuration ( $M = 64.3$ ),  $SE = 4.0$ ,  $t(9) = 2.47$ ,  $p = 0.04$ ,  $d = 0.87$ . However bilateral CNC phoneme recognition for the eight subjects was not statistically significant different when participants were

tested in the mismatched rate configuration ( $M = 86.3$ ) than in the matched rate configuration ( $M = 81.3$ ),  $SE 2.9$ ,  $t(9) = 1.76$ ,  $p = .122$ .

### **Speech Perception in noise – CRISP**

The Children's Realistic Intelligibility Speech Perception test (CRISP) was used to obtain a speech reception threshold (SRT) in noise. Spondee target words were presented through the loudspeaker directly in front of the participant. The competing noise was presented 90 degrees azimuth from the participant for one condition and at 270 degrees azimuth for another condition. An SRT was obtained and converted to a signal-to-noise ratio. Participants were tested with the modified CI alone, non-modified CI alone, and bilateral CIs.

### **Impact of starting condition and the order of stimulation rate configuration**

A mixed effects regression analysis was used to test whether the phase number and baseline rate configuration status (matched vs. mismatched) significantly predicted participants' CRISP bilateral signal-to-noise ratios (SNR). The results of the analysis indicated that there was no significant relationship between test phase and the speech reception threshold (i.e. an order effect) for either of those participants who entered the study with mismatched rates or those who entered using matched rates at baseline. The order in which the participants experienced the conditions also did not impact results did not impact performance. There is no systematic trend across phases or time. Performance is similar for both groups, matched and mismatched at baseline. CRISP SNRs for individual participants at each phase, with the competing noise source near the modified CI (90 degrees azimuth) are presented in Figures 10A -12A of the Appendices and with the competing noise source near the non-modified CI (90 degrees azimuth) in Figures 13A – 15A of the Appendices.

### **Impact of stimulation rate Configuration: Paired t-tests of final sessions**

In order to test the impact of CI rate configurations on bilateral CRISP performance, paired t-tests of the final two sessions (one with mismatched and one with matched rate configurations) were analyzed. The data set analyzed were signal-noise-ratios (SNRs) with the noise presented near the modified CI vs. non-modified CI, obtained during the last two phases of the study protocol, when the listeners had the most experience with both rate configurations. SNRs with the noise presented near the modified CI and non-modified CI were analyzed separately. These data include comparisons for the six listening conditions (modified CI, non-modified CI, and bilateral; noise near the modified and non-modified CIs) for the eight participants who completed the data sets in both matched and mismatched rate configurations. This data reflects changes in performance during the research only. The results of the paired t-test analyses for SNRs obtained from the CRISP during the last two phases of the study protocol are shown in Table 8. There was no significant improvement in SNR when participants were evaluated wearing the mismatched or matched configurations with the modified CI alone, non-modified CI alone, or bilateral CIs. Also, there was no significant difference in SNR as a function of the source of the competing noise.

Paired-samples t-tests indicated that SNRs were not significantly different with a mismatched rate configuration than with a matched rate configuration with the modified CI alone, non-modified CI alone, and with bilateral CIs when the competing noise source was located near the modified CI or the non-modified CI (Table 8). Mean and standard error for bilateral SNRs in the matched and mismatched conditions with noise near the modified CI and with noise near the non-modified CI are shown in Figures 10 and 11 respectively.

Bilateral CRISP SNR, obtained during the final two phases of the study protocol, were analyzed to see if there was any significant difference between matched and mismatched

stimulation rates (Figures 12 and 13) and Phase 3 and Phase 4 SNR results (Figures 14 and 15) for each individual participant. Participants SH2 and SS2 were unable to perform the CRISP task and therefore are not included. When the noise source was near the modified CI, four of the eight participants demonstrated similar SNRs with either rate configuration. Three participants had poorer SNRs with the mismatched rates and one participant improved. When the noise source was near the non-modified CI, four participants demonstrated slightly improved SNRs with the mismatched rates, and the others either demonstrated poorer SNRs or no difference in SNR results (see Figures 12 and 13).

Similar to CNC results, bilateral CRISP SNRs were also not influenced by time in the experiment (phase). Figures 14 and 15 display bilateral CRISP SNRs obtained during the last two phases of the study protocol for each individual participant (Phase 3 and Phase 4). Results appear to be variable among participants for both conditions (noise near the modified CI or noise near the non-modified CI).

#### CORRELATIONS BETWEEN SPEECH PERCEPTION IN QUIET AND NOISE.

In order to determine whether CNC word and phoneme identification and CRISP SNRs when noise was presented near the modified CI or near the non-modified CI for individual participants, using matched and mismatched rates depend on some underlying skill, correlations between performance on the two tasks obtained (Figures 16 and 17 (words); Figures 16A and 17A (phonemes) of the Appendices. Participants SH2 and SS2 were unable to perform the CRISP test due to poor ability to discriminate speech in noise, therefore their data are not included. When noise was presented near the non-modified CI individuals that correctly identified more words had better SNR thresholds, indicating that good performance on CNC testing was correlated with good performance on CRISP testing, and vice versa, regardless of

rate configuration (see Figure 15, matched  $r = -0.83$ ,  $p = 0.005$ , mismatched  $r = -0.90$ ,  $p = 0.001$ ). However, when noise was presented near the modified CI, there was no correlation between percent correct CNC word identification and CRISP SNRs when the stimulus rates were matched (see Figure 16,  $r = -0.12$ ,  $p = 0.38$ ), but were significantly correlated when the rates were mismatched (words  $r = -0.64$ ,  $p = 0.04$ ). Similar plots for phoneme recognition can be seen in the Appendices Figures 16A and 17A. Less significant effects for phonemes were evident probably because patients were performing near ceiling.

In order to determine if the amount of change in performance was similar for the two speech tests, percent correct CNC word and phoneme identification and CRISP SNRs were normalized by subtracting the mismatched score from the matched score. Improvements with the matched and mismatched conditions were compared between the CNC and CRISP tests. The results obtained when the noise was presented near the modified CI or near the non-modified CI for individual participants, are presented in Figures 18 and 19 (words); Figures 18A and 19A (phonemes) of the Appendices. Correct CNC word and phoneme identification improved with the mismatched rates compared with the matched rates for half the participants. Greater improvements were observed for CNC than for CRISP in all conditions. Slight improvements were noted in CRISP SNRs for five out of eight participants when noise was presented near the non-modified CI, three of which also improved on the CNC task (Figure 18 and Figure 18A). When the noise was near the modified CI, only one participant (SH1) experienced improved SNRs with the mismatch (Figure 19 and Figure 19A).

Normalized bilateral CRISP data for matched vs. mismatched configurations in Phases 3 and 4 of the study protocol are displayed in Figure 20. Results indicate that the majority of the participants (five out of eight) demonstrated improved SNRs when the competing noise source

was located near the non-modified CI. In this condition the modified CI is farther from the noise source. Once again, participants SH2 and SS2 are not included in the figures because they could not perform the task.

Upon completion of the study protocol, eight out of the 10 participants preferred the mismatched stimulation rate configuration. This mapping configuration was then set on their speech processors upon the participant's request.

## Chapter 4. Discussion

When individuals have sequential cochlear implants and the original implant is not programmed to use high stimulus rates, is it important to match stimulation rates when fitting bilateral implants? Alternatively, should a clinician make use of the higher stimulation rates in the newer second implant? Can the user benefit from the mismatched electrode stimulation rates or will s/he have difficulty integrating the information produced by the two ears? By evaluating speech perception in quiet and in competing noise when the same participants listened with mismatched or matched bilateral cochlear implant stimulation rates it was observed that the use of high stimulation rates in the second implant ear (mismatched rate) provided better speech perception in quiet in some participants. Speech perception ability, in quiet, improved when participants used the mismatched rates when wearing bilateral implants, relative to the matched rates. However, no improvement was evident for speech perception in noise in either rate. The majority of the participants also preferred the mismatched rates to the matched rates and asked to continue wearing them once the study protocol was completed. Since some of the participants entered the study with an older implant limited to slow stimulation rates and others had no experience with high rates in the older implant, it was not possible to explore performance with matched high stimulations rates on this group of participants. Consequently, it is possible that the improved performance is simply due to availability of a high stimulation rate in one ear. However, the improvement was only noticed when both implants were activated, suggesting that it is the mismatch that is important.

When all ten participants were analyzed, bilateral word and phoneme recognition in quiet, using the CNC test, significantly improved with the mismatched rates (see Figures 5 & 6 and Table 6). However, word and phoneme recognition was not significantly different with

mismatched or matched rates with just the modified CI alone (2<sup>nd</sup> CI). Also, with the non-modified CI alone (1<sup>st</sup> CI) there was minimal change in speech recognition. The pattern of results were very similar for both phoneme and word recognition.

When the two participants who could not perform the CRISP (SS2 and SH2), were excluded from the analysis, bilateral word recognition in quiet for eight participants (for the CNC test) also significantly improved with the mismatched rates with greater statistical power. Similar to the results with all ten participants, performance with the modified CIs was not significantly improved with the high rates. However, the non-modified CIs alone were significantly different during the matched and mismatched phases (see Table 7). The improvement in CNC performance when the implant stimulation rates were mismatched supports the hypothesis that an increase in electrode stimulation rate of the second CI may improve speech recognition in bilateral CI users. There is some evidence that increased stimulation rate helps unilateral CI users (Chadha et al., 2011; Chen, & Zhang, 2006; Johnston et al., 2009; Litovsky et al., 2009; Litovsky et al., 2006; Litovsky et al., 2004; Simon, 2005; Muller et al., 2002; Nopp et al., 2004; Sparreboom et al., 2011; Strelnikov et al., 2011; Tyler et al., 2002; e.g., van Hoesel & Tyler, 2002; Van Hoesel et al., 2005; van Hoesel & Tyler, 2003; Van Hoesel & Clark, 1997; van Hoesel et al., 1993), which could lead to a hypotheses that this might also help in bilateral implants.

The CNC lists are commonly used in clinical and research settings to measure patient word recognition skills because they can provide an estimate of patients' ability to understand meaningful speech (Olsen, Van Tasell, & Speaks, 1997). CNC lists are useful in testing as they are phonetically balanced and have good test retest reliability (Causey, Hood, Hermanson, & Bowling, 1984; Peterson & Lehiste, 1962). Consequently, these word lists may be used to

monitor speech reception ability over time with minimal learning effects. The lists are used for both the typically hearing and hearing-impaired. This speech perception data may be a useful tool for the cochlear implant programmer as well as for the speech pathologist working with the patient as it demonstrates benefit of the cochlear implant(s) over time, especially when standardized using recorded stimuli. The information may be used in order to demonstrate utility of speech therapy or to inform the clinical audiologist which areas to focus on during mappings or programming, based on perception errors.

Speech in noise, using the CRISP test, was not significantly affected by immediate experience with matched or mismatched stimulation rates with the modified CI alone and for bilateral CIs, regardless of the noise source location (see Figures 10 & 11 and Table 8). Again, we did not expect improvement with the non-modified CI alone (1<sup>st</sup> CI), as no rate changes were made on this device. Although benefits from the mismatch were not apparent in this study, others have recorded improvements in speech in noise for unilateral CI users (Dunn et al., 2006; Frijns et al., 2003; McLaughlin et al., 2013; Plant et al., 2007).

Speech reception threshold (SRT) measurement is an integral part of the audiologic evaluation because it provides information to the tester regarding how the participant uses the audible sound to discriminate speech. Providing information about how a listener may perform in the presence of competing noise (SNR) indicating how they may function in everyday life. This information may be used to improve mapping strategies created for noisy situations. Improving speech in noise during auditory therapy can be performed and monitored via speech in noise testing.

Although we failed to see overall benefits in noise with the CRISP test, we did see individual participant benefits. There is little data on test/retest reliability (Misurelli & Litovsky,

2012), in adults so the amount of change in SNR as a function of rate configuration greater than this can be considered potentially significant is not sufficiently established to determine whether the patterns of change are significant

A potential explanation for the significant improvements with the mismatched rates which emerged for speech in quiet (CNC) but not for speech in noise (CRISP), may be that the CNC task is a familiar test to cochlear implant patients as it is a part of a typical periodic cochlear implant progress evaluation. The CRISP, on the other hand, was an unfamiliar task for all the participants in this experiment, as it is not typically used clinically. It was a difficult task for all participants, two participants were unable to perform the task and so their data was not included in the study. The task involved computer interaction, which may come easier to some individuals than others.

Participants SS2 and SH2 were tested with the CRISP once they revealed that they had difficulty performing the task. SS2 was a prelingually deafened CI user. This participant's word and phoneme recognition in quiet was very poor. Their overall poor speech recognition in quiet may have had bearing on his/her abilities in noise. Although SH2 was postlingually deafened, s/he was the eldest in the study. Although SH2's overall speech recognition in quiet was fair to poor, performance on the CRISP was very poor. This may have been due to the participant's discomfort with the computer or possible poor auditory processing abilities, both of which may be a function of age.

In order to observe whether the data from these two participants (SS2 and SH2) affected the outcome of the CNC analysis, we re-analyzed the CNC data eliminating these two participants. We found a more significant overall benefit with mismatched rates for CNC words in the bilateral condition with the remaining eight participants. However, bilateral benefit for

phonemes were not significant (possibly due to the performance near ceiling in some participants).

Interestingly, the CNC analysis with the eight participants also showed significant benefit for the non-modified CI during a mismatched phase for both CNC words and phonemes. We also find that the variability of these scores are low and conclude that since the scores for the non-modified ear were stable, any small changes which may have occurred from phase to phase became more evident (see Table 7).

Another way to look at change in performance when implants were matched and mismatched was to normalize performance relative to baseline performance. Bilateral CNC word and phoneme recognition improved when rates were mismatched, but improvement in CRISP SNRs were small or none. Since both tests are expected to evaluate the CI users' speech perception ability, it is relevant to determine whether performance on the two speech tasks are correlated and under what conditions. A relationship exists between CNC word and phoneme recognition and CRISP SNRs in individual participants. Good speech recognition in quiet (CNC) was correlated with good speech recognition in noise (CRISP), for both the matched and mismatched rates when the noise was noise presented near the non-modified CI (Figure 16, 17, 16A & 17A). If participants performed well on the CNC task, they also tested well on the CRISP. This implies that the skills needed for performing well on one task are similar to those needed for the other and vice versa. However, when the noise was near the modified CI, we only saw correlation in performance when the stimulation rates were mismatched (Figures 17 and 16A). We may have seen this result because the noise may have masked the non-modified CI (slow rate) and most of the information was obtained from the modified CI (high rate). Perhaps the mismatch or high rates from the modified side were being utilized in order to improve

performance. When the noise was presented near the modified side, the non-modified CI was primarily in use. Here, we saw a correlation for the mismatched condition only, and not for the matched. This may indicate that during the matched condition, the participant did not have the advantage of the mismatched, higher rates, which could have influenced performance.

Our failure to see clear evidence of enhanced speech perception in noise with the rate mismatch, does not imply that there were no benefits in noise. It is possible that the specific test simply did not detect these benefits. This may have been a result of a small number of participants included in the study. Including an additional speech in noise task, in future research, may help answer this question.

It was not possible to recruit a large number of participants with sequential implants, due to the inaccessibility of patients with the appropriate implants. The small 'n' reduced the power of the results. A more robust result may have emerged from a larger more consistent participant base. Another consequence of the difficulty in recruiting participants is the variability of the participants. In this study, there is a wide range in participant age, age at implantation, onset of deafness, and number of participants enrolled in the experiment. Participants' ages ranged from 15 years to 73 years (Table 1). However, speech recognition scores were not dependent of age. Theories are mixed on whether age at implantation determines cochlear implant success (Pasanisi et al., 2003; Lenarz et al., 2012). The mean age was similar for participants entering with slow stimulation rates on both implants (slow/slow) and those entering with one slow and one faster rate (slow/high).

Another factor which may influence the clinician's decision or ability to increase stimulation rate may be the non-perceptual effects of stimulation rate. Non-perceptual effects often observed in the clinic may include battery life, battery efficiency, FM signal, and

compliance. Some clinicians may try to increase stimulation rate, but sometimes cannot due to other factors which may deter the change. Increased rate often results in raised threshold and comfort levels. As these levels increase, we can approach or exceed the voltage limits of the device capabilities or compliance. If this occurs, it can degrade the signal.

The thickness of the skin flap above the internal device could also influence the necessary voltage for optimal signal transmission. The thicker the skin, the more voltage is needed to transmit the signal across the skin to the internal device. The device will have to work much harder to do this, and thus, use more energy. If this occurs, stimulation rate may need to be reduced in order to stay within the voltage compliance and deliver a consistent signal to the internal implant.

Higher stimulation rate can also decrease battery life of the speech processor of the CI device. Some patients may find it inconvenient to have to change batteries often and will sacrifice sound quality or performance for ease of use, and therefore opt to use a reduce rate. Other users may want their bilateral devices to have similar battery life. Since stimulation rate can control battery life, often clinicians are required to increase or reduce rate in order to satisfy patient needs. Battery efficiency varies between cochlear implant manufacturers.

Using a FM system will also drive the battery efficiency of the speech processor. If battery efficiency is already compromised by high stimulation rates, additional battery drain from an FM system connection could further degrade the signal and/or result in even more of a reduction in battery life. Although FM systems are more frequently used by children, it is a consideration for some adults as well.

Despite these potential disadvantages of higher stimulation rates, when participants were asked at the end of the study protocol, which mapping rate configuration they preferred and

whether they would like to wear that configuration home, the majority (8/10) of the participants verbally stated they preferred the mismatched rates to the matched rates. No formal questionnaire was administered but their choice suggests that they did find benefit. The preference information obtained at the end of the study protocol provided interesting information. Four of the participants entering the study with matched rates preferred mismatched rates by the end of the study protocol, three of which improved using mismatched rates. Of the slow/high group, four preferred the mismatch and two of those participants performed best with mismatched rates. Although participant SH5 performed best with the mismatched rate s/he preferred the matched rate configuration. SH2 performed slightly poorer with the mismatched rates and SH3 remained the same, however, both SH2 and SH3 preferred the mismatch.

The information learned during this study has important clinical relevance. Clinicians must understand that there is no need to hesitate to try rate manipulations for fear of doing a disservice to their sequential bilateral cochlear implant patients. Increasing the rate of the second CI device, creating a mismatched signal may not hurt the patient, but often help them. Mapping audiologists may not always be able to make major rate manipulations due to the various constraints of the device and patient restrictions, however, it can be well worth the attempt.

It is critical for clinicians to try state of the art mapping procedures in caring for their sequential bilateral cochlear implant patients, as mapping procedures can affect cochlear implant performance. Remaining safe, using older procedures or technology may put patients at a disadvantage. It is possible to obtain an enhanced result for these patients, even if the stimulation rates of the two devices are mismatched. Of course, monitoring is always important whenever significant changes are made on cochlear implant programming.

Future research may include recruitment of a greater number of participants in order to provide more powerful statistics. A similar study protocol, designed for children may provide beneficial clinical information regarding programming of pediatric bilateral CI users. The current test protocol was too long and rigorous for children. A future protocol could include a shorter test time, possibly using only the CRISP test for children, as it is interactive and entertaining for the pediatric population. A similar study, with an additional high/high group, in which first and second CIs enter the research with high rates, may also provide valuable clinical information. It may also be interesting to examine whether matched or mismatched rates affect sound localization.

#### **4. 1. Conclusions**

Evaluating the impact of matched and mismatched stimulation rates in the same participants who had experience with both matched and mismatched stimulation rates permitted the determination that mismatched stimulation leads to better speech discrimination in quiet. No significant benefit was noted for speech in noise. However, the majority of the participants preferred the mismatched rates and asked to keep those programs on their speech processors following completion of the study protocol.

Matching stimulation rates in sequentially implanted bilateral cochlear implants does not seem to be necessary. Patients may benefit from the mismatched rates. Consequently, clinicians can make use of the higher stimulation rates available in the newer second implant.

Many clinicians are hesitant to change the mapping on the second CI, fearing that they may degrade the overall bilateral speech signal. However, we have found that the user can integrate the different information coming from the two ears well. Not only can they function with the two different signals, but they are able to do better with two different signals.

## 5. Tables

*Table 1.* Participant ear characteristics, including age, age at implantation for first and second implants, onset of deafness, and time between surgeries. Participants SS5 and SH5 marked with \* went through the protocol several months prior to the other participants, while the study protocol was being developed. These patients experienced the identical study protocol, with the exception of a baseline evaluation. SS = slow/slow baseline rate condition; SH = slow/high baseline rate condition; R = Right; L = Left; CA = Contour Advance.

<b>Participant Code</b>	<b>Prelingual/Postlingual</b>	<b>Age at Time of Testing (years)</b>	<b>Age at 1st Implant (years)</b>	<b>1st CI</b>	<b>Age at 2nd Implant (years)</b>	<b>2nd CI Modified</b>	<b>Interval between Implants (years)</b>
SS1	Postlingual	48	46.9	R	47.3	L	0.4
SS2	Prelingual	39	34.1	R	37	L	2.9
SS3	Postlingual	51	50.1	L	50.5	R	0.4
SS4	Postlingual	68	64.1	R	67.8	L	3.7
SS5*	Postlingual	73	67.3	L	70.9	R	3.6
<b>Mean (s.d.)</b>		<b>55.8 (14.2)</b>	<b>52.5 (13.5)</b>		<b>54.7 (14.3)</b>		<b>2.2 (1.7)</b>
SH1	Postlingual	66	54.7	L	60.7	R	6
SH2	Postlingual	72	68.1	R	75.3	L	7.2
SH3	Postlingual	61	55.8	L	60.6	R	4.8
SH4	Prelingual	15	7.3	R	15.7	L	8.4
SH5*	Prelingual	22	14.4	L	21.7	R	7.3
<b>Mean (s.d.)</b>		<b>47.2 (26.6)</b>	<b>40.0 (27.3)</b>		<b>46.3 (26.4)</b>		<b>6.7 (1.4)</b>

*Table 2.* Participant internal and external implant characteristics for both ears are displayed, including internal electrode models for the first and second implanted ear and external speech processors for the first and second implanted ears. Participants SS5 and SH5 marked with \* went through the protocol several months prior to the other participants, while the study protocol was being developed. These patients experienced the identical study protocol, with the exception of a baseline evaluation. SS = slow/slow baseline rate condition; SH = slow/high baseline rate condition; R = Right; L = Left; CA = Contour Advance.

<b>Participant Code</b>	<b>Electrode Type 1st Implant</b>		<b>Electrode Type 2nd Implant</b>	
	<b>Internal Implant</b>	<b>External Processor</b>	<b>Internal Implant</b>	<b>External Processor</b>
SS1	Freedom (CA)	Freedom	Freedom (CA)	Freedom
SS2	NU24 Contour	Freedom	Freedom (CA)	Freedom
SS3	Freedom (CA)	Freedom	Freedom (CA)	Freedom
SS4	Freedom (CA)	Freedom	N5	N5
SS5*	NU24 Contour	Freedom	Freedom (CA)	Freedom
SH1	HiRes90K	Harmony	HiRes90K	Harmony
SH2	NU24 Contour	Freedom	Freedom (CA)	Freedom
SH3	HiRes 90K	Harmony	HiRes90K	Harmony
SH4	NU24 Contour	Freedom	N5	N5
SH5*	C1 HiFocus 1.2	Harmony	HiRes 90K	Platinum

*Table 3.* Participant’ implant stimulation rates for both CIs prior to enrollment in the experiment and during experimental conditions. The preference for a specific rate configuration at end of the experiment is also displayed. Participants SS5 and SH5 were went through the protocol several months prior to the other participants, while the study protocol was being developed and are marked with \*. These patients experienced the identical study protocol, with the exception of a baseline evaluation. SS = slow/slow baseline rate condition; SH = slow/high baseline rate condition; R = Right; L = Left; CA = Contour Advance.

Participant Code	Modified CI	Electrode Stimulation Rate (Hz) 1st CI	Electrode Stimulation Rate (Hz) 2nd CI		Phase 2 Condition	Preference at end of Study
		Pre-Study Rate	Pre-Study Rate	Modified Rate		
SS1	L	900	900	3500	Mismatch	Match
SS2	L	900	900	1800	Match	Mismatch
SS3	R	900	900	2400	Match	Mismatch
SS4	L	900	900	1800	Mismatch	Mismatch
SS5*	R	900	900	2400	Mismatch	Mismatch
SH1	R	1450	3867	1650	Mismatch	Mismatch
SH2	L	1200	2400	1200	Match	Mismatch
SH3	R	1856	3712	1856	Match	Mismatch
SH4	L	900	2400	900	Mismatch	Mismatch
SH5*	L	720	3712	750	Match	Match

*Table 4.* Repeated Measures ANOVA for bilateral CNC word recognition to test whether the phase number and baseline rate configuration (matched vs. mismatched) significantly predicted CNC bilateral word recognition. The order in which participants experienced the conditions did not impact results. There is no systematic trend across phases or time. Performance was similar for individuals using mismatched or matched stimulation rates at baseline.

<b>Bilateral Word Score</b>	<u>Coefficient</u>	<u>Standard Error</u>	<u>z</u>	<u>P&gt; z </u>	<u>95% Confidence Interval</u>
<b>Phase</b>	0.66	2.39	0.28	0.78	-4.02 5.33
<b>Baseline Rate Configuration</b>	4.29	14.23	0.30	0.76	-23.61 32.19
<b>Interaction Phase x Baseline</b>	-2.05	3.37	-0.61	0.54	-8.66 4.56
Intercept	65.27	10.06	6.48	0.00	45.53 84.99
<u>Random-effects Parameters</u>		<u>Estimate</u>	<u>Standard Error</u>		<u>95% Confidence Interval</u>
<u>Subjects</u>					
Variance within subjects (Standard Deviation Constant)		16.77	4.69		9.70 29.02
Variance of fixed effects (Standard Deviation Residual)		11.21	1.55		8.54 14.71

*Table 5.* Repeated Measures ANOVA for bilateral CNC Phoneme recognition to test whether the phase number and baseline rate configuration (matched vs. mismatched) significantly predicted CNC bilateral phoneme recognition. The order in which the participants experienced the conditions did not impact results. There is no systematic trend across phases or time. Performance was similar for individuals using mismatched or matched stimulation rates at baseline.

<u>Bilateral Phoneme Score</u>	<u>Coefficient</u>	<u>Standard Error</u>	<u>z</u>	<u>P&gt; z </u>	<u>95% Confidence Interval</u>
<b>Phase</b>	1.30	1.57	0.83	0.41	-1.78 4.38
<b>Baseline Rate Configuration</b>	5.25	9.01	0.58	0.56	-12.40 22.90
<b>Interaction Phase x Baseline</b>	-2.88	2.22	-1.30	0.20	-7.24 1.47
<b>Intercept</b>	79.71	6.37	12.52	0.00	67.23 92.20
<u>Random-effects Parameters</u>		<u>Estimate</u>	<u>Standard Error</u>		<u>95% Confidence Interval</u>
<u>Subjects</u>					
Variance within subjects (Standard Deviation Constant)		10.25	2.91		5.88 17.87
Variance of fixed effects (Standard Deviation Residual)		7.38	1.02		5.63 9.68

*Table 6:* Results of paired sample t-tests comparing CNC word and phoneme recognition mean percent correct for matched and mismatched rate configurations with the modified CI alone, non-modified CI alone, and bilateral CIs. Significantly higher mean word and phoneme recognition when participants were obtained only with the bilateral CIs. Bold type indicates significance.

	<i>Mismatch (Mean)</i>	<i>Match (Mean)</i>	<i>Difference (Mismatch – Match)</i>	<i>Difference (Std. Err)</i>	<i>t Stat.</i>	<i>Pr( T &lt; t ) 2-tail</i>	<i>Cohen's d</i>
<b>Percent Correct CNC <u>Word</u> Recognition</b>							
Modified CI	45.8	41.4	4.4	7.1	0.62	0.55	
Non-modified CI	59.2	53.8	5.4	2.3	2.30	0.05	0.73
Bilateral	70.4	60.6	9.8	3.8	2.61	<b>0.03</b>	0.83
<b>Percent Correct CNC <u>Phoneme</u> Recognition</b>							
Modified CI	67.2	60.0	7.2	4.8	1.51	0.16	
Non-modified CI	78.9	75.4	3.4	2.1	1.66	0.13	
Bilateral	85.1	78.3	6.7	2.7	2.49	<b>0.03</b>	0.84

Table 7: Results of paired sample t-tests comparing CNC word and phoneme recognition mean percent correct for matched and mismatched rate configurations with the modified CI alone, non-modified CI alone, and bilateral CIs (Excluding participants SS2 and SH2).

	<i>Mismatch (Mean)</i>	<i>Match (Mean)</i>	<i>Difference (Mismatch – Match)</i>	<i>Difference (Std. Err)</i>	<i>t Stat.</i>	<i>Pr( T &lt; t ) 2-tail</i>	<i>Cohen's d</i>
<b>Percent Correct CNC <u>Word</u> Recognition</b>							
Modified CI	49.3	42.3	7.0	8.7	0.80	.45	
Non-modified CI	65.5	59.8	5.8	1.9	3.02	<b>0.02</b>	1.07
Bilateral	74.0	64.3	9.8	4.0	2.47	<b>0.04</b>	0.87
<b>Percent Correct CNC <u>Phoneme</u> Recognition</b>							
Modified CI	69.7	60.6	9.1	5.8	1.56	.162	
Non-modified CI	83.4	79.7	3.7	1.4	2.63	<b>.034</b>	.95
Bilateral	86.3	81.3	5.0	2.9	1.76	.122	

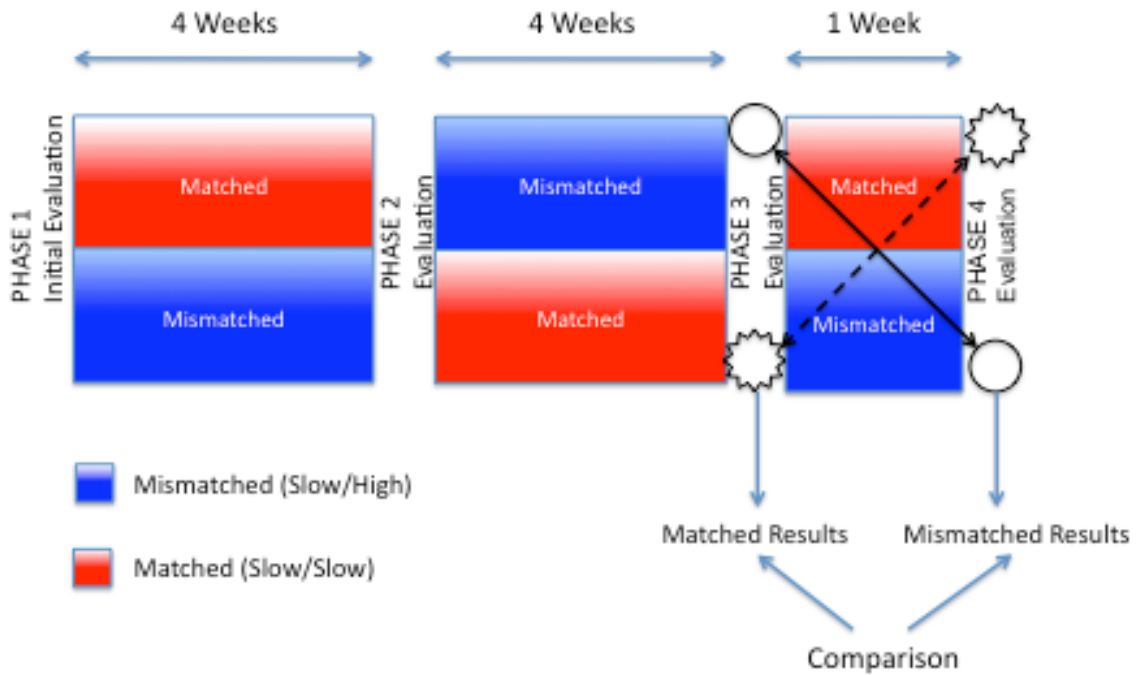
Table 8: Repeated Measures ANOVA bilateral CRISP results to test whether the phase number and baseline rate configuration (matched vs. mismatched) significantly predicted participants' CRISP bilateral SNR. No significant relationship between test phase and the speech reception threshold (i.e. an order effect) for either of those participants who entered the study with mismatched rates or those who entered using matched rates at baseline was observed.

<u>Bilateral SNR</u>	<u>Coefficient</u>	<u>Standard Error</u>	<u>z</u>	<u>P&gt; z </u>	<u>95% Confidence Interval</u>
<b>Phase</b>	-0.63	0.87	-0.73	0.46	-2.33 1.06
<b>Baseline Rate Configuration</b>	-1.18	1.64	-0.72	0.47	-4.40 2.03
<b>Interaction Phase x Baseline</b>	-0.90	0.97	-0.93	0.35	-2.81 1.00
Intercept	-8.55	2.66	-3.21	0.001	-13.76 -3.34
<u>Random-Effects Parameters</u>		<u>Estimate</u>		<u>Standard Error</u>	<u>95% Confidence Interval</u>
<u>Subjects</u>					
Variance within subjects (Standard Deviation Constant)		16.77		4.69	9.70 29.02
Variance of fixed effects (Standard Deviation Residual)		11.21		1.55	8.54 14.71

Table 9: Results of paired sample t-tests comparing CRISP Signal-to-Noise Ratios for matched and mismatched rate configurations (Excluding two participants who could not do the test).

	<i>Mismatched (Mean)</i>	<i>Matched (Mean)</i>	<i>Difference Mismatched – Matched)</i>	<i>Difference (Standard Error)</i>	<i>t Stat</i>	<i>Pr( T &lt; t ) 2-tail</i>
<b>Signal-to-Noise Ratio Noise near the Modified CI</b>						
Modified CI	-4.0	-1.5	-2.5	2.6	0.95	0.37
Non-modified CI	-12.8	-14.1	1.4	1.8	0.76	0.47
Bilateral	-10.9	-14.0	3.0	2.8	1.34	0.22
<b>Signal-to-Noise Ratio Noise near the Non-Modified CI</b>						
Modified CI	-6.7	-4.5	-2.1	2.2	0.98	0.36
Non-modified CI	-7.2	-9.6	2.4	1.9	1.31	0.23
Bilateral	-10.7	-10.2	-0.56	1.4	0.41	0.69

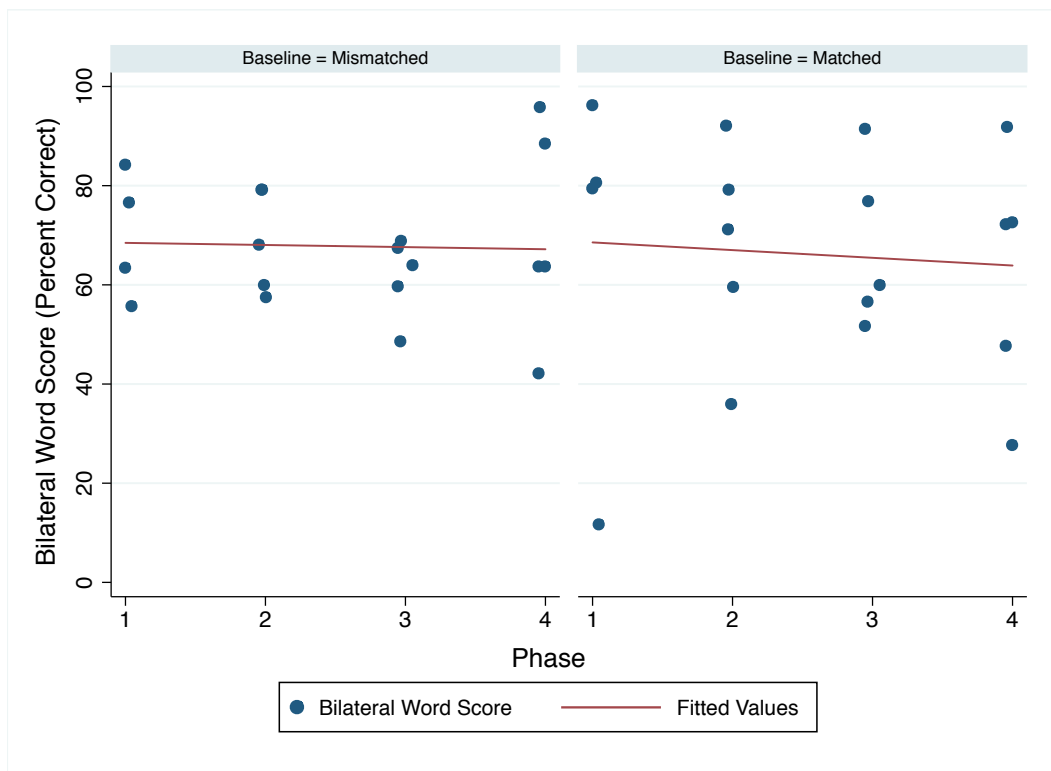
6. Figures



*Figure 1.* Experimental Timeline. An illustration of the interleaved pattern of speech testing and CI fitting and experience with the new configurations. The red boxes represent the matched rate condition and the blue boxes represent the mismatched rate conditions.



*Figure 2.* CRISP Test Set Up. Left. Target speech signal from the front (zero degrees azimuth). Noise source located at the side of the participant (270 degrees azimuth). Right. Target speech signal from the front (zero degrees azimuth). Noise source located at the side of the participant (90 degrees azimuth).



*Figure 3.* Percent correct word score as a function of experimental rate for all participants as a function of the test phase. Participants entering with mismatched rate configurations are in the left plot and participants entering with the matched rate configurations are on the right. Phase 1 represents the baseline pretest with the rate configuration that the participants entered the test with. Phase 2 represents the test after four weeks with the initial experimental rate configuration, Phase 3 with the second experimental rate configuration and Phase 4 the final test with the rate configuration used in Phase 2. The blue symbols show the scores for the individual participants and the line is the best fit. **There was no systematic effect of time or baseline configuration.**

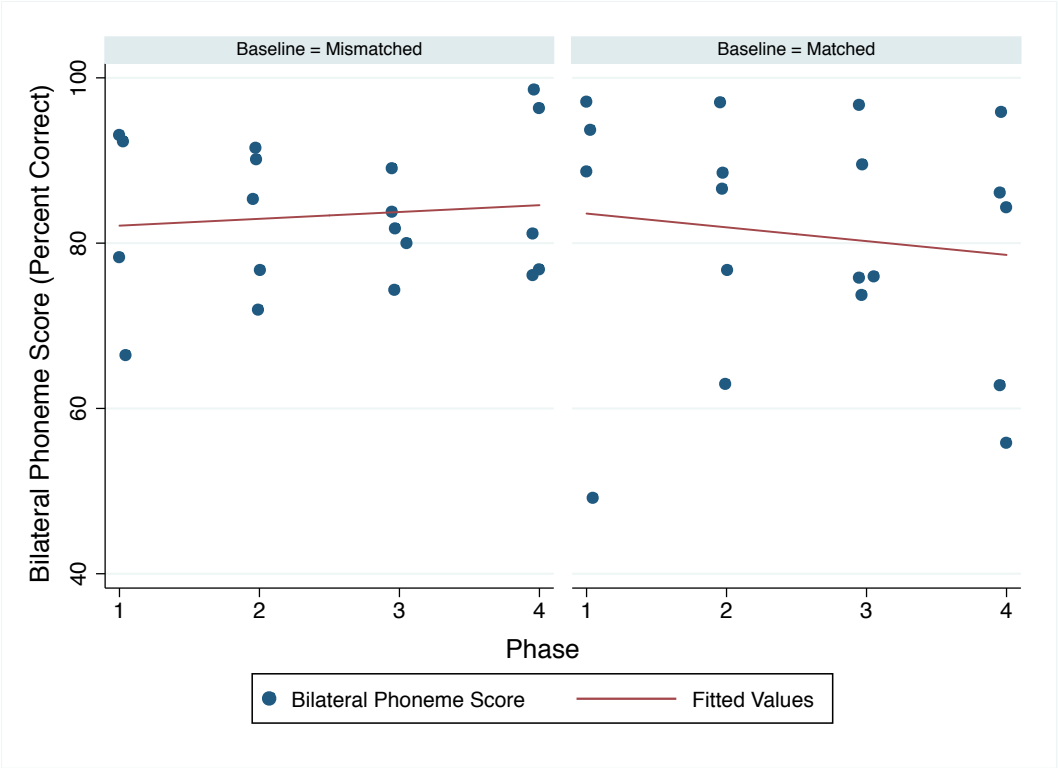


Figure 4. Percent correct phoneme score as a function of experimental rate for all participants as a function of the test phase. The format is the same as Figure 1.

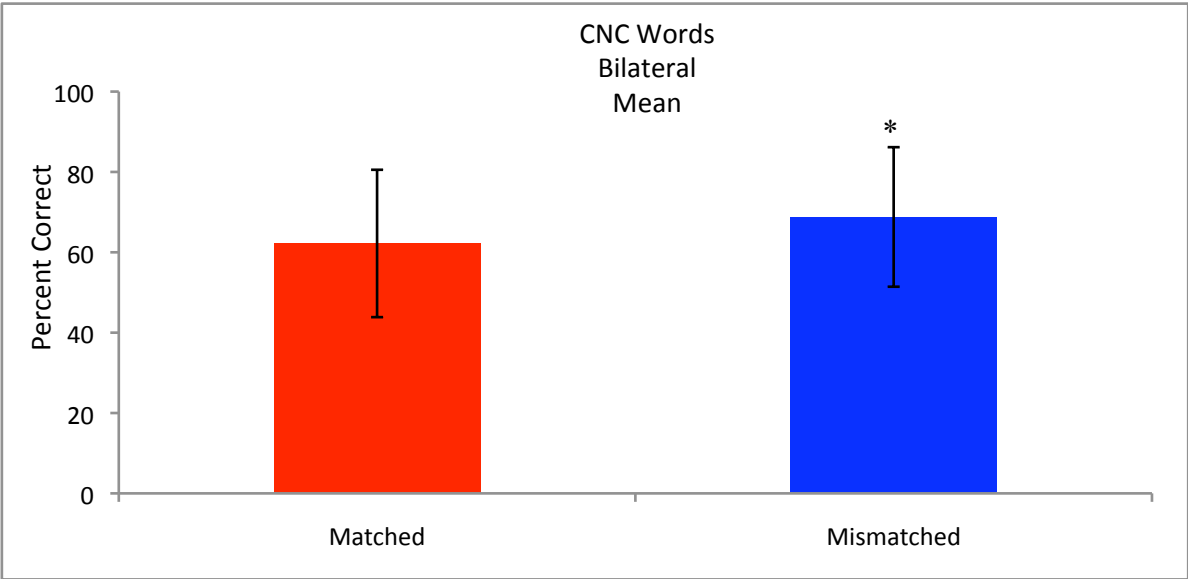


Figure 5: Mean Bilateral CI CNC Percent Correct Word Recognition as a function of Cochlear Implant Configuration. Error bars represent standard error. Asterisk indicates statistical significant for  $p < 0.05$ .

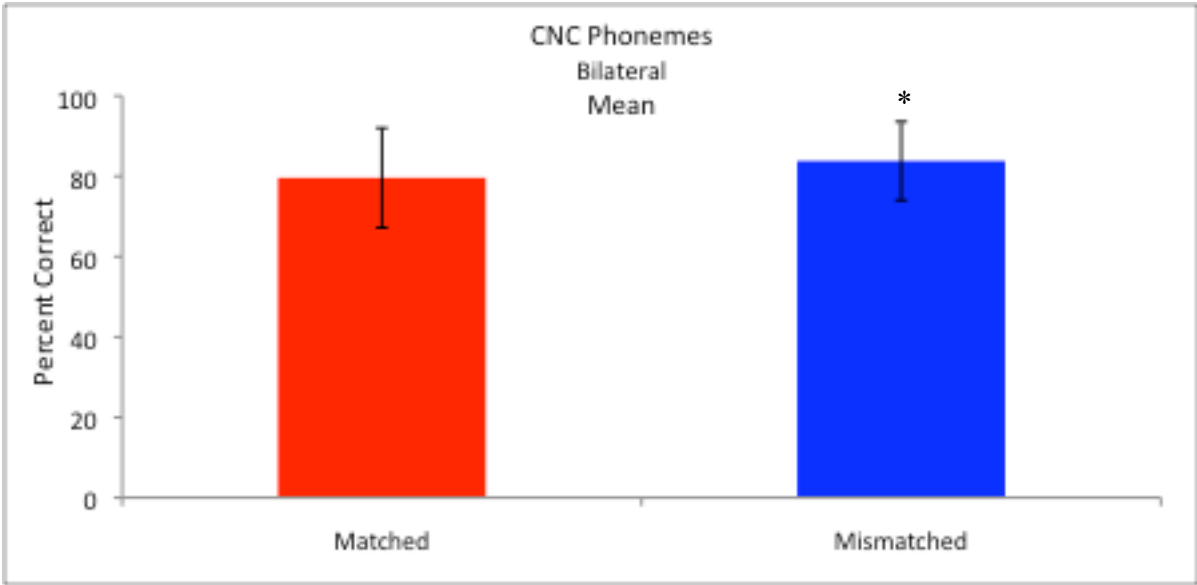
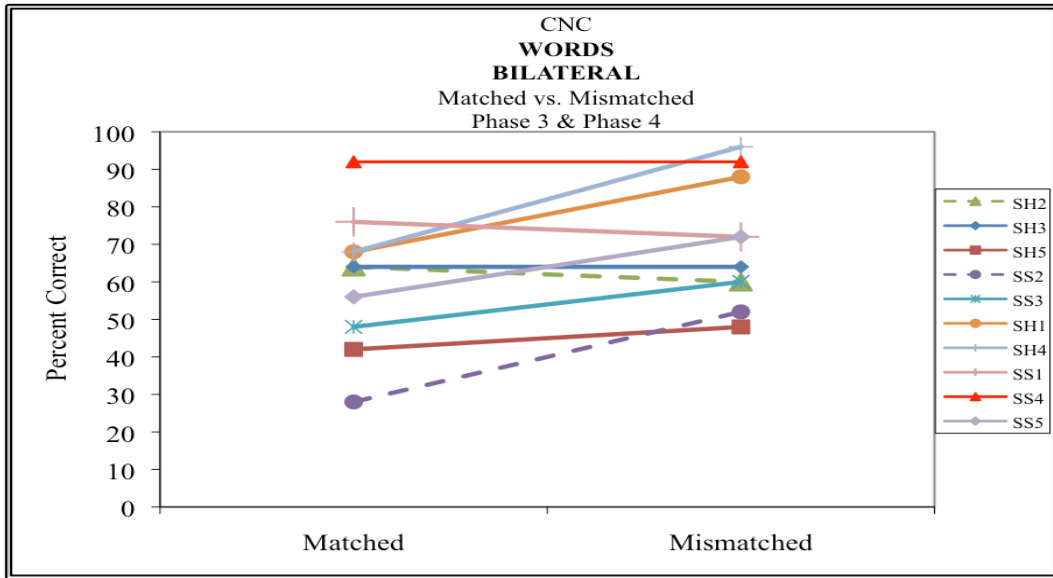


Figure 6: Mean Bilateral CI CNC Percent Correct Phoneme Recognition as a function of Cochlear Implant Configuration. Error bars represent standard error. Asterisk indicates statistical significant for  $p < 0.05$ .



*Figure 7.* Bilateral CI CNC word recognition (percent correct) for matched and mismatched rate configurations during the last two phases of the study protocol for each individual participant. Five participants performed better with mismatched configurations. Others showed minimal change. The two participants not included in the CRISP testing are shown with dashed lines.

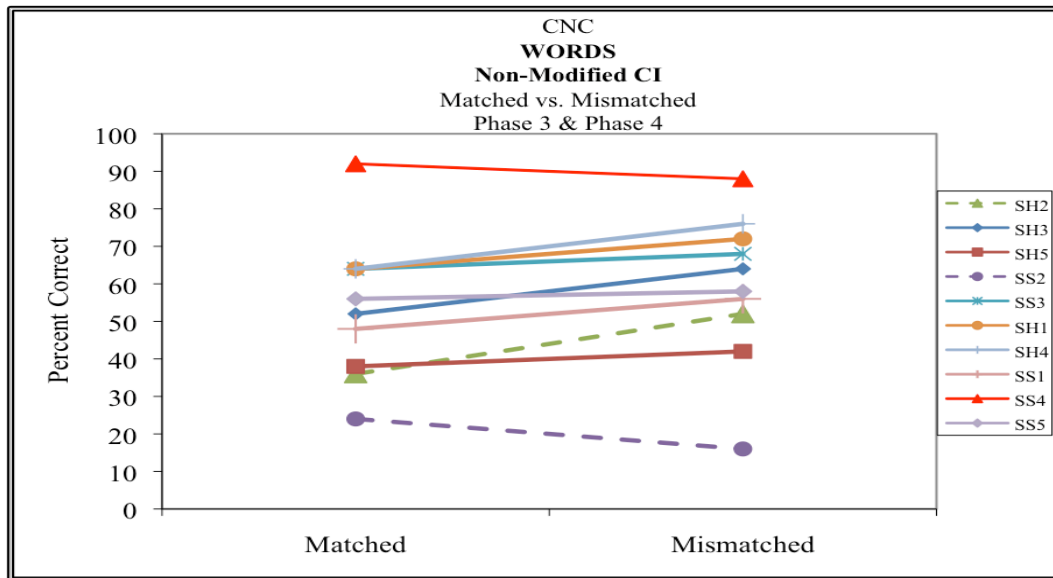
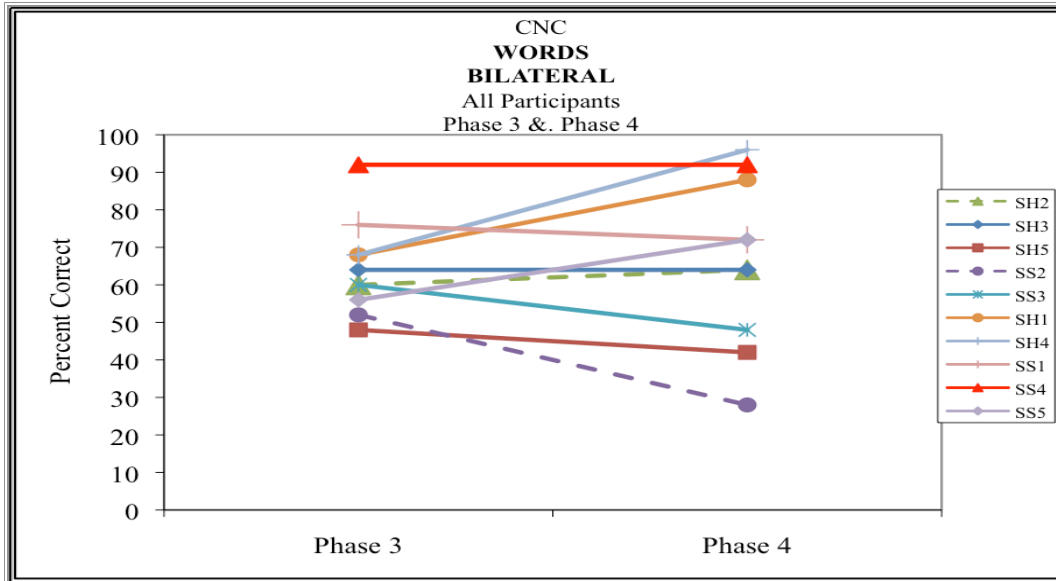


Figure 8. Non-Modified CI CNC word recognition (percent correct) for matched and mismatched rate configurations during the last two phases of the study protocol for each individual participant. Five participants performed better with mismatched configurations. Others showed minimal change. The two participants not included in the CRISP testing are shown with dashed lines.



*Figure 9.* Bilateral CI CNC Word recognition (percent correct) for Phases 3 and 4 of the study protocol for each individual participant. There was no consistent pattern in either phase. The two participants not included in the CRISP testing are shown with dashed lines.

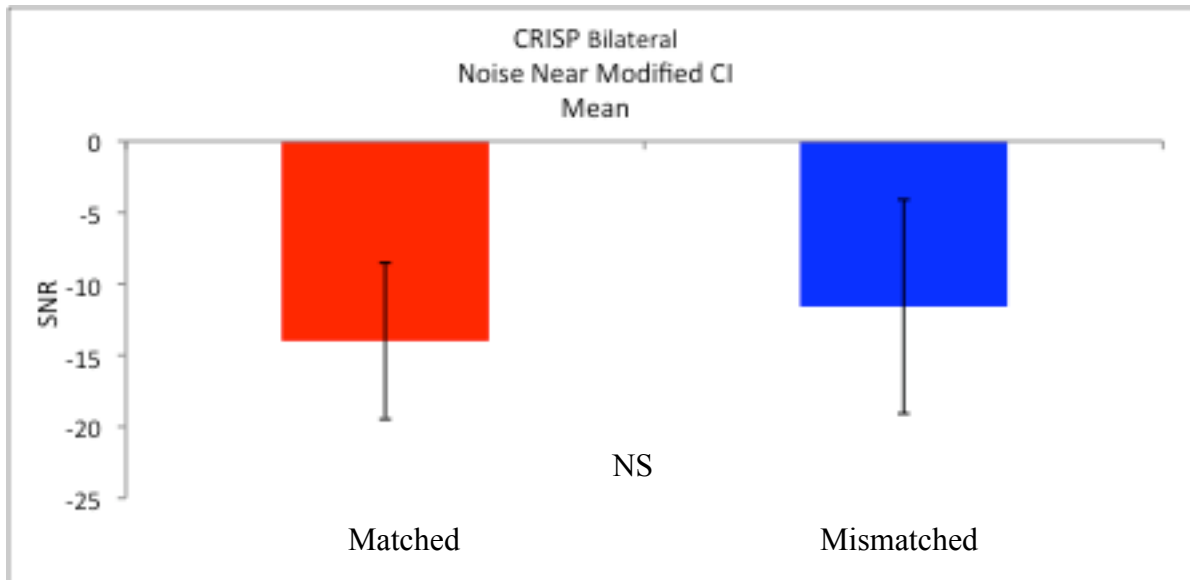


Figure 10: Mean Bilateral CI CRISP Signal-to-Noise Ratio as a function of Rate Configuration.

Competing Noise presented near the Modified CI. Error bars represent standard error. NS indicates results are not significant.

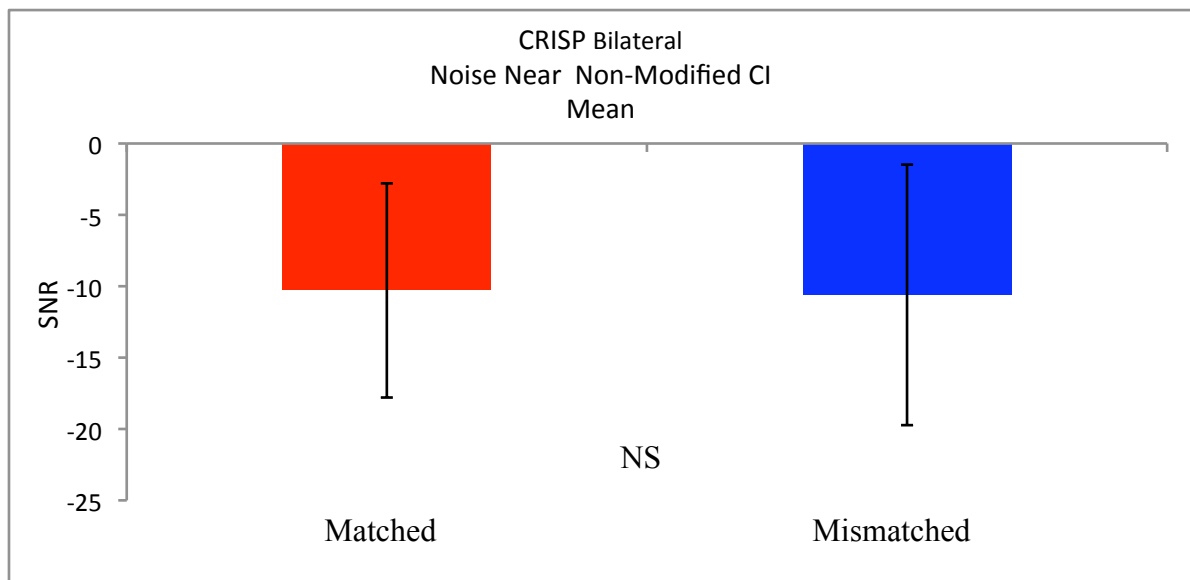


Figure 11: Mean Bilateral CI CRISP Signal-to-Noise Ratio as a function of Rate Configuration.

Competing Noise presented near the Non-Modified CI. Error bars represent standard error.

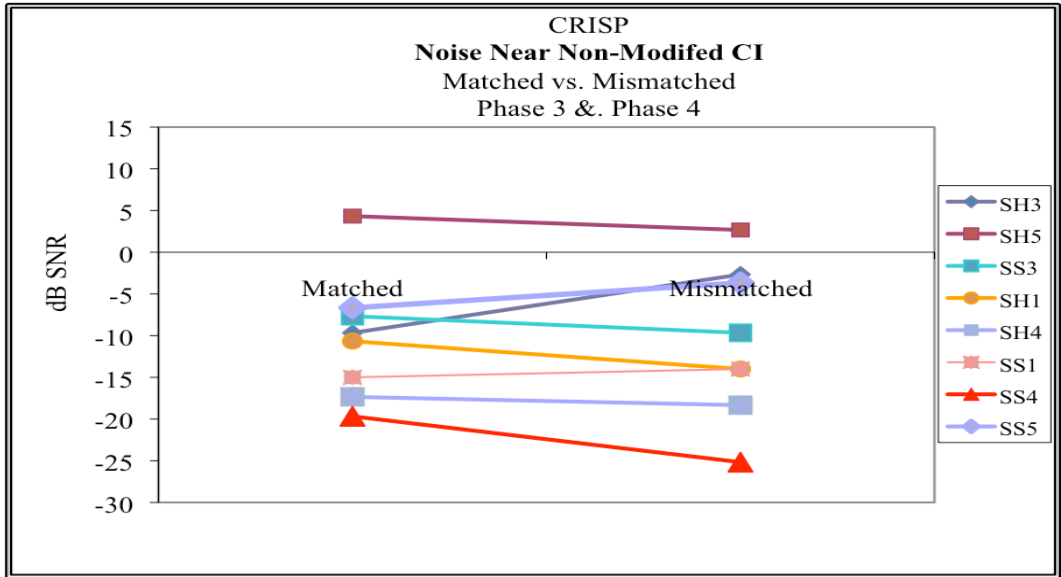


Figure 12. Bilateral CI CRISP SNRs with noise near the non-modified CI for matched and mismatched rate configurations during the last two phases of the study protocol for each individual participant.

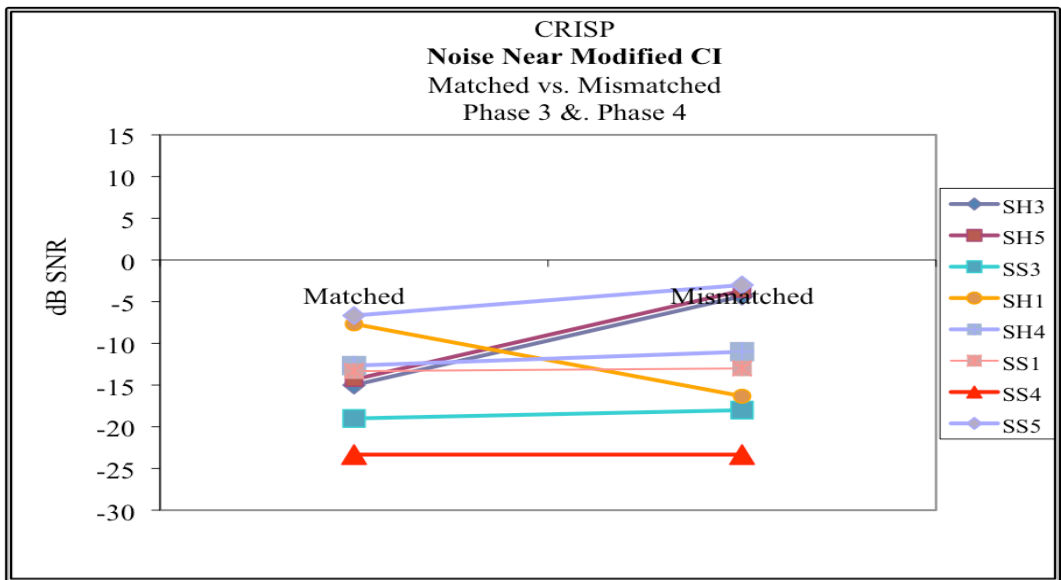


Figure 13. Bilateral CI CRISP SNRs with noise near the modified CI for matched and mismatched rate configurations during the last two phases of the study protocol for each individual participant.

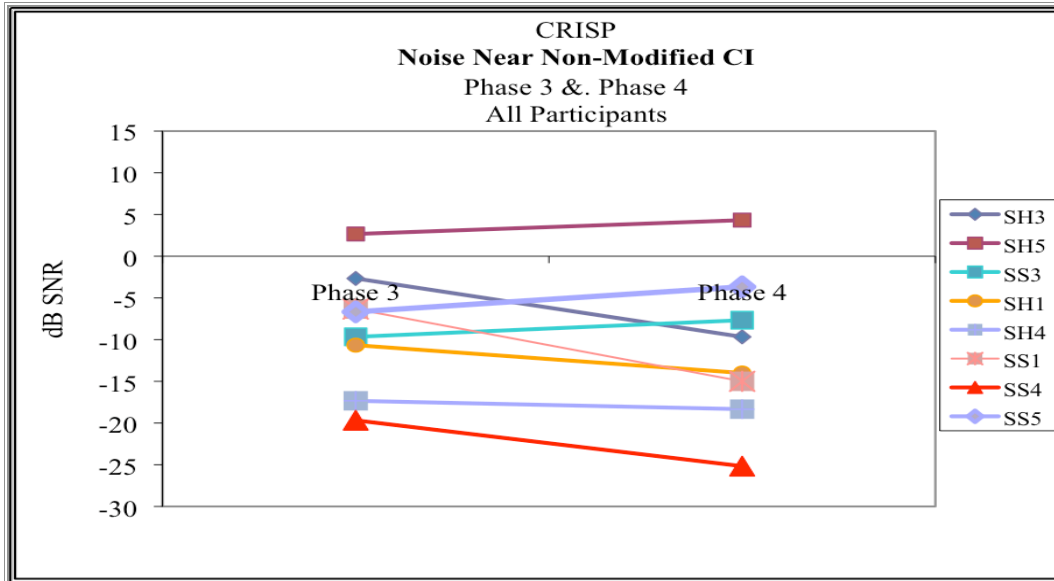


Figure 14. Bilateral CI CRISP SNRs with noise near the non-modified CI, for Phases 3 and 4 of the study protocol for each individual participant.

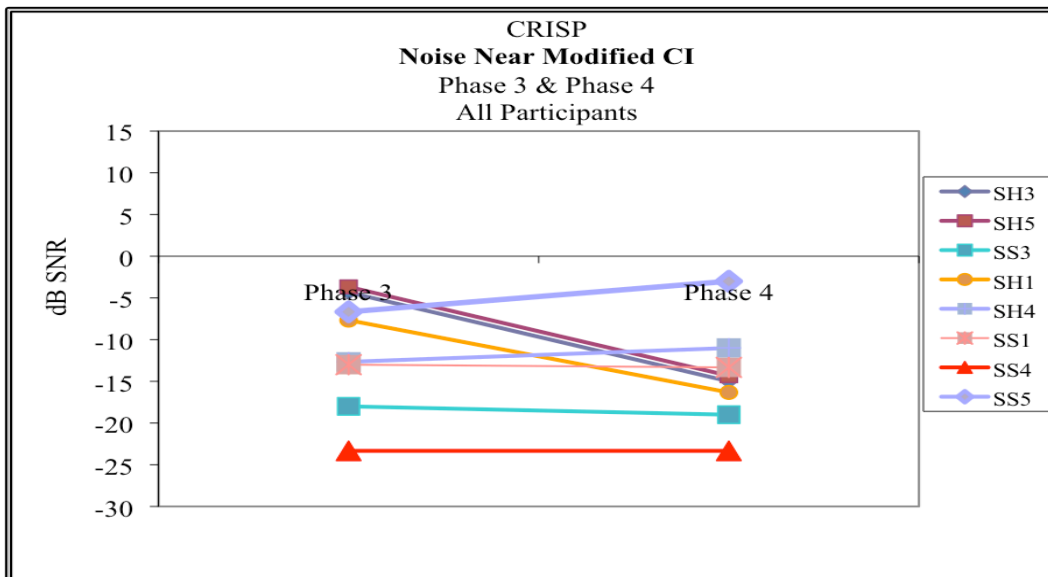


Figure 15. Bilateral CI CRISP SNRs with noise near the modified CI, for Phases 3 and 4 of the study protocol for each individual participant.

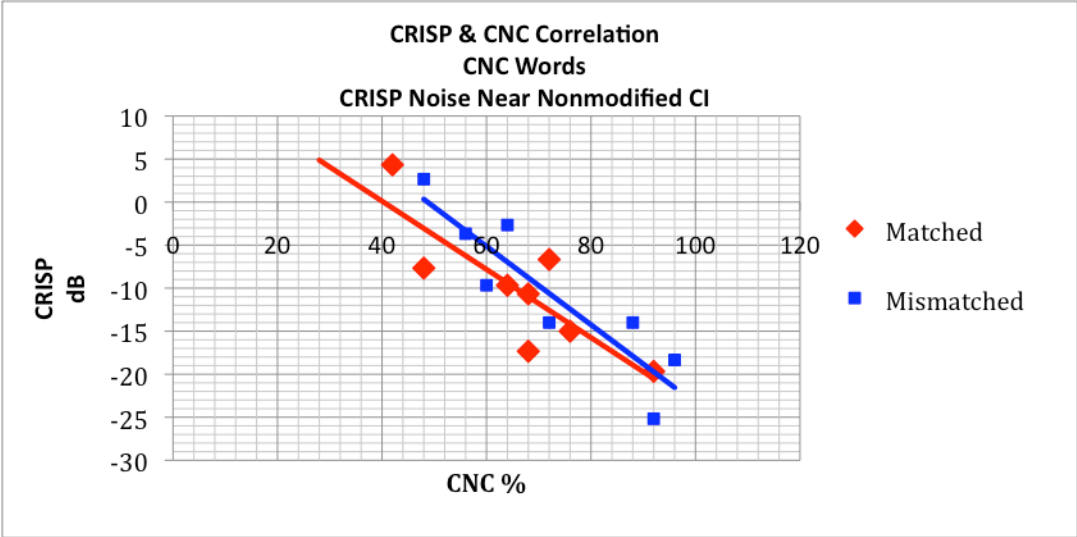


Figure 16. Correlation between bilateral CI CNC Words (percent correct) and CRISP (SNRs) when noise was presented near the non-modified CI. Matched scores  $r = -0.83$ ,  $p = 0.005$  (red triangles) vs. Mismatched scores  $r = -0.90$ ,  $p = .001$  (blue squares) for all participants.

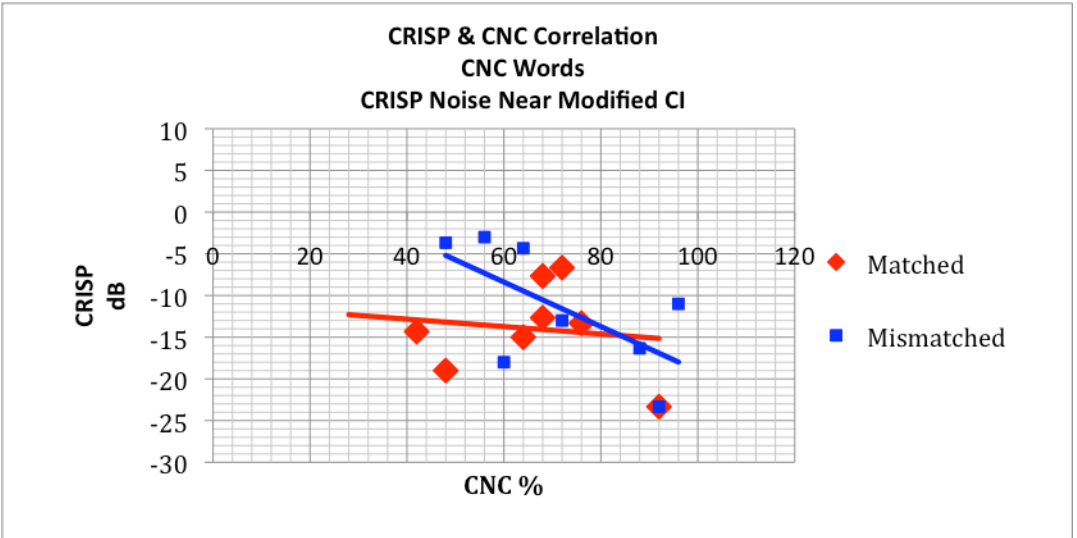


Figure 17. Correlation between bilateral CI CNC Words (percent correct) and CRISP (SNRs) when noise was presented near the modified CI. Matched scores  $r = -0.12$ ,  $p = 0.38$  (red triangles) vs. Mismatched scores  $r = -0.64$ ,  $p = 0.04$  (blue squares) for all participants.

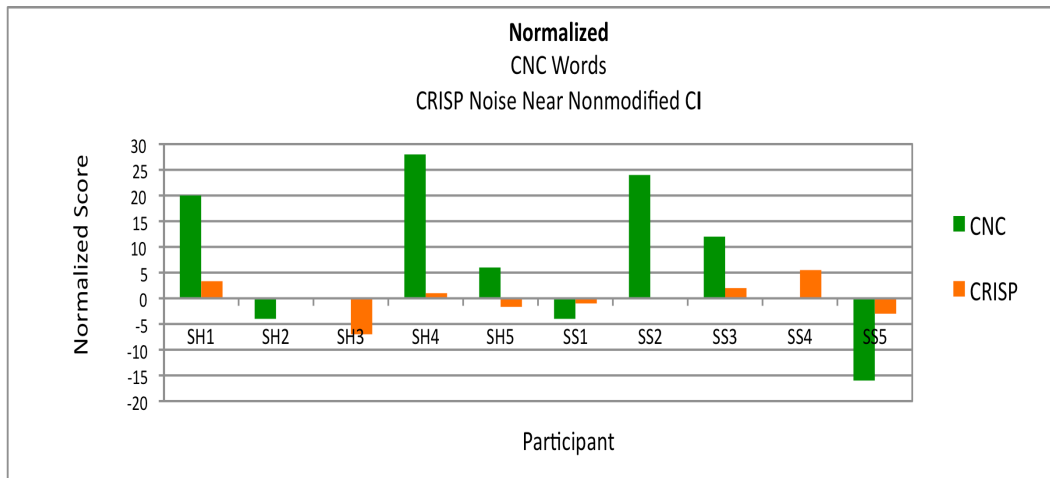


Figure 18. Normalized (Mismatched Score minus Matched Score) Plot for individual participants. Bilateral CI CNC Words (green bars) and CRISP (orange bars) when noise was presented near the non-modified cochlear implant. Upward bars represent improved SNRs. Participants SH2 and SS2 were unable to perform the CRISP task.

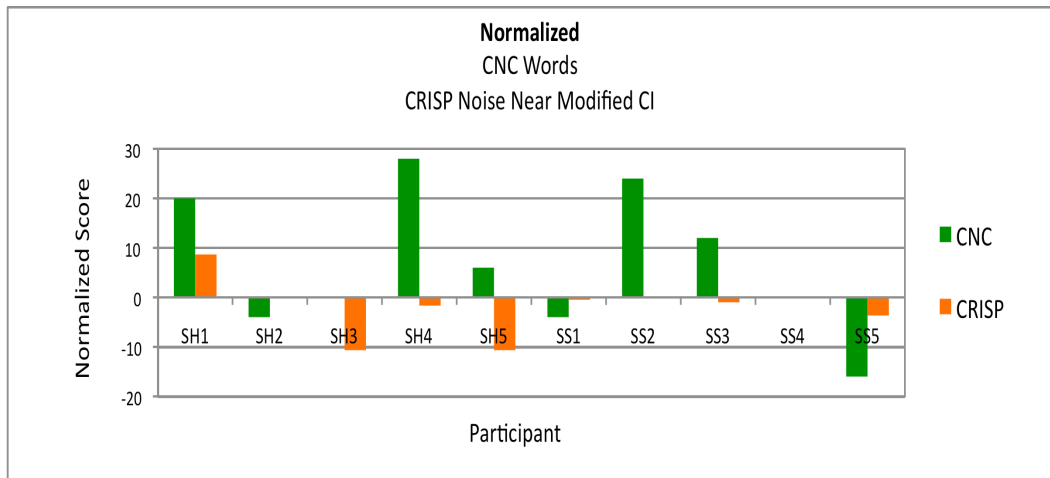


Figure 19. Normalized (Mismatched Score minus Matched Score) Plot for individual participants for Bilateral CI CNC Words (green bars) and CRISP (orange bars) when noise was presented near the modified CI. Upward bars represent improved SNRs. Participants SH2 and SS2 were unable to perform the CRISP task.

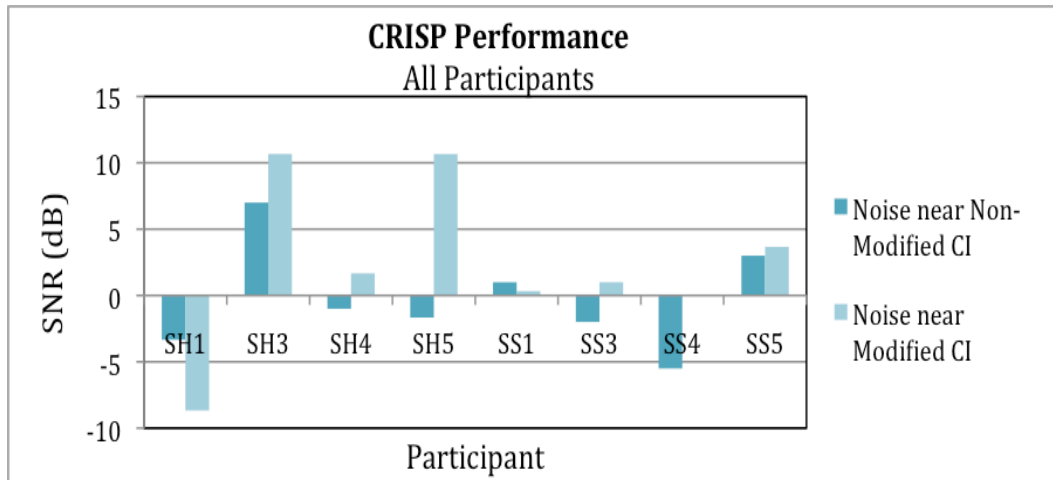
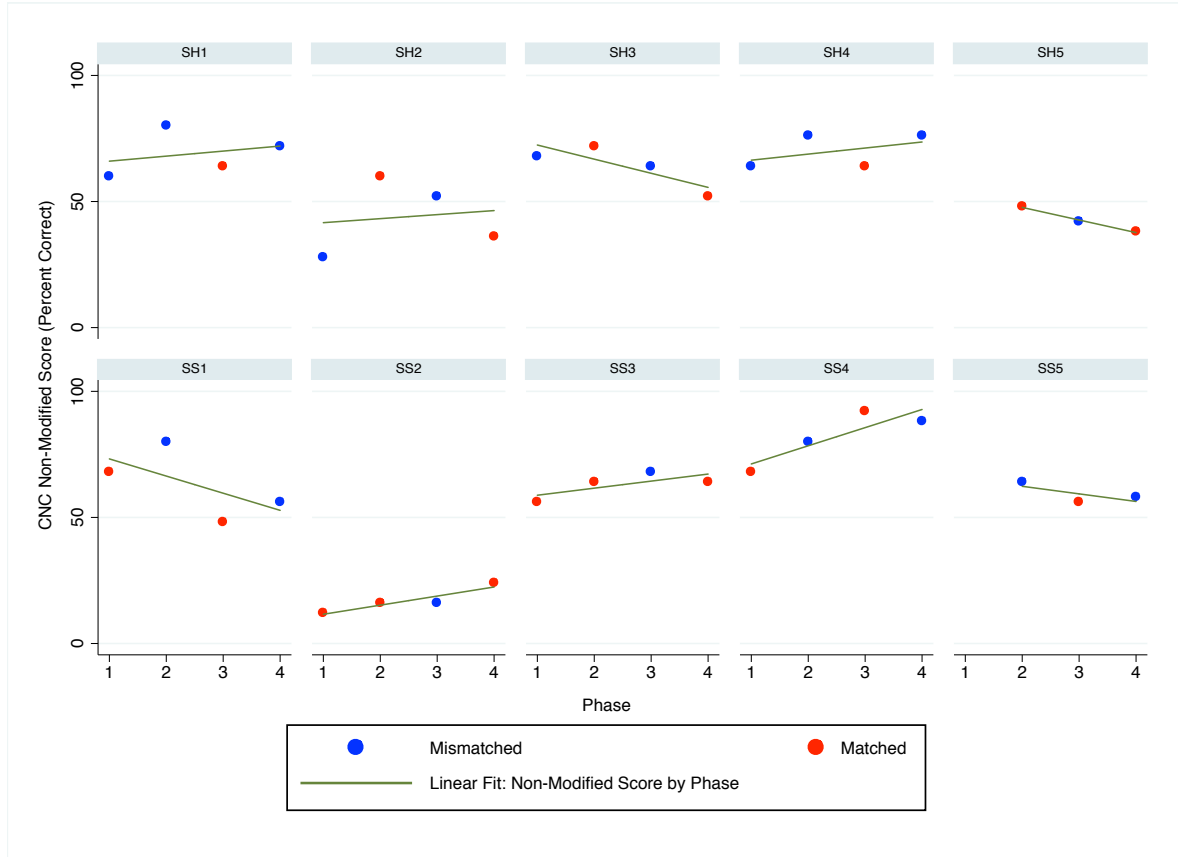


Figure 20. All normalized Bilateral CI CRISP data when noise was presented either near the non-modified CI (light blue bars) or near the modified CI (dark blue bars). Downward bars represent improved SNRs. Participants SH2 and SS2 were unable to perform the CRISP task.

## 7. Appendices



*Figure 1A. Non-Modified CI alone. CNC Percent Correct Word Recognition as a function of Cochlear Implant Configuration for individual participants as a function of phase. Conditions in which each user experienced a mismatched configuration are shown in blue. Matched configurations are shown in red. The top row presents data from participants who came into the study with mismatched configurations and the bottom row participants that came in with a matched configuration. There is no data for the baseline condition from one participant in each group.*

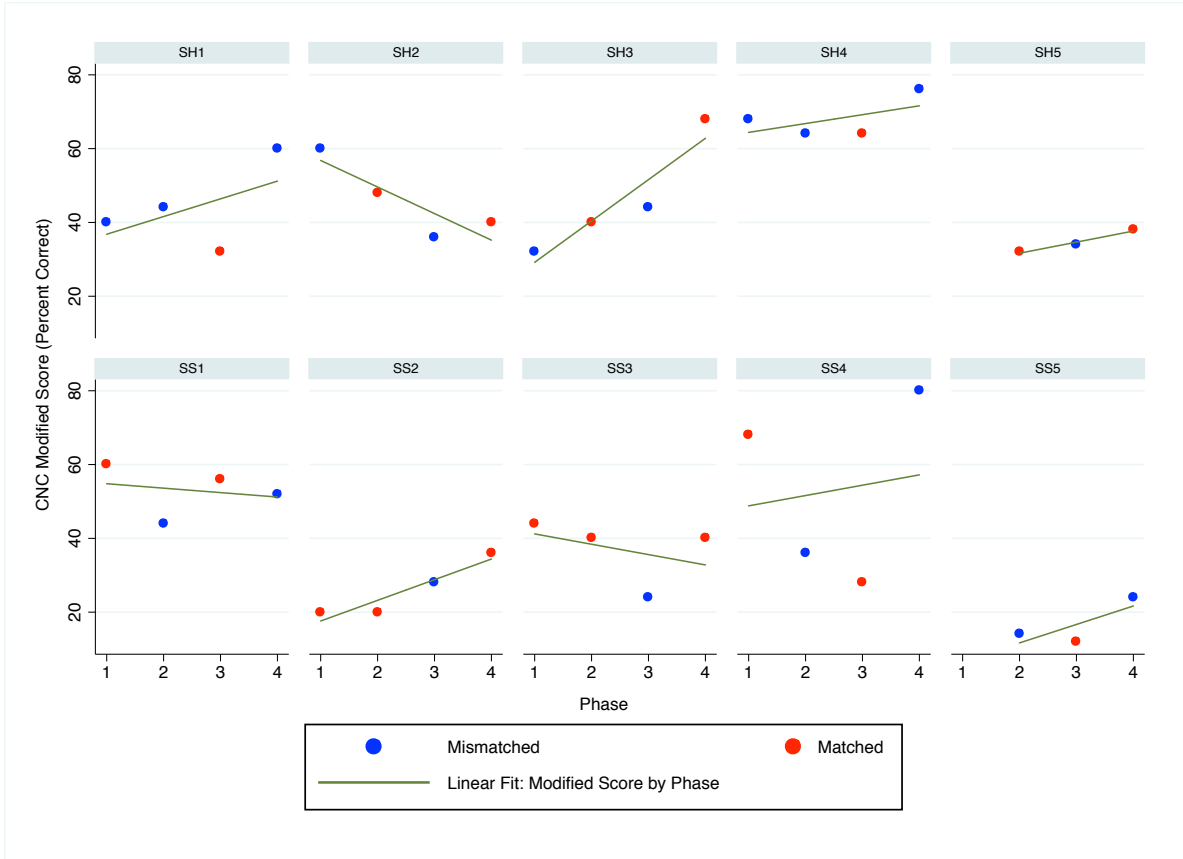


Figure 2A. Modified CI alone. CNC Percent Correct Word Recognition as a function of Cochlear Implant Configuration and Phase for individual participants. The format is the same as Figure 1A.

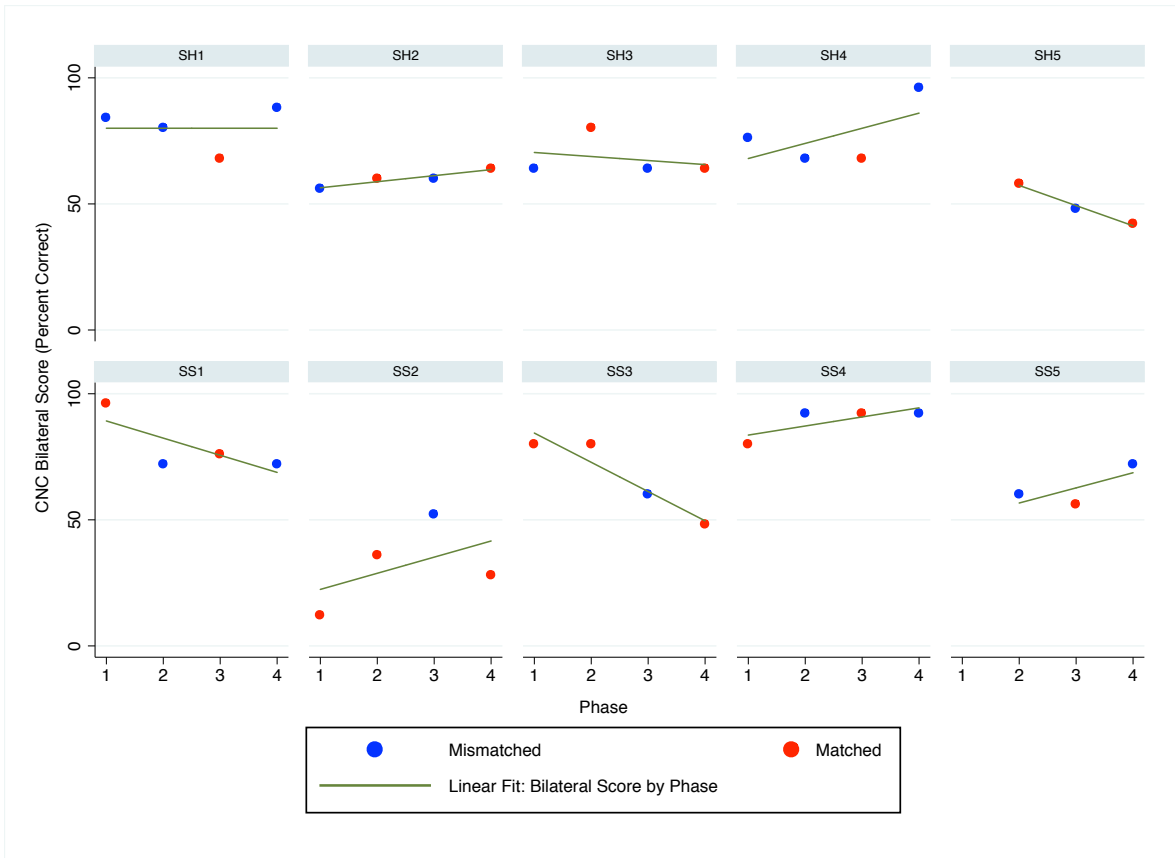


Figure 3A. Bilateral CIs. CNC Percent Correct Word Recognition as a function of Cochlear Implant Configuration and Phase for individual participants. The format is the same as Figure 1A.

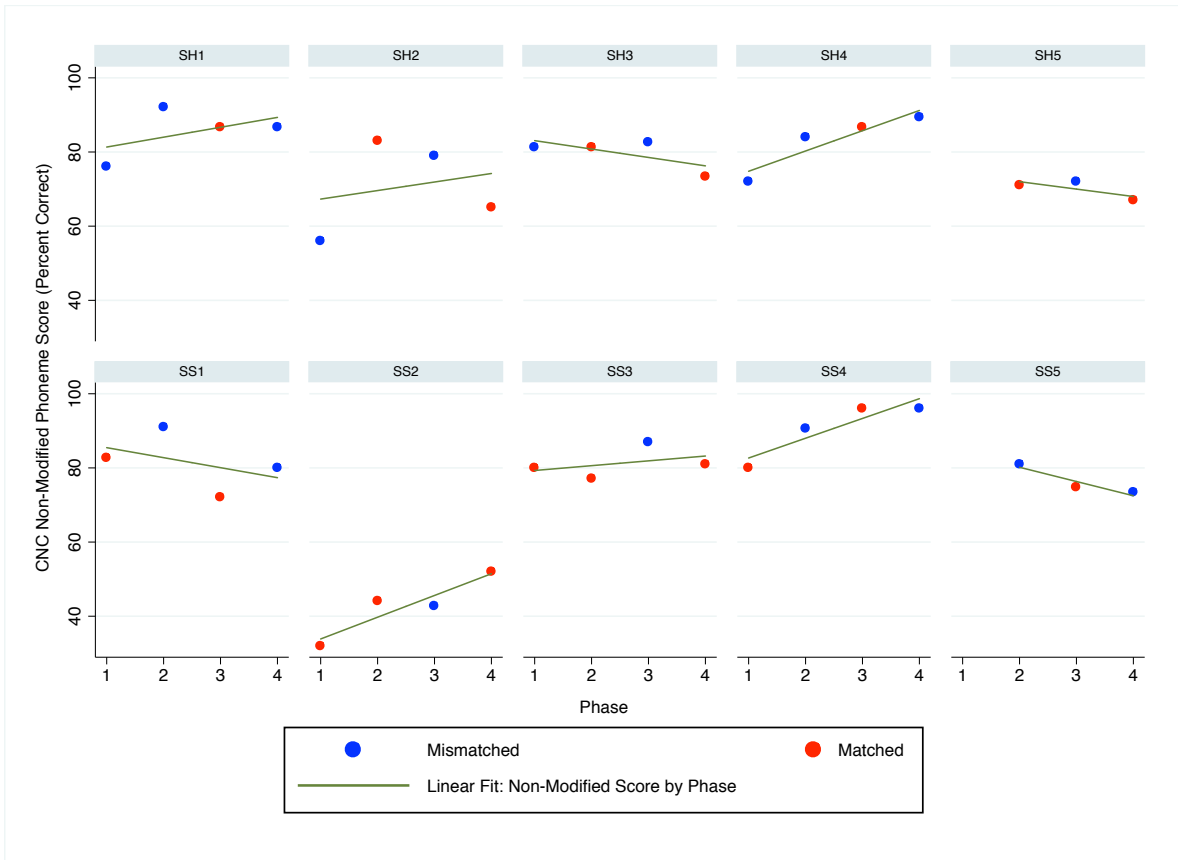


Figure 4A. Non-Modified CI alone. CNC Percent Correct Phoneme Recognition as a function of CI Configuration and Phase for individual participants. The format is the same as Figure 1A.

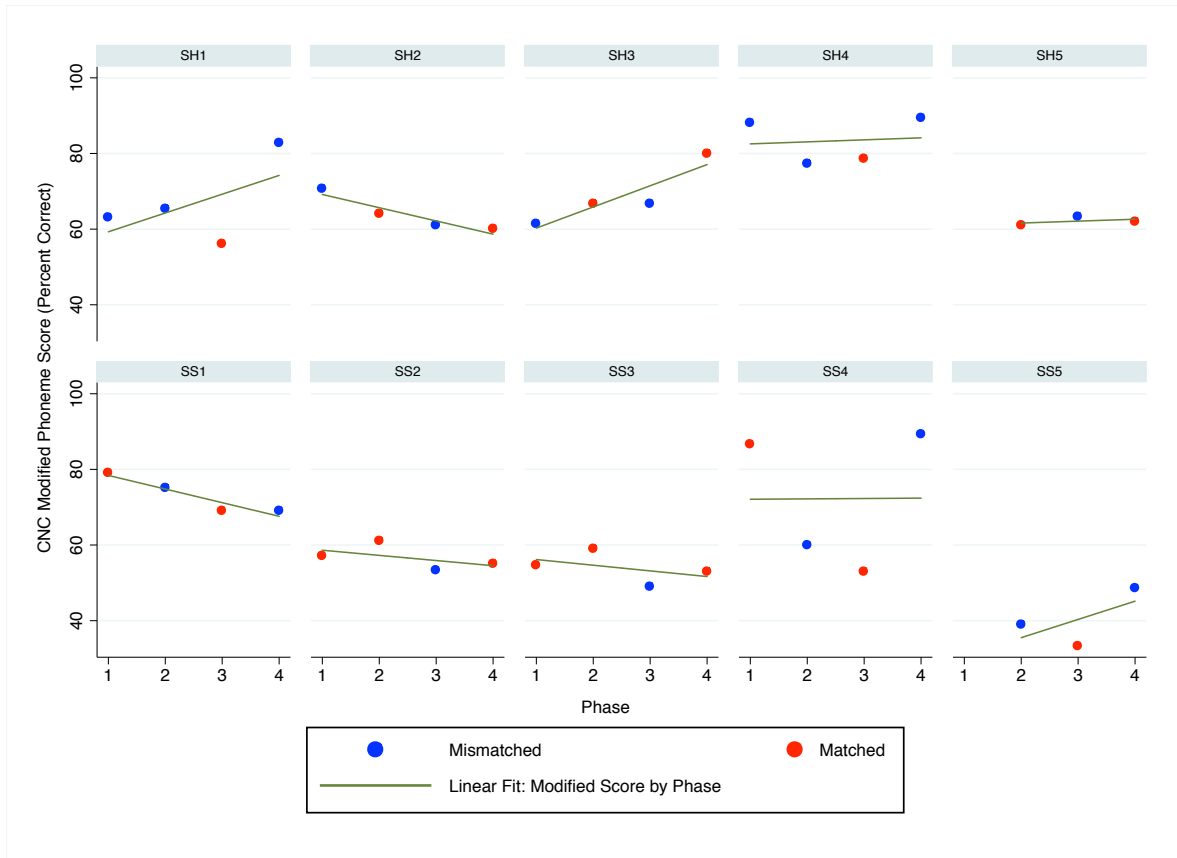


Figure 5A. Modified CI alone. CNC Percent Correct Phoneme Recognition as a function of Cochlear Implant Configuration and Phase for individual participants. The format is the same as Figure 1A.

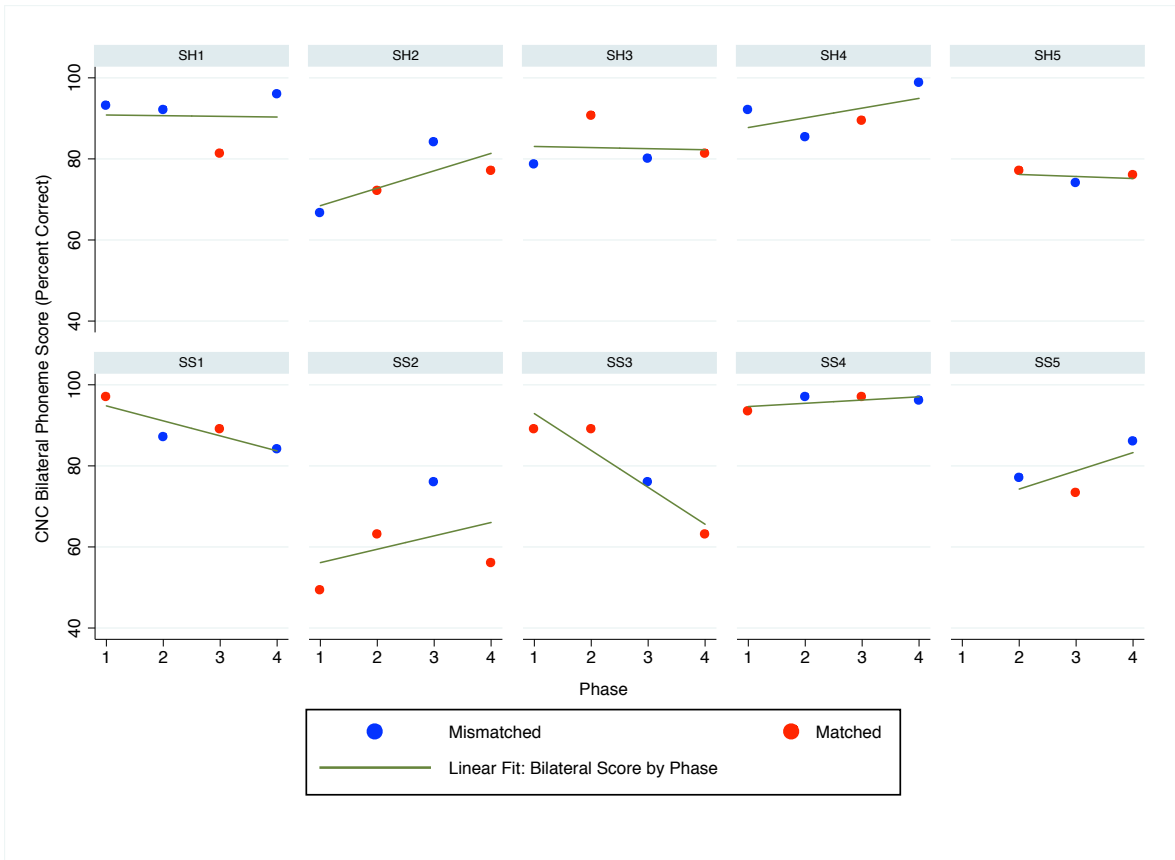


Figure 6A. Bilateral CIs. CNC Percent Correct Phoneme Recognition as a function of Cochlear Implant Configuration and Phase for individual participants. The format is the same as Figure 1A.

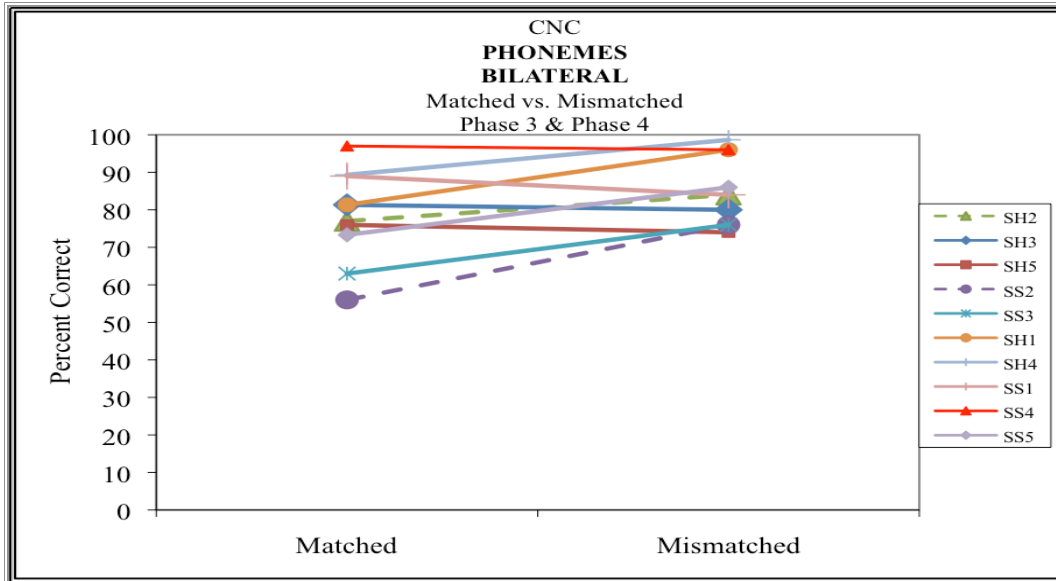
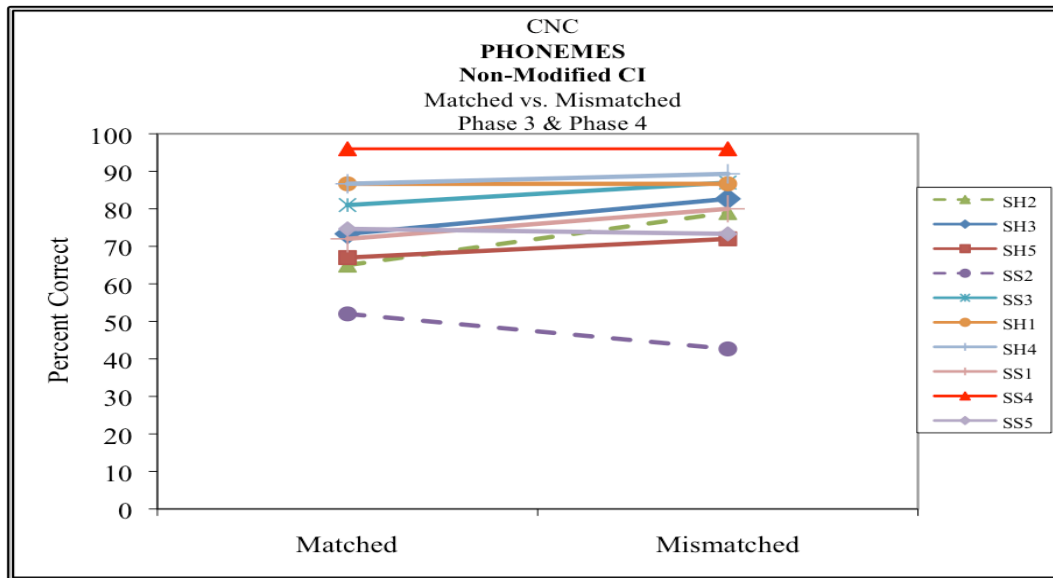
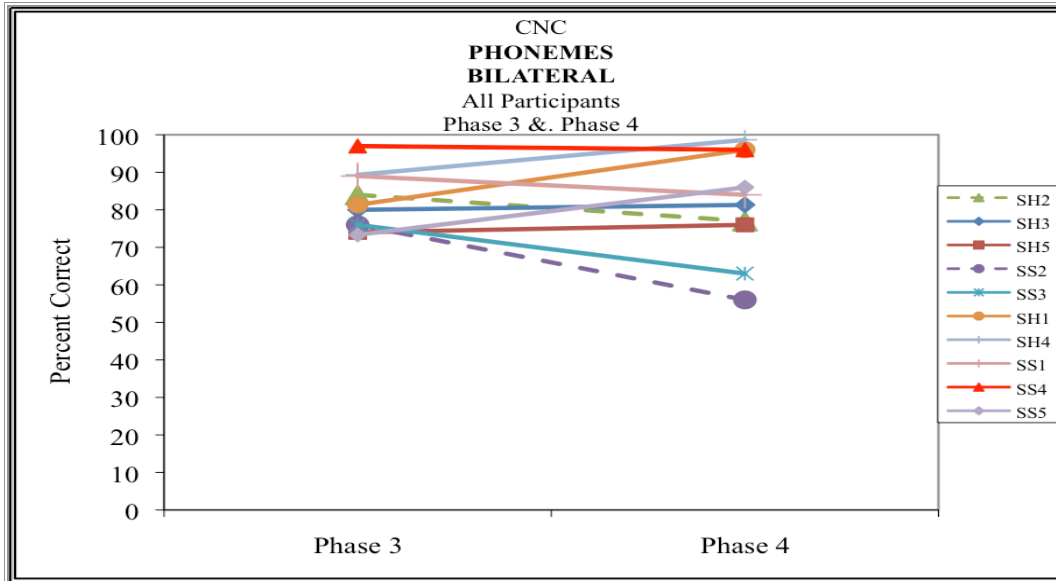


Figure 7A. Bilateral CI CNC phoneme recognition (percent correct) for matched and mismatched rate configurations during the last two phases of the study protocol for each individual participant. The two participants not included in the CRISP testing are shown with dashed lines.



*Figure 8A.* Non-Modified CI CNC phoneme recognition (percent correct) for matched and mismatched rate configurations during the last two phases of the study protocol for each individual participant. The two participants not included in the CRISP testing are shown with dashed lines.



*Figure 9A.* Bilateral CI CNC Phoneme recognition (percent correct) for Phases 3 and 4 of the study protocol for each individual participant. The two participants not included in the CRISP testing are shown with dashed lines.

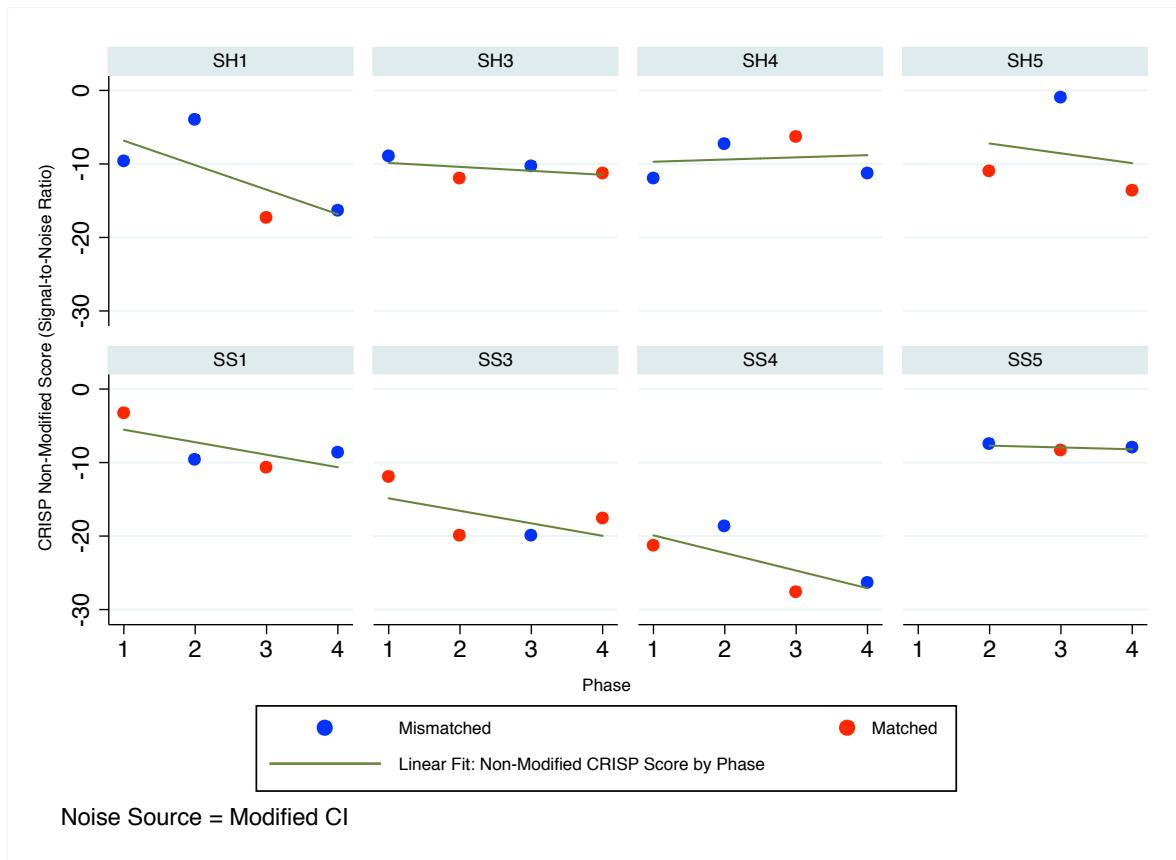


Figure 10A. Non-Modified CI alone. CRISP SNR by Participant, Phase and Rate

Configuration. Noise was presented on the side near the modified CI. The blue markers represent the mismatched condition and the red markers represent the matched condition. The top row presents data from subjects who came into the study with mismatched configurations and the bottom row subjects that came in with a matched configuration. There is no data for the baseline condition for one subject in each group.

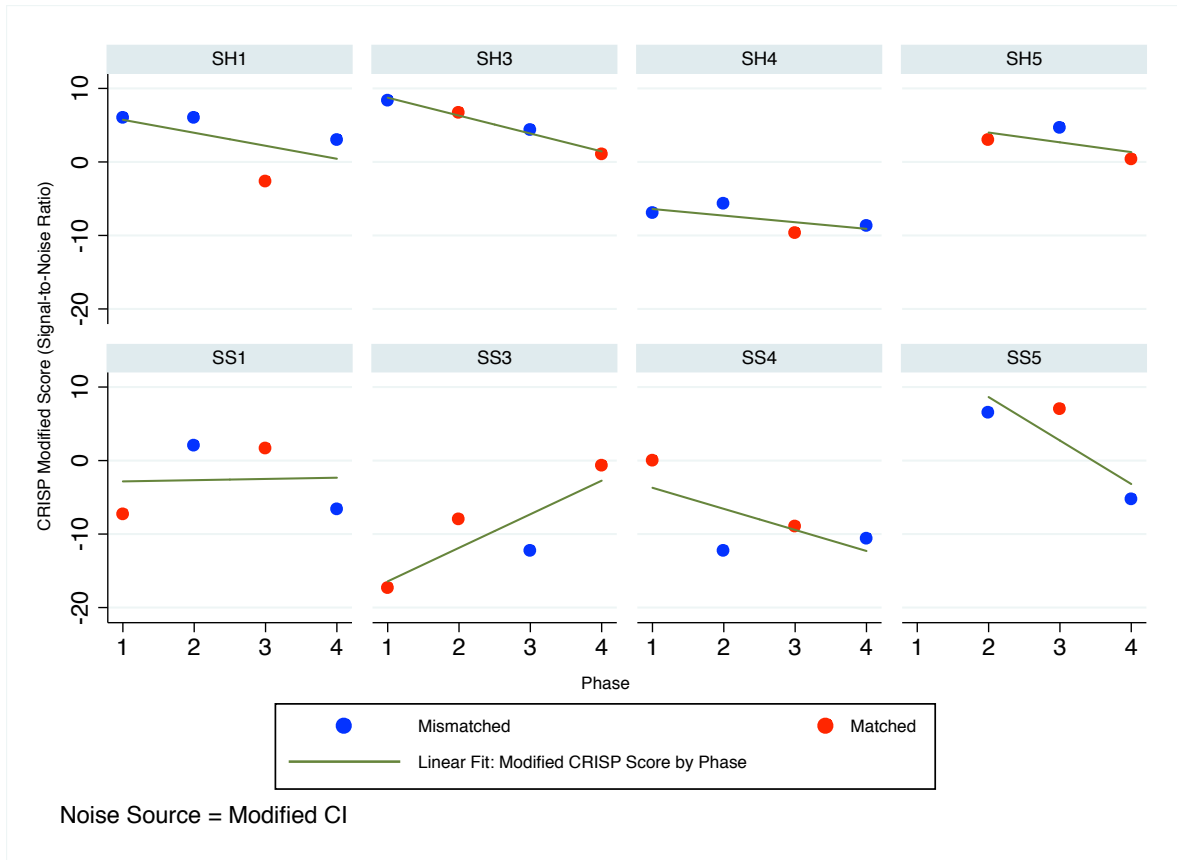


Figure 11A. Modified CI alone. CRISP SNR by Participant, Phase and Rate Configuration.

Noise was presented on the side near the modified CI. The format is the same as Figure 10A.

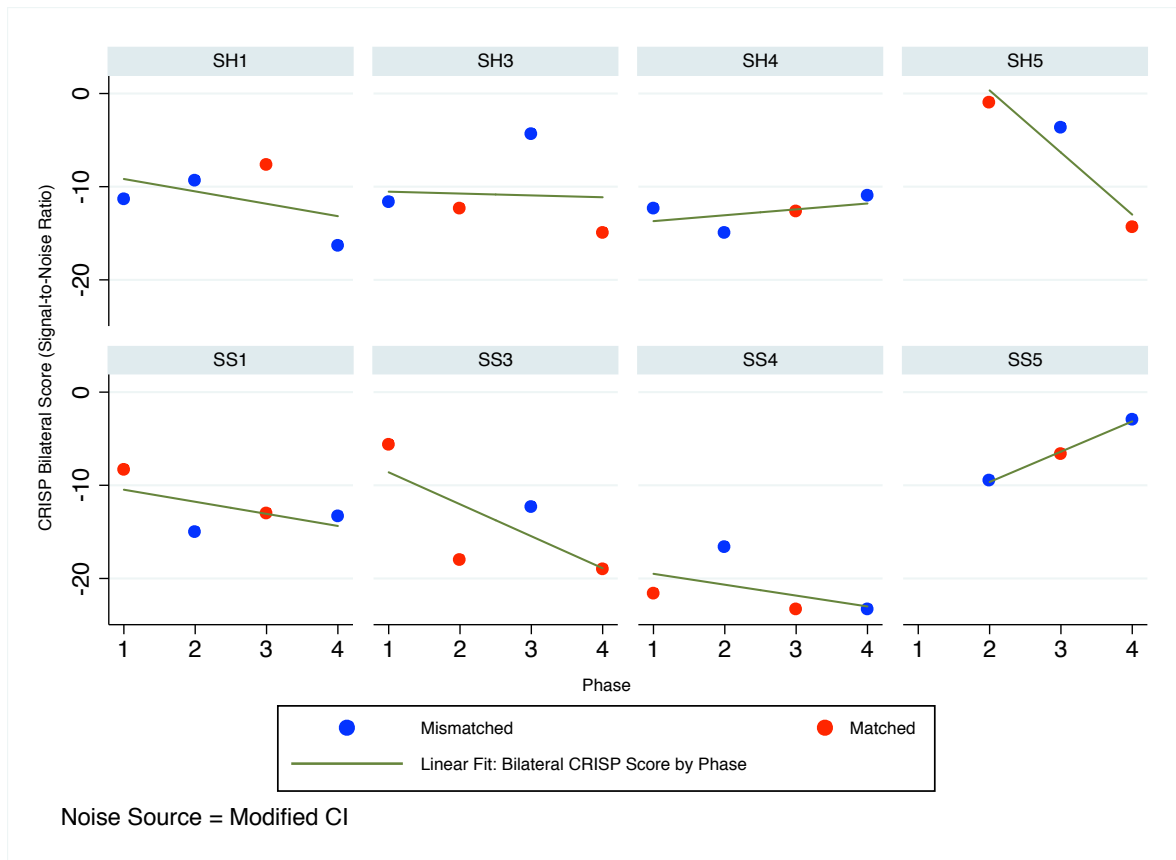


Figure 12A. Bilateral CIs. CRISP SNR by Participant, Phase and Rate Configuration. Noise is presented near the modified CI. The format is the same as Figure 10A.

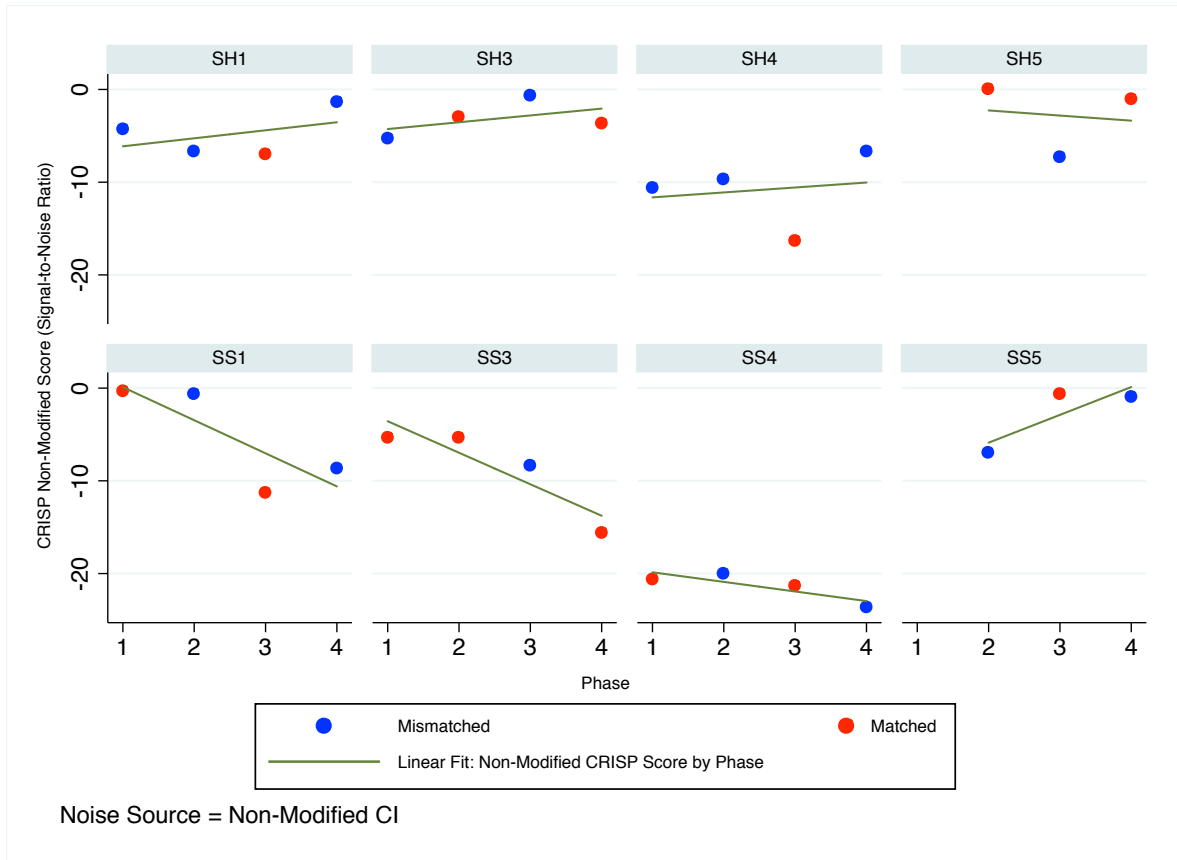


Figure 13A. Non-Modified CI alone. CRISP SNR by Subject, Phase and Rate Configuration. Competing noise was presented near the non-modified CI. The format is the same as Figure 10A.

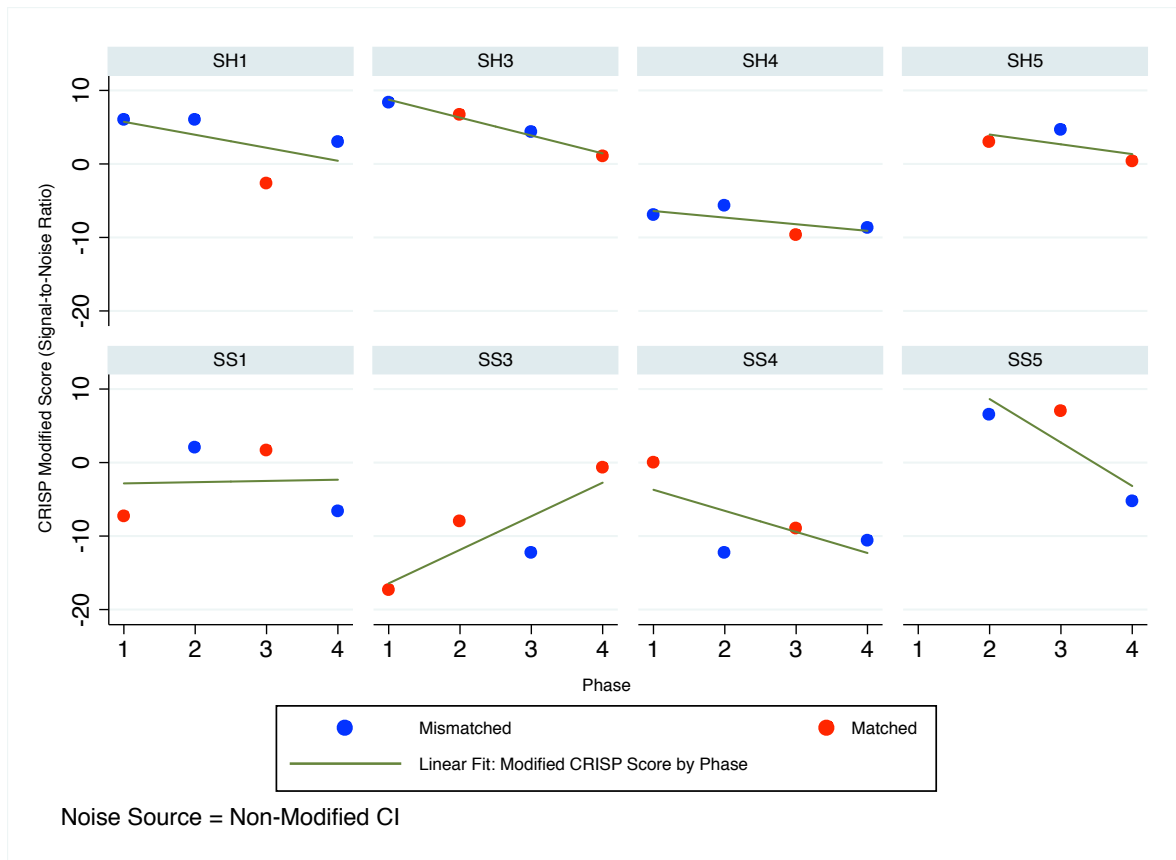


Figure 14A. Modified CI alone. CRISP SNR by Participant, Phase and Rate Configuration. Competing noise was presented near the non-modified CI. The format is the same as Figure 10A.

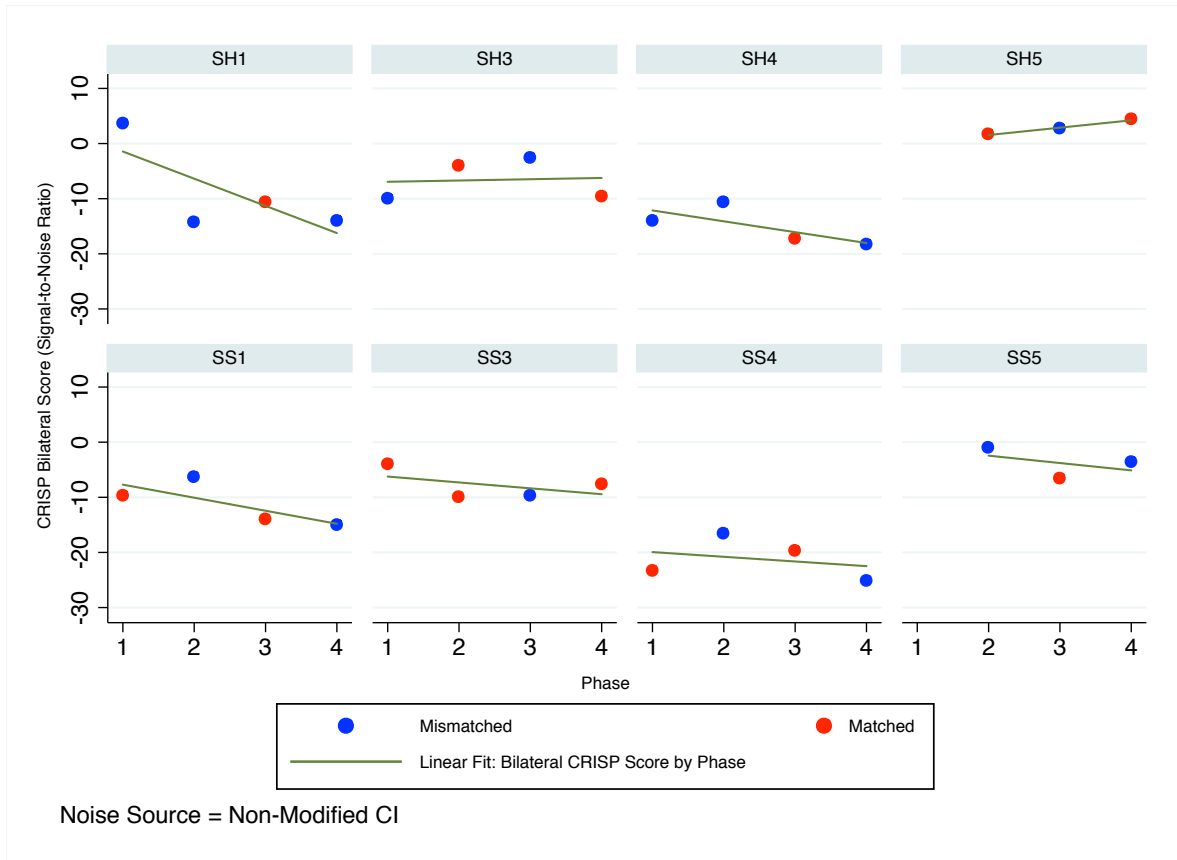


Figure 15A. Bilateral CIs. CRISP SNR by Subject, Phase and Rate Configuration. Competing noise was presented near the non-modified CI. The format is the same as Figure 10A.

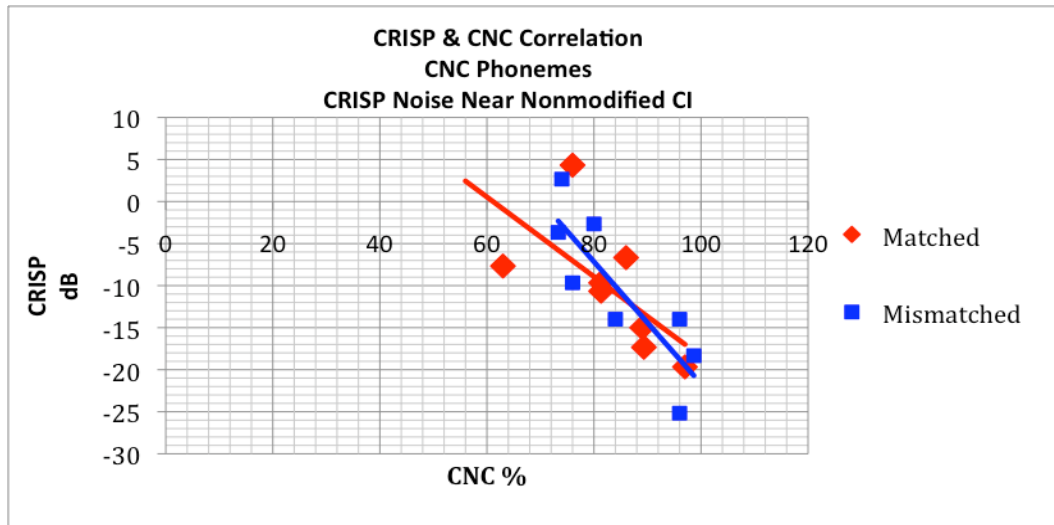


Figure 16A. Correlation between bilateral CI CNC Phonemes (percent correct) and CRISP (SNRs) when noise was presented near the non-modified CI. Matched scores  $r=-0.65$ ,  $p=0.04$  (red triangles) vs. Mismatched scores  $r=-0.85$ ,  $p=0.003$  (blue squares) for all participants.

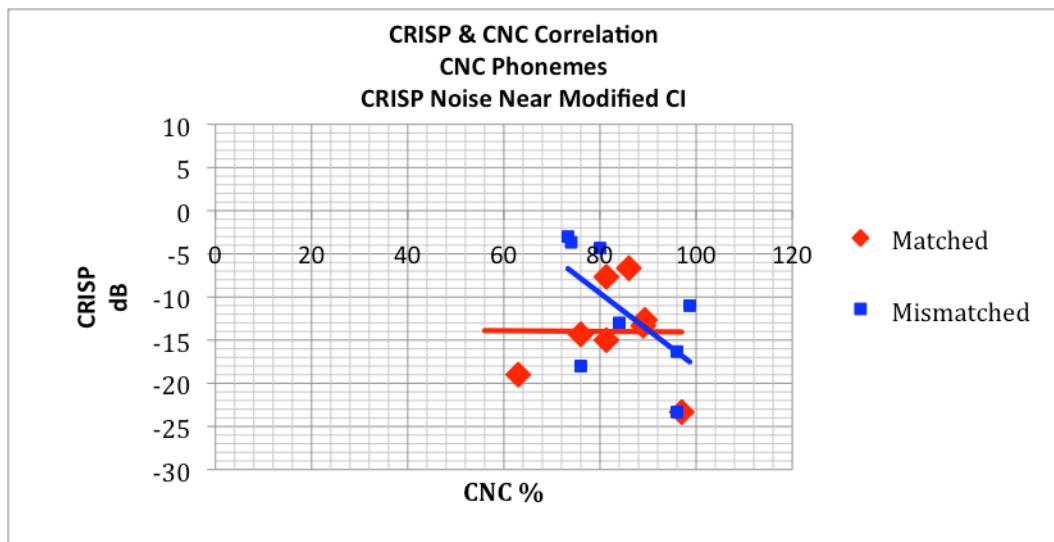


Figure 17A. Correlation between bilateral CI CNC Phonemes (percent correct) and CRISP (SNRs) when noise was presented near the modified CI. Matched scores  $r=-0.007$ ,  $p=0.49$  (red triangles) vs. Mismatched scores  $r=-0.605$ ,  $p=0.054$  (blue squares) for all participants.

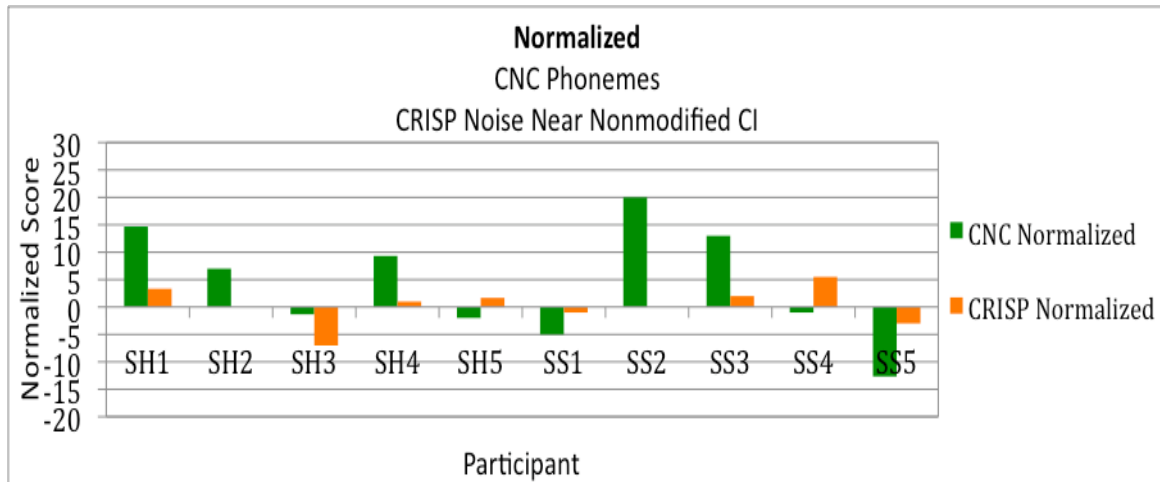


Figure 18A. Normalized (Mismatched Score minus Matched Score) Plot for individual participants for Bilateral CI CNC Phonemes (green bars) and CRISP (orange bars) when noise was presented near the non-modified cochlear implant. Upward bars represent improved SNRs. Participants SH2 and SS2 were unable to perform the CRISP task.

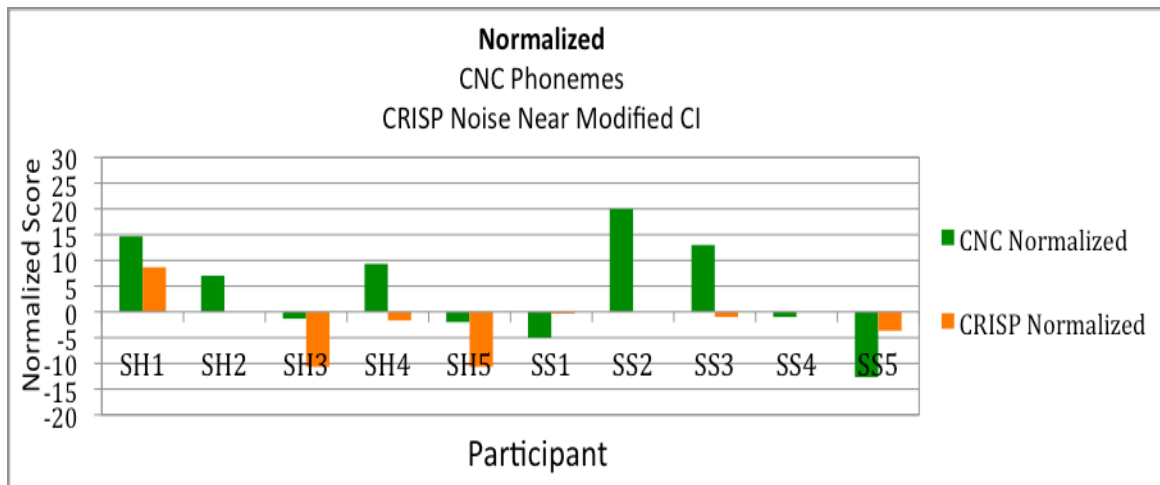


Figure 19A. Normalized (Mismatched Score minus Matched Score) Plot for individual participants for Bilateral CI CNC Phonemes (green bars) and CRISP (orange bars) when noise was presented near the modified cochlear implant. Upward bars represent improved SNRs. Participants SH2 and SS2 were unable to perform the CRISP task.

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