BINAURAL INTEGRATION BY COCHLEAR-IMPLANT USERS DURING VOICE MATCHING TASKS

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The capacity for bilateral cochlear-implant users, bimodal cochlear-implant users, and normal-hearing control subjects to match auditory information presented independently to both ears was examined. Spondee words were re-synthesized to produce three sets of voice stimuli where pitch and spectrum were manipulated independently or together. Children (ages 5-18) were asked to turn a knob to make the voice presented to one ear match a model voice presented simultaneously to the opposite ear. The children were also asked to match voices presented sequentially, either to the same ear or to opposite ears. Statistical comparison of the bilateral cochlear-implant and normal-hearing groups showed that cochlear-implant users had lower sensitivity to the acoustic properties of speech tested, but that their ability to match and integrate them binaurally followed a normal-like pattern. Hearing in noise was tested for conditions where the voice presented to each ear was the same (diotic) or different (dichotic).

LIST OF ABBREVIATIONS USED

AGC	Automatic Gain Control
ANOVA	Analysis of Variance
ANSI	American National Standards Institute
BCI	Bilateral Cochlear Implant
BCIG	Bilateral Cochlear Implant Group
CI	Cochlear Implant
DAI	Direct Audio Input
f_0	Fundamental frequency
FDA	Food and Drug Administration
HINT-C	Hearing in Noise Test for Children
HRTFs	Head-Related Transfer Functions
ILD	Interaural Level Difference
ITD	Interaural Time Difference
JND	Just-Noticeable Difference
NH	Normal-hearing
NIDCD	National Institute on Deafness and Other Communication Disorders
NIH	National Institutes of Health
NSHSC	Nova Scotia Hearing and Speech Centres
pps	pulse per second
RMS	Root Mean Square
SNR	Signal-to-Noise Ratio
USB	Universal Serial Bus

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CHAPTER 1 - INTRODUCTION

Central integration of signals present at the two ears is required for truly binaural hearing. Two ears working independently may provide some functional benefit over just one ear, but far greater benefits are possible when the two ears work cooperatively. One argument for bilateral cochlear implantation is that it ensures the “better ear” is implanted; however, in scenarios where each ear detects different parts of a target sound, using only the better ear is not as beneficial as combining two signals, one from each ear, to hear a more complete message. The current study represents a step in assessing the capacity for cochlear-implant users to integrate auditory information presented independently to both devices in a manner similar to how sounds are presented to the two ears of normal-hearing (NH) listeners. If stimuli are presented dichotically but the listener perceives only a single source containing the information from both signals, then the two signals have been integrated centrally. In normal listening situations, auditory stimuli arriving at the two ears from the same source will have very similar spectral properties. For example, the fundamental frequency of a person’s voice will be the same at both ears. By determining how well listeners can identify that sounds are coming from the same source, we may be able to predict their ability to take advantage of the binaural hearing mechanisms that arise from auditory integration. In this study we evaluated listeners’ ability to match stimuli between the ears based on spectral properties.

1.1 BACKGROUND / BRIEF HISTORY OF COCHLEAR IMPLANTATION

A cochlear implant (CI) is a surgically implantable electronic device used to provide a sense of hearing to a person with a severe-to-profound sensorineural hearing loss. The device consists of an internal part and an external part. In current models, the external component rests behind the ear and resembles a behind-the-ear hearing aid. It contains a microphone, a speech processor, and a transmitter. The microphone collects the acoustic vibrations (i.e., sound) from the environment, the speech processor converts the acoustic signal into an electrical signal, and the transmitter sends the coded electrical signal across the skin to an implanted receiver via radio-frequency induction. The receiver rests just under the skin in a shallow recess bored into the mastoid bone of the skull. It decodes the signal from the transmitter and generates a stimulus of electrical impulses. A multi-wire cable relays the stimulus from the receiver to an electrode array implanted in the scala tympani of the cochlea. The electrodes stimulate surviving afferent neurons (spiral ganglion cells) in the auditory nerve and the person’s brain interprets the signal as sound. Cochlear implants do not restore normal hearing and functional auditory performance varies between individuals, but the practice of cochlear implantation has been revolutionary for improving the communicative abilities and overall quality of life of many patients with significant bilateral hearing impairments. Adults with post-lingual profound hearing loss can now regain an awareness of environmental sounds and a clear understanding of speech in quiet. Infants and young children who are completely deaf can acquire speech and language skills and attend regular classrooms along with their normal-hearing peers.

In 1957, Djourno and Eyriès became the first to design and implant a device that electrically stimulated the human auditory nerve. Although the device failed several months later, the patient’s ability to detect environmental sounds and discriminate between low frequency tones later inspired efforts to make electrical stimulation of the cochlea a viable treatment for deafness (Wilson & Dorman, 2008[1]). In 1975, the United States National Institutes of Health (NIH) commissioned a study to evaluate the performance of all 13 patients in the U.S. who had functioning single-channel CIs at that time. The study confirmed that CIs served as an effective aid for lip-reading and for recognizing environmental sounds (Bilger et al., 1977). Systems with multiple channels of processing and multiple sites of stimulation in the cochlea were developed during the 1980’s. With these early multichannel devices about five percent of patients were able to have normal conversation without lip-reading (National Institutes of Health [NIH], 1988). The U.S. Food and Drug Administration (FDA) approved single-channel CIs for commercial use in both children and adults in the mid 1980’s (U. S. Food and Drug Administration [FDA], 2010). Through the late 1980’s and early 1990’s new processing strategies were developed and shown to be especially effective for improving speech reception by CI users (Wilson & Dorman, 2008). Paediatric cochlear implantation for multichannel systems received approval from Health Canada and the FDA in 1990 and CIs have since become the standard of care in North America for children with bilateral severe-to-profound hearing loss (Johnston et al., 2009). CIs have become so successful in restoring auditory function that researchers have begun designing new tests for sentence intelligibility because ceiling effects are threatening the effectiveness of older measures (Wilson and Dorman, 2008). As of December 2010, over 219,000 people worldwide had undergone CI surgery (National Institute on Deafness and Other Communication Disorders [NIDCD], 2011).

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[1] Note: the timeline for this history was found in Wilson & Dorman (2008).

Originally, a person needed to have a bilateral profound sensorineural hearing loss to be considered a candidate for cochlear implantation and each candidate received only one implant. As implant technology has improved, the candidacy requirements have become more inclusive. Patients with lower audiometric thresholds (e.g., thresholds in the severe range), who do not gain enough functional hearing benefit from hearing aids, can also be considered for implant candidacy. Recently, CI centres have begun to give candidates the option to receive two implants – one in each ear. These bilateral operations are being performed routinely due to mounting evidence that bilateral cochlear-implant (BCI) users have the abilities to localize sound and to understand speech in quiet and noisy conditions significantly better than unilateral implant users (Dunn et al., 2008; Dunn et al., 2010; Galvin et al., 2008; Grantham et al., 2007; Johnston et al., 2009; Mosnier et al., 2009; Scherf et al., 2007; van Hoesel & Tyler, 2003). Although there are no age-based restrictions for cochlear-implantation in Canada, the finite nature of funding has led most centres to offer bilateral implants almost exclusively to children. This practice is in line with evidence that early bilateral implantation may be vital for the development of binaural auditory mechanisms in deaf children. Several professional societies have released position statements endorsing bilateral cochlear implantation as an acceptable medical practice. Examples of such groups include, but are not limited to: the British Cochlear Implant Group (BCIG), the Canadian Cochlear Implant Centres Group, and the William House Cochlear Implant Study Group (British Cochlear Implant Group [BCIG], 2008; Schramm, 2010; William House Cochlear Implant Group, 2008). All of these groups support bilateral cochlear implantation but acknowledge a need for additional research regarding the use of binaural mechanisms with BCIs. Many studies describe functional benefits for having two devices when performing standard listening tasks, but few studies demonstrate the mechanisms by which these benefits are achieved. The following sections will provide background information on binaural hearing mechanisms, a summary of the current literature regarding the benefits and limitations of BCIs, and information on how cochlear implants process the spectral properties manipulated in this study.

1.2 NORMAL BINAURAL HEARING MECHANISMS

The term “binaural hearing” denotes our ability to combine, compare, and contrast acoustic signals at the two ears. These skills are useful because they allow us to detect and interpret the sounds in our environment in a meaningful way. The normal human auditory system can use binaural cues to determine the location of sound sources and/or improve the intelligibility of target signals masked by noise.

1.2.1 Detection of Interaural Time and Level Differences

Despite often having a common source, the acoustic signals arriving at the two ears are usually different. For example, one ear may be closer to the source and therefore receives the signal slightly before the second ear. The term for this difference in arrival time across the ears is “interaural time difference (ITD)”. When an ITD exists the signal arrives at the two ears with a different phase spectra; consequently, a synonymous term, “interaural phase difference (IPD)” is also found in the literature. Human ears are located on opposite sides of a nearly spherical acoustic barrier - the head. More often than not, one of the two ears will be at least partially in the acoustic shadow cast by the head and the intensity level of the signal will be lower in the sheltered ear. This difference is called the “interaural level difference (ILD)”. ILD is also termed “interaural intensity difference (IID)” or “interaural amplitude difference (IAD)”. All real world sounds generate ITD and ILD (Akeroyd, 2006). The ability to detect these interaural differences is a basic example of binaural hearing because it requires the signals presented at each ear to be contrasted at some level. These two basic binaural cues play a dominant role in sound localization and other complex binaural functions.

The traditional duplex theory of sound localization (Rayleigh, 1907) postulates that, for NH listeners, ITD provides localization cues for low frequencies while ILD provides cues for higher frequencies. The theory is based on the wavelength properties of different frequencies. Low frequencies have long wavelengths that are diffracted around the head to the opposite ear. When a sound is presented to a subject in any horizontal location that is neither directly in front (0^o azimuth) nor directly behind the head (180^o azimuth), the low-frequency wavelengths will arrive at the far ear slightly later than the near ear because they must follow a longer path. High frequencies have wavelengths that are too short to diffract around the head and are thus blocked in their path to the far ear. This reduces the intensity of the signal at the far ear and creates a difference in the level or intensity of the signal received by each ear. High-frequency waves not blocked by the head will reach the far ear, but their short wavelengths may make phase differences ambiguous. The timing and intensity differences between the ears indicate the direction of the sound source. If the source of a signal is on a person’s left side, the signal will arrive at the left ear sooner and/or with a greater intensity than it will arrive at the right ear. Interaural time and level differences can be used to identify the precise location of sound in the horizontal plane. Two different terms are used to describe the identification of source location.

The term “localization” describes the identification of the location of extra-cranial sound images. For example, when a signal is presented with speakers in a sound-field or when head-related transfer functions (HRTFs) are used with earphones to create a virtual sound-field. The term “lateralization” is used for tasks that employ earphones (without HRTFs) and thus create an intra-cranial sound image. These terms are clearly differentiated in the literature for NH listeners, but are occasionally used synonymously in the BCI literature.

The human auditory system can detect remarkably small differences in ITD. Low-frequency pure tones (500-1000 Hz) provide the optimal stimuli for ITD detection. With these low-frequency tones, the just-noticeable difference (JND) in ITD by normal-hearing listeners has been measured as 10 µs or less (Seeber & Fastl, 2008; Yost, 1974). Consequently, ITD can provide a precise cue for the localization of low-frequency tones. The capacity for inner hair cells in the cochlea to phase-lock to the fine structure of a pure-tone stimulus diminishes as the frequency of the tone increases. Consequently, the fidelity of fine structure information encoded by the normal human auditory system decreases dramatically between 1 and 2 kHz (Akeroyd, 2006) and ITDs for simple pure-tones above 1.5 kHz cannot be detected or are not measurable experimentally (Akeroyd, 2006; Colburn et al., 2006). Studies using sinusoidally amplitude-modulated signals, instead of pure tones, have indicated that listeners are sensitive to ITD cues in the envelope of sounds (Akeroyd, 2006). The JND for envelope ITDs depends on the shape of the envelope (Senn et al., 2005). Bernstein and Trahiotis (2002) used a procedure called “transposition” to generate high-frequency stimuli with envelopes that would provide high-frequency auditory channels with information normally available only at low frequencies. They found that threshold ITDs for transposed stimuli with modulation frequencies of 128 and 64 Hz were equal to or lower than threshold ITDs for pure tones of the same frequencies. These results indicate that, for certain stimuli, sensitivity to timing information carried in the envelope of sound can be quite good. Timing information derived from the envelope of high-frequency sounds may be useful for localization of high-frequency sounds when the dominant ILD cues are ambiguous (van Hoesel, 2004). However, envelope ITDs are not usually necessary for localization of low-frequency sounds due to the presence of more perceptually salient fine-structure ITDs.

The JND for ILD is approximately 0.5-1 dB for all frequencies (Akeroyd, 2006; Colburn, 2006; Mills, 1960). The magnitude of ILD is determined by the angle and distance of the sound source as well as by the frequency of the sound and the individual characteristics of the listener's head, pinnae, and shoulders (Akeroyd, 2006). The higher the frequency of the sound, the greater the ILD will be. The acoustic shadow of the head created with high-frequency tones is deep because diffraction of the sound wave around the head is minimal. In contrast, low-frequency sounds have long wavelengths which easily diffract around the head, as if it is no obstacle. Interaural level difference increases with the angle of a source from the listener's midline. When a sound originates from a lateral source, one ear will be completely in the acoustic shadow of the head and a significant ILD will be present. Distance to the sound source is most important when it is less than 0.5 m; at this proximity even low-frequency sounds can be attenuated by the head to create a large ILD (Akeroyd, 2006). Individual physical characteristics of the listener influence how sound waves are reflected into the acoustic shadow to affect the magnitude of ILD. The physical features of the pinnae and shoulders have a greater effect on high-frequency sounds because they are more likely to reflect off of these surfaces than low-frequency sounds with longer wavelengths.

1.2.2 Main Effects of Binaural Hearing

Interaural differences are critical for sound localization, but they also contribute to binaural mechanisms in complex acoustic environments. The psychoacoustic literature has identified three main effects that are responsible for improvements in auditory function during binaural listening in NH human adults: the head-shadow effect, the binaural-squelch effect, and the binaural-summation effect (Brown & Balkany, 2007). The head-shadow effect occurs when a target signal such as speech and an undesired signal ("noise") are spatially separated. When one ear is sheltered from a noise source by the acoustic shadow of the head, the ILD of the noise creates a disparity in the signal-to-noise ratio (SNR) present at each ear. The sheltered ear will have a better SNR and improved intelligibility of the target signal when compared to the opposite ear. The one binaural benefit of the head-shadow effect is the option to attend to the ear with the better SNR whilst ignoring the noisy input from the opposite ear. This is why the head-shadow effect is also commonly called "the better ear effect" (Akeroyd, 2006). This effect is generally calculated as the threshold difference between right and left monaural conditions. The size of the head-shadow effect depends on ILDs and is therefore influenced by factors such as the angle of the source from the midline and the signal frequency. The head-shadow effect does not require any central auditory processing (Senn et al., 2005).

Binaural squelch also occurs when the signal and interfering noise are spatially distinct. Whereas the head-shadow effect involves shifting attention to the ear receiving the best physical signal, binaural squelch requires processing and integrating the signals from both ears in the auditory nuclei of the brainstem (Brown & Balkany, 2007). Differences in the phase, amplitude, and spectral properties of the signals are analysed to create a better auditory separation of target and noise. Binaural squelch is measured as a threshold difference between the binaural condition and the monaural condition for the better ear. Consequently, it reflects binaural benefit over and above the head-shadow effect. Binaural squelch is related to binaural unmasking and is described as an improvement in internal SNR (van Deun et al., 2009). A practical use of binaural squelch is when a person focuses on a single talker in a room with many competing voices. The unique acoustic information arising from the location and pitch of the source make it possible to selectively attend to that talker while the brain suppresses other signals. Although ILD cues will contribute to squelch, ITD cues are truly mandatory (Senn et al., 2005). The central processing of ITD cues differentiates squelch from the head-shadow effect because squelch can occur when the SNR is equal at the two ears (Ching et al., 2005).

Binaural summation is also known as binaural redundancy and is the result of having two samples of a similar signal from which to extract meaningful information. The binaural-summation effect requires central processing and results in a perception of loudness increase when listening to the same signal with two ears instead of one (Brown & Balkany, 2007; Ching et al., 2005). It is measured as the threshold difference between the binaural condition and the monaural condition when neither ear has a physical advantage over the other. The perception of loudness can theoretically increase by up to 3 dB (Brown & Balkany, 2007). This would be a doubling of the loudness perceived when listening monaurally. The increased loudness allows for improved sensitivity to fine spectral details and to dynamic changes in the properties of sound such as level and frequency. When a signal is present in noise, the binaural-summation effect typically improves the SNR by about 1-2 dB for NH listeners (Bronkhorst & Plomp, 1988). Unlike squelch, binaural summation does not require a spatial separation of noise and signal. Binaural summation of pure tones is largest when the frequency of the tones is identical in the two ears; the size of this effect decreases as the difference in frequency between the tones increases (Porsolt & Irwin, 1967).

In order to use summation and squelch to enhance perception of a signal in noise, the components of the auditory signals at each ear that are from the target source must be integrated together and/or segregated from the noise. When two signals share certain spectral properties, they are more likely to be integrated together and segregated from other sounds.

For example, one talker's voice can be segregated from interfering speech. By combining or integrating the signals arriving at the two ears from the source of interest, the listener will have improved reception of the target speech.

1.3 BINAURAL HEARING WITH BILATERAL COCHLEAR IMPLANTS

Studies published on the listening abilities of BCI users consistently show that having two devices, instead of one, provides distinct advantages for sound localization and speech intelligibility in noise (Brown & Balkany, 2007; Johnston et al., 2009; Murphy & O'Donoghue, 2007). There is currently a lack of consensus about which of the three main binaural effects are exploited by BCI users, and how well each is employed. BCI users must overcome several challenges before they can detect ITDs and ILDs and apply these cues to complex binaural hearing tasks. The challenges may be due to endogenous factors such as the aetiology of deafness and the state of internal auditory pathways, or they may be due to exogenous factors related to the devices. Some examples of challenges related to CI technology are as follows: First, CIs restrict the amount of fine-timing and amplitude information that is made available to the auditory system (Grantham et al., 2008; Rubenstein, 2004). Second, commercially available BCI devices currently function as two separate systems, each with their own internal and external components and with no interaction or co-ordination for the processing of acoustic input. Individual devices cannot communicate with each other so the arrays are implanted independently and the devices are programmed separately. If the patient is lucky, the clinician will ask them about the balance of loudness; if the clinician is lucky, the patient will give accurate feedback. This may restrict the perception of real interaural timing and level differences and/or generate new and ambiguous interaural disparities (Gordon, Valero, & Papsin, 2007b). Endogenous factors that challenge binaural hearing are related to the development and/or plasticity of neural pathways in the binaural auditory system. These issues are presented in section 1.4.

1.3.1 Detection of Interaural Time and Level Differences by BCI Users

Source localization or lateralization is a basic demonstration of the ability to integrate dichotic signals that are from the same source. To detect and utilize interaural time and level differences to estimate the horizontal location of a sound image, the dichotic signals must seem to arise from the same source. Bilateral cochlear-implant users are able to localize sound to some degree, but this ability is limited by perception of timing and level cues.

Most current CI processors are worn behind the ear. The microphone may be located on the body of the processor or in an ear-hook that loops over the pinna and extends down towards the opening of the external auditory canal. With the microphones at ear-level, the head will act as an acoustic barrier and the ILDs at the microphones will be similar to the ILDs at the eardrums (Grantham et al., 2008). Normally the acoustic signal is transduced by the microphone and then passed through an initial compression (AGC) circuit. The compression reduces the wide dynamic range of the acoustic signal down to the narrow (i.e., approximately 20 dB) dynamic range of electrical hearing (Rubinstein, 2004). Compressing the signal at each ear alters the ILD information originally present in the signal and reduces the listener's sensitivity to the original cues. In experiments where the AGC circuit is circumvented, either by sending electrical pulse trains directly to the electrodes or by delivering the stimulus to the CI auxiliary inputs, the JNDs measured for ILD are very small and not much larger than those described for NH listeners (Grantham et al., 2008). For example, using electrical pulse trains delivered directly to the electrodes with a SPEAR research processor, van Hoesel and Tyler (2003) measured sensitivity levels for ILD from less than 0.17 to 0.68 dB across five participants. Senn et al. (2005) found JNDs of 1 to 2 dB when the stimulus was presented to the auxiliary input of the speech processor. Grantham et al. (2008) measured ILD sensitivity when stimuli were presented to CIs via large headphones placed over the external processors. This method allowed the signal to follow the typical pathway through the processor, including passage through the initial compression circuit. The mean threshold for ILD was 3.8 dB; however, when the compression circuit was turned off, the mean threshold improved to 1.9 dB. The results from these studies illustrate that compression has a negative effect on a BCI user's threshold for ILD, but the exact magnitude of the effect for each individual will depend on the compression ratio set for their specific device. In summary, CIs have the potential to deliver accurate level cues to BCI users, but the use of uncoordinated compression circuits impairs the ability to perceive ILDs.

Although compression circuits may alter ILD cues, their effects are not nearly as deleterious as the effects of speech processing strategies on ITD cues. The processing strategies currently used in CIs virtually eliminate the important fine-structure timing information normally used for ITD perception. The speech processor splits the incoming signal into multiple frequency bands and then samples the envelope of the signal at the output for each band. The envelope information from each band is then used to amplitude-modulate a fixed-rate pulse train that is delivered to the electrode corresponding to the frequency band (Smith & Delgutte, 2008; van Hoesel & Tyler, 2003). Studies measuring the JNDs for fine-structure ITD have confirmed that CI users cannot access or use fine-structure timing information with current clinical processing strategies. For example, Senn et al. (2005) found that none of the bilateral CI users in their study could discriminate fine-structure ITDs up to 16 ms, the maximum difference tested. Van Hoesel and Tyler (2003) tested ITD sensitivity using a signal processing strategy designed to preserve fine-structure timing information. The processing strategy, called "peak derived timing", stimulated electrodes at rates corresponding to the timing of the positive peaks in the fine-timing at each filter-band output. With this processing strategy, BCI users demonstrated sensitivity to ITDs of about 100 µs, but only to stimuli containing low-frequency information. This suggests that CI users may be able to use some fine-structure ITD cues if their signal processors would preserve and electrically code for that information. As previously mentioned, some timing information is also present in the envelope of sound and NH listeners may use this information when other cues are ambiguous. Current evidence suggests that CI users may be sensitive to envelope ITD cues. Senn et al. (2005) found that when the envelope ITD was available in a signal, the JND for CI users was about 250 µs. This was worse than the mean envelope ITD performance by NH listeners in the same study (100 µs), but the difference was not statistically significant. This is important because it indicates that CI users are able to compare/integrate certain binaural signals in a way that is not significantly different from NH listeners. Van Hoesel and Tyler (2003) found that when they introduced low-frequency modulation (50 Hz) to a stimulus with a high pulse rate (800 pps), the ITD sensitivity was comparable to an un-modulated stimulus with a low pulse rate (50 pps).

External processors alter ITD and ILD cues as side-effects of input compression and speech processing. Better representation of these cues is available with alternate signal processing strategies; therefore, at least some of the restrictions to binaural mechanisms caused by the processor are inflicted by design priorities rather than technology. The alternate signal processing strategies used in research studies may improve detection of ITD and ILD for BCI users, but they do not close the performance gap between BCI users and their normal-hearing peers. That is, the JNDs detected by BCI users are rarely as small as those noticed by normal-hearing control subjects. This indicates that there are other factors hampering the perception of binaural cues by BCI users. Another limiting factor may be the internal electrode arrays and/or the disparate positioning of arrays in the two cochleae. The surgical insertion of electrode arrays into the scala tympani of the cochlea is a precise and delicate task. Although techniques exist to attempt a similar alignment and programming of electrodes, it is unlikely that the BCI user will have identical neural stimulation in both ears. Neural survival and other anatomical differences further complicate matters for this clinical population. This raises questions about the effects of mismatches in the place of stimulation within the two cochleae. In the Jeffress model (1948) binaurally matched neurons act as coincidence detectors that fire maximally when the neural inputs to them arrive simultaneously (Blanks et al., 2007). If the neurons being stimulated in each ear are mismatched, then fewer coincidences will occur and firing rates will decrease (even for simultaneously arriving signals), as will ITD sensitivity.

To explore the possible effects of binaural frequency mismatches on ITD discrimination Blanks et al. (2008) used amplitude-modulated high-frequency tones (4 kHz) to present low-frequency envelope-timing cues to different high-frequency auditory channels in NH listeners. This provided a good simulation of the binaural cues that may be experienced by bilateral CI listeners. Testing NH listeners instead of bilateral CI users provided confidence that the place of the cochlea being stimulated would have responsive and normally functioning afferent neurons. The results of this experiment showed an effect for frequency mismatch; that is, thresholds for ITD sensitivity rose in response to increasing frequency mismatch between carriers. Therefore, when a signal containing timing information stimulates binaurally mismatched areas of the cochleae there is a reduction in ITD sensitivity. For bilateral CI users, this could mean that mismatched placement and/or mapping of binaural electrode pairs contribute to impairments in ITD sensitivity. As this study was a simulation of cochlear-implant listening, conclusions about the actual clinical population must be made cautiously. It is not known whether the auditory system can adapt to use binaural cues carried by binaurally mismatched carriers specifically, but plasticity in binaural processing has been demonstrated for other bilateral asymmetries such as conductive hearing losses (Hall, Grose, & Pillsbury, 1995) and experimentally induced unilateral time delays (Javer & Schwarz, 1995). Consequently, the data from Blanks et al. (2008) may underestimate the ability of BCI users to benefit from ITDs carried by mismatched frequency channels.

Long et al. (2003) performed a case study with a BCI user to examine the effect of interaural electrode position on sensitivity to binaural cues. They presented dichotic stimuli to various interaural pairs of electrodes and found that electrode pairing had a strong influence on ITD sensitivity. ITDs were most likely to be detected when the subject perceived the pitch elicited by the two electrodes to be similar. At the same time, pitch comparisons were not enough to reliably predict significant sensitivity to ITDs. The evidence from this study, along with the results for NH listeners in the study by Blanks et al. (2008), helps to substantiate the notion that mismatches in binaural electrode placement and/or mapping can be detrimental for ITD sensitivity in BCI users. However, like the study by Blanks et al. (2008) the participant in the study by Long et al. (2003) did not have a chance to adapt to the mismatched electrode pairs.

Given the lack of fine-structure timing information in the electrical signals delivered by CIs and the other challenges for ITD detection, it is no surprise that ILD is the dominant cue for sound localization by BCI users. Grantham et al. (2007) evaluated the roles of ITD and ILD cues in localization using a source-identification task with noise signals that had either the high-frequency or low-frequency content removed. Performance on the tasks was significantly poorer when high-frequency content was missing, but it did not change in the absence of low-frequency content. This indicated that only the high-frequency content provided useful information about source location. The authors interpreted these results using the duplex theory and concluded that ILDs contributed the most to the localization ability of bilateral CI users. In a separate localization study by Seeber and Fastl (2008) the microphones of one subject's processor were held above his or her head, but the distance between them was maintained. This removed the head-shadow effect but maintained the distance necessary for ITD. Localization was poor until they placed a head-sized piece of cardboard between the processors, essentially re-establishing the head-shadow effect and ILD. These studies demonstrate the dominance of ILD cues for localization by CI users. Further evidence was provided by Aronoff et al. (2010) who used direct-connect testing with head-related transfer-functions (HRTFs) to test localization in a simulated sound-field while maintaining complete control over ITD and ILD cues. The addition of ITD cues to a stimulus already containing ILD cues did not significantly improve localization performance. Direct-connect testing, like that used by Aronoff et al. (2010) ensures that localization results are due to binaural listening and not monaural listening strategies such as head-turning. However, to create a single sound image from two different signals presented to opposite ears, the two signals must be integrated as though they are from the same virtual source – otherwise the listener will hear two sounds. In order to exhibit localization behaviour, BCI users must centrally compare the timing and level cues in the signals at their two ears.

1.3.2 Binaural Hearing Effects with Bilateral Cochlear Implants

Despite the challenges presented to BCI users by current CI technology and signal processing strategies, there is some evidence that they are able to use binaural mechanisms commonly used by normal-hearing listeners. There is strong evidence for the influence of the head-shadow effect on hearing with BCIs (Brown & Balkany, 2007; Gantz et al., 2002; Litovsky et al., 2006). Of the three main effects, however, the head-shadow effect is the only one that researchers have been able to consistently find evidence for in comparison studies of binaural and monaural listening by CI users. The head-shadow effect can be used to explain most of the functional gains that are achieved with binaural implants for localization and hearing in noise. It is important to note, however, that the head-shadow effect is the only binaural effect that does not require central integration of the signals reaching both ears (Senn et al., 2005).

Evidence from the current body of literature is inconclusive regarding the ability of BCI users to take advantage of the binaural-squelch or binaural -summation effects; some researchers have reported significant effects while others have found no supporting evidence (Schafer et al., 2007). Variation between testing methods used and participants selected for different studies may explain some of the inconsistency. However, there is sufficient evidence to conclude that at least some BCI users can benefit from squelch and summation. For example, Gantz et al. (2002) tested 10 adult patients that had received simultaneous implants. They found that all of the participants demonstrated some level of the head-shadow effect while squelch and summation effects were observed in only a few (2-4) participants. Litovsky et al. (2006) tested 34 participants under different presentation conditions for the BKB-SIN and found that 32 (94%) participants showed a binaural benefit related to the head-shadow effect for at least one of two possible presentation conditions (noise left or noise right). Meanwhile, 15 (44%) participants demonstrated a binaural advantage that could be attributed to summation. Interestingly, 2 of the 34 participants in that study performed worse in the binaural condition than in the monaural condition when speech and noise were both presented at 0 degrees azimuth. Only 16 (47%) of the participants demonstrated a binaural-squelch effect in at least one of the two presentation conditions (noise left or noise right). Chan et al. (2008) tested binaural functions of five BCI users in both soundfield and direct-connect conditions. Although the mean effect measured for squelch was only 2 dB, one subject demonstrated an effect of about 5 dB in both the soundfield and direct-connect conditions. Normal-hearing subjects in the same study had a mean squelch effect of 7 dB.

Cochlear-implant technology is constantly improving, not only the processing strategies, but also the manufacturing and surgical insertion of the internal electrode array. These improvements will help device recipients to realize their potential for auditory functioning. Consequently, ongoing and future research may soon reveal stronger support for the use of binaural mechanisms by BCI users. Other important factors to consider in clinical research with BCI users include the demographic and medical history of the participants. Unfortunately, many studies (including the current study) are forced to use a convenience sample due to the small population from which to draw subjects. It is important to study the effectiveness of BCIs for treating diverse patterns and types of hearing loss, but to judge the maximum potential of BCI use, investigators need to find the most ideal test subjects.

1.4 THE IMPORTANCE OF BINAURAL STIMULATION FOR CENTRAL AUDITORY DEVELOPMENT

The hardware and software currently used in CI devices have been shown to present challenges to the perception of binaural auditory cues. As technology continues to improve, some of these problems will be amended. However, there are also endogenous factors related to plasticity of the deaf auditory system that may influence the potential for any individual BCI user to maximize binaural benefits.

Children must have exposure to sound, speech, and language within a critical period in order to learn to communicate orally and to develop auditory pathways at higher levels of processing. Children who are congenitally and/or pre-lingually deaf and who receive a unilateral implant after a critical period of about 7 years often exhibit abnormal patterns of cortical activation in response to sound. This is a result of reorganization of the central auditory pathways during the period of auditory deprivation (Gilley, Sharma, & Dorman, 2006). Consequently, unilateral implant users that are implanted early tend to have better success adapting to their device than those who are implanted beyond the critical period. Early unilateral implantation has a high success rate for establishing reading and language skills similar to age-matched NH peers (Geers, 2003). However, unilateral implants cannot promote the development of binaural mechanisms. There is increasing evidence that the maturation of the binaural auditory system may also face critical periods. If this is the case, then the timing of bilateral implants is important for determining whether or not a recipient will be able to maximize the benefit of having two devices. Electrophysiological studies with auditory brainstem and cortical responses provide insight about the neural consequences of auditory deprivation and/or prolonged unilateral stimulation on the development of the binaural auditory system. The capacity to develop or maintain normal binaural auditory pathways is an endogenous factor that affects the ability for BCI users to employ typical binaural hearing mechanisms.

Gordon, Wong, and Papsin (2010) suggest that children who experience long inter-implant delays have abnormally organized auditory pathways. Children who receive both implants simultaneously or with a short inter-implant delay tend to have auditory pathways that are more normally organized. Gordon et al. (2010) report that normal-hearing children listening to unilateral pure-tone stimuli exhibit lateralization of cortical activity (P1) to one hemisphere. The activity is predominantly in the primary and secondary auditory cortex of the contralateral hemisphere. When the stimulation shifts ears, the cortical response lateralizes to the opposite hemisphere. These authors measured evoked cortical responses of BCI recipients in response to electrical pulse trains. The children who had short inter-implant delays (0 - 0.8 years) responded similarly to the normal-hearing children and their cortical responses lateralized to the auditory cortex in the contralateral hemisphere of the stimulated ear. Children with long inter-implant delays (2.6 – 5.8 years) had abnormal cortical responses. Stimulation to their second implant resulted in cortical activity in the ipsilateral parietal cortex. This is somewhat consistent with the abnormal parietotemporal activity observed in children who receive a unilateral implant following a critical period of about seven years of age (Gilley et al., 2006). However, in these late-implanted unilateral device users, the parietotemporal activity is lateralized to the side contralateral to the stimulated ear.

Sharma et al. (2007) measured P1 latency of the cortical response in children who had been implanted bilaterally before the age of 3.5 years and divided them into two groups based on whether their ears were implanted simultaneously or sequentially. The inter-implant delay for the sequential group ranged from 0.25 years to 1.68 years. Although no significant differences were detected, the sequential group demonstrated a trend for having unequal P1 latencies between the ears at activation of the second implant. This difference was resolved after 3 months of experience with both CIs, and the two groups showed P1 latency values within normal limits by 3.5 months after implantation. The authors contrast these results with those from children who received their second implant later in childhood after early implantation with a unilateral device. These children often exhibit interaural P1 latency differences that fail to resolve even three years after activation of the second device (Sharma et al., 2007). The authors propose that a sensitive period exists during which the central auditory pathways can develop normally regardless of whether the implants are received simultaneously or sequentially.

Studies of auditory-brainstem activity in children using BCIs have demonstrated that electrical stimulation can be integrated in the auditory brainstem. Gordon, Valero, and Papsin (2007a) measured the binaural interaction component (BIC) in children with bilateral implants. The BIC is the mathematical difference between the evoked response to binaural stimulation and the summation of the responses evoked by monaural stimulation to each ear. The researchers found a trend for longer latency delay of the BIC in children who had longer periods of unilateral implant use prior to implantation of the second ear.

In general, any ear that has had little-to-no auditory stimulation will initially have longer latencies for evoked responses than experienced ears. Response latency decreases with experience and shows the greatest progress during the first year of implant use (Gordon et al., 2007a). The question is whether the second ear to be implanted can eventually develop response latencies equal to that of the ear with more experience. Gordon et al. (2007a) found latency differences in the auditory brainstem responses of children who were implanted simultaneously vs. sequentially. The latency of an evoked eV wave was equal between the left and right ears of simultaneous bilateral-implant recipients and both latencies decreased as the patients gained more experience with the implants. Latencies evoked in the newly implanted ears of sequential implant recipients were prolonged relative to the experienced ear, but the initial latencies of the second (sequential) ear were similar to the latencies of newly implanted unilateral subjects. Based on repeated longitudinal measures, the researchers used linear regression to predict that the difference in latency would resolve in subjects with short inter-implant delays (0.75 ± 0.13 years) in about 1.5 to 2.0 years. The difference in latency would resolve more slowly for children with longer inter-implant delays (3.54 ± 1.47 years), taking more than 2.5 years. Children who received their initial implant when they were older than three years of age, and who also had a long inter-implant delay (5.50 ± 0.19 years), showed no trend for decreasing the latency difference between ears. In other words, the two ears would likely never be the same and an "internal" interaural time difference would persist (Gordon et al., 2007a). Differences in the speed of neural transmission for signals from the two ears might impair binaural mechanisms – especially ones that use ITDs, but this has not been studied specifically.

Providing a single implant to a child with a bilateral hearing loss could cause unusual changes to the auditory pathways in the inferior colliculi in the same way that unilateral cochlear ablation has done in animal models. Brain plasticity makes processing centres, such as the auditory cortex, susceptible to reorganization caused by cross-modal stimulation. That is, input from other sensory systems changes the function of the auditory cortex in a deaf individual (Kral, 2007; Lee et al., 2001). The auditory brainstem does not receive input from other sensory modalities and so auditory deprivation should result in arrested development rather than plastic changes in function (Gordon et al., 2007a). Animal models of induced unilateral hearing loss have shown that the neural projections from the ipsilateral cochlear nucleus to the ipsilateral and contralateral inferior colliculi increase in the absence of competing stimulation to the opposite ear (Moore & King, 2004, p. 128). More excitatory projections reach the ipsilateral inferior colliculus and more inhibitory projections reach the contralateral inferior colliculus (Clopton & Silverman, 1977 and Nordeem et al., 1983, as cited by Gordon et al., 2007a). This abnormal expansion of the connections innervating the stimulated ear may have lasting consequences on the previously undeveloped binaural pathways. Although long-term deprivation may also have consequences to the auditory brainstem, these effects are not as permanent or as strong as the consequences of reinforcing abnormal pathways with unilateral stimulation. It is possible that a similar expansion of innervation pathways can occur in a human ear with a CI when the other ear is left without stimulation. Long-term use of such pathways during a long inter-implant delay could potentially inhibit binaural function even once a second device is implanted (Gordon et al., 2007a).

In summary, children with bilateral profound sensorineural hearing loss may require early and simultaneous bilateral cochlear implantation to maintain and/or develop the neural pathways required for the central processing of binaural auditory cues. Many early studies on the functional performance of BCI users recruited children who had received their implants sequentially and after a long period of unilateral implant use. Newer studies contrasting functional performance by simultaneous versus sequential BCI recipients have found greater binaural benefit for simultaneously or near-simultaneously implanted recruits on tasks of speech perception in quiet and in noise (Gordon & Papsin, 2009). Similar effects are seen for children who receive their second implant before a critical age – though the age varies from study to study (Galvin, et al., 2008; Scherf et al., 2007). These functional benefits to simultaneous implantation are consistent with the electrophysiological evidence discussed here and suggest that studies using sequentially implanted participants may underestimate the capacity for BCI users to use binaural hearing mechanisms. The current body of literature has a paucity of evidence to support bilateral integration by BCI users; studies with children who are implanted early and simultaneously in both ears may be needed to reveal the potential for BCI users to integrate signals binaurally.

1.5 BINAURAL INTEGRATION OF DICHOTIC STIMULI BY COCHLEAR-IMPLANT USERS

With or without ideal test subjects, very few studies have directly tested the ability for BCI users to combine or centrally fuse the auditory information received at the two ears. Squelch and summation effects are presumed to arise from the central integration of binaural signals; therefore, by detecting a squelch and/or summation effect, researchers infer that auditory integration is occurring. However, more direct tests are needed to confirm that the binaural benefits observed are in fact due to central integration.

Mani et al. (2004) used a series of dichotic listening experiments to test binaural integration by BCI users. They tested word recognition in quiet and in noise when the spectral information in each word stimulus was presented dichotically. That is, they divided the spectral information from each word into two distinct halves and simultaneously presented one half to each ear. Two dichotic conditions were used: In the first condition, only the low-frequency channels were presented to one ear while only the high-frequency channels were presented to the opposite ear. The second condition was interleaved such that the odd-index frequency channels were presented to one ear while the even-index frequency channels were presented to the opposite ear. Control trials included presentations of each half stimulus (low-frequency only, high-frequency only, odd-only, or even-only) to each ear, as well as presentations of the full stimulus to each ear individually and to both ears simultaneously (diotic condition). Bilateral-implant users performed significantly better on the word recognition task in the low-high dichotic condition than in the low-frequency only or high-frequency only conditions. When words were presented in quiet, the participants performed equally well on the dichotic trials as they did on the diotic control trials. When the words were presented in noise, the same participants demonstrated a weaker performance in the dichotic condition. The authors concluded that BCI users are able to integrate spectral information presented dichotically, but that this ability is more accurate in quiet than in noise. The authors did not report the results for the monaural control conditions with unfiltered speech and no comparison of performance in the monaural and dichotic conditions was included; consequently, it is impossible to determine whether the participants had truly integrated the dichotic stimuli. Nevertheless, this study suggests that two incomplete signals can be fused centrally by the BCI user to form a meaningful percept. If BCI users can truly integrate the signals at their two ears, then the benefits of having a second implant can well exceed the benefits of having a spare or alternate ear.

1.6 PITCH, SPECTRUM, AND TALKER DISCRIMINATION

Two properties of a speech signal are used by NH listeners to identify a talker and to perceptually group the sound arriving from that talker as continuous speech. These properties are vocal pitch and spectrum. When presented with speech to both ears through headphones and told to attend to a specific talker, a listener must sense whether they hear the same talker or different talkers at the two ears. If the talker is the same in both ears, the listener can use central integration to enhance the speech signal from that talker. If the talkers are different, the listener may ignore one in favour of the other. We designed a task to test how well BCI users can match voices based on pitch and spectrum. The task measures how different two voices can be from each other and still be identified by BCI users as the same person. We created a second task to compare hearing in noise for one voice presented diotically versus two voices presented dichotically. The presumption was that speech signals at the two ears would be integrated when the voices were the same but not when the voices were different. Our hypotheses for the two tasks are based on the known limitations of CI devices (previously discussed) and conventional knowledge of speech perception. The following sections will introduce the background information that supported our hypotheses. More details about the specific hypotheses are presented in section 1.9.

Pitch is an auditory sensation which depends on the frequency content of the sound stimulus (American National Standards Institute [ANSI], 1995). Fundamental frequency (f_0) is the lowest frequency or first harmonic produced by a vibrating system. In speech and other harmonic complex waveforms, the frequency component equal to f_0 provides the primary reference for pitch (Plack & Oxenham, 2005, p. 13). The f_0 of speech is related to the rate of opening and closing of the vocal folds, which is determined by the vocal cord length, size, and mass. Consequently, voice pitch can convey information about the age and sex of a talker. Most people with normal hearing can easily identify familiar talkers by the “sound” their voice. Although speaker identification is a complicated process, vocal pitch provides an important cue. Average f_0, or vocal pitch, is used to perceptually group speech sounds produced by the same talker as a continuous signal distinct from other sounds in the environment (Bregman, 1990, p.

537-538; Darwin, 1981). Normal-hearing listeners can segregate voices when they differ in f_0 (Cullington & Zeng, 2008).

Spectrum refers to the distribution of energy across frequencies in a sound. Formant frequencies, or formants, are the peaks in the speech spectrum that occur due to vocal tract resonances. Formants can be harmonic or non-harmonic components of the source signal (Clear, Pisoni, & Kirk, 2005). The frequencies and relative amplitudes of formants in a speech signal are determined by the shape of the vocal tract and indicate the vowels being produced. The frequency range of the formants also suggests vocal-tract size and provides an additional cue for talker identification. Formants also help a listener to group speech from one talker; this is explained by Bregman (1990) in the following passage:

> Since the formants are caused by the filtering that comes from the shape of the vocal tract, and this tract does not snap instantly from one setting to the next, the formants in successive sounds tend to be continuous with one another. This is most easily seen when the two successive sounds are both voiced. (p. 543)

Two mechanisms have been described to explain how the normal cochlea codes for the frequency characteristics of an acoustic signal. Place coding refers to the tonotopic organization of the basilar membrane and suggests that when a sound causes the membrane to vibrate, the location of maximal displacement indicates the pitch of the sound (Plack & Oxenham, 2005, p. 11). Phase-locking, or temporal coding, refers to the temporal pattern of nerve responses and suggests that the firing-rate of auditory neurons reflects the temporal fine structure of the signal (Plack & Oxenham, 2005, p. 11). In other words, the rate of neural action potentials can synchronize with the period of an incoming signal to transmit pitch information. Place-coding explains pitch perception for frequencies above 4-5 kHz where the refractory period of auditory neurons limits the capacity for phase-locking (Plack & Oxenham, 2005, p. 12). Temporal-coding is the dominant strategy for frequencies below 50 Hz because the place of maximal displacement on the basilar membrane does not change between frequencies in this range. The two mechanisms presumably overlap and complement each other for frequencies between 50 Hz and 4 kHz, but how the two mechanisms interact is not well understood. Phase-locking is believed to be the more dominant cue for identifying the relatively low fundamental frequencies of human voices (Varenberg et al., 2011).

Cochlear implants are able to provide some measure of place and temporal coding, though both are limited compared to normal cochlear mechanisms. The distribution of electrodes along the intracochlear array attempts to preserve a tonotopic map for place coding while the rate of electrical stimulation can provide some temporal coding. The amount of place coding actually available from CIs is restricted by the small number of electrodes or stimulation sites and the tendency for electrical current to spread (Rubinstein, 2004). The depth of electrode array insertion is also limited, which prevents the most apical region of the basilar membrane from being stimulated directly. This results in a significant frequency mismatch between the normal tonotopical mapping of the cochlea and the areas of stimulation by the electrodes in the array. Brain plasticity and former experience with stimulation to the basilar membrane may determine the relevance or impact of the mismatch. For example, the mismatch may not matter for children with congenital deafness because their auditory system may develop around the stimulation that is available. Another limiting factor for place coding by electrical stimulation is the pattern of neural survival in the deaf cochlea. Some individuals may have areas in their cochleae where no nerve fibres are present to be stimulated. Such locations are termed "dead regions". The location of these regions is not currently predictable pre-implantation, and current electrode arrays have standard and evenly distributed electrodes; therefore, it is possible that some electrodes rest in cochlear locations where there are no surviving neurons to detect and transmit the signal. This would reduce the number of functional electrodes available for mapping. Despite these limitations, the capacity for multi-channel implants to indicate the presence of different frequency bands in a signal allows for some representation of spectral shape.

The temporal fluctuations in the envelope of speech can provide information about the f_0 of the signal. Envelope-based processing strategies preserve these fluctuations by modulating trains of biphasic pulses in each frequency band. The high-frequency cut-off of the low-pass filter in each envelope detector is at least 200 Hz (Wilson & Dorman, 2009). This means that the f_0 for speech can be represented in the modulated pulse-train (Wilson & Dorman, 2009). Consequently, CI users have access to some voice pitch discrimination cues through the envelope of the speech signal.

There is currently no published research on voice or talker discrimination by BCI users, but evidence from other cochlear-implant studies has shown that talker discrimination is possible in successful unilateral cochlear-implant users. Surveys of telephone use by cochlear-implant users have cited self-report data that listeners could recognize familiar voices and identify an unfamiliar speaker's gender or age range (Anderson et al., 2006). Studies that have investigated talker discrimination or voice gender identification by unilateral CI users have found individual variability in performance. For example, Kovacic and Balaban (2009) presented speech samples from 40 different professional radio announcers and found that only 18 of 41 (44%) child CI users could correctly identify the gender of the talkers at a rate that was better than chance when one voice was presented at a time. In the same study, NH control subjects had maximal or near-maximal performance. By capturing the stimulus-induced electrode output patterns from the CI devices worn in the experiment, Kovacic and Balaban (2009) were able to show that the CI users who could identify gender appeared to use temporal cues and not place cues. It is not clear whether the participants who could not perform the gender identification task had poor perception of vocal pitch or unusual categorization, but the authors confirmed that the output from the CIs were no different for participants that were successful or unsuccessful at the task. A sub-group of the participants who were unsuccessful at identifying the genders of speakers in isolated sound clips were able to perform the task if two contrasting stimuli were presented in succession. This suggests that the subjects had the ability to discriminate between voices but required a contrasting voice as a reference for gender category.

Cleary, Pisoni, and Kirk (2005) used a series of voices that were increasingly dissimilar from one another to measure difference limens for both pitch and spectral differences. They created the stimuli by systematically altering the mean f_0 and formant frequencies of pre-recorded sentences. Child participants were asked to classify presentations of paired utterances as spoken by a single person or by two different people. A group of 5-year-old children with normal hearing sensitivity perceived voices speaking the same sentence as different when the spectral characteristics varied by at least 2 to 2.5 semitones. A group of CI users (5 to 12 years of age) that had several years of experience with their implants showed highly variable performance. Most subjects exhibited only chance performance on the tasks, but at least one child with a CI performed at the same level as the normal-hearing children. The researchers noted a sub-group of CI listeners with higher-than-chance performance on the discrimination tasks. These children perceived voices speaking the same sentence as being different when the mean f_0 difference was at least 2.87 semitones. Several different CI systems and processing strategies were represented in the study, but the authors did not statistically compare results from the CI users of different systems or processing strategies. Several comparison studies of unilateral CI systems, however, have included simple tests of talker discrimination and found no significant difference in test scores between users of different devices (Spahr, et al., 2007; Spahr & Dorman, 2004).

1.7 HEARING SPEECH IN NOISE

Many of the mechanisms used for hearing speech in noise have been discussed (see sections 1.2 and 1.3). The capacity to understand speech in noise is one of the most cited arguments for bilateral cochlear implantation (Brown & Balkany, 2007; Johnston et al., 2009; Sparreboom et al., 2010). Unilateral CI users who perform very well in quiet situations commonly show a marked decrease in speech reception when background noise is introduced (Wackym et al., 2007). Within-subject tests comparing speech intelligibility in noise for BCI users in monaural and binaural conditions have demonstrated a bilateral advantage (e.g., Mosnier et al., 2009). Comparison studies of bilateral and unilateral cochlear-implant users have also provided evidence for a bilateral advantage for speech intelligibility in noise. For example, Dunn et al. (2010) tested speech perception in noise using three different tests. They found that bilateral CI users could withstand more background speech noise than unilateral CI users for all of the tests. The authors deduced that the bilateral advantages came from improved source localization and a better ability to filter out spectral and informational masking. In the present study, we investigate whether the binaural advantage for understanding speech in noise depends on the signals at both ears being from the same voice or source. We did not use informational masking and instead presented dichotic voices speaking the same sentences simultaneously so that only spectral masking was present.

A modified version of the Hearing in Noise Test for Children (HINT-C) was used in this study. Information about HINT-C administration and our re-synthesized stimuli is found in sections 2.4.2 and 2.2.2, respectively.

1.8 BIMODAL HEARING

Unilateral cochlear-implant users who have residual hearing in the opposite ear can sometimes benefit from a hearing aid. The cochlear implant provides an electric signal to one ear while the hearing aid amplifies the acoustic signal to the opposite side. This combination is called bimodal stimulation. Occasionally it is called “electroacoustic hearing”, but lately that term has been used to refer, more specifically, to combined electric and acoustic hearing to the same ear. In this study we use the term bimodal to refer to unilateral CI users who use a hearing aid in the non-implanted ear. Studies have found binaural advantages for sound localization and speech intelligibility in quiet and noise for bimodal users (Ching et al., 2006; Ching, Incerti, & Hill, 2003; Dorman et al., 2008; Flynn & Schmidtke, 2004).

Most guidelines for cochlear-implant candidacy require a patient to have at least a severe level of hearing loss in both ears. In a survey of Canadian CI clinics, audiometric thresholds of 70 dB HL up to 90 dB HL were reported as 'borderline' for candidacy (Fitzpatrick et al., 2009). In other words, the amount of residual hearing for patients with unilateral CIs is usually very limited or they would not have been candidates in the first place. Cullington and Zeng (2010) had the rare opportunity to test an individual with a CI in one ear and normal hearing in the opposite ear. They systematically assessed the contribution of low-pass and high-pass acoustic sound to speech recognition in the presence of a competing talker. The results demonstrated a benefit for low-frequency acoustic sound in the bimodal condition. The bimodal benefit observed for low frequencies did not occur for high-frequency sounds. The authors concluded that CI users should benefit from bimodal stimulation as long as they have some low-frequency residual hearing. Anecdotally, the residual hearing in the ear contralateral to a cochlear-implant is most often represented by a low-frequency corner audiogram. That is, hearing thresholds are only present for low-frequency sounds and there are no detectable thresholds for the mid- to high-frequencies.

Patients using bimodal stimulation report binaural benefit for speech understanding in noise, localization, perception of their own voice, and perception of music (Flynn & Schmidtke, 2004). Bimodal users have been shown to take advantage of the head-shadow effect and summation effect (Ching et al., 2006) and squelch (Schafer et al., 2007), but each person's capacity to access binaural cues is limited by the amount of residual hearing in the aided ear and the previously discussed confines of cochlear-implant processing. This study included bimodal users, but recruitment was limited because there were very few bimodal users in the area.

1.9 JUSTIFICATION AND EXPECTATIONS

Cochlear implants and the necessary follow-up therapy are currently available across Canada and worldwide. This treatment is expensive but has been revolutionary at improving the communicative abilities and overall quality of life of many patients with severe hearing impairments. Recently, there has been an increase in demand for bilateral cochlear implantations. New patients are requesting to receive one implant in each ear and current patients with unilateral implants are inquiring about candidacy for an additional device.

Bilateral cochlear implantations can consume nearly double the amount of health resources as unilateral, especially when performed sequentially. Every ear implanted requires a new cochlear device, a surgical operation, years of maintenance, and possibly auditory-verbal therapy. Because more time and resources must be spent on each patient receiving bilateral implants, the overall number of Canadians who can access this treatment through the public health sector will decrease if health-care budgets fail to expand with the increase demand. Meanwhile, the candidacy requirements for CIs are otherwise becoming more inclusive and the number of patients seeking this treatment is growing. Children as young as 12 months of age can be eligible for cochlear-implant surgery and there is no upper age-limit for candidacy. Patients with profound hearing loss should be provided with current and accurate information about the potential risks and benefits of bilateral cochlear implantation if they are to give informed consent for their treatment and form realistic expectations of the results.

Although bilateral devices have been shown to have some functional benefits over unilateral devices, the extent to which BCI users can actually use binaural cues is under investigation. In this study, we tested whether BCI users could match stimuli across the ears on the basis of acoustic similarity. If BCI users can recognize when dichotic stimuli are from the same source, then they may be capable of taking full advantage of binaural cues. Sensing which parts of a dichotic stimulus are from the target signal is the first step to integrating the binaural signals from the target appropriately. The ability to identify when two signals match indicates the capacity to perceive signal similarities at lower levels of processing. We also tested whether speech recognition for sentences in noise would be affected when the voice signal to one ear was spectrally altered to sound like a different voice. We compared performance by BCI users to a group of normal-hearing control subjects.

1.9.1 Voice Matching Task

Bilateral surgeries in Canada are, at this time, unofficially reserved for children, or adults with special circumstances. Consequently, the participants in this study were all children. Testing children can be a challenge because their ability to remain focused and attentive during quiet listening tasks is highly variable. The time available to collect data is limited by a child's attention span for the task. Psychoacoustic studies often use adaptive staircase methods of presentation with a two-interval forced choice at each step. While this style of testing could have been used for the current study, we were concerned it would consume too much time for the small amount of data it could produce. The current study gave participants control over stimulus manipulation and provided them with a glowing blue knob to perform the tasks. This was intended to be more interactive for the children and we hoped that it would reduce the overall time required for each threshold measured (because skilful listeners could skip past the unnecessary steps that occur in staircase methods). By reducing the time for each trial, we could complete more trials while the children were attentive to the task.

Participants used the knob to change the properties of the speech stimulus presented to one ear to match a model voice in the other ear. We used STRAIGHT (Kawahara, Masuda-Katsuse, & de Cheveigné, 1999) - a speech analysis, modification and re-synthesis system - to create three sets of stimuli that manipulated a) pitch, b) spectrum, or c) both pitch and spectrum together. We presented each of these stimulus sets under three different listening conditions. In one condition the stimuli were presented to opposite ears at the same time – we refer to this as the simultaneous or binaural simultaneous condition. This is the condition where binaural integration could occur. If binaural integration did not occur we wanted to know if this was because the listener did not perceive acoustically matched stimuli as being the same when presented to different ears. Consequently, in the second condition the voices were presented to only one ear – this is called the monaural sequential condition because stimuli were presented to one ear in a continuously alternating or sequential pattern. In the third condition the stimuli were presented sequentially so that the voice presented to one ear was silent while the second voice was being presented in the opposite ear; these voices alternated continuously during the task. We call this the binaural sequential presentation condition. This condition allowed us to compare matching performance between monaural and binaural conditions with equal memory effects. That is, the possible effects of presenting stimuli sequentially rather than simultaneously.

The CI is one of the most successful examples of a neural prosthesis, but CIs cannot replace or restore normal hearing. Consequently, we expected NH participants to perform better than CI users on the matching task. Since the pitch-only and spectrum-only conditions are measuring different auditory functions, we expected performance between the two conditions to be different. Where both pitch and spectrum were manipulated together we expected performance to be at as least as good as performance with only the better of the two. We did not expect BCI users to perform the same way as NH listeners because CIs alter and reduce pitch and spectrum cues.

The results from the binaural simultaneous presentation conditions should represent the ability for listeners to appropriately integrate signals present at the two ears. In order to use binaural mechanisms such as squelch and summation to enhance speech perception in noise, a listener must sense which parts of a dichotic stimulus, if any, form the target signal. The parts of the stimuli to each ear that are from the target signal can then be integrated with each other and segregated from the background noise. If the listener has no way to discern whether the parts of a dichotic stimulus belong to the same speaker, he or she will not be able to take advantage of many binaural mechanisms. If the listener can integrate binaural signals, but does so inappropriately (for example: integrating the signal with the noise), then binaural disadvantages such as interference can occur. The binaural simultaneous pitch condition tests how similar two stimuli must be before the listener will fuse them centrally. In other words, it measures how similar dichotic stimuli must be for the auditory system to deem them appropriately similar for integration. The binaural simultaneous spectrum condition tests whether the listener will fuse the dichotic stimuli in a way that is a disadvantage for the task. In this condition, segregation of the dichotic stimuli would theoretically allow for better comparison of the stimuli and would result in better performance on the matching task; instead, listeners are expected to always integrate the stimuli and perceive only one voice.

When two identical voice stimuli are presented simultaneously to the two ears of a NH individual, he or she will perceive a single talker. If the pitch of the stimulus to one ear is changed by a large enough difference, the NH listener will perceive two talkers speaking in chorus. Manipulating only the spectrum of the stimulus to one ear does not have the same effect; as long as pitch is held constant, the percept remains as a single talker, though the vocal characteristics of that talker will change according to the spectral changes made to the shifting stimulus. Consequently, for the binaural simultaneous condition, we expected NH listeners to perform equally well with the pitch and combined stimulus sets. We expected the NH group to perform poorly on the spectrum set. Because the percept remains as one talker during the spectrum task, we expected that participants would be unable to compare between the two ears and would perform no better than what they could have achieved by chance. Sequential presentation conditions allow the NH listener to compare the stimuli, but (for stimuli differing in pitch) the listener cannot use the number of talkers heard as a cue to indicate a perfect match. Therefore, we expected to see an increase in performance on spectrum matching and a decrease in performance on the pitch and/or combined matching conditions for NH listeners in the binaural sequential condition – compared to the binaural simultaneous condition. We did not expect any differences in performance between the monaural and binaural sequential conditions for NH listeners because their hearing was equal in their two ears and memory effects were equal.

Contrary to the expected performance of NH listeners, we expected BCI and bimodal users to perform better in the monaural sequential condition then in either of the binaural presentation conditions. BCI and bimodal users are unlikely to have equal hearing and pitch/spectrum perception in both ears and they were asked to use their better ear for the monaural task. We did not know if BCI users would be able to integrate the voices presented in the binaural simultaneous condition and could not predict how the binaural simultaneous and binaural sequential conditions would differ, but we believed they would interact differently than with NH listeners. We expected bimodal listeners to have lower performance than BCI users on the binaural conditions due to limited amounts of residual hearing in the non-implanted ear and evidence from previous studies showing that the binaural benefits for BCI listening to be greater than the binaural benefit for bimodal listening (Litovsky, Johnstone, & Godar, 2006).

In summary, the hypotheses for the matching task were as follows:

- Overall, the NH group will perform better than the BCI group.
- Spectrum and pitch matching performance will differ from each other. This will occur within both groups.
- Performance for the combined stimulus (pitch + spectrum) will be at least as good as performance for the better of the two properties alone. This will occur within both groups and within each presentation condition.
- The NH group will demonstrate no difference in performance between the monaural sequential and binaural sequential conditions.
- The BCI group will demonstrate better performance for the monaural sequential condition than for the binaural sequential condition.
- The NH group will demonstrate worse performance for the binaural simultaneous spectrum condition than for either sequential spectrum condition (monaural or binaural).
- It is unknown whether the BCI group will perform differently for the binaural simultaneous spectrum condition than for the binaural sequential spectrum condition.

- The NH group will demonstrate better performance for the simultaneous pitch condition than for either of the sequential pitch conditions (monaural or binaural).
- It is unknown whether the BCI group will perform differently for the simultaneous pitch condition than for the binaural sequential pitch condition.

1.9.2 Modified Hearing in Noise Test for Children (HINT-C)

The HINT-C test was used to test hearing in noise in three different conditions. One condition was the dichotic presentation of two voices speaking in chorus. One of these voices was the standard male recording on the audio compact disc. The second voice was a female-like voice created from the first by manipulating pitch and spectrum using STRAIGHT. The two other HINT conditions were diotic presentations of either the male or the female voice.

When the voice was the same in both ears we expected a NH listener to be able to use binaural-summation to improve (i.e., lower) the SNR needed to hear the sentence. We expected that summation and squelch would not occur when the two speech signals was perceived as coming from two different sources or talkers. Since the SNR in each ear was equal, there was no opportunity for the head-shadow effect to improve speech recognition in one ear on the dichotic task. Consequently, we expected NH listeners to perform worse on the dichotic condition than on the diotic conditions. Since understanding speech in noise is a known weakness for CI users, we expected them to perform worse than the NH controls on all conditions. We believed BCI users were unlikely to use summation and are more likely to attend only to their “better” ear – in this case “better” ear refers to the listener’s favourite implant, rather than an ear that has a physical advantage for signal detection. We expected their performance on the dichotic condition to be as good as the better of the two diotic conditions. We expected bimodal users to achieve similar SNR scores to the BCI group.

In summary, the hypotheses for the matching task were as follows:

- Overall, the NH group will perform better than the BCI group.
- NH listeners will perform better in the diotic conditions than in the dichotic condition. There will be no difference between the male and female diotic conditions.
- BCI users will exhibit no difference in performance between the dichotic condition and the better of the two diotic conditions. It is unknown if there will be a difference between the male and female diotic conditions.

CHAPTER 2 - METHOD

2.1 PARTICIPANTS

Twenty-seven participants took part in this study. Participants were male (12) and female (15) children between the ages of 5 and 18 years. The children were divided into three groups: children who use bilateral cochlear implants (bilateral, n = 8), children who use a cochlear implant in one ear and a hearing aid on the opposite ear (bimodal, n = 2), and children with normal hearing (n = 17). Bilateral participants ranged in age (years; months) from 6; 0 to 13; 0 (M = 9; 5, SD = 2; 4). The two bimodal participants were ages 6; 10 and 17; 8 (M = 12). The mean age of initial CI activation for children with congenital or early-onset hearing loss was 17.3 months. The mean age of initial CI activation for children with progressive hearing loss was 149 months (12; 5). The average duration of implant use at the time of testing was 5; 3 for the first CI and 2; 0 for the second CI. For bilateral CI users, the mean delay between the two implant activations was 3; 7.6. Normal-hearing participants ranged in age from 4; 11 to 13; 11 (M = 8; 7, SD = 2; 8). All of the participants spoke English at home.

Cochlear-implant users were recruited through the cochlear-implant program at the Nova Scotia Hearing and Speech Centres (NSHSC). In accordance with NSHSC policy, an audiologist from the cochlear-implant program made first contact with a parent and/or guardian of each potential participant during a regularly scheduled appointment or by telephone. The audiologist was given a script (see appendix A) to use during this first contact. The audiologist asked the parent or guardian if they would grant permission for NSHSC to share their contact information with the principal investigator. The NSHSC then forwarded the contact information for consenting individuals to the principal investigator who subsequently telephoned each parent or guardian to invite their child to participate in the study. Additional cochlear-implant users were recruited in Kingston, Ontario using the same protocol with current or former patients of Hotel Dieu Hospital. Participants in the bilateral and bimodal groups met the following selection criteria: (a) cochlear-implant/s were successfully activated and programming adjustments for the device/s have stabilized; (b) at least five years of age; (c) understands the concepts of same and different. Due to the small population of CI users available, inclusion in the study was not limited by make or model of CI. Details about each CI user's hearing history were not factors for inclusion, but are recorded in Table 1. One participant in the bimodal group had Down syndrome – no other cognitive disabilities or disorders were identified in the bilateral or bimodal groups.

Participants for the normal-hearing group were recruited in, or near, the communities of Halifax, Nova Scotia and Kingston, Ontario. Participants in the normal-hearing group met the following criteria: (a) at least five years of age, (b) understands the concepts of same and different, (c) has normal hearing in both ears as determined by a simple pure-tone hearing screening administered on the same day as the experiment. We defined normal hearing as a maximum sensitivity level of 25 dB HL at octave-spaced audiometric frequencies from 500 Hz to 4000 Hz. All of the volunteers passed the screening test and were eligible for participation in the study. No cognitive disabilities or disorders were identified in the normal-hearing group.

All participants were under 18 years of age; consequently, we obtained informed consent from a parent or guardian in all cases. The test administrator also orally explained the tasks and the right to withdraw to each child and asked for the child's assent. Volunteers chose a small toy as a prize for their participation in the study. No other compensation was provided. This study was approved by the Dalhousie University Health Sciences Research Ethics Board.

Three of the bilateral participants who use devices produced by Cochlear Corporation were tested twice due to technical difficulties with the apparatus during the initial testing sessions. Although these children attempted the matching task, they reported that they could not hear anything when they were asked to repeat the HINT sentences, even when the volume was set to the maximum. The test was repeated after a period of over 6 months using a slightly different apparatus (see Table 2, section 2.3) and the results from the first testing session were discarded. One child who participated initially was subsequently unavailable for a retest. This child's results were discarded and are not represented in this study. It is unlikely that practice effects would impact performance for the three children that were retested; the period of time between tests was long and it is most likely that they were not hearing the stimulus very well, if at all, during the first session. We obtained informed consent prior to each of the two sessions and asked the children to choose a toy following each sitting. All participants were able to complete the listening tasks.

Table 1. Demographic and hearing history information for cochlear-implant users.

		Implant 1		Implant 2 / Hearing aid			
Subject	Age (years)	Experience (years)	Processor	Experience (years)	Processor	Inter-implant Delay	Aetiology
7	12;5	0;8	Harmony	0;8	Harmony	0	Bilateral progressive
8	9;1	7;11	Nucleus 5	2;5	Freedom	5;6	CMV congenital
10	10;6	1;6	Harmony	0;1*	Harmony	1;5	Bilateral progressive
12	7;11	6;7	Nucleus 5	2;7	Nucleus 5	4;0	Unknown congenital
13	8;2	6;6	Nucleus 5	2;4	Freedom	4;2	Enlarged IAC congenital
14	17;8	1;0	Harmony	-	Phonak Naida III SP	-	Bilateral progressive
25	6;0	4;11	Harmony	0;11	Harmony	4;0	Unknown congenital
26	6;10	5;8	Harmony	-	Phonak PowerMax 411	-	Suspected ototoxic medication
27	13;0	11;3	Platinum	1;7	Harmony	9;8	Suspected ototoxic medication
28	8;6	6;6	Freedom	5;9	Nucleus 5	0;9	Waardenberg syndrome

*Participant had less than one month of BCI experience

2.2 STIMULI

The present study consisted of two dichotic listening tests. The first test measured the accuracy with which participants could change one voice stimulus to match another. The second test assessed performance on the Hearing in Noise Test for Children (HINT-C) under three conditions. We created new stimulus materials for this study by modifying standard stimuli with the STRAIGHT system by Hideki Kawahara. STRAIGHT is a high-quality speech analysis, modification and re-synthesis system which permits independent manipulation of fundamental frequency and formant frequencies (Kawahara, 1997; Kawahara et al., 1999; Liu & Kewley-Port, 2004).

2.2.1 Spondee Word Re-synthesis

Stimuli for the voice-matching task were created from AUDiTEC™ digital recordings of spondee words. Spondees are two-syllable words with equal stress on each syllable. As part of the standard audiological battery, they are typically used to obtain speech reception thresholds. In the present study, the spondee words provided stimuli that were long enough to be perceived as a distinct person's voice, but short enough to compare when presented sequentially. Three sets of 51 re-synthesized spondee words were created for this task. The same 51 spondee words were used for each set. The spondees were re-sampled to 11025 Hz. Each word was then transformed using STRAIGHT to create a continuum of 201 steps for each of the three sets. The sets varied by the voice parameters that were transformed. In the first set, only the fundamental frequency (f_0) was manipulated logarithmically both up and down. In the second set, spectrum was logarithmically scaled both up and down. In the third set both f_0 and spectrum were transformed together. In each continuum of 201 steps, the original, unmodified recording always formed the central step with 100 steps below and 100 steps above where each step represents 0.01 octaves. Each step represented a change of approximately 0.7%. However, the highest and lowest steps that subjects could select ranged between plus or minus 0.9 octaves from the original stimulus. The highest and lowest 0.1 octaves were never accessible in the adjustment task. This limited the adjustable range for the matching task so that voice pairs were never separated by a full octave, which could create perceptual confusions in the matching task. The relationship between stimulus parameters and step index was:

$$f_{0\ \text{original}} \times 2^{(i\ /\ 100)}$$

Where i = the index of the step

A similar transformation was applied to the frequency axis to modify spectrum:

$$F_{original} \times 2^{(i / 100)}$$

Where i = the index of the step

Figure 1 demonstrates the transformations for the spondee “sidewalk” under each of the three property conditions. The vertical striations in the figure indicate individual glottal pulses and the spacing between them is inversely proportional to the fundamental frequency f_0—these lines become closer together as pitch is increased while the vertical lines move further apart when pitch is decreased. Changing the spectrum shifts the formant frequencies or vocal-tract resonances that appear in the figure as dark horizontal patches. Increasing the spectral properties shifts these formants up and apart. Decreasing the spectral properties shifts the formants down and compresses them together.

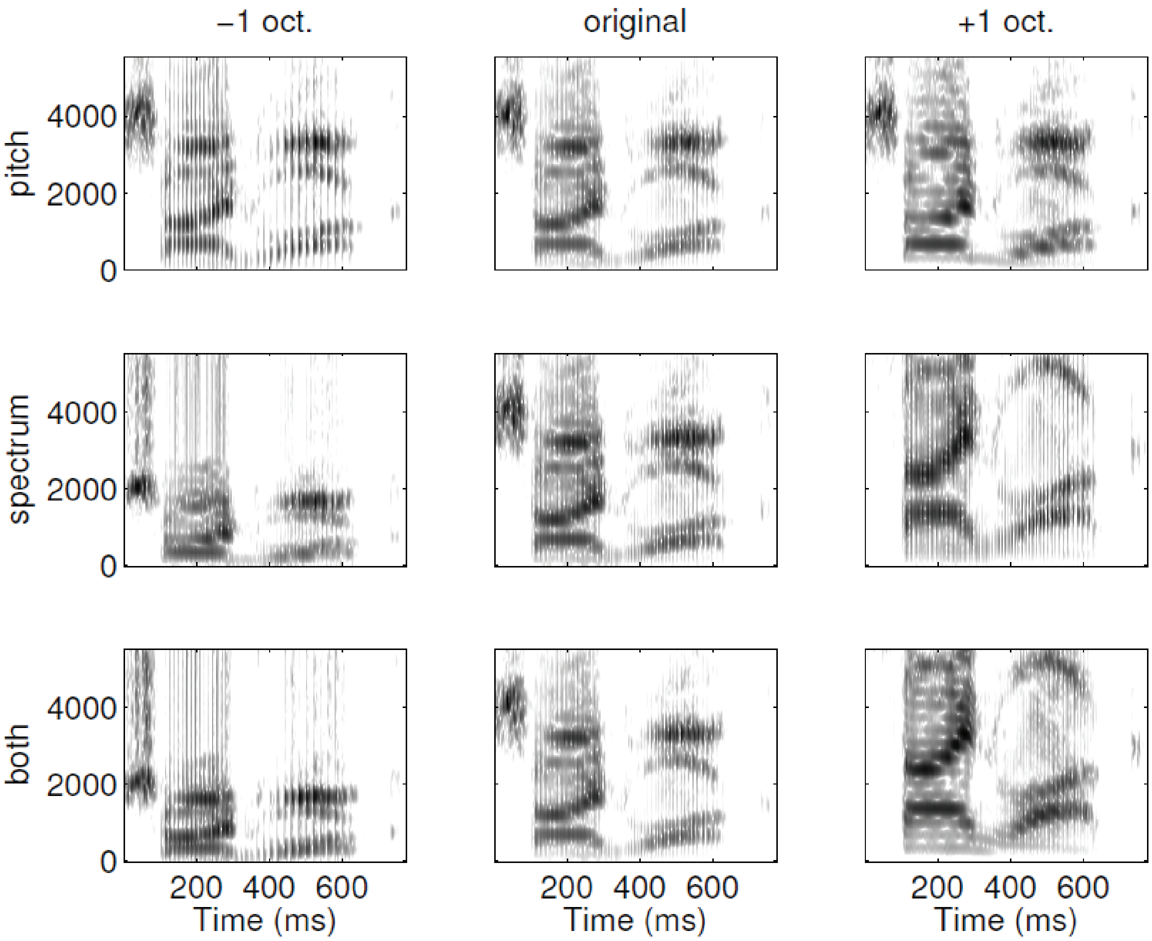

Figure 1. Spectrograms illustrating the range of transformations made for pitch and spectrum for the spondee "sidewalk". The center column is the original stimulus and is present for comparison with the right and left columns, which illustrate the most extreme transformations made.

Once transformed, a spondee was loaded as a sound file with 201 channels—one for each step. During the listening task participants rotated a knob that changed the channel output to the headphones. Although 181 steps were available (201 less the highest and lowest stimuli near the ±1 octave steps), the range of change during each trial was limited to 1.6 octaves, or 161 steps, randomly selected from the larger array. This shifted the location of the matching point from trial to trial so that it was not always in the center of the series. The starting step for each trial was randomly selected with the condition that it could not be within 20 steps of the matching stimulus. The device beeped to notify the participants when they reached the limits of the range. Audible clicks were avoided when moving from one channel to another by overlapping the two channels by 5 ms and increasing the offset of the previous channel and the onset of the new channel by a 5-ms half-Hamming window. The duration of the individual spondees ranged from 565 ms to 948 ms (M = 755 ms). The spondee was presented continuously until the participant pushed down on the knob. At this point the stimulus stopped and the response was recorded as a percentage of the original stimulus where 0% is an identical match, 100% is +1 octave and -50% is -1 octave. Due to the restriction on responses near ±1 octaves, responses could range from -46.4% to 86.6%, but were also restricted by the range selected for the given trial. Output values were then converted to octaves.

2.2.2 HINT-C Sentence Re-synthesis

Stimuli for the modified HINT-C test were created from digital recordings on compact disc. The recordings of 16 sentence lists were re-sampled to 11025 Hz and transformed using STRAIGHT. The original unaltered male recording was used as the male voice stimulus. To create a female-like voice the original f_0 was transformed by 1.9 (+0.93 octaves) and the original spectrum was transformed by 1.1 (+0.14 octaves). Figure 2 shows the spectrograms of the two voices saying the sentence, “the boy fell from the window”. The original male voice is depicted above the newly created female voice. The increased spacing of the vertical striations or “glottal pulses” for the female voice represents the increase in pitch. The increases to individual formant frequencies represent the change in spectrum.

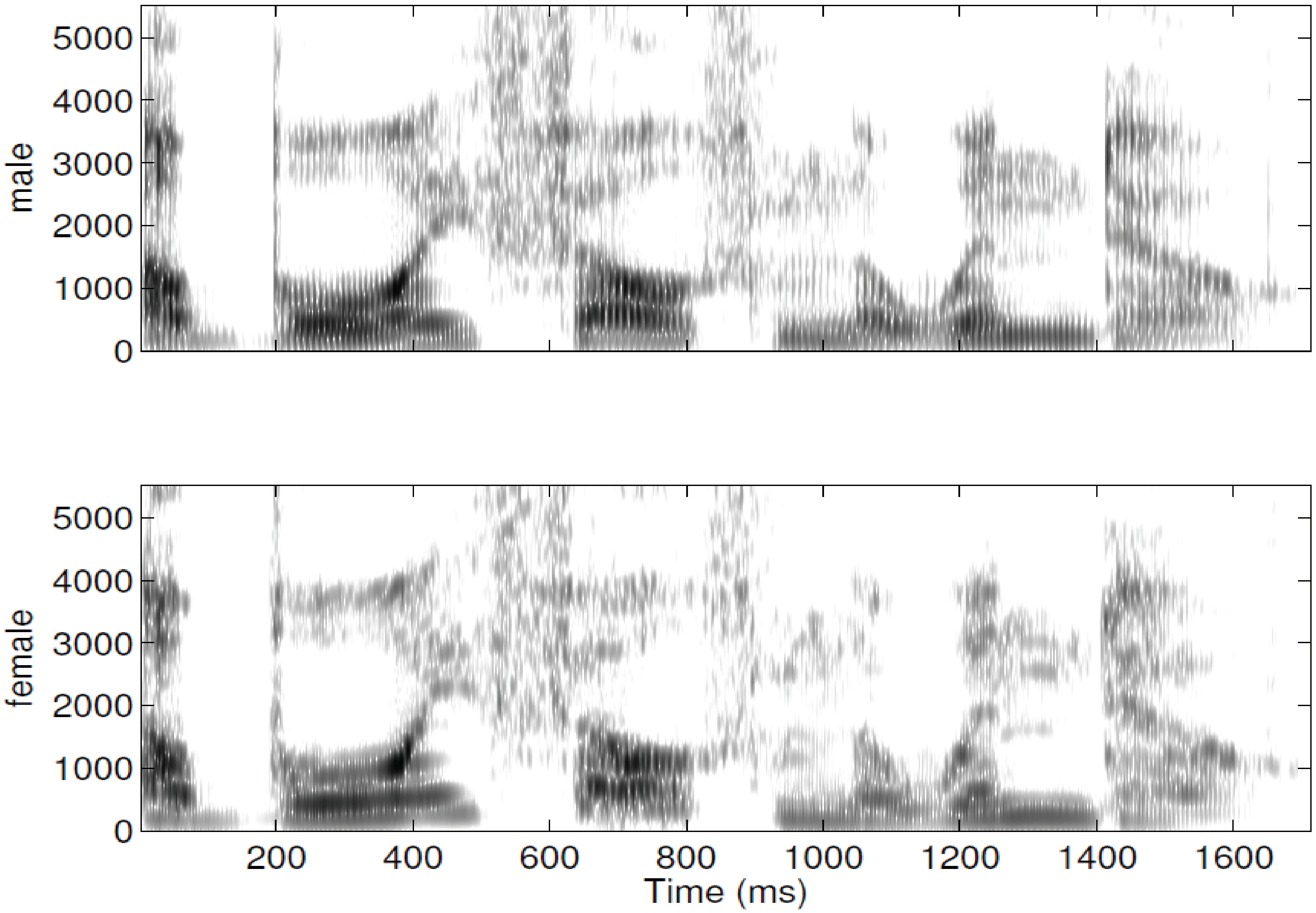

Figure 2. Spectrograms for the two voice stimuli used in the modified HINT-C task. Both voices are saying the HINT sentence, “the boy fell from the window”.

The HINT-C is typically administered with a standard background noise, which was formulated for use with the recorded male voice. We created a new background noise for this study so that the SNR scores for the male and female voices could be compared without bias caused by characteristics of the noise. The new background noise was generated by equally mixing the original recorded noise and a noise transformed from the original to match the female voice (i.e., rescaled by 110%) and matching the overall level to the original noise. This new noise was used for all of the three listening conditions: (a) male voice only, (b) female voice only, (c) both male and female voices together.

2.3 APPARATUS

We conducted all tests in a quiet room at the Nova Scotia Hearing and Speech Centres, at the School of Human Communication Disorders, or in the participant's home. The listening tasks were administered through MATLAB on a battery-powered laptop computer. A USB Audio Capture device (EDIROL by Roland UA-25EX, 24bit 96Hz, Class B digital apparatus) was connected to the laptop and provided separate left and right audio output jacks as well as a monitor jack and a volume control dial. The EDIROL was connected to the cochlear-implant devices and/or hearing aids via direct audio input. Table 2 lists the specific parts and cables used with each model of cochlear-implant processor and/or hearing aid. The left audio output jack delivered the stimulus for the monaural testing condition; for this reason, we directed the left output to the cochlear implant of bimodal participants and to the self-identified favourite or better ear of bilateral participants. During the binaural matching tasks the left audio output jack delivered the original model stimulus and the right output jack delivered the stimulus controlled by the participant. The normal-hearing group listened through supra-aural TDH-39 headphones connected to the EDIROL. The ear receiving the left output was counterbalanced so that half of the normal hearing participants listened to it with their right ear and the other half listened to it with their left ear.

Participants used a Griffin PowerMate2 USB multimedia controller to manipulate the stimulus in the matching task. This controller is a multifunction knob that can be spun in either direction or pressed down to "click" like a computer mouse. Twisting the knob to the right increased the frequency or spectral characteristics whereas twisting the knob to the left decreased them. Pushing down on the controller stopped the stimulus and reported the response.

Responses from the listening tasks were documented on the recording and scoring sheets found in appendix B. Parents/guardians of CI participants in Halifax, Nova Scotia signed a *release of medical information form* (appendix C) to allow the principal investigator to obtain demographic information from the medical files at the NSHSC. Parents/guardians of CI participants in Kingston, Ontario completed the *demographic information form* found in appendix D. The hearing screening for normal-hearing listeners was performed with a portable audiometer calibrated to ANSI standards. A Grason-Stadler, Inc. (GSI 17) audiometer was used with participants in Halifax, Nova Scotia. A Maico (MA 39) audiometer was used with participants in Kingston, Ontario.

Table 2. Audio Shoes, ear hooks, patch cords, and adapters used for direct audio input connection – listed in order from hearing instrument to EDIROL stereo phone jack.

Hearing Device	Parts Used
Cochlear Ltd. Freedom	Nucleus Freedom Personal Audio Cable, Nexxtech audio channel separation adapter, Nexxtech 3.5 mm stereo phone jack to 6.35 mm stereo phone plug adapter.
Cochlear Ltd. Nucleus 5	Nucleus 5 Freedom Accessories Adapter, Nucleus Freedom Personal Audio Cable, Nexxtech audio channel separation adapter, Nexxtech 3.5 mm stereo phone jack to 6.35 mm stereo phone plug adapter.
Advanced Bionics Harmony	Auria Direct Connect earhook, Auria 36" Direct Connect Cable, Advanced Bionics Audio Interface Cable, Nexxtech 3.5 mm stereo phone jack to 6.35 mm stereo phone plug adapter.
Advanced Bionics Platinum (body worn)	Advanced Bionics Audio Interface Cable, Nexxtech 3.5 mm stereo phone jack to 6.35 mm stereo phone plug adapter.
Phonak PowerMAXX 411	Phonak Audio Shoe 5A (for PICO / PICO-FORTE / MAXX), Phonak monaural 3.5 mm adapter-cord, Nexxtech 3.5 mm stereo phone jack to 6.35 mm stereo phone plug adapter.
Phonak Naida III SP	Phonak Audio Shoe 11 (for Naida SP). Phonak monaural 3.5 mm adapter-cord, Nexxtech 3.5 mm stereo phone jack to 6.35 mm stereo phone plug adapter.

2.4 PROCEDURE

The voice matching task was administered first, followed by the modified HINT-C task. The knob for the matching task was an interesting and novel tool for the participants and using it did not require a verbal response. Administering the matching task first allowed children who were shy about participating to become more comfortable before they were asked to repeat sentences for the HINT-C task.

2.4.1 Voice Matching Procedure

The test administrator told participants they would hear two voices repeating the same word and they were to change one of the voices, by turning the knob, until it was "exactly the same as" the other voice. An oral demonstration followed where the child's understanding of same and different was tested. The administrator repeated a spondee word in two tones-of-voice (either the same both times, or as extremely different as possible) and asked the participant if the two demonstrations were the same or different. A visual cue was also provided – the administrator held her hand at a height relative to the pitch of her voice. The demonstration was repeated twice; once where tone-of-voice was the same, and once where it was different. All participants included in this study were able to correctly identify whether tone-of-voice was the same or different.

To set the loudness of the stimulus for a CI user, the volume control on the EDIROL was set to the minimum setting and gradually increased until the child reported they could hear the stimulus at a comfortable level. To confirm that he or she was truly hearing the stimulus, the child was asked to report or imitate the stimulus being heard. Once an appropriate presentation level was determined, the volume control was kept at that point for all of the test trials. The level of the stimulus was initially set at 65 dB SPL for NH participants. The option to reduce the loudness was available if a NH child found the stimulus too loud, but all of the children were content with the initial level.

We gave the same task instructions to all three groups of participants. Detailed initial instructions were given to NH participants before the earphones were put into place. Detailed instructions were given to children in the bilateral and bimodal groups after the direct audio input connection was established and tested. When the listening condition changed the participants were reinstructed and given additional instructions specific to the new condition. In the monaural sequential condition the two talker stimuli were presented sequentially to the same ear and participants were instructed to adjust the knob until it sounded like they heard exactly the same voice every time. For the bilateral sequential condition, the talker stimuli were presented sequentially to opposite ears. Participants were instructed to adjust the knob until they heard exactly the same voice in both ears. In the bilateral simultaneous condition the talker stimuli were presented at the same time to opposite ears. Participants were instructed to adjust the knob until they heard exactly the same voice in both ears. We provided the additional clue that when the voices are a perfect match it can sound as if there is only one person talking (as opposed to a chorus of two voices). The children were told to listen carefully to the voices of the people talking.

The presentation order for the three listening conditions was counterbalanced between participants. The testing for each condition began with a practice trial in which the experimenter encouraged the child to turn the knob back and forth until the child reported they had found the matching point. The children were not explicitly guided to the "correct" response, but the task instructions were repeated if the response was incorrect. If the child reached the limits of the range the experimenter would explain the need to turn the knob in the opposite direction. The participant then independently completed nine trials. The nine trials consisted of three groups of three trials, one group for each of the three changing voice parameters: (a) frequency only, (b) spectrum only, (c) both frequency and spectrum together ("combined"). The presentation order for the three parameter types was counterbalanced between participants but within the presentation conditions. That is, all of the trials for a given presentation condition (e.g., monaural sequential) were presented in succession in order to keep the task instructions simple; at the same time, the order of presentation of the three property conditions (pitch, spectrum, or combined) within the presentation condition was counterbalanced between participants. General verbal encouragement was delivered throughout the tests but no feedback was provided regarding performance. If participants reported that they had accidentally pushed the knob before they had found the match they were permitted to repeat that trial. Participants were given as much time as they needed to complete each trial. The spondee used was randomly selected from the possible 51. The variety of 51 spondees was available to keep the task interesting while the participants completed the 27 test trials and 3 practice trials.

2.4.2 Modified HINT-C Procedure

The Hearing in Noise Test for Children (HINT-C) is commonly used by audiologists as a measure of a child's ability to hear speech. This test is normally conducted in a soundfield with loudspeakers and it may be conducted in quiet or in noise. The HINT-C is essentially the same as the regular HINT except the sentences are more child-friendly. When conducted in quiet the test is scored as a percentage of total words correct for a list presented at a constant level. The test administrator records the number of words correctly identified in each of the ten sentences and when the list is complete the percent of total words correct is calculated. When conducted in noise the test is scored to determine the signal-to-noise ratio (SNR) where the listener can correctly repeat a sentence 50% of the time. The noise stimulus is generally presented at a constant level of 65 dB HL. The initial presentation level for the speech stimulus is set to 5 dB lower than the noise and the first sentence is presented. If the listener correctly repeats the entire sentence the presentation level is decreased by 4 dB for the following sentence. If the listener makes an error the level is increased by 4 dB for the following sentence. This adaptive procedure continues until the fourth sentence after-which the presentation level is changed by increments of only ±2 dB. The presentation level for each sentence is recorded. Following the presentation of the tenth sentence, the level that would have been used for an eleventh sentence is also recorded and the presentation levels for the fifth through eleventh sentences are averaged. Subtracting the average sentence presentation level from the presentation level of the noise provides the final SNR score.

In the present study, the test was administered through DAI so the input to each ear could be controlled independently. The new stimuli described in section 2.2.2 were used for this task. The noise output was calibrated to 65 dB SPL in the headphones used for normal-hearing participants. There is no accurate way to predict the sensation level of direct-audio input to a cochlear-implant user; consequently, the DAI could not be calibrated to a constant level across participants. Instead, each CI user adjusted the volume wheel on the EDIROL until speech was presented at a comfortable level. The noise for the HINT-C was presented at this level for all conditions. The presentation level of the sentences was adjusted by selecting the appropriate SNR in the MATLAB program. The final SNR score for each list was determined by documenting the SNR for each sentence and averaging the SNR for sentences (5-11). That is, the average was taken of the final six sentences (5-10) plus the SNR that would be used for the sentence after the last one (sentence 11). This procedure is equivalent to the standard scoring method, but it made administration and scoring simple and standardized, despite the varying presentation levels for speech and noise across CI participants. Three listening conditions were tested: (a) male voice only bilaterally, (b) female voice only bilaterally, and (c) male voice in one ear with female voice in the opposite ear.

Normal-hearing listeners can easily score 100% on the HINT-C when tested in quiet. To eliminate this ceiling effect and compare performance under the three listening conditions, all NH participants were tested using the “in noise” protocol. Initially, we believed that the “in noise” protocol would be too challenging for most CI users listening through DAI and so we planned to use the “in quiet” protocol for the bilateral and bimodal groups. However, the testing in quiet proved to be too easy when several CI users reached the 100% correct ceiling. The procedure for CI users was adapted accordingly; if a score of 100% was achieved on the first sentence list, the participant graduated to the “in noise” protocol and testing began anew. This protocol was used on all but one BCI user.

Participants were instructed to listen carefully to each sentence and repeat as much of the sentence as they could. The children were told that they would hear the same sentence in both ears, even when it sounded like two different people were talking. Sentences from list 1 were used for practice; if the first sentence was not correctly repeated, then another sentence was practised. All of the participants learned the task easily and all of the CI users likely had previous experience with the HINT test. Testing began by randomly choosing a sentence list. NH participants were tested in noise. CI users completed the first sentence list in quiet. If the participant scored 100% correct, the test was restarted in noise with a new list. This occurred for seven of the eight BCI participants. The order of presentation for the three listening conditions was counterbalanced between participants. A new ten-sentence list was completed and scored for each of the three conditions.

After presenting each sentence, the experimenter paused the test and gave the child as much time as he or she needed to respond. The children were encouraged to guess and/or complete their responses. Before a sentence list was presented in noise the participant was warned that the background noise would make it difficult to hear the sentence, but that he or she should try his or her best to guess as many of the words as possible.

CHAPTER 3 – RESULTS

3.1 MATCHING TASK

The response for each trial in the matching task was originally recorded as the difference between the response and the model stimulus as a ratio between -50% and +100%, where 0% represented no difference or perfect accuracy. The range of the adjustable stimulus was limited so that the upper and lower limits were less than one octave from the model stimulus. This meant that the maximum response above the model (0%) was 0.9 octaves or 86.6%. At the opposite extreme, the maximum response below the model was -0.9 octaves or -46.4%. This imbalance between upper and lower limits would make interpretation of mean scores difficult. To make the data more suitable for analysis, each response was converted from a percentage to a number of octaves using the formula:

$$\text{Octaves} = \log_2 (\text{Percent score} / 100 + 1)$$

Each participant completed three trials for each of the nine conditions in the matching task. The root mean square (RMS) value was calculated for each condition for all individuals. This generated a single RMS score for each condition completed by a participant. The RMS score for a condition represented the average error from the three trials, where the model stimulus was the correct or expected response. The score acted as a measure of sensitivity to stimulus differences. The RMS scores were used for all analyses of the matching task results. The means and standard deviations for the RMS scores are reported by group in Table 3. As expected, the NH listeners had lower (better) scores for all conditions compared to the BCI group. The bimodal group also scored worse than the normal-hearing group on most conditions (except monaural sequential pitch), but the small sample size prevents any statistical comparison of the means. There is no clear pattern of performance differences between the bimodal and BCI groups; the BCI group performed slightly better on 5 of the 9 conditions, but the standard deviations show large overlap in all scores.

Table 3. Mean scores (octaves) and standard deviations for matching task conditions by group.

		Mean			Standard Deviation		
		NH	BCI	Bimodal	NH	BCI	Bimodal
Monaural Sequential	Pitch	.275	.466	.180	.128	.127	.167
	Spectrum	.118	.257	.388	.093	.198	.392
	Combined	.103	.211	.524	.106	.165	.073
Binaural Sequential	Pitch	.287	.305	.508	.191	.145	.123
	Spectrum	.085	.282	.448	.058	.157	.234
	Combined	.117	.354	.207	.125	.223	.088
Binaural Simultaneous	Pitch	.297	.400	.396	.203	.174	.149
	Spectrum	.265	.479	.536	.117	.074	.182
	Combined	.147	.450	.413	.169	.178	.131

N = 17 for NH, N = 8 for BCI, N = 2 for bimodal.

3.1.1 Mixed Model ANOVA for Matching Task

A mixed-effects repeated-measures ANOVA for the matching task was performed in SPSS. Because there were only two bimodal participants, only BCI and NH groups were compared in the ANOVA. An alpha level of .05 was used for all statistical tests. Mauchly's test of sphericity indicated that the assumption of normal distribution of errors was not significantly violated for the main effect of property (i.e., pitch, spectrum, or combined), but that this assumption was violated for the main effect of presentation χ^2 (2) = 8.060, $p < .05$, and the presentation x property interaction, χ^2 (9) = 21.295, $p < .05$. The degrees of freedom for these comparisons were corrected using Greenhouse-Geisser estimates ($\varepsilon = 0.765$ for property, $\varepsilon = 0.673$ for the interaction). The repeated-measures results are presented in Table 4. As expected, NH listeners performed generally better than BCI users. The between-subjects effect for hearing was significant, F (1, 23) = 263.925, p = .000, η^2 = .920. There were significant main effects for both presentation, F (2, 46) = 9.264, p = .001, η^2 = .287 and property, F (2, 46) = 16.882, p = .000, η^2 = .423. There were also significant effects for the two-way interaction between property and hearing status, F (2, 46) = 4.170, p = .022, η^2 = .153, as well as a two-way interaction between presentation and property, F (4, 92) = 5.123, p = .004, η^2 = .182. These interactions are illustrated in Figure 3. The interaction between presentation and hearing was not significant. The three-way interaction between presentation, property, and hearing did not reach significance, but it was marginally significant, F (4, 92) = 2.514, p = .073, η^2 = .099. This interaction, though not significant, is illustrated in Figure 4.

Post-hoc, pairwise comparisons with a Bonferroni correction for three-tests ($\alpha = .05$) indicated that the main effect for presentation was due to the mean scores from the binaural simultaneous condition being significantly different (worse) than the monaural sequential (Mean Difference = .101) and binaural sequential (Mean Difference = .101) presentation conditions. There was no significant difference between the means for the two sequential presentation conditions. Despite performance on the simultaneous condition being generally worse than the other two presentation conditions, three normal-hearing participants obtained perfect scores (0) for the binaural simultaneous combined condition. Obtaining a perfect score requires matching the target exactly during all three trials of that condition. No other perfect scores were obtained on the matching task, but 30 additional perfect matches were attained across individual trials and listening conditions. Notably, 10 of these matches were achieved in the binaural simultaneous pitch condition.

The main effect for property was due to significant differences between the mean scores for pitch and the other two property conditions, spectrum (Mean Difference = .091, $p < 0.05$) and combined (Mean Difference = .108, $p < 0.01$). There was no significant difference between the mean scores for the spectrum and combined conditions. Theoretically, performance on the combined condition could not be worse than performance for either pitch or spectrum alone. The absence of a significant difference between the spectrum and combined conditions indicates that performance on the combined condition is largely due to perception of spectrum.

Table 4. ANOVA results for the voice matching task.

Source of Variance	df	F	η^2	p
Between-Subjects Effects				
Intercept	1	263.925	.920	.000
Hearing	1	25.134	.522	.000
Error	23			
Within-Subjects Effects				
Presentation	2	9.264	.287	.001
Presentation by Hearing	2	.775	.033	.437
Error	46	-	-	-
Property	2	16.882	.423	.000
Property by Hearing	2	4.170	.153	.022
Error	46	-	-	-
Presentation by Property	4	5.123	.182	.004
Presentation by Property by Hearing	4	2.514	.099	.073
Error	92	-	-	-

Note: The p-values shown are the corrected values using the Greenhouse-Geisser estimate of sphericity. When sphericity is assumed p = .047 for the three way interaction presentation by property by hearing.

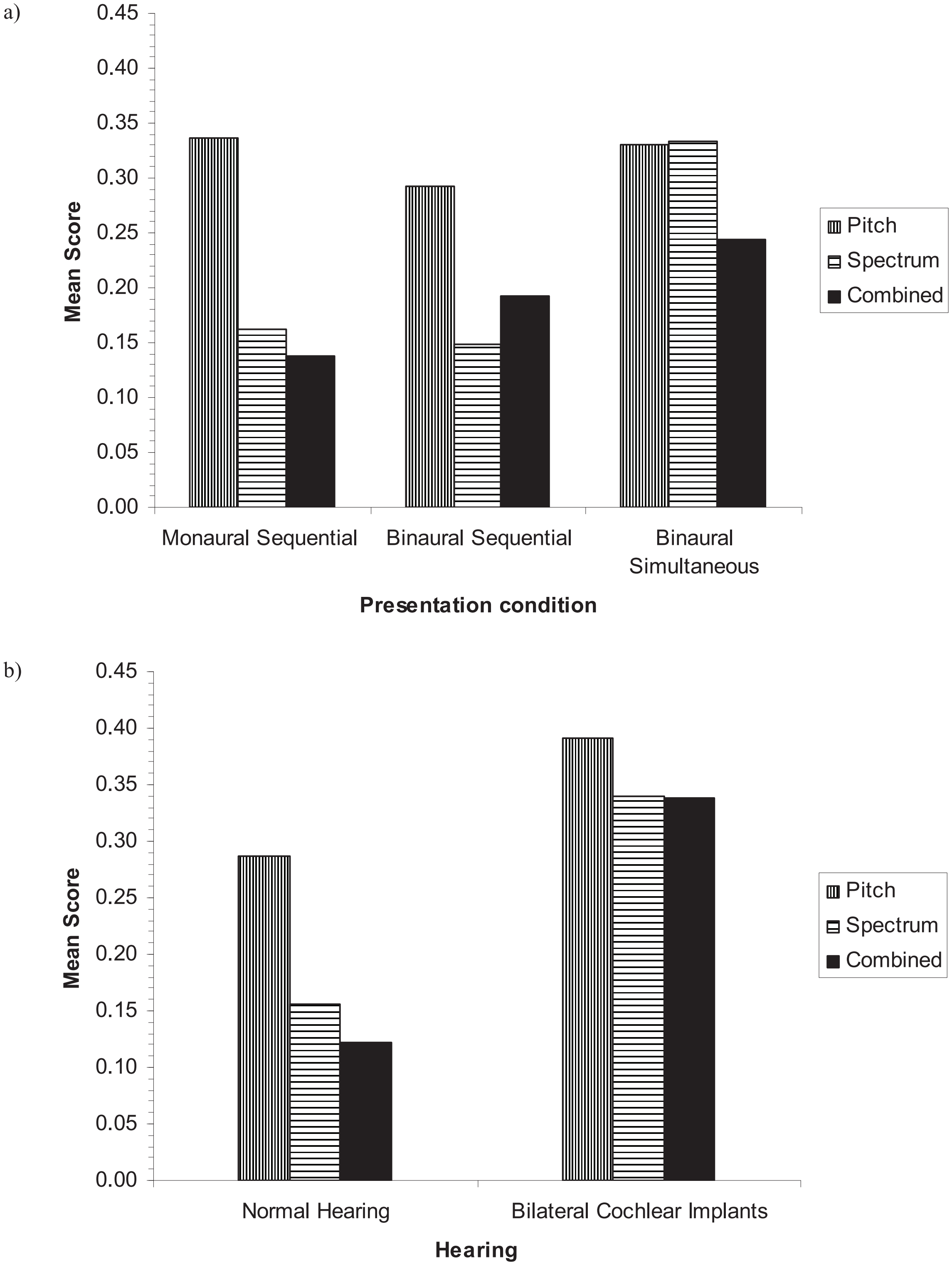

Figure 3. Significant interaction effects from the matching task: a) Presentation by property, b) property by hearing.

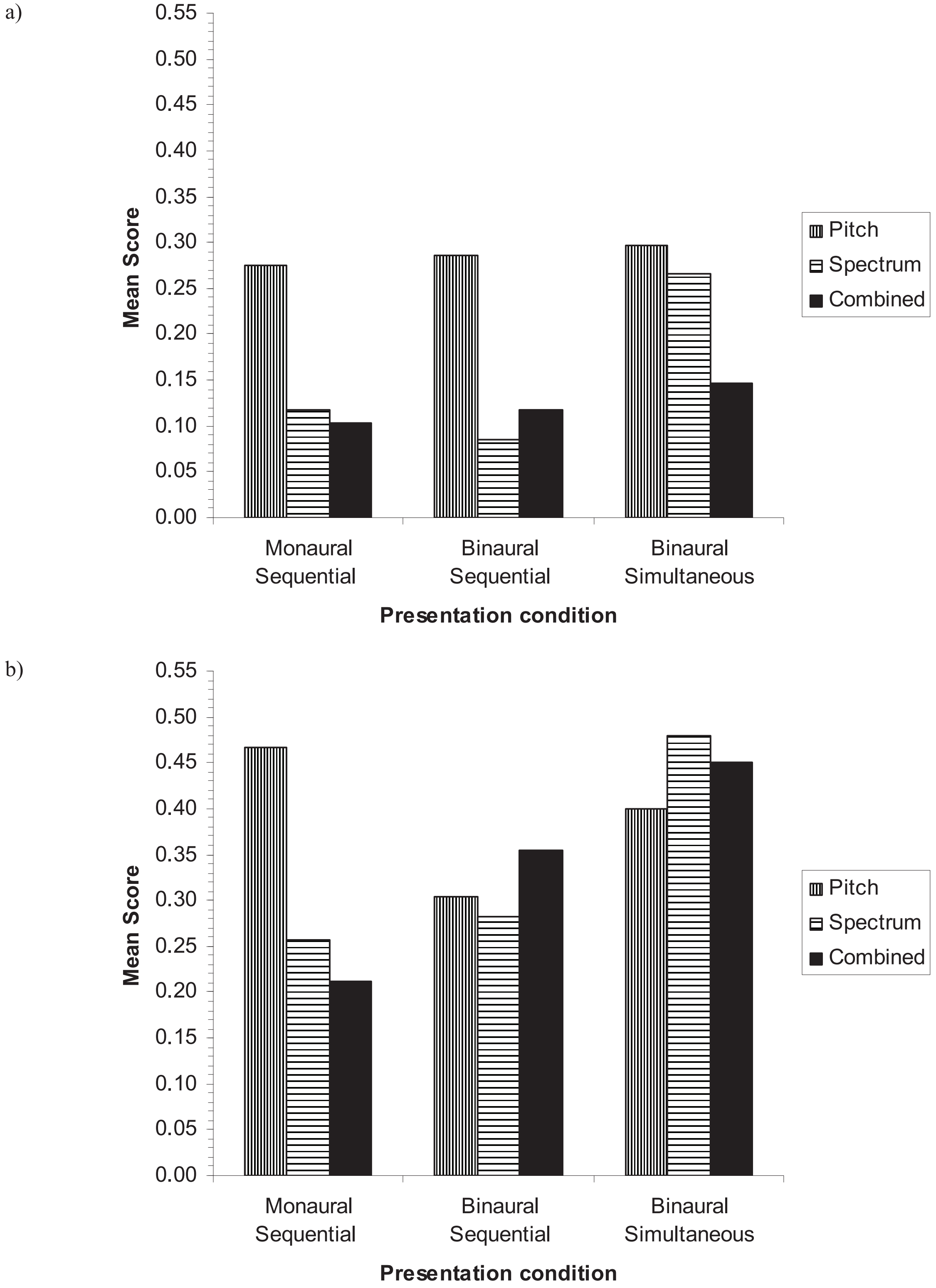

Figure 4. Non-significant three-way interaction for presentation by property by hearing: a) Interaction for normal-hearing participants, b) interaction for BCI participants.

3.1.2 Correlation Analyses with Demographic Variables

Nonparametric correlation analyses (Spearman, two-tailed) were performed between the scores for each of the nine listening conditions and age, length of CI experience, length of BCI experience, and implant delay for BCI participants. There was a significant correlation for the BCI participants between the length of experience with the first CI and performance on the binaural sequential combined listening condition ($r = -.743$, $p < 0.05$). The length of experience with the first CI was also significantly correlated with the delay between the two implantations ($r = .862$, $p < 0.01$). None of the other demographic variables were significantly correlated with each other or with performance on the nine listening conditions.

Nonparametric correlation analyses (Spearman, two-tailed) were also conducted between the scores for each of the nine listening conditions and age for NH participants. Age was negatively correlated with the scores for the monaural sequential pitch ($r = -.764$, $p < 0.01$) and monaural sequential combined ($r = -.766$, $p < 0.01$) conditions indicating that performance on these two conditions was generally better for older NH participants.

3.1.3 Comparison of Individual Results with Predicted Chance Performance

An individual with good performance on the matching task is expected to have lower scores and less deviation between scores than someone performing poorly or someone providing random responses. If a participant was unable to do the task, for the simple reason that all stimuli sound equally close to the model target, there are a couple of ways he or she could respond. First, the participant could push the button without ever turning the knob. With this response pattern, the participant would never score within 20 steps or 0.2 octaves of the target but would otherwise vary randomly along with the assigned starting points for the stimulus with a flat distribution—this is the distribution imposed by the presentation software for the stimulus starting points. In other words, the middle 41 steps (±0.2 octaves) would have zero probability of being selected while the probability of selecting any one of the other steps was equal. The second possible pattern is to select a response after moving the knob in a completely random manner. At the extreme, all responses are then equally likely. To summarize individual performance on the matching task, we calculated the RMS of each participant's original 27 responses (in octaves). This provided an RMS_{total} for each participant. We then calculated the RMS_{total} that would be expected for each of the two random responding patterns. The RMS_{total} expected by chance with the subject turning the knob in a completely random manner is .466. If the knob is never turned, the expected $\mathrm{RMS}_{\mathrm{total}}$ is .532. All of the participants in this study had $\mathrm{RMS}_{\mathrm{total}}$ that were less than .466 suggesting that at least a large proportion of the responses were not random. However, the $\mathrm{RMS}_{\mathrm{total}}$ for BCI users (Mean = .395, SD = 0.064) were notably higher than those for NH listeners (Mean = .234, SD = .083). These results show that participants were all responding better than what is expected for a set of random responses.

One way to decidedly show that a participant is not responding randomly is to compare the lower bound of the 95% confidence-interval for the expected $\mathrm{RMS}_{\mathrm{total}}$ of a set of random responses to the individual's $\mathrm{RMS}_{\mathrm{total}}$. For this study, if a participant's $\mathrm{RMS}_{\mathrm{total}}$ is under .360 we can say with 95% certainty that he or she was not responding randomly. Only one participant in the BCI group had an $\mathrm{RMS}_{\mathrm{total}}$ less than .360. This participant was the star performer in the group and his/her performance is discussed in section 3.1.4. In contrast to the BCI group, all but one NH listener had an $\mathrm{RMS}_{\mathrm{total}}$ less than 0.360. This participant performed particularly poorly and had the worst scores in the group for five of the nine listening conditions.

3.1.4 A Star Performance

The star performer for the BCI group had an $\mathrm{RMS}_{\mathrm{total}}$ of 0.254. This participant scored better than the mean score for the normal-hearing group on all sequential presentations (both monaural and binaural) of the spectrum and combined conditions. The participant also scored better than the mean for NH participants on the binaural simultaneous pitch condition and only slightly worse (< 0.002 difference) than the NH mean on the monaural sequential pitch condition. This child was the oldest of the BCI participants. He was implanted with his first CI before he was two years of age; consequently, he also had the most CI experience in the group. This child had less than two years of experience with his second CI and had the longest delay between implants in the group by 4 years and 2 months.

3.2 MODIFIED HEARING IN NOISE TEST FOR CHILDREN (HINT-C)

The mean signal-to-noise ratio scores and standard deviations for the HINT task are reported for the NH and BCI groups in Table 5. As expected, the NH participants had better scores (lower SNR) for all conditions of the HINT when compared to BCI participants. The two bimodal participants were both tested in quiet and using the percent-of-words-correct protocol. Their mean scores were as follows: a) HINT-male (M = 49.12%, SD = 6.91), b) HINT-female (M = 38.08%, SD = 2.18), c) HINT-dichotic (M = 58.15%, SD = 4.60). One bilateral participant was also tested in quiet. This individual scored 37.7%, 56.1%, and 38% for the HINT-male, HINT-female, and HINT-dichotic conditions, respectively.

The top BCI performer on the matching task also had the best score on the HINT-dichotic condition for his group. He was surpassed by other BCI users for the HINT-male and HINT-female conditions but he was fairly consistent across conditions with SNR scores of 3.0, 3.57, and 3.29 for the HINT-male, HINT-female, and HINT-dichotic conditions, respectively. These scores are better than the means for the BCI group, but notably worse than the means for the NH group. When the mean of the three HINT scores was calculated, this child had the second best mean HINT score in the BCI group. The best mean HINT score in the BCI group was better than two of the mean HINT scores in the NH group. The child with the best mean HINT score in the BCI group had an RMS_{total} of .415 in the matching task. This combination of low HINT scores with large deviations in the matching task responses is incongruous with the strong positive correlation (spearman, two-tailed) between mean HINT score and RMS_{total} ($r = .772$, $p < .01$).

The worst NH performer on the matching task did not have the worst score for any of the individual HINT conditions, but all scores were above (i.e., worse than) the mean for the group. The child with the worst mean HINT score in the NH group had the third highest RMS_{total} for that group and was the second youngest child tested.

Table 5. Mean signal-to-noise ratio scores for HINT-C task conditions by group.

	Mean		Standard Deviation	
	NH	BCI	NH	BCI
HINT – Male	.697	6.755	1.698	4.274
HINT – Female	.815	4.878	3.066	2.695
HINT – Dichotic	-.109	8.020	2.462	5.008

N = 17 for NH, N=7 for BCI.

3.2.1 Mixed Model ANOVA for the Modified HINT-C Task

A repeated measures ANOVA was performed on the HINT data. Mauchly's test indicated that the assumption of sphericity was not significantly violated, but no main effect was found for HINT condition. As with the matching task, the normal-hearing group performed better than the BCI group on the HINT-C task. The between-subjects effect of Hearing was significant, F (1, 22) = 30.580, $p < .01$, $\eta^2 = .582$. There was a significant interaction effect between Hint score and Hearing, F (2, 44) = 4.487, $p < .05$, $\eta^2 = .169$. Figure 5 demonstrates this interaction. The normal-hearing subjects performed best (lowest SNR) in the HINT-Dichotic condition, with performance on the HINT-male and HINT-female being nearly equivalent. There is more variability between the HINT conditions for the BCI users. They performed the worst on the HINT-dichotic condition and the best on the HINT-female condition.

3.2.2 Paired Sample t-test and Correlation Analyses for the Modified HINT-C Task

Paired sample t-tests within the bilateral cochlear-implant and normal-hearing groups indicated no significant difference between scores on the three versions of the HINT. This was likely the case because Bonferroni correction is considered very conservative. However, because this was a between-subjects design, no other post-hoc tests are valid. The mean of the three scores was calculated for each individual to provide a mean HINT score. Mean HINT performance was negatively correlated with age for the normal-hearing subjects ($r = -.789$, $p < .01$). For BCI users, however, mean HINT had no significant correlation with age, experience with the first CI, experience with bilateral CIs, or the delay between implant activations.

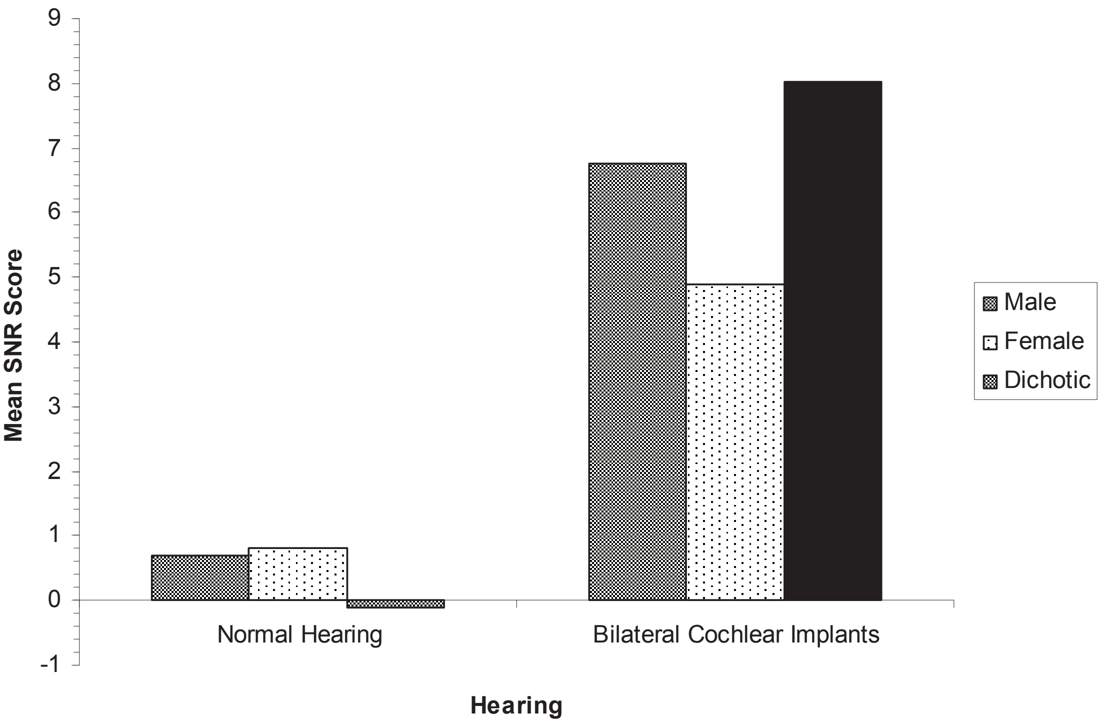

Figure 5. Statistically significant interaction effect for HINT condition by hearing.

CHAPTER 4 - DISCUSSION

The results of this study provide some evidence that BCI users may be able to integrate binaural signals in a manner similar to NH users. However, the results are complicated and perhaps difficult to interpret. Two different tasks were used in this study: A newly designed matching task and a modified version of the HINT-C. We expected that NH users would have better mean performance on the tasks and this was true. However, there was some overlap between the two groups and one BCI user even achieved scores comparable to the mean scores of NH listeners on several matching task conditions.

4.1 Matching Pitch and Spectrum

The matching task involved nine conditions and we compared the performance of BCI users and NH listeners using a repeated-measures ANOVA. The bimodal group was too small (n = 2) to compare with the other groups statistically. In general, the bimodal CI users performed worse than NH participants and similar to the BCI participants. The between-subjects effect for hearing status (NH versus BCI) was statistically significant. The NH listeners performed better than BCI users on all matching task conditions. We expected this outcome for all conditions except for the binaural simultaneous spectrum condition where we predicted NH listeners would not be able to segregate the signals in the two ears and would therefore not be able to perform the task with a high-degree of accuracy.

We expected to see different results between the pitch and spectrum property conditions because they are fundamentally different perceptual tasks. The normal auditory system detects these properties with different types of coding (temporal coding versus place coding) and cochlear implants mimic this approach; spectrum is represented by the pattern or place of electrode stimulation while pitch is represented in the rapid modulations of the biphasic pulse train (Rubinstein, 2004). There was indeed a significant main effect for property and the pairwise comparison indicated that pitch results were significantly worse than the other two property conditions. The results from the sequential presentation conditions indicate that the spectrum matching task was easier than pitch matching for both groups—i.e., lower (better) scores were attained for spectrum in both groups. However, these results should not be interpreted as an indication of the relative importance of pitch and spectrum cues for identifying or matching real voices because the stimuli used in this study do not represent natural-sounding speech. Specifically, the transformation used for spectrum created a range of stimuli that extended well beyond the natural range for human voices. Therefore, the spectrum task was easier, not because spectrum is more perceptually salient than pitch, but because the stimulus set used for the spectrum task contained a smaller range of responses (number of steps) about the matching point that could have seemed like reasonable responses.

The two-way interaction between property and presentation suggests possible binaural integration for both groups. The pattern by which spectrum matching scores change between the presentation conditions is of particular interest. While the mean scores for sequential presentations, either monaural or binaural, are very similar, there is a marked decrease in performance for the binaural simultaneous condition. Since no post-hoc statistics could be conducted on the two-way interaction, we must try to infer whether the pattern observed for spectrum matching across presentation conditions was significant. If we look at Figure 3a, it is obvious that the largest change in performance within a property condition (i.e., pitch, spectrum, or combined), occurred between the binaural sequential presentation and the binaural simultaneous presentation of spectrum. The main effect for presentation was due to significant differences between the simultaneous condition and each of the sequential conditions, as indicated by post-hoc Bonferroni comparisons. From these two results, we can infer that the difference in mean score for spectrum matching between the binaural sequential and binaural simultaneous conditions is significant. This is what we expected to observe for NH listeners.

We believed that NH listeners would always integrate spectrum information presented simultaneously to the two ears – even when the spectrum in opposite ears was very different. As long as pitch was equal in the two ears, the listener would only perceive one talker or source and this would make comparison of the two signals extremely difficult. This is consistent with research by Cutting (1976) who found that listeners almost always heard only one sound when the f_0 of dichotically presented syllable formants were equal. However, the same listeners identified two sounds when the difference in f_0 of the two syllables was as little as 2Hz (Bregman, 1990, p. 565; Cutting, 1976). We did not venture to predict that the same pattern would occur for BCI users because we were unsure how well they could match spectrum or if they could integrate pitch and spectrum cues presented binaurally. The pattern we expected for NH listeners occurred across both groups in the study is illustrated in Figure 3a of the significant two-way interaction for property and presentation. The three-way interaction was not statistically significant. This may suggest that both groups responded with the same pattern across property and condition, or it may be the consequence of a small sample size. Nevertheless, the two-way interaction seems to represent the pattern of responses for both groups. Figure 4 clearly shows that the same pattern of responding between presentation conditions for spectrum occurred in both groups. The fact that this pattern exists suggests perceptual integration across the ears for both NH and BCI listeners. We can conclude that both NH listeners and BCI users exhibited evidence for integrating the spectrum stimuli when it was presented dichotically. This is owing to the difficulty both groups experienced when listening to simultaneous dichotic stimuli.

Although the NH listeners showed the expected pattern for the spectrum condition, they also demonstrated a capacity to match the binaural simultaneous spectrum stimuli that was unexpected. A possible explanation is that the children attempted to match the single voice they heard in that condition – which was a fusion of the signals to both ears – to the standard male voice used as the model for all conditions. Since the model stimulus was always the original recorded voice it is possible that some of the children tried to find that voice when matching spectrum in the simultaneous condition. If this was the case, then they were repeating the binaural sequential condition but comparing the stimulus heard to the percept in their memory. Along the same line, the listeners may have simply realized that if the voice sounded too strange or unnatural it was probably not the correct answer.

The significant two-way interaction between property and hearing (Figure 3b) indicates that BCI users responded in a different pattern across properties than NH listeners. Both groups showed better performance for spectrum than for pitch. Again, this means that the spectrum task was easier, not that spectrum cues are more perceptually salient. Nevertheless, we expected performance on the combined condition (where both pitch and spectrum were manipulated) to be at least as good as performance on the better of the two individual property conditions. This proved to be true, but it manifested itself slightly differently for each group. BCI participants had nearly the same mean score for the combined condition as for spectrum (across all presentation conditions). This suggests that, for BCI users, spectrum was the primary cue used in the combined condition and the presence of pitch information was of no added benefit. The NH group showed a different pattern. Their mean score for the combined condition, across presentation conditions, was better than either of the mean scores for pitch and spectrum. This indicates that, for NH listeners, the presence of pitch and spectrum cues in the combined condition had an additive effect for stimulus-matching performance. Why the BCI users did not benefit additionally from the presence of pitch information in the combined condition cannot be determined exactly. However, their sensitivity for pitch cues was likely too poor to provide useful information.

In general, the pattern of scores across presentation conditions for pitch was not as expected. We expected that normal-hearing listeners would show a marked improvement in the binaural simultaneous condition compared to the two sequential conditions. We were unsure how the BCI users would perform in the simultaneous condition, but we predicted they would perform the best in the monaural sequential condition. Neither of these expectations was met.

Normal-hearing listeners performed consistently well across presentation conditions for pitch matching. This is illustrated in Figure 4a of the non-significant three-way interaction. We had predicted that an improvement in mean scores for pitch matching would occur for the binaural simultaneous condition because the listeners could use the fusion of two voices into one (caused by integration of the signals when pitch was equal) as a definitive cue for a perfect stimulus match. The absence of any improvement in mean score for the binaural simultaneous condition therefore suggests that either, a) the NH listeners did not gain any benefit from the integration of pitch in the simultaneous condition, b) the task was not sensitive enough to measure the benefit gained, c) they always integrated binaural pitch, whether or not it was the same, or d) the NH listeners did not integrate pitch binaurally. I believe the absence of noticeable improvement in the simultaneous condition was possibly related to the instructions given for the task, which may have affected the ability of the test to detect the advantages of binaural pitch integration. Specifically, the fused percept that was supposed to be the primary cue for the task was never explicitly demonstrated. The instructions included a statement that the (binaural simultaneous pitch) stimulus would sound like two different people talking at the same time, until the point where pitch was exactly the same in both ears. We told participants that they would hear one clear-sounding voice, originating from a central location, when the match was found. Despite the best attempt to describe a perfect match, the lack of an unambiguous demonstration was probably met with a lack of comprehension by the child participants.

Consequently, I do not think the pattern observed across presentation conditions accurately rejects the potential for NH listeners to integrate identical signals at the two ears and to use the fused percept as a cue for binaural listening. Anecdotally, children who were able to find the exact matching point in the binaural simultaneous pitch or combined conditions were often able to repeat the task with equal accuracy. This type of behaviour was evident in the three children who obtained three perfect trials, or a perfect score, for the combined binaural simultaneous condition. A grand total of 39 perfect matches were found by all participants in this study across all of the conditions; of these, 12 were for trials in the binaural simultaneous combined condition, and 10 were for trials in the binaural simultaneous pitch condition. In contrast, only one perfect match was found for pitch in the binaural sequential condition and only two perfect matches were found in the monaural sequential condition. This shows that, although the average performance for matching pitch in the bilateral simultaneous condition was not great, individual trials were more likely to be perfect in this condition than for any sequential condition presentation of pitch. This makes it seem likely that the NH children could have shown the expected improvement on the binaural simultaneous condition if they had been given an example of the exact matching point. However, we deliberately did not provide an example of the matching point in this study because we did not know if that would be the true matching point for BCI users, and we did not want to influence their responses by providing a confusing example. We did not provide any additional examples or instructions to NH listeners because they were a control group. In future studies it would be interesting to see how the children in both groups could perform on the binaural simultaneous conditions following a demonstration of the perfect match.

Despite the issues with the pitch-only stimulus set, results from the binaural simultaneous combined condition (Figure 4a) provide evidence of pitch integration by NH users. The mean score for the stimulus in which both pitch and spectrum varied together (i.e., combined) is much better than that observed for spectrum in the same presentation condition. If we consider that the scores for the sequential presentations of this stimulus set were determined by sensitivity to spectrum we would expect the mean score in the simultaneous condition to increase along with spectrum. Instead, the mean score for the binaural simultaneous combined condition remained very good. Therefore, the NH listeners must be using pitch information because it was the only other cue available. It is possible that the mean score from the binaural simultaneous combined condition is a better representation of the improved pitch matching we expected to see in the pitch-only condition. Perhaps, the spectrum cues in the stimulus were a useful aid to help some participants figure out the task. Although binaurally presented spectrum provides only weak cues for when the two signals are identical, it does affect the quality of the voice heard. If the voice sounded unnatural, a listener would be more likely to continue searching for the exact matching point and would then have a better chance of happening across the fused percept and figuring out the trick to the task.

The pattern of responses across presentation conditions was not as expected for BCI users. Rather than showing the best performance in the monaural sequential condition, they showed the best performance in the binaural sequential condition and the worst performance in the monaural sequential condition. The mean score for BCI users in the binaural sequential pitch condition was only 0.018 octaves worse (higher) than the mean score for NH participants in the same condition. In other words, BCI users could seemingly match voices differing only in pitch nearly as well as NH children when the voices were presented sequentially to opposite ears. Mean performance on the monaural sequential pitch condition was 0.161 octaves worse than the binaural sequential condition. We cannot determine with the analyses used in this study if this difference is significant. However, since neither the two-way interaction between hearing and presentation nor the three-way interaction between hearing, presentation, and property were significant, it is possible that the three pitch conditions for BCI users are not significantly different from each other. It is difficult to explain why the monaural sequential condition could be worse than the binaural sequential condition for BCI users. One possible explanation is random, non-statistically significant error resulting from the small sample size of the BCI group. A few observations support this notion: Firstly, this was the only condition where the two groups had mean scores that were close to overlapping – which makes it an anomaly. Secondly, the best and most consistent performer in the BCI group did not exhibit this pattern. Thirdly, we have no reason to believe BCI users are as good at pitch matching as NH listeners. Current CI processors provide some pitch information in envelope modulations of the pulse-train, but temporal fine structure is not represented (Rubinstein, 2004). Sensitivity to modulation frequency determines the CI user's access to periodicity cues and it may be quite poor (Fu et al., 2005). While normal-like pitch matching abilities by BCI users would be a welcome surprise, the discordance with the monaural condition, is disconcerting. In the monaural condition, factors such as speech processing strategy, mapping, and/or placement of the internal electrode array are controlled for between presentations of the model and manipulated stimulus. Although it is possible that these factors do not inhibit pitch matching as we expected, we still do not expect matching stimuli presented to two different devices to be any easier than hearing the stimuli through exactly the same device. This is why we expected performance on the binaural sequential pitch condition to be no better than performance on the monaural sequential pitch condition. There are, however, a couple of reasons why the monaural task could have been unexpectedly challenging.

One explanation for the monaural task being unexpectedly difficult for BCI users is that it was tricky to follow the manipulations being made with the knob. The stimuli were presented continuously to the better ear, altering constantly between the model voice and the manipulated voice. As the voices became more alike, it became easier to lose track of which voice the knob movements were affecting. Although, this would not change the fact that the voices sounded different, it could make the task more confusing because the listener would lose track of which way they needed to turn the knob to increase the similarity of the voices. The difficulty of the task could have led the participants to be less diligent in finding the exact match. However, if this was true, we would expect a similar behaviour to appear in the control group – this did not occur. It is also possible that the BCI users were grouping the two stimuli as one whole utterance, rather than two different repetitions of the same word by different talkers. This would make any pair of stimuli sound like the same pattern repeated over and over. However, the task instructions for the monaural condition clearly stated how the stimuli would be presented and an imitation was provided by the test administrator; consequently, it is unlikely that the BCI group would exhibit an unusual pattern of grouping not observed in the control group.

In summary, it is most likely that the differences in pitch matching scores across presentation conditions for BCI users are not really significant. To make this conclusion we sacrifice the prospect that BCI users were superb at matching binaural pitch cues, but we propose that the pattern of responding across conditions by BCI users is normal-like and that matching across two ears is not as problematic as previously thought. This study did not make any attempt to monitor or record the activity of the cochlear-implant devices, nor did we seek to learn whether there were any mismatches in electrode array placement; therefore, we cannot determine if stimulation at the two ears was mismatched. Whether or not such mismatches were present, they did not seem to inhibit BCI performance on binaural tasks. This idea contradicts studies such as those by Blanks et al. (2008) and Long et al. (2003) who found that deliberately imposed bilateral mismatches inhibited binaural hearing functions such as the detection of interaural time differences.

For the binaural simultaneous condition, there was a large improvement for NH listeners from the spectrum to the combined stimulus set. We have already attributed this to the use of pitch information within the combined stimulus set. For BCI users, a similar improvement is present, but too small to be significant (0.029 octaves). The small difference between the binaural simultaneous pitch and binaural simultaneous combined conditions (0.05 octaves) prevents us from ruling out that pitch information was used in the binaural simultaneous combined condition. The non-significance of the three-way interaction may lend support to the notion that BCI users may be able to integrate pitch information, as NH listeners did, for the combined stimulus. However, a larger sample size is required before a three-way interaction can be ruled out, especially since marginal significance was observed.

4.2 A Note about the Matching Task Procedure

We chose the matching task procedure as a way to limit the testing time required for multiple comparisons and make the task interactive and engaging for the participants. The alternative was an adaptive-staircase procedure – a staple for psychoacoustic research. For example, Cleary et al., (2005) used an adaptive staircase method to test talker discrimination in children with unilateral cochlear implants. They used a 13-point continuum with half-semitone (0.042 octaves) increments. In contrast, our procedure allowed for greater precision and range; we used a 161 step continuum which varied in 0.01 octave increments. Whereas their procedure took a fixed amount of time for each condition, the time required for the matching task trials in this study was highly variable. The test was quick when a participant developed an efficient strategy for finding the match, but it could take a long time if the match was difficult to perceive (as in the binaural simultaneous spectrum condition) or if the child did not develop an efficient strategy. In my opinion, the matching procedure used in this study has the potential to be a highly efficient way to test adult subjects or older children. An adaptive staircase method, however, may be just as efficient for young children and/or subjects that need more guidance on developing a strategy for comparing stimuli.

4.3 Demographic Variables and Matching Task Performance

Correlation analyses between the scores of the nine listening conditions and four of the demographic variables did not reveal many significant correlations. A larger sample size is necessary to observe such relationships and make any legitimate conclusions. Age was correlated with performance on two of the nine listening conditions for NH participants. This is not surprising as many auditory functions show improvements with age during childhood.

It is intriguing that the BCI user with the longest implant delay (9 years and 8 months) also had the best overall performance within his/her group. This occurrence may be inconsistent with the many studies that indicate that early and simultaneous implantation is preferable for the development of binaural listening skills (Galvin et al., 2008; Gordon & Papsin, 2009; Scherf et al., 2007), but it requires further investigation because these studies refer mostly to children with congenital hearing loss. This child's demographic information was obtained by parent report; consequently, it was both limited in scope (see appendix D) and unverifiable. The cause of deafness was attributed to ototoxicity and the hearing loss was diagnosed at "13 months corrected" age, as identified by the mother. It would have been interesting to further investigate this child's hearing history, but that information was not available for this study. It is unclear how much auditory stimulation the child had before the hearing impairment was diagnosed, but previous experience with acoustic stimulation may explain why the long delay between implants was not as detrimental to binaural listening as expected. This child was the oldest BCI user tested and he was very cooperative during testing. The mother reported that he participates in many research projects related to cochlear implants. This child's maturity and focus on the tasks likely contributed to his success.

4.4 Modified HINT-C

The NH controls performed better than the BCI group and bimodal users on the HINT task. This group difference was unsurprising. However, the BCI group exceeded our expectations on this task. We had planned to test the BCI users in quiet with the percent-of-words-correct scoring method used clinically. It became obvious that this method of testing would be inappropriate for comparing the three HINT conditions when the second BCI participant to perform the task achieved 100 percent on all three conditions. We changed the testing method so that any BCI user who achieved 100 percent on the first set of sentences in quiet would be subsequently tested in noise for all three conditions. All of the remaining BCI participants had perfect performance on the sentence set presented in quiet and were subsequently tested in noise. Neither of the bimodal participants met the criteria to be tested in noise. There is an abundance of evidence from studies comparing the functional benefits of bilateral cochlear implants over unilateral that shows a definite bilateral advantage for speech reception in both quiet and in noise (e.g., Dunn et al., 2010; Scherf et al., 2007; van Hoesel & Tyler, 2003). In Canada, cochlear-implant hearing-impaired patients must usually have at least a severe bilateral hearing loss to be considered for candidacy (Fitzpatrick et al., 2009). Consequently, the residual hearing in the aided ear of the bimodal participants was probably limited – though this information was not recorded. While the use of limited residual acoustic hearing through amplification can help to provide balance and a better quality of sound it may not have contributed much to speech recognition, leaving the bimodal users to rely on their single implant for the HINT-C task. One of the bimodal users had a cognitive delay, which challenges the reliability of her results.

Contrary to our predictions, there was no main effect for HINT speaker. This means that, across the NH and BCI groups, there were no significant differences in the scores for the male, female, or dichotic voices. There was, however, a significant two-way interaction effect between hearing status and HINT condition. The interaction explains the absence of a significant main effect for condition because the pattern of responses across groups was reversed and the main effect of HINT speaker converged on a global mean. Figure 5 illustrates the interaction. We predicted that scores for the diotic male and female conditions would be equal but that the summation effect would lead NH listeners to have better SNR scores than in the dichotic, two-voice condition. The results contradicted our prediction. Signal-to-noise ratio scores by the NH group were indeed equivalent for the male and female diotic conditions, but the mean SNR score from the dichotic voices condition was unexpectedly better. We cannot determine if this difference was significant, but even if it is not, we would need to explain why performance in the dichotic condition was as at least as good as performance in the diotic conditions.

One explanation is that we observed a squelch-like effect in the dichotic condition. By presenting different voices to each ear we created a spatial separation between the noise and the signals. Since the noise was always identical in both ears, it was always perceived as coming from a central location. When the same voice was presented in both ears a single centralized talker was perceived, but when different voices were presented to opposite ears each voice lateralized to the ear of presentation. The spatial separation alone could provide a dichotic advantage, but an additional advantage may have been obtained by integrating the information from the dichotic voices. As Cutting (1976) described and Darwin (1981) later confirmed, accurate perception of vowel category is possible when the vowel formants are presented dichotically; this is true even when the formants are excited at different fundamental frequencies and the listener reports hearing two sounds. If we extrapolate these findings to the current study we may conclude that in the dichotic HINT condition the NH listeners heard two distinct voices, but integrated the spectral content for enhanced perception of the sentences. However, the aforementioned studies and their findings may not necessarily apply to longer stimuli such as the full sentences used in the current study. Another explanation for the relatively good performance on the dichotic HINT condition by NH listeners is that spectral integration was not actually required for binaural advantages to occur. For example, perhaps the linguistic content of the sentences was integrated at a higher order of signal processing, despite the perception of multiple talkers. If this is the case, then functional benefits for perceiving speech with two ears instead of one, may not actually rely on the signals at the two ears being from the same source, or sounding as such. Further investigation is recommended, but in the debate regarding the benefit of bilateral cochlear implantation it may be interesting to note that binaural processing does not have to be perfectly normal to be functionally advantageous. That is, even a source is perceived differently in the two ears, functional improvement may still be attainable with the addition of a second device.

The BCI users required the highest SNR on the dichotic voices condition and they performed the best—i.e., had the lowest SNR score—for the female-only diotic condition. We can be confident that this difference was significant because it was the largest difference between mean scores in the two-way interaction, which itself was significant in the ANOVA. We do not know for certain that performance for the female condition was significantly better than the male condition, but the trend was apparent. The possibility for practice and/or order effects, however, made us question if the female condition was really easier for BCI users than the male or dichotic conditions. These concerns, and the reasons we rejected them, are discussed below:

It is know that the HINT test can have practice effects. Practice sentence sets are provided with the test to be administered before the initial testing condition in quiet and in noise. The first troubleshooting situation listed in the test manual is for “improvement in performance between the first and second test administration” (House Ear Institute, p. 32). The correction for this situation is to “be sure to use one practice list before testing in quiet and another practice list before the first noise condition…” (House Ear Institute, p. 32). In the current study, adding practice trials was not seen as a favourable option due to the added time it would take to administer them. We chose instead to counterbalance the order of presentation of the three HINT conditions to counteract possible practice effects. Unfortunately, the attrition of one subject (the child that was not available for retesting), and the testing of one BCI user with the percent-correct scoring method, disrupted the counterbalancing for the BCI group included in the repeated measures ANOVA. This group had a sample size of seven (n=7). The disruption in counterbalancing introduced the possibility of order effects for the HINT conditions presented to the BCI group. The female condition was presented in the first and third presentation order three times each and in the second presentation order only once. The male and dichotic conditions were each presented in the first and third presentation order twice, and in the second presentation order three times. Practice effects for the task would presumably give the condition presented third the greatest advantage, and the female condition was third more than any other condition. Closer inspection of the data, however, showed that the HINT condition presented third was never the best of the three presentations for BCI users (except for one participant who scored equally well in the second and third conditions and worse in the first). Overall, this shows that being presented third more often than the other two conditions did not provide any real advantage for the female condition. NH listeners showed no indication for order effects.

We ruled out that the third order of presentation carried no specific advantages in our study, but we had a separate reason to suspect an advantage for the condition that was presented first. When we adapted the testing procedure to screen BCI users with a sentence set in quiet, we used the first condition in the pre-determined presentation order for each individual. This was logical because if they did not score 100% we could continue with the percent-correct testing in quiet. However, it inadvertently introduced a practice trial for the first test condition. Although the participant would be well trained at the task by the time the second and third conditions were presented, they would not have any practice specific to those conditions. We observed that 50% of the time (i.e., for 4 of the 8 participants) the first condition to be presented to a participant also had the best score of the three conditions. However, the second condition to be presented had an equal number of best scores (4 of 8, one of which was tied with a third condition). In short, being presented first more often than the other conditions does not explain why BCI users had the best mean score for the female condition. Of the four times where the first condition presented had the best SNR score, it was twice the male condition and twice the female condition. Therefore, practice effects for the condition and the task are not reasonable explanations for the advantage observed with the female HINT condition for BCI users.

The distinct features of the female voice were increased pitch and wider spacing of formant peaks. We do not know which electrodes were activated for any cochlear implant user in any task, but it is possible that a wider spacing of formant peaks resulted in a better-resolved place coding of the spectral details in the female voice over the male voice. However, the results from the matching task contradict this explanation by indicating that the difference in spectrum between the male and female voices in the HINT task may not have been large enough to be resolved by the cochlear implant devices. The spectrum of the male voice was transformed by +0.14 octaves to generate the spectrum for the female voice. In the matching task BCI users achieved a mean RMS score of 0.257 octaves. This indicates that, on average, BCI listeners would not have perceived the difference between the spectra of the male and female HINT voices.

The mean score for the female HINT condition was better than the mean score for the dichotic HINT for BCI users. However, we did not counterbalance how the dichotic condition was presented to BCI users. The devices were connected to the apparatus so that the better ear would receive the monaural stimulus for the matching task. This meant that the better ear received the left output of the EDIROL. We did not change this set-up for the HINT task. Therefore, the male talker was always sent to left output and the better ear of the BCI user in the dichotic HINT condition. In other words, the mean SNR score for the dichotic condition is the result of hearing the male voice in the better ear. We do not know for certain that the difference between the male and dichotic conditions was not significant because we had to use the very conservative Bonferroni correction for the t-test between these two conditions, however, the t-test showed no significant difference. This may indicate that BCI users were only using their better ear for the task, but this is merely speculation as no monaural presentations of the HINT stimuli were conducted for comparison.

Something to consider for future research applications of the HINT-C is the scoring method used. The SNR scoring method for the HINT test requires that subjects repeat all of the content words exactly correct. Allowances are made for changes in articles (e.g., a / the) or verb tense (e.g., is / was), but the main words must be correct. During the test administration for the current study we observed that some children, especially BCI users would make a slight error on one sentence, but increasing the SNR would not result in a perfect repetition of the following sentence. One BCI participant had very poor performance for the HINT sentences in noise even though she had previously achieved a perfect score on the sentences presented in quiet. This child would start to repeat the sentence perfectly and then stop and say that she "forgot the rest". Despite coaxing to guess or finish the sentence anyway, the child would not continue. Consequently, the SNR scores recorded for this child were the highest (worst) attainable in two conditions (male and dichotic). This child performed the female condition with reasonable success and this likely contributed heavily to the interaction effect between hearing and HINT condition. These observations are consistent with those by Cullington and Zeng (2008) who adopted a "loose keyword scoring method" (p.452) for the HINT sentences after preliminary results indicated that the CI users in their study would often fail to repeat a sentence exactly, even when they appeared to understand it.

4.5 Demographic Variables and HINT-C Task Performance

There were no significant correlations between performance on the HINT and the demographic variables from the BCI group. A larger sample size is necessary before such comparisons can be meaningful. The mean score on all HINT-C conditions was negatively correlated with age for the NH group, which indicates that older children were better at the task. This is not surprising as age adjusted norms are usually recommended for auditory tasks such as the HINT and HINT-C.

4.6 Conclusion

The results from this study were somewhat difficult to interpret. However, the pattern of mean scores for spectrum matching across presentation conditions offers some evidence that both normal-hearing listeners and bilateral cochlear-implant users integrate spectrum cues presented dichotically. We cannot conclude whether or not BCI users can integrate binaural pitch cues, but further investigation into this matter is recommended due to the importance of pitch for talker identification. Of the three HINT conditions, normal-hearing listeners had superior performance on the dichotic condition – where two different talkers or voices were heard in opposite ears. This suggests that the detection of a common source for the signals at the two ears may not be necessary for integration afterall.

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APPENDIX A – Telephone Recruiting Script for NSHSC

Script for Telephone Contact with Potential Research Participants

Hello may I speak with Mr./Mrs./Ms. _____________________

My name is _________________. I am calling from the Nova Scotia Hearing and Speech Centres. You indicated on the patient consent form when you registered with the Centres that you could be contacted about participating in research. A student at Dalhousie University School of Human Communication Disorders is conducting research on cochlear implant use and would like to contact you regarding her research project. Please be aware that your/your child's participation in a study will not in any way affect your/his/her eligibility for services through the Centres. Any information used in a study will remain strictly confidential.

The purpose of this study is to test the ability of cochlear implant users to recognize whether two voices are the same or different when one voice is heard in one ear and the second voice is heard in the opposite ear.

As a participant you/your child will be asked to complete two different tasks. In the first task you will listen carefully to several pairs of voices and turn a dial to change one voice to match the other as closely as possible. In the second task you will listen carefully to several sentences and repeat what you hear after each sentence. The testing can be done at the Centre, at the School of Human Communication Disorders or in your home and will take about 45 minutes.

Would you be willing to participate/have your child participate in this project?
( ) yes ( ) No

(At this point the caller will thank the person and/or inform them that Nicole will be contacting them shortly to set up an appointment)

APPENDIX B - Response Recording and Scoring Sheets

Matching Task

ID #:

Date:

Results Table:

		Simultaneous Dichotic	**Sequential Bilateral**	**Sequential Monaural**
Pitch	Trial 1			
	Trial 2			
	Trial 3			
Spectrum	Trial 1			
	Trial 2			
	Trial 3			
Both	Trial 1			
	Trial 2			
	Trial 3			

Presentation Order:

Order	**Condition**
	Simultaneous Dichotic - Pitch
	Simultaneous Dichotic – Spectrum
	Simultaneous Dichotic – Both
	Sequential Bilateral – Pitch
	Sequential Bilateral – Spectrum
	Sequential Bilateral – Both
	Sequential Monaural – Pitch
	Sequential Monaural – Spectrum
	Sequential Monaural – Both

ID #:

Date:

Processor:

	List	**Presentation Order**	**Average SNR for # 5-11**
Condition 1 (male speaker)			
Condition 2 (female speaker)			
Condition 3 (both speakers)			

Hearing in Noise Test – Children (HINT-C)

List 1	**SNR**
1. (A/The) boy fell from (a/the) window.	
2. (A/The) lady went to (a/the) store.	
3. Big dogs can be dangerous.	
4. Her shoes (are/were) very dirty.	
5. He got mud on his shoes.	
6. The children helped their teacher.	
7. (A/The) fire (is/was) very hot.	
8. She's drinking from her own cup.	
9. (A/The) picture came from (a/the) book.	
10. They're pushing an old car.	
11.	
Score (average of 5-11):	

List 2	**SNR**
1. (A/The) boy ran down (a/the) path.	
2. Flowers grow in (a/the) garden.	
3. Strawberry jam (is/was) sweet.	
4. (A/The) shop closes for lunch.	
5. (A/the) bus leaves before (a/the) train.	
6. She looked in her mirror.	
7. It's getting cold in here.	
8. (A/The) man called the police.	
9. The mailman shut the gate	
10. (A/The) tub faucet (is/was) leaking.	
11.	
Score (average of 5-11):	

List 3	**SNR**
1. They heard (a/the) funny noise.	
2. He found his brother hiding.	
3. (A/The) dog sleeps in (a/the) basket.	
4. (A/The) book tells (a/the) story.	
5. The matches (are/were) on (a/the) shelf.	
6. The milk (is/was) by (a/the) front door.	
7. (A/The) broom (is/was) by (a/the) front door.	
8. (A/The) new road (is/was) on (a/the) map.	
9. She lost her credit card.	
10. (A/The) team (is/was) playing well.	
11.	
Score (average of 5-11):	

List 4	**SNR**
1. (A/The) little boy left home.	
2. They’re going out tonight.	
3. The kitchen clock was wrong.	
4. He wore his yellow shirt.	
5. They finished dinner on time.	
6. He needs his vacation.	
7. She’s washing her new silk dress.	
8. (A/The) cat drank from (a/the) saucer.	
9. The police cleared (a/the) road.	
10. (A/The) lady packed her bag.	
11.	
Score (average of 5-11):	

List 5	**SNR**
1. (A/The) boy did (a/the) handstand.	
2. They took some food outside.	
3. The young people (are/were) dancing.	
4. (A/The) grocer sells butter.	
5. The shirts (are/were) in (a/the) closet.	
6. They watched (a/the) scary movie.	
7. A tree fell on the house.	
8. They went on vacation.	
9. (A/The) girl (is/was) fixing her dress.	
10. (A/The) baby broke his cup.	
11.	
Score (average of 5-11):	

List 6	**SNR**
1. (A/The) clown (has/had) (a/the) funny face.	
2. (A/The) dishcloth (is/was) soaking wet.	
3. They (have/had) some chocolate pudding.	
4. (A/The) bus stopped suddenly.	
5. (An/The) oven door (is/was) open.	
6. She’s paying for her bread.	
7. (A/The) dinner plate (is/was) hot.	
8. He broke his leg again.	
9. (A/The) lady wore (a/the) coat.	
10. The baby has blue eyes.	
11.	
Score (average of 5-11):	

List 7	**SNR**
1. School got out early today.	
2. They’re running past the house.	
3. (A/The) boy ran away from school.	
4. Sugar (is/was) very sweet.	
5. The two children (are/were) laughing.	
6. (A/The) fire truck (is/was) coming.	
7. He (is/was) washing his car.	
8. She found her purse in (a/the) trash.	
9. (A/The) ball broke (a/the) window.	
10. The old gloves (are/are) dirty.	
11.	
Score (average of 5-11):	

List 8	**SNR**
1. (A/The) neighbor's boy (has/had) black hair.	
2. The rain came pouring down.	
3. (A/The) dog came home at last.	
4. They're clearing the table.	
5. Children like strawberries.	
6. Her sister stayed for lunch.	
7. (A/The) train (is/was) moving fast.	
8. Mother shut (a/the) window.	
9. (A/The) bottle (is/was) on (a/the) shelf.	
10. (A/The) road goes up (a/the) hill.	
11.	
Score (average of 5-11):	

List 9	**SNR**
1. They (have/had) two empty bottles.	
2. (A/The) woman cleaned her house.	
3. (A/The) sharp knife (is/was) dangerous.	
4. (A/The) child ripped open (a/the) bag.	
5. (A/The) kitchen window (is/was) clean.	
6. She's helping her friend move.	
7. They ate (a/the) lemon pie.	
8. Father forgot the bread.	
9. The sun melted the snow.	
10. (A/The) little girl (is/was) happy.	
11.	
Score (average of 5-11):	

List 10	**SNR**
1. (A/The) house (has/had) nine bedrooms.	
2. They're shopping for school clothes.	
3. They're playing in (a/the) park.	
4. She took off her fur coat.	
5. The (are/were) coming for dinner.	
6. (A/The) child drank some fresh milk.	
7. (A/The) baby slept all night.	
8. (A/The) table (has/had) three legs.	
9. (A/The) policeman knows the way.	
10. There (is/was) a bad train wreck.	
11.	
Score (average of 5-11):	

List 11	**SNR**
1. Mother picked some flowers.	
2. (A/The) puppy played with (a/the) ball.	
3. (An/The) engine (is/was) running.	
4. (An/The) old woman (is/was) at home.	
5. They're watching (a/the) train go by.	
6. (An/The) oven (is/was) too hot.	
7. They rode their bicycles.	
8. (A/The) truck carries fresh fruit.	
9. They laughed at his story.	
10. They walked across the grass.	
11.	
Score (average of 5-11):	

List 13	**SNR**
1. Mother read the instructions.	
2. (A/The) dog (is/was) eating some meat.	
3. (An/The) apple pie (is/was) good.	
4. (A/The) jelly jar (is/was) full.	
5. (A/The) girl (is/was) washing her hair.	
6. (A/The) girl played with (a/the) baby.	
7. (A/The) cow (is/was) milked every day.	
8. The paint dripped on the ground.	
9. They (are/were) drinking coffee.	
10. He’s washing his face with soap.	
11.	
Score (average of 5-11):	

List 14	**SNR**
1. (A/The) boy got into trouble.	
2. The yellow pears taste good.	
3. (A/The) front yard (is/was) pretty.	
4. (An/The) old man (is/was) worried.	
5. The pond water (is/was) dirty.	
6. (A/The) rancher (has/had) (a/the) bull.	
7. The ground (is/was) very hard.	
8. They painted (a/the) wall white.	
9. Dad stopped to pick some pears.	
10. She made her bed and left.	
11.	
Score (average of 5-11):	

List 15	**SNR**
1. Men normally wear long pants.	
2. (A/The) house (has/had) (a/the) nice garden.	
3. (A/The) little girl (is/was) shouting.	
4. (A/The) driver waited for me.	
5. The three girls (are/were) listening.	
6. (An/The) ice-cream was melting.	
7. She bumped her head on (a/the) door.	
8. (An/The) apple pie (is/was) baking.	
9. She’s calling her daughter.	
10. (A/The) park (is/was) near (a/the) road.	
11.	
Score (average of 5-11):	

List 16	**SNR**
1. (A/The) boy forgot his book.	
2. (A/The) mouse ran into (a/the) hole.	
3. The leaves turned brown and dry.	
4. He closed his eyes and jumped.	
5. (A/The) floor looks clean and shiny.	
6. She writes to her friend daily.	
7. The two farmers (are/were) talking.	
8. Father paid at (a/the) gate.	
9. They’re climbing (an/the) old oak tree.	
10. The sky (is/was) very blue.	
11.	
Score (average of 5-11):	

ID #:

Date:

Processor:

	List	**% correct**
Condition 1 (male speaker)		
Condition 2 (female speaker)		
Condition 3 (both speakers)		

Hearing in Noise Test – Children (HINT-C)

List 1	**Words correct**
11. (A/The) boy fell from (a/the) window.	
12. (A/The) lady went to (a/the) store.	
13. Big dogs can be dangerous.	
14. Her shoes (are/were) very dirty.	
15. He got mud on his shoes.	
16. The children helped their teacher.	
17. (A/The) fire (is/was) very hot.	
18. She's drinking from her own cup.	
19. (A/The) picture came from (a/the) book.	
20. They're pushing an old car.	
Words correct	/55
Percent correct	%

List 2	**Words correct**
11. (A/The) boy ran down (a/the) path.	
12. Flowers grow in (a/the) garden.	
13. Strawberry jam (is/was) sweet.	
14. (A/The) shop closes for lunch.	
15. (A/the) bus leaves before (a/the) train.	
16. She looked in her mirror.	
17. It's getting cold in here.	
18. (A/The) man called the police.	
19. The mailman shut the gate	
20. (A/The) tub faucet (is/was) leaking.	
Words correct	/51
Percent correct	%

List 3	**Words correct**
11. They heard (a/the) funny noise.	
12. He found his brother hiding.	
13. (A/The) dog sleeps in (a/the) basket.	
14. (A/The) book tells (a/the) story.	
15. The matches (are/were) on (a/the) shelf.	
16. The milk (is/was) by (a/the) front door.	
17. (A/The) broom (is/was) by (a/the) front door.	
18. (A/The) new road (is/was) on (a/the) map.	
19. She lost her credit card.	
20. (A/The) team (is/was) playing well.	
Words correct	/57
Percent correct	%

List 4	**Words correct**
11. (A/The) little boy left home.	
12. They're going out tonight.	
13. The kitchen clock was wrong.	
14. He wore his yellow shirt.	
15. They finished dinner on time.	
16. He needs his vacation.	
17. She's washing her new silk dress.	
18. (A/The) cat drank from (a/the) saucer.	
19. The police cleared (a/the) road.	
20. (A/The) lady packed her bag.	
Words correct	/50
Percent correct	%

List 5	**Words correct**
11. (A/The) boy did (a/the) handstand.	
12. They took some food outside.	
13. The young people (are/were) dancing.	
14. (A/The) grocer sells butter.	
15. The shirts (are/were) in (a/the) closet.	
16. They watched (a/the) scary movie.	
17. A tree fell on the house.	
18. They went on vacation.	
19. (A/The) girl (is/was) fixing her dress.	
20. (A/The) baby broke his cup.	
Words correct	/51
Percent correct	%

List 6	**Words correct**
11. (A/The) clown (has/had) (a/the) funny face.	
12. (A/The) dishcloth (is/was) soaking wet.	
13. They (have/had) some chocolate pudding.	
14. (A/The) bus stopped suddenly.	
15. (An/The) oven door (is/was) open.	
16. She's paying for her bread.	
17. (A/The) dinner plate (is/was) hot.	
18. He broke his leg again.	
19. (A/The) lady wore (a/the) coat.	
20. The baby has blue eyes.	
Words correct	/50
Percent correct	%

List 7	**Words correct**
11. School got out early today.	
12. They're running past the house.	
13. (A/The) boy ran away from school.	
14. Sugar (is/was) very sweet.	
15. The two children (are/were) laughing.	
16. (A/The) fire truck (is/was) coming.	
17. He (is/was) washing his car.	
18. She found her purse in (a/the) trash.	
19. (A/The) ball broke (a/the) window.	
20. The old gloves (are/are) dirty.	
Words correct	/52
Percent correct	%

List 8	**Words correct**
11. (A/The) neighbor’s boy (has/had) black hair.	
12. The rain came pouring down.	
13. (A/The) dog came home at last.	
14. They’re clearing the table.	
15. Children like strawberries.	
16. Her sister stayed for lunch.	
17. (A/The) train (is/was) moving fast.	
18. Mother shut (a/the) window.	
19. (A/The) bottle (is/was) on (a/the) shelf.	
20. (A/The) road goes up (a/the) hill.	
Words correct	/50
Percent correct	%

List 9	**Words correct**
11. They (have/had) two empty bottles.	
12. (A/The) woman cleaned her house.	
13. (A/The) sharp knife (is/was) dangerous.	
14. (A/The) child ripped open (a/the) bag.	
15. (A/The) kitchen window (is/was) clean.	
16. She’s helping her friend move.	
17. They ate (a/the) lemon pie.	
18. Father forgot the bread.	
19. The sun melted the snow.	
20. (A/The) little girl (is/was) happy.	
Words correct	/50
Percent correct	%

List 10	**Words correct**
11. (A/The) house (has/had) nine bedrooms.	
12. They’re shopping for school clothes.	
13. They’re playing in (a/the) park.	
14. She took off her fur coat.	
15. The (are/were) coming for dinner.	
16. (A/The) child drank some fresh milk.	
17. (A/The) baby slept all night.	
18. (A/The) table (has/had) three legs.	
19. (A/The) policeman knows the way.	
20. There (is/was) a bad train wreck.	
Words correct	/53
Percent correct	%

List 11	**Words correct**
11. Mother picked some flowers.	
12. (A/The) puppy played with (a/the) ball.	
13. (An/The) engine (is/was) running.	
14. (An/The) old woman (is/was) at home.	
15. They’re watching (a/the) train go by.	
16. (An/The) oven (is/was) too hot.	
17. They rode their bicycles.	
18. (A/The) truck carries fresh fruit.	
19. They laughed at his story.	
20. They walked across the grass.	
Words correct	/50
Percent correct	%

List 13	**Words correct**
11. Mother read the instructions.	
12. (A/The) dog (is/was) eating some meat.	
13. (An/The) apple pie (is/was) good.	
14. (A/The) jelly jar (is/was) full.	
15. (A/The) girl (is/was) washing her hair.	
16. (A/The) girl played with (a/the) baby.	
17. (A/The) cow (is/was) milked every day.	
18. The paint dripped on the ground.	
19. They (are/were) drinking coffee.	
20. He’s washing his face with soap.	
Words correct	/54
Percent correct	%

List 14	**Words correct**
11. (A/The) boy got into trouble.	
12. The yellow pears taste good.	
13. (A/The) front yard (is/was) pretty.	
14. (An/The) old man (is/was) worried.	
15. The pond water (is/was) dirty.	
16. (A/The) rancher (has/had) (a/the) bull.	
17. The ground (is/was) very hard.	
18. They painted (a/the) wall white.	
19. Dad stopped to pick some pears.	
20. She made her bed and left.	
Words correct	/52
Percent correct	%

List 15	**Words correct**
11. Men normally wear long pants.	
12. (A/The) house (has/had) (a/the) nice garden.	
13. (A/The) little girl (is/was) shouting.	
14. (A/The) driver waited for me.	
15. The three girls (are/were) listening.	
16. (An/The) ice-cream was melting.	
17. She bumped her head on (a/the) door.	
18. (An/The) apple pie (is/was) baking.	
19. She’s calling her daughter.	
20. (A/The) park (is/was) near (a/the) road.	
Words correct	/53
Percent correct	%

List 16	**Words correct**
11. (A/The) boy forgot his book.	
12. (A/The) mouse ran into (a/the) hole.	
13. The leaves turned brown and dry.	
14. He closed his eyes and jumped.	
15. (A/The) floor looks clean and shiny.	
16. She writes to her friend daily.	
17. The two farmers (are/were) talking.	
18. Father paid at (a/the) gate.	
19. They’re climbing (an/the) old oak tree.	
20. The sky (is/was) very blue.	
Words correct	/56
Percent correct	%

APPENDIX C – Release of Medical Information Form

Consent for Release of Medical Information Form

This research project seeks to determine whether demographic details such as age, age of first implant, time delay between implantations, type(s) of implant, original cause and timing of deafness, and delay between diagnosis of deafness and implantation are related to performance on the research tasks. In order to collect this information Nicole would like to review your (or your child's) file at the Nova Scotia Hearing and Speech Centres (NSHSC). All information collected will be coded to remove all identifying information and stored in a password protected file.

Please check one:

☐ I give permission to Nicole Jackson to review my/my child's file at the NSHSC for the purpose of this research project.
☐ I do not give permission for my/my child's file to be reviewed for this project.

Signature: ________________________________ Date:______________________

APPENDIX D – Demographic Information Form

ID #:

Test Date:

Date of Birth:

Date of 1st CI activiation:

Date of 2nd CI activation:

Implant Type: Please indicate which side was implanted/activated first.

Right Side:

Left Side:

Cause of deafness (if known):

Date or age diagnosed with hearing impairment/deafness: