Ear-Specific Cochlear Implant Outcomes in Younger and Older Adults

Capstone Document

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Audiology
in the Graduate School of The Ohio State University

By

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2016

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ABSTRACT

Auditory information is transmitted from the ear to the brain along an intricate network of structures that comprise the central auditory nervous system. It is well documented that the neural pathway from the ear to the contralateral auditory cortex is stronger and more efficient than the pathway from the ear to the ipsilateral auditory cortex (Lazard et al., 2012; Lipschutz et al., 2002). In the majority of individuals, a functional specialization of the left cerebral hemisphere exists for language processing (Geschwind, 1972; Geschwind & Levitsky, 1968; Kimura, 1961; Jancke et al., 2002; Tervaniemi & Hugdahl, 2003). Due to this crossed nature of the central auditory system, the right ear has direct access to the language-dominant cerebral hemisphere, which results in superior right ear performance, or the Right Ear Advantage (REA), on dichotic listening tasks (Kimura, 1967).

A body of literature reveals that the REA becomes more exaggerated with increased age (Martin & Cranford, 1991; Strouse et al., 2011; Roup et al., 2006; Jerger et al., 1995; Jerger & Johnson, 1992; Bellis & Wilber, 2001). The increase in the REA in older adults, in the presence of symmetrical hearing sensitivity, is thought to reflect age-related degradation of the corpus callosum, which compromises the transfer of auditory information between the cerebral hemispheres (Bellis & Wilber, 2001). Speech information presented to the left ear preferentially stimulates the right auditory cortex and must be transmitted by way of the corpus callosum in order to be processed in the language-rich left auditory cortex. Superior right-ear performance is therefore demonstrated in older adults, due to the primary projection of the right ear to the dominant hemisphere.

The present study aimed to determine if ear-specific differences in speech understanding exist in younger and older adults who underwent unilateral cochlear implantation. Post-operative performance on speech outcome measures (Consonant-Nucleus-Consonant words and AZ-Bio Sentences) was compared between younger adults (18-69 years) and older adults (70+ years). Results revealed significant benefits in speech perception following implantation for both younger and older adults. Ear of implantation had no significant effect on post-operative speech outcomes in either group.

ACKNOWLEDGEMENTS

I would like to extend my most sincere gratitude to Gail Whitelaw, Ph.D., my advisor and esteemed friend. Thank you for your unending encouragement, guidance, and patience. I would also like to thank my committee members, Eric Bielefeld, Ph.D. and Julie Hazelbaker, Ph.D. for their support and counsel.

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CHAPTER 1

INTRODUCTION

A cochlear implant is a medical device that provides direct electrical stimulation to the auditory nerve, affording the sensation of sound to individuals with severe to profound sensorineural hearing loss. In listeners with normal hearing, sound enters the ear acoustically and travels through the outer ear and middle ear, and stimulates sensory receptors, the outer and inner hair cells, in the inner ear. These sensory receptors stimulate the auditory nerve, and auditory information is transmitted along the ascending auditory pathway to the brain. The sensory receptors are the primary site of injury in the majority of sensorineural hearing losses (Budenz et al., 2011; Pirvola et al., 2000; Wong & Ryan, 2015). Individuals with sensorineural hearing loss may benefit from use of digital hearing aid technology, which amplifies acoustic input and transmits this information to the surviving sensory cells and along the auditory nerve. For individuals with severe to profound hearing loss, damage to the sensory cells is often so great that even the most advanced digital hearing technology is insufficient in providing meaningful stimulation of the auditory nerve. For these individuals, cochlear implantation is indicated. A cochlear implant picks up acoustic signals via a microphone, and converts them into a digital signal. The output is transmitted via radio waves through the skull to the surgically implanted internal receiver, which delivers the coded signal to an electrode array that has been inserted into the cochlea. The electrode array takes the place of the dysfunctional sensory receptors and stimulates the fibers of the auditory nerve directly. Auditory information is transmitted along the auditory nerve up the ascending auditory pathway to the central auditory cortex in the brain, where it is perceived as the sense of hearing

The ascending auditory pathway consists of an intricate network of structures that transmit auditory information from the ear to the brain. When sound is processed through the ear, auditory information is then transmitted to the ipsilateral cochlear nucleus (Lazard et al., 2012; Langers, van Dikj, & Backes, 2005; Ponton et al., 2001). From the level of the cochlear nucleus, there are axonal projections to the auditory structures in both the ipsilateral pathway, by way of uncrossed fibers, and the contralateral pathway, by way of crossed fibers (Lazard et al., 2012). The superior olivary complex represents the first source of binaural hearing in the auditory nervous system. Auditory input is transmitted along the ascending auditory pathway, up to the superior olivary complex, lateral lemniscus, inferior colliculus, medial geniculate nucleus, and finally reaches the auditory cortex (Lazard et al., 2012). There is a functional asymmetry in the organization of the central auditory nervous system, in that the majority of information processed by an ipsilateral ear is preferentially stimulating the contralateral auditory cortex. This is due to the fact that the pathway from each ear to the contralateral auditory cortex is comprised of far more afferent auditory nerve fibers than is the pathway from each ear to the ipsilateral auditory cortex (Lazard et al, 2012). The contralateral connection from the ear to the auditory cortex is hence stronger than the ipsilateral connection. Further, an asymmetry exists in the organization of the auditory nervous system for expressive and receptive language, in favor of left hemispheric dominance. In approximately 90% of individuals, the core language centers in the brain, Broca's area and Wernicke's area, are located within the left temporal lobe (Jung et al., 2003).

The predominantly crossed nature of the central auditory nervous system and the left hemispheric dominance of language processing are thought to result in more accurate representation of speech information presented to the right ear than speech information presented to the left ear, a phenomenon referred to as the Right Ear Advantage (REA) (Kimura, 1967). Because auditory stimuli reaching the right ear appears to preferentially activate the language-rich left temporal lobe, the right ear typically out-performs the left ear when competing speech information is presented to both ears simultaneously (Kimura, 1967). Research on the REA suggests that older adults exhibit a larger REA than younger adults. This finding cannot be entirely explained by differences in hearing sensitivity, but rather, is thought to reflect age-related changes in the central auditory nervous system and decreased interhemispheric transfer of auditory information (Bellis and Wilbur, 2001; Johnson et al., 1979; Jerger and Jordan, 1992; Martin and Jerger, 2005; Roup, Wiley, & Wilson, 2006).

The United States Food and Drug Administration (FDA) initially approved cochlear implantation for post-lingually deafened adults with profound sensorineural hearing loss in both ears in 1984 (NIH, 2010). Since this time, significant advancements in cochlear implant technology, extensive clinical trials, and reduction in surgical risk have led to expanded criteria for cochlear implant recipients, including infants and older adults. From an audiologic standpoint, implant centers around the world are now routinely implanting individuals with varying degrees and configurations of hearing loss, including unilateral severe to profound hearing loss, mixed hearing loss, asymmetric sensorineural hearing loss, and precipitously sloping sensorineural hearing loss. Due to less restrictive candidacy criteria, individuals with aidable hearing but poor speech understanding in at least one ear are now able to receive a cochlear implant. In patients with bilateral hearing loss, there is debate among researchers and clinicians as to whether it is more advantageous to implant the better hearing ear or the poorer hearing ear (Patki & Tucci, 2014; Chen et al., 2001). Some argue that implanting the poorer hearing ear allows for the possibility of bimodal stimulation, or the option of using a cochlear implant in one ear and a hearing aid in the other ear. However, others contest that the implant could be more beneficial on the better hearing ear, as this ear is thought to have less damage to auditory structures and deprivation to the auditory pathway. For individuals who demonstrate similar pre-operative word understanding, vestibular function, and comparable hearing aid usage between ears, the patient may choose a preferred ear.

Cochlear implants have been found to be an effective means of providing the perception of sound in both pediatric and adult populations; however, post-operative performance on speech understanding outcome measures varies widely (van Dijk et al., 1999). A body of cochlear implant research aims to determine factors that are predictive of positive cochlear implant outcomes. Patient variables, including duration of deafness, age at implantation, previous hearing aid use, etiology of deafness, preoperative speech understanding, and residual hearing following implantation may influence post-operative speech perception (Gantz et al., 2002; Budenz et al., 2011; van Dijk et al., 1999; Battmer et al., 1995; Blamey et al., 2013; Green et al., 2007; Friedland, Venick, & Niparko, 2003). Given what is known about the REA and the well documented age-related changes in the auditory system, the ear of implantation may influence post-operative performance in older adults (Budenz et al., 2011).

The present study aims to investigate if ear-specific differences in speech understanding exist between older adults and younger adults who received unilateral cochlear implants. This study aims to answer the following questions:

(1) What is the relationship between ear of implantation and speech perception outcome measures in older adults (70+ years)?

(2) What is the relationship between ear of implantation and speech perception outcome measures in younger adults (18-69 years)?

(3) How does the relationship between ear of implantation and speech perception outcome measures in older adults compare to younger adults?

CHAPTER 2

LITERATURE REVIEW

Anatomical Differences Between the Right and Left Auditory Cortices

A large body of research supports a functional specialization of the left cerebral hemisphere for speech processing in the majority of individuals (Geschwind, 1972; Geschwind & Levitsky, 1968; Kimura, 1961; Jancke et al., 2002; Tervaniemi & Hugdahl, 2003). An anatomical asymmetry between the right and left temporal lobe has been demonstrated through neuroanatomical studies and is believed to contribute, in part, to the left-hemispheric lateralization for speech processing. The primary auditory cortex lies within the lateral Sylvian fissure on the transverse gyrus of Heschl (Tervaniemi & Hugdahl, 2003). The secondary auditory cortex lies within the superior temporal gyrus, in the planum temporale. Neuroanatomic studies indicate that there are gross asymmetries between the left and right Sylvian fissure, Heschl's gyri and planum temporale. The left Heschl's gyrus and planum temporale are significantly larger than the homologous structures in the right hemisphere in the majority of individuals (Tervaniemi & Hugdahl, 2003; Good et al., 2001). Geschwind and Levitsky (1968), a seminal paper on this topic, revealed that on average, the left planum temporale was almost one-third larger than the right, observed through post-mortem evaluation. Geshwind and Levitsky (1968) asserted that the size differences observed were "easily of sufficient magnitude to be compatible with the known functional asymmetries [in speech processing between the left and right hemispheres]" (p. 187). Wada, Clarke, and Hamm (1975) revealed this asymmetry in the size of the planum temporale in roughly 90% of both adult (17-96 years) and infant brains (18 weeks gestation- 18 months), through post-mortem evaluation. This asymmetry was observed as early as 29 weeks gestation, revealing a pre-lingual disposition to left-hemispheric dominance. Additionally, this asymmetry was found to be greater in adults than children, suggesting a developmental component to hemispheric differences. The left Heschl's gyrus has been found to have significantly greater white matter volume than the right, observed through magnetic resonance imaging (Penhune, 1996; Dorsaint-Pierre et al., 2006). This difference in white matter volume was hypothesized to contribute to more rapid transmission of temporal information, critical for speech understanding, in the left hemisphere. The left Sylvian fissure, Heschl's gyrus, and planum temporale have also been found to be significantly longer than the right (Musiek & Reeves, 1990). Structures in the left temporal hemisphere are believed to have higher density of neurons and more inter- and intra-hemispheric neuronal connections due to their increased size, when compared to those in the right hemisphere (Musiek & Reeves, 1990; Samelli & Schochat, 2008). Armstrong et al. (2004) revealed significantly higher density of cerebral white matter in the left hemisphere than the right hemisphere in healthy adults through magnetic resonance imaging. When investigated further, the parietal and occipital lobes showed no significant hemispheric differences. The posterior frontal lobe (motor cortex) and lateral temporal lobe (auditory cortex) accounted for the significant hemispheric asymmetry. Ninety-six percent of subjects demonstrated dominance in the left lateral temporal lobe, and 78% demonstrated dominance in the left posterior frontal region. These findings are consistent with language and motor lateralization in the left temporal lobe (Armstrong et al., 2004). The structural asymmetry between the left and right temporal hemisphere is believed to contribute to the functional asymmetry of auditory system for speech processing.

Language Processing and Handedness

Language processing and handedness are two of most lateralized functions in the human brain (Gotts et al., 2013). Right-handed individuals constitute approximately 80-95% of the population (Llaurens et al., 2009; Uomini, 2009; Faurier et al., 2005). The relationship between handedness and lateralization of speech processing has been investigated for over a century. In the 1860's, Paul Broca and Gustave Dax published reports that speech processing appeared to be lateralized to the left hemisphere of the brain (Knecht et al., 2000). Broca and Dax investigated the association between brain lesions and language, and uncovered that insults to the superior left temporal lobe could result in complete loss of expressive language abilities. At this time, it was widely accepted that the afferent and efferent neural pathways decussate; meaning the left hemisphere predominantly controls the right side of the body and vice versa (Knecht et al., 2000). The relationship between handedness and language processing was believed to be fixed, in that right-handed individuals are left-language dominant and left-handed individuals demonstrate right-language dominance, commonly referred to as "Broca's

Rule" (Knecht et al., 2000). Unfortunately, the Broca and Dax experiments on language lateralization in the brain could only be performed in individuals with acute brain lesions or posthumously, limiting the generalizability to living humans. In the 1960's, however, a body of literature emerged indicating that exceptions to Broca's Rule exist. This literature arose after Juhn Wada, a neurologist, developed a test for cerebral hemispheric dominance of language function. Known as the Wada test, this procedure involved injecting the barbiturate sodium amobarbital the internal carotid arteries of an alert patient. The barbiturate completely inhibited the side of the body in which it was injected, and tests of cognitive function, including speech and memory tasks, were performed (Knecht et al., 2000). If an individual is left-hemispheric dominant for language, for example, an injection to the right carotid artery should not negatively impact language abilities. Rasmussen and Milner (1977) investigated speech lateralization in 134 patients with known left-sided brain injuries and 262 patients without injury. Results of this study revealed that 96% of right-handed individuals and 70% of non-right handed individuals (ambidextrous or left-handed) demonstrated left-hemispheric lateralization for speech processing (Rasmussen & Milner, 1977). The results of the 122 non-right handed individuals revealed a significantly less predictable pattern of speech lateralization. Fifteen percent of non-right handed individuals demonstrated significant speech deficits with injections to either side, indicating bilateral language representation. Another 15% demonstrated right-sided speech lateralization (Rasmussen & Milner, 1977). Based on Wada's results, speech is more accurately represented in the temporal lobe of the left hemisphere for the majority of both right-handed and left-handed individuals.

Steinmetz et al., (1991), examined the relationship between handedness and structural hemispheric asymmetries in healthy adults using magnetic resonance imaging. Results of this study revealed that handedness and structural asymmetries were correlated. Right-handed adults were found to have a significantly greater degree of leftward asymmetry than left-handed adults, which was believed to reflect the left-hemispheric language lateralization of right-handed individuals. This reduced functional asymmetry in left-handed individuals was believed to demonstrate the relationship between anatomical and functional differences between the left and right hemispheres.

Decussation of the Central Auditory Nervous System

Speech cues are represented bilaterally at all structures in the ascending auditory nervous system central to the cochlear nuclei (Lazard et al., 2012; Langers, van Dikj, & Backes, 2005; Ponton et al., 2001). Though the ascending auditory nervous system projects bilaterally, an asymmetry between the ipsilateral and contralateral pathway has been demonstrated in physiologic studies (Lazard et al., 2012; Lipschutz et al., 2002). Functional imaging research revealed stronger excitation of the auditory cortex contralateral to the ear of stimulation when auditory stimuli are presented monaurally. This activation pattern has been found for a variety of auditory stimuli, including noise, monosyllables, and pure tones (Suzuki et al., 2002; Scheffler et al., 1998; Langers et al., 2005; Jancke et al., 2002). Contralateral pathway dominance is also observed in studies measuring magnetoencephalography (MEG) recordings of auditory steady state responses (Lazzouni et al., 2010, Ross et al., 2005, Kaneko et al., 2003). These experiments revealed larger amplitudes and shorter latencies in the hemisphere contralateral to the ear of stimulation compared to the ipsilateral hemisphere, which indicates that the contralateral pathway is stronger and more efficient than the ipsilateral pathway, which indicates that the neural pathway from the ear to the contralateral auditory cortex is stronger and more efficient than the pathway from the ear to the ipsilateral auditory cortex.

Fukiki, Jousmaki, and Hari (2002) recorded neuromagnetic cortical activation arising from monaural and binaural presentation of auditory signals. Auditory information presented to each ear was characterized by amplitude modulations of different frequencies so that input could be mapped from each ear to the cortex. When information was presented monaurally, results revealed significantly stronger contralateral cortical activation than ipsilateral activation (Fukiki, Jousmaki, & Hari, 2002). The contralateral dominant stimulation of the auditory cortex has also been observed through electrophysiological studies. Hine and Debener (2007) measured electroencephalographic (EEG) recordings from adult listeners with normal hearing. Auditory evoked potentials (N100) revealed significantly larger amplitudes and shorter latencies in the hemisphere contralateral to the ear of stimulation compared to the ipsilateral hemisphere for both tones and white noise stimuli (Hine & Debener, 2007). Khosla et al. (2003) found similar results with auditory evoked potentials (N1/P2 and

Ta/Tb) using click stimuli. The greater excitation of the contralateral auditory pathway results in preferential stimulation of the language-rich left temporal lobe when auditory information is presented to the right ear. The right ear has direct access to the dominant hemisphere, which results in superior right ear performance, or the REA, when there is auditory competition between the right and left ears.

Behavioral Measures of Hemispheric Asymmetry

The left-hemispheric dominance for speech processing has been demonstrated through behavioral studies. The neural pathways of the central auditory nervous system are intrinsically redundant (Chermak, 2001). Auditory information is represented bilaterally and transmitted rapidly along serial and parallel pathways. Human listeners can capitalize on this redundancy to help fill in missing auditory information in adverse listening environments. Due to the flexibility and redundancy of the central auditory nervous system, tests of auditory processing abilities must tax the auditory system in order to uncover hemispheric differences (Chermak, 2001). A widely-used metric of interhemispheric differences in auditory processing is the dichotic listening test. In dichotic listening tasks, two different signals are presented to the right and left ears simultaneously. The listener is then asked to repeat which of the two stimuli was perceived (Chermak, 2001).

Kimura (1961a) used a dichotic digits task to further define the functional asymmetry between the right and left cerebral hemispheres in adults with unilateral cerebral damage. Performance on dichotic listening tasks was measured at baseline and after participants underwent unilateral lobectomy. Results of this study revealed three significant findings: 1) Regardless of site of lesion, auditory signals presented to the right ear were reported with more accuracy than signals presented to the left ear; 2) Individuals who underwent left temporal lobectomy performed more poorly than individuals who underwent right temporal lobectomy on repeating digits; and 3) Significant impairment of digit perception was observed in the ear contralateral to the excision (Kimura, 1961a). This impairment was not found in individuals who underwent unilateral frontal lobectomy. Together, these findings reflect the decussation of the central auditory nervous system and the left hemispheric dominance for speech processing (Kimura, 1961a). Kimura (1961b) replicated these findings in individuals with epileptogenic lesions of various parts of the brain and right-handed controls. Participants were divided into two groups: left-hemisphere language dominant and right-hemisphere language dominant, confirmed by the Wada sodium amobarbital procedure discussed earlier. Results revealed that auditory stimuli presented to the ear contralateral to the dominant hemisphere were repeated more accurately than stimuli presented to the ipsilateral ear. Mean performance of the control group also revealed a significant REA, though hemispheric dominance was not confirmed with the Wada procedure for this group. The REA has been demonstrated with a variety of stimuli, including words (Roup, 2011; Shukla, Behere, & Mandal, 1993; Roup, Wiley, & Wilson, 2006), digits (Kimura, 1961a; Kimura 1961b; Martin & Cranford, 1991; Strouse, Wilson, & Bush, 2011), sentences (Jerger et al., 1994), and nonsense syllables (Kimura, 1967).

Older adults have been found to demonstrate a larger REA than younger adults across stimulus types (Martin & Cranford, 1991; Strouse et al., 2011; Roup et al., 2006; Jerger et al., 1995; Jerger & Johnson, 1992; Bellis & Wilber, 2001). Jerger et al. (1994) investigated how aging affects dichotic listening abilities in individuals aged 9-91 years. All age groups demonstrated greater accuracy for signals presented to the right ear; however, the magnitude of the REA grew progressively larger with increasing age. The REA increased from less than 5% in the youngest age group (9-29 years) to greater than 40% in the oldest age group (80-89 years) for verbal stimuli. Information presented to the right ear has preferential access to the language-rich left temporal lobe. Information presented to the left ear, rather, predominantly stimulates the right auditory cortex and must transfer via the corpus callosum to reach the dominant left hemisphere. The increase in the REA in older adults, in the presence of symmetrical hearing sensitivity, is thought to reflect degradation and loss of efficiency in the transfer of auditory information between the two hemispheres of the brain (Bellis & Wilber, 2001; Jerger et al., 1994; Jerger et al., 1995).

Age-related Changes in the Central Auditory Nervous System

The prevalence of sensorineural hearing loss increases with age (Humes et al., 2012; Stach, Spretnjak, & Jerger, 1990; CHABA, 1987; Jerger et al., 1989; Gates & Mills, 2005). Age-related hearing loss, or presbycusis, is characterized by decreased hearing sensitivity in both ears, predominantly in the high frequencies, decreased speech understanding in noise, and slowed central processing of auditory information (Kim &

Chung, 2013; Huang & Tang, 2010; CHABA, 1987; Gates & Mills, 2005). Sensorineural hearing loss has been found to be a primary factor contributing to speech understanding difficulties in the elderly (Humes, 1996). However, the listening challenges that the elderly face are often disproportionate to the degree of peripheral hearing loss, especially in adverse listening conditions (Kim et al., 2006; Noordhock, Houtgast, & Festen, 2001; Halling & Humes, 2000; Gordan-Solant & Fitzgibbons, 1993). Stach et al. (1990) investigated the speech understanding performance of 700 individuals over 50 years of age. Participants were divided in seven equal groups in five-year increments. Results revealed performance on *Phonetically Balanced Words (PB-Words),* an open-set word recognition task performed in quiet, and *Synthetic Sentence Identification (SSI),* a closed-set sentence recognition task performed in noise (0 dB signal-to-noise ratio), declined systematically with increasing age. The difference in scores between the youngest and the oldest age groups were 34% and 61% for monosyllables and synthetic sentences, respectively (Stach et al., 1990). Performance-intensity functions for *PB-words* and *SSI* tasks were established for all participants in each ear. Participants were considered to demonstrate central presbycusis if (1) rollover of *SSI* performance-intensity function exceeded 20%; (2) discrepancy between monosyllables and sentences in quiet exceeded 20%; or (3) absolute *SSI* score was lower than the expected performance based on degree of hearing loss (Stach et al., 1990). The prevalence of central involvement was found to increase systematically with age. The percentage of individuals demonstrating disproportionate speech understanding deficits increased from 17% in the youngest group to nearly 95% in the oldest group. When degree of peripheral hearing loss was controlled for, the relationship between age and prevalence of central involvement remained unchanged (Stach et al., 1990). The documented discrepancy between degree of hearing loss and speech understanding is thought to reflect, in part, age-related changes in the central auditory nervous system.

Myelination of auditory nerve fibers allows for efficient conduction of signals between the ear and the brain (Peters, 2002). Armstrong et al. (2004) revealed that by the 8th decade of life, significant deterioration of myelin occurs in the healthy adult brain. Consequences of demyelination include slowed neural transmission and disrupted neural synchrony, which are believed to contribute significantly to the documented cognitive deterioration in elderly individuals (Peters, 2002). The corpus callosum is known to play a critical role in the interhemispheric transfer of information in the brain (Musiek & Weihing, 2011; Bellis & Wilber, 2011). Neurophysiologic studies indicate that specific regions of the corpus callosum are responsible for the transfer of different sensory information (Musiek & Weihing, 2011). Specifically, the sulcus, the posterior portion of the corpus callosum, has been found to be responsible for the transfer of auditory information between hemispheres in humans (Musiek & Weihing, 2011). Several studies reveal age-related neural degeneration of the corpus callosum in healthy adults (Sullivan, Rohlfing, & Pfefferbuam, 2010; Moseley, 2002; Janowsky et al., 1996; Bastin et al., 2008; Bastin et al., 2010; Raz et al., 2010). Rapid interhemispheric transfer of auditory information relies on the heavily myelinated nerve fibers in the corpus callosum (Musiek

& Weihing, 2011). Silver et al. (1997) revealed significant reduction in callosal myelin and cerebral white matter with increased age through magnetization transfer ratio (MTR) measurements. Documented age-related changes of the auditory system, specifically the neural degeneration and demyelination of the corpus callosum, are believed to explain the increase in REA with age.

Right Ear Advantage and Cochlear Implantation

Given the (1) contralateral dominance of the auditory nervous system; (2) left hemispheric dominance of speech processing; and (3) increasing right ear advantage in older adults, it is of interest to determine if an ear advantage can be observed in adults that receive a unilateral cochlear implant. This work is based on a study out of New York University School of Medicine that compared post-operative speech outcomes between younger adults (18-69 years) and older adults (70+ years) who underwent unilateral cochlear implantation (Budenz et al., 2011). Results revealed a significant REA for older adults on speech understanding tasks (CNC words, CNC phonemes, CUNY sentences) in quiet and in noise. This finding was not demonstrated in the younger group. Results of this study were viewed as surprising, as the REA is not typically demonstrated comparing word recognition abilities in the monaural condition in quiet.

CHAPTER 3

METHODS

The present study aimed to replicate the findings of Budenz et al. (2011). It was expected that older adults who received cochlear implantation in the right ear would demonstrate superior post-operative speech understanding than those implanted in the left ear. Further, this advantage was not expected to exist in younger adults with greater neural redundancy. Since ear of implantation may have predictive value for success with cochlear implants in older adults, this research may subsequently influence clinical decision making in working with this population.

Data Collection

The present study was a retrospective chart review of audiologic records of adults receiving cochlear implant programming from the Oregon Health and Science University Cochlear Implant Program in Portland, Oregon. Approval for this study was obtained through the Oregon Health & Science University Institutional Review Board (IRB# STUDY00015443). The Oregon Clinical and Translational Research Center's (OCTRI) research data warehouse service was utilized to identify patients who had a billing code for cochlear implant activation in EPIC Health Record software. Two data queries were run: one for individuals implanted between the ages of 18-69 years and one for individuals implanted at age 70 years and older. OCTRI released a data set of 2819 medical record numbers of individuals who met criteria for inclusion in this chart review. All of the medical record numbers included in the data set were assigned an identification number, and stripped of all protected health information. The medical records of 270 individuals were reviewed, and 45 individuals were found to meet the defined inclusion criteria.

Participants

All participants were post-lingually deafened adults who underwent unilateral cochlear implantation within the last five years and received implant programming at Oregon Health & Science University Department of Otolaryngology-Head and Neck Surgery. Of the 2819 medical records released from OCTRI data warehouse, 270 medical records were reviewed. Although the data query defined the younger group as individuals 18-69 years, the youngest individual selected for review was implanted at age 45 years. The younger group, therefore, is comprised of individuals implanted between 45-69 years (M=58.66 years, SD= 6.41 years, n=27). This group was comprised of 13 males and 14 females. Twelve individuals in this group were implanted in the right ear and 15 were implanted in the left ear. The older group was comprised of individuals implanted between 70-92 years (M= 78.55 years, SD= 6.05 years, n=18). This group was comprised of 9 males and 9 females. Nine individuals in this group were implanted in the right ear and nine were implanted in the left ear. All three cochlear implant manufacturers (Cochlear Americas, Med-El, Advanced Bionics) are represented in this sample, though

Cochlear Americas and Med-El comprise the majority of implanted devices. *For participant demographics, see Tables 1 and 2*.

Table 1.

Subject ID	Age at Implantation	Gender	Ear Implanted	Device	Etiology
A19	57	M	Right	Cochlear Americas	Ototoxicity
A20	58	M	Right	Cochlear Americas	Genetic
A55	49	F	Right	Advanced Bionics	Infection
A87	60	F	Right	Cochlear Americas	Unknown
A93	53	F	Right	Cochlear Americas	Genetic
A140	63	M	Right	Cochlear Americas	SSHL
A131	59	F	Right	Med-El	Unknown
A21	58	M	Right	Cochlear Americas	Genetic
A1149	56	F	Right	Med-El	Unknown
A125	68	M	Right	Med-El	SSHL
A638	67	M	Right	Med-El	Unknown
A1043	63	F	Right	Med-El	AIED
A255	50	F	Left	Cochlear Americas	Unknown
A261	65	M	Left	Cochlear Americas	Unknown
A27	59	M	Left	Cochlear Americas	Genetic
A24	63	M	Left	Cochlear Americas	Unknown
A82	59	F	Left	Med-El	Genetic
A60	45	F	Left	Med-El	Unknown
A62	49	M	Left	Med-El	Infection
A109	69	F	Left	Cochlear Americas	Unknown
A131	60	F	Left	Med-El	Unknown
A1188	61	F	Left	Med-El	Genetic
A22	58	M	Left	Cochlear Americas	Genetic
A155	60	F	Left	Med-El	Unknown
A352	65	M	Left	Med-El	Noise Exposure
A126	68	M	Left	Med-El	SSHL
A25	69	F	Left	Med-El	Unknown

Table 1. Demographic information of younger adults

Table 2.

Subject ID	Age at Implantation	Gender	Ear Implanted	Device	Etiology
A9	71	F	Right	Advanced Bionics	Unknown
A12	72	F	Right	Cochlear Americas	Unknown
A17	79	F	Right	Cochlear Americas	Meniere's Disease
A23	92	M	Right	Cochlear Americas	Noise Exposure
A151	81	F	Right	Cochlear Americas	Unknown
A197	74	F	Right	Cochlear Americas	Unknown
A648	78	M	Right	Cochlear Americas	Unknown
A1164	88	M	Right	Med-El	Unknown
A240	75	M	Right	Med-El	Noise Exposure
A188	78	M	Left	Cochlear Americas	Infection
A260	75	F	Left	Med-El	Meniere's Disease
A262	77	M	Left	Med-El	Unknown
A2	83	M	Left	Cochlear Americas	Unknown
A12	72	F	Left	Cochlear Americas	Unknown
A38	70	M	Left	Cochlear Americas	Meniere’s Disease
A44	82	F	Left	Cochlear Americas	Unknown
A297	84	F	Left	Cochlear Americas	Unknown
A228	83	M	Left	Cochlear Americas	Unknown

Table 2. Demographic information of older adults

Exclusion Criteria

Individuals were excluded from this review based on a number of factors, including non-native English speakers (n=16), diagnoses of developmental disability or neurological disorder (n=3), care from other clinics prior to OHSU (n=47), explanted and re-implanted (n=4), implanted with a Hybrid electrode array (n=1), underwent an alternative speech testing protocol (n=50), and 10 or more years or more without the use of amplification (n=1). Individuals who had incomplete chart notes due to the age of EPIC electronic medical record software (n=60), and individuals who had not yet been implanted (n=43) were included in the extracted data set, but were not included in actual data collection. In total, 225 patients were excluded from data collection out of the 270 patient records that were reviewed.

Speech Perception Measures

This study examined performance on two speech perception outcome measures: 1) *Consonant-Nucleus-Consonant Word* test; 2) *AZ Bio Sentences* test. All speech perception measures were administered in a sound-attenuated booth in quiet, with participants sitting at 0 degrees azimuth, 3 ft. away from the speaker. All participants were tested in the unilateral-CI condition. All speech perception materials were pre-recorded and administered at 45 dB HL.

The *Consonant-Nucleus-Consonant (CNC) Word test* consists of 500 monosyllabic words organized into phonemically balanced open-set 50-word lists (Lehiste & Peterson, 1959). Each word follows a consonant-nucleus-consonant model, in which the nucleus of the word is either a vowel or diphthong. See Appendix A for a sample *CNC Word* list. Elkins (1970) found the *CNC Word* lists to have balanced phonetic composition to the English language. The patient was instructed to repeat the target word that was preceded by the carrier phrase “Ready”. Scores were reported as the percent of words correctly identified, with three points given for each correct response (Lehiste & Peterson, 1959).

The *AZ Bio Sentences* test consists of 1500 sentences organized into 20-sentence lists (Spahr & Dorman, 2004). Each list consists of sentences spoken with normal conversational inflection and rate by multiple male and female talkers. Each sentence contains 4-12 words. See Appendix B for a sample *AZ Bio Sentences* list. The patient was instructed to repeat as many of the words in the sentence as possible, with one point given for each word repeated correctly. Scores were reported as the percent of words correctly identified out of the total number of words in the sentence list (Spahr & Dorman, 2004).

Procedures

Demographic information, including gender, etiology of hearing loss, age at implantation, ear of implantation, and cochlear implant manufacturer were recorded for each patient. Pre-implantation performance on *AZ Bio Sentences* and *Consonant-Nucleus-Consonant (CNC) Words* in quiet were recorded for each patient. Post-implantation performance was tracked at each patient’s 1-, 3-, 6-, and 12-month diagnostic visits. Participants were divided into two main groups: older adults (70-92 years) and younger adults (45-69 years). Participants were further subcategorized by ear of implantation (right ear or left ear).

The mean performance on *CNC Words* and *AZ Bio Sentences* was compared between groups (younger vs. older adults) using a two-tailed t-test. Improvement on speech perception measures (pre-implantation vs. 6 months post-implantation) was compared between younger and older adults by ear of implantation using a two-tailed t-test. A one-way ANOVA was also used to compare performance at 6 months post-implantation between age groups and ear of implantation. Based on the most complete data set being available at the six-month post-implantation time point, it was selected for analysis. The combination of these results provides information on whether ear-specific differences in performance on speech perception measures exist between and within groups.

CHAPTER 4

RESULTS

All subjects, regardless of age, demonstrated significant improvement on speech perception measures at 6 months post-implantation compared to pre-implantation scores, when ear of implantation was not considered. Younger adults demonstrated significant improvement on *AZ Bio Sentences* (p<.001; paired two-tailed t-test) and *CNC Words* (p<.001; paired two-tailed t-test). Older adults demonstrated significant improvement on *AZ Bio Sentences* (p<.001; paired two-tailed t-test) and *CNC Words* (p<.01; paired two-tailed t-test). When younger adults were compared to older adults, there was no significant difference in performance on *AZ Bio Sentences* (p>.05; two-tailed t-test) and *CNC Words* (p>.05; two-tailed, non-paired, t-test). This suggested that in the select population used in this retrospective study, there was no detectable difference in speech perception performance between younger and older adults when ear of implantation was not considered.

Figure 1.

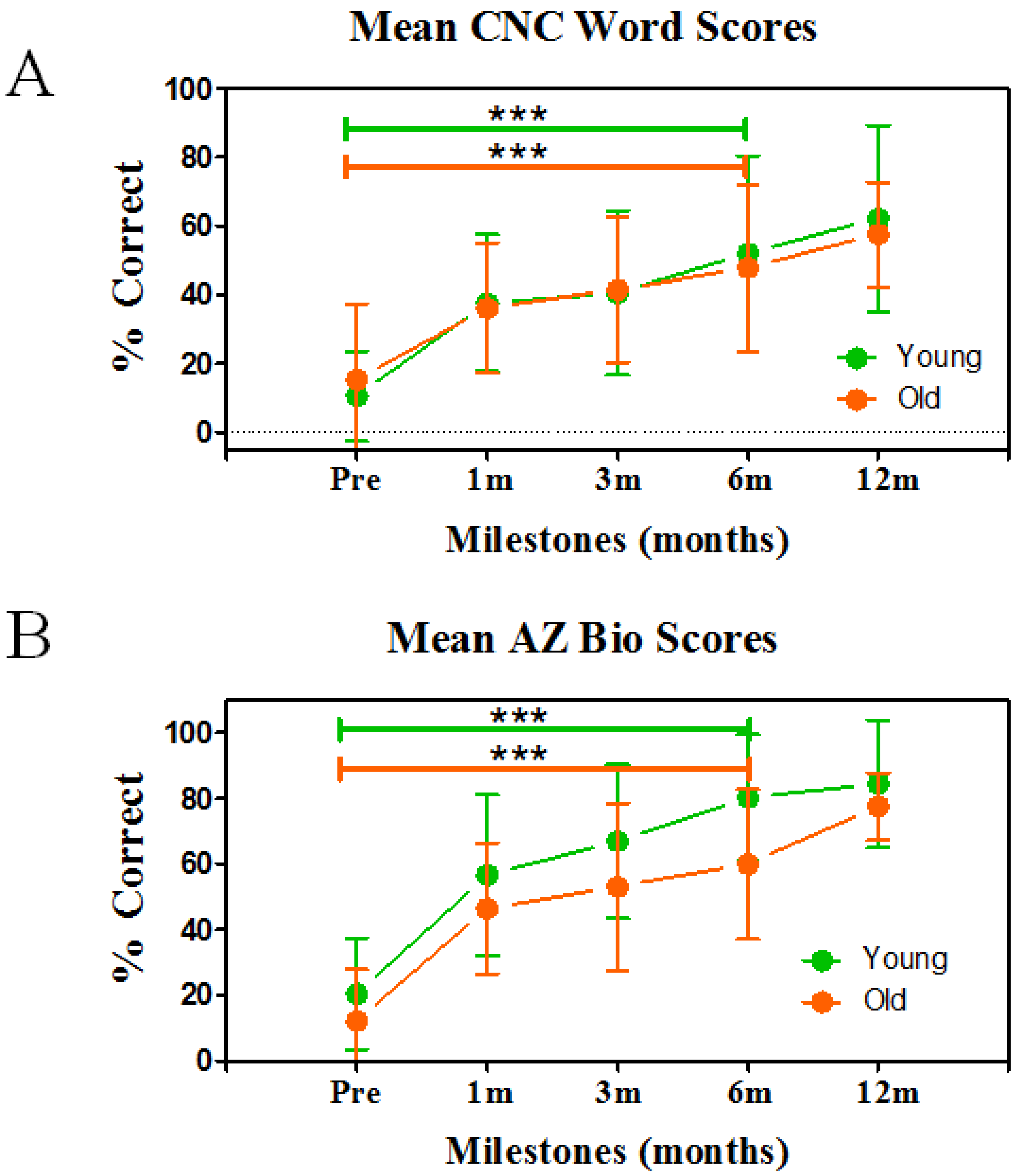


Figure 1. Between-group comparison (younger adults vs. older adults) of mean scores on *AZ Bio Sentences* (A) and *CNC Words* (B).

Within group analysis confirmed significant improvement on speech perception tasks in both younger and older adults, regardless of ear of implantation. A significant improvement on *AZ Bio Sentences* was observed for younger adults implanted in the right ear (p<.001; paired two-tailed t-test) and younger adults implanted in the left ear (p<.001; paired two-tailed t-test). A significant improvement on *CNC Words* was observed for younger adults implanted in the right ear (p<.001; paired two-tailed t-test) and younger adults implanted in the left ear (p<.01; paired two tailed t-test). There was no significant difference in performance on *AZ Bio Sentences* in younger adults implanted in the right ear compared to younger adults implanted in the left ear at six months post-implantation (p>.05; non-paired two-tailed t-test). Younger adults implanted in the right ear performed significantly better on *CNC Words* than younger adults implanted in the left ear at six months post-implantation (p<.05; non-paired two-tailed t-test). These results suggested a possible REA in the younger adult population on *CNC words*. When all subjects (younger adults and older adults) were examined together, there was no significant difference in performance on *AZ Bio Sentences* or *CNC words* between those implanted in the right ear and those implanted in the left ear (p >.05).

Figure 2.

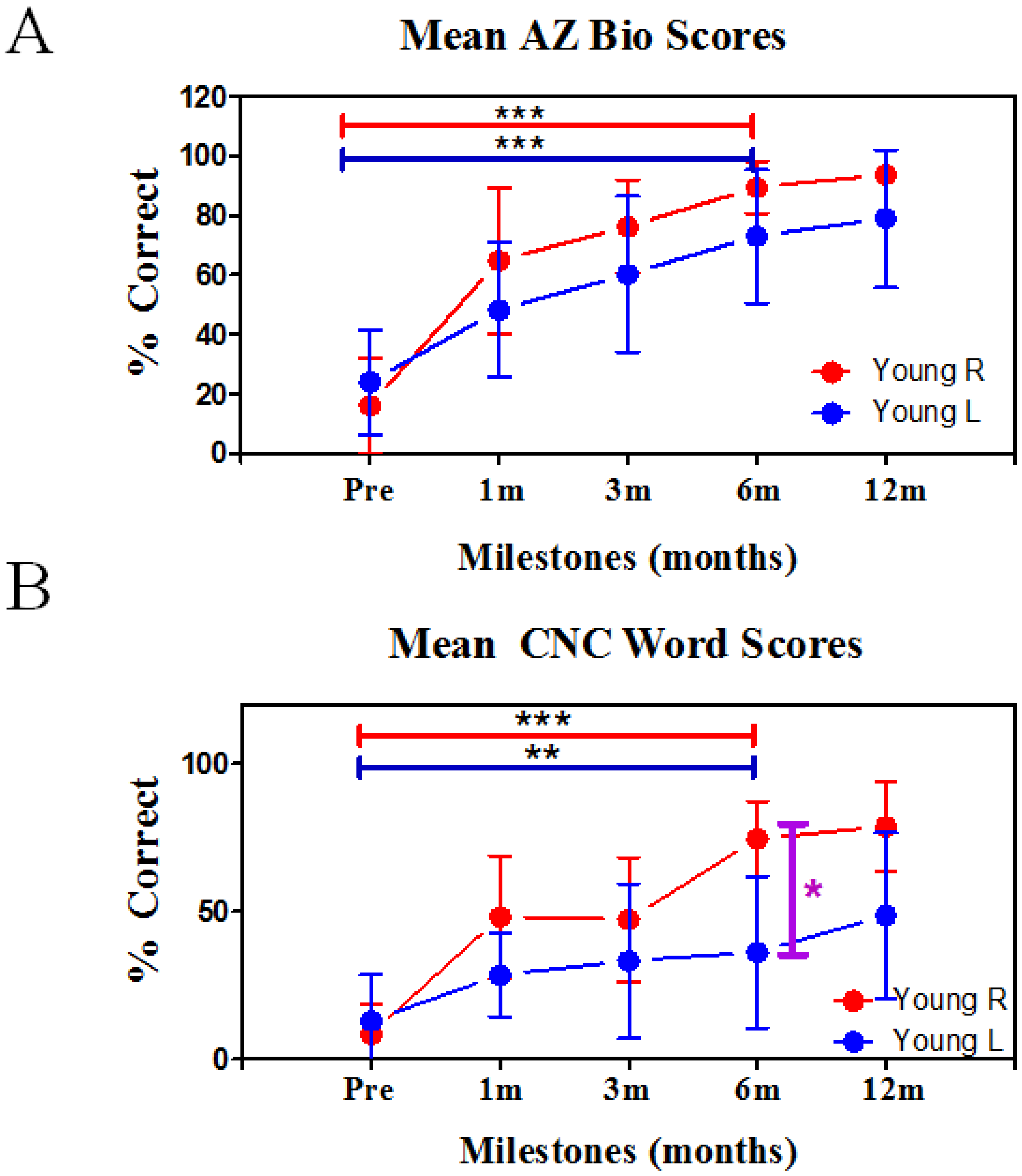


Figure 2. Within-group comparison of mean scores on *AZ Bio Sentences* (A) and *CNC Words* (B) in younger adults by ear of implantation.

Figure 3.

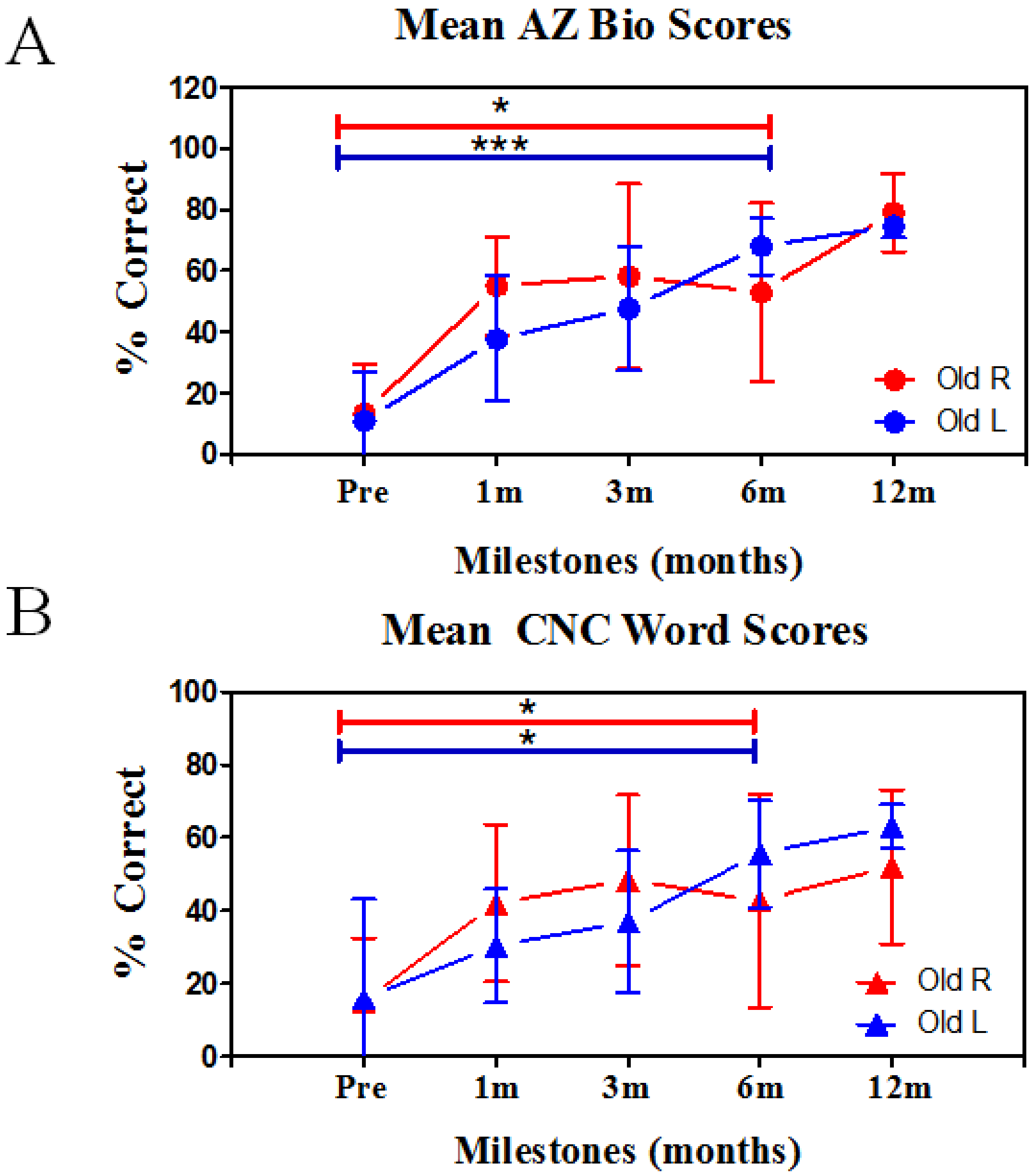


Figure 3. Within-group comparison of mean scores on *AZ Bio Sentences* (A) and *CNC Words* (B) in older adults by ear of implantation

A significant improvement on *AZ Bio Sentences* was observed for older adults implanted in the right ear (p<.001; paired two-tailed t-test) and older adults implanted in the left ear (p<.001; paired two-tailed t-test). A significant improvement on *CNC Words* was observed for older adults implanted in the right ear (p<.001; paired two-tailed t-test) and older adults implanted in the left ear (p<.01; paired two-tailed t-test). There was no significant difference in performance on CNC Words or AZ Bio Sentences between older adults implanted in the right ear and older adults implanted in the left ear (p>.05, non-paired two-tailed t-test).

Table 3.

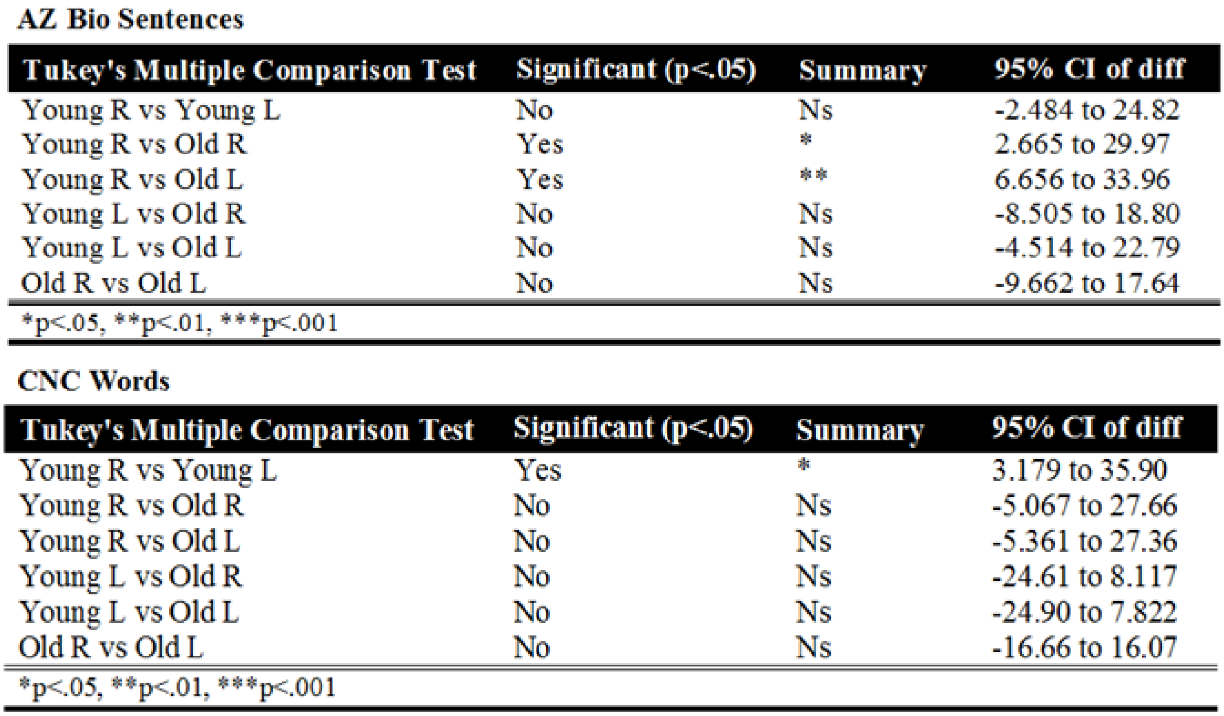
Comparison	Type	Significant (p<.05)	Number of subjects	Summary
Overall Improvement				
Pre CNC vs 6m CNC (Young)	Paired	Yes	10	***
Pre CNC vs 6m CNC (Old)	Paired	Yes	9	***
Pre AZ Bio vs 6m AZ Bio (Young)	Paired	Yes	16	***
Pre AZ Bio vs 6m AZ Bio (Old)	Paired	Yes	13	***
Ear-Specific Improvement (AZ Bio)				
Young Right Pre vs 6m post (AZ Bio)	Paired	Yes	7	***
Young Left Pre vs 6m post (AZ Bio)	Paired	Yes	9	***
Old Right Pre vs 6m post (AZ Bio)	Paired	Yes	7	*
Old Left Pre vs 6m post (AZ Bio)	Paired	Yes	6	***
Ear-Specific Improvement (CNC)				
Young Right Pre vs 6m post (CNC)	Paired	Yes	6	***
Young Left Pre vs 6m post (CNC)	Paired	Yes	8	**
Old Right Pre vs 6m post (CNC)	Paired	No	5	*
Old Left Pre vs 6m post (CNC)	Paired	Yes	3	*
Within Group Right vs Left				
Young Right vs Left at 6m (AZ Bio)	Non-paired	No	7v9	Ns
Old Right vs Left at 6m (AZ Bio)	Non-paired	No	7v6	Ns
Young Right vs Left at 6m (CNC)	Non-paired	Yes	6v8	*
Old Right vs Left at 6m (CNC)	Non-paired	No	5v3	Ns
All Ages Right vs Left at 6m				
Right vs Left (AZ Bio)	Non-Paired	No	14v15	Ns
Right vs Left (CNC)	Non-Paired	No	10v10	Ns

*p<.05, **p<.01, ***p<.001

Table 3. Comparison of improvement on *AZ Bio Sentences* and *CNC Words* (pre-implantation vs. six months post-implantation) by age and ear of implantation using two-tailed t-tests.

When ear-specific performance was compared between the older and younger adult populations at six months post-implantation, younger adults implanted in the right demonstrated superior performance on *AZ Bio Sentences* to older adults implanted in the right ear ($p<.05$; one-way ANOVA). Younger adults implanted in the right ear also performed better than older adults implanted in the left ear on *AZ Bio sentences* ($p<.01$; one-way ANOVA) and *CNC Words* ($p<.05$; one-way ANOVA).

Table 4.



AZ Bio Sentences

Tukey's Multiple Comparison Test	Significant (p<.05)	Summary	95% CI of diff
Young R vs Young L	No	Ns	-2.484 to 24.82
Young R vs Old R	Yes	*	2.665 to 29.97
Young R vs Old L	Yes	**	6.656 to 33.96
Young L vs Old R	No	Ns	-8.505 to 18.80
Young L vs Old L	No	Ns	-4.514 to 22.79
Old R vs Old L	No	Ns	-9.662 to 17.64

*p<.05, **p<.01, ***p<.001

CNC Words

Tukey's Multiple Comparison Test	Significant (p<.05)	Summary	95% CI of diff
Young R vs Young L	Yes	*	3.179 to 35.90
Young R vs Old R	No	Ns	-5.067 to 27.66
Young R vs Old L	No	Ns	-5.361 to 27.36
Young L vs Old R	No	Ns	-24.61 to 8.117
Young L vs Old L	No	Ns	-24.90 to 7.822
Old R vs Old L	No	Ns	-16.66 to 16.07

*p<.05, **p<.01, ***p<.001

Table 4. One-Way ANOVA comparison of performance on *AZ Bio Sentences* and *CNC Words* between younger and older adults by ear of implantation.

CHAPTER 5

DISCUSSION

The present study aimed to determine if ear-specific differences in speech understanding existed in younger and older adults who underwent unilateral cochlear implantation. Three main questions were examined: (1) What is the relationship between ear of implantation and speech perception outcome measures in older adults (70+ years)? (2) What is the relationship between ear of implantation and speech perception outcome measures in younger adults (18-69 years)? and (3) How does the relationship between ear of implantation and speech perception outcome measures in older adults compare to younger adults? Given what is known about the REA and the well-documented age-related changes in the auditory system, it was hypothesized that older adults who received cochlear implantation in the right ear would demonstrate superior post-operative speech understanding to those implanted in the left ear. Further, this advantage was not expected to exist in younger adults who are thought to have greater neural redundancy in the auditory system.

In the current population of younger and older adults used in this retrospective study, there appeared to be a favorable performance for the younger adults group implanted in the right ear. Results indicated that the younger group implanted in the right ear performed significantly better on *AZ Bio Sentences* than older adults implanted in the right ear. Younger adults implanted in the right ear also performed significantly better on *AZ Bio Sentences* and *CNC Words* than older adults implanted in the left ear.

It was not expected that the younger adult group, thought to have greater neural redundancy in the auditory system, would demonstrate a REA. However, it should be noted that the youngest individual selected for review in the present study was implanted at age 45 years. The mean age at implantation of the younger group in the present study was 58.8 years (SD= 6.41 years). The younger group analyzed in the present study is therefore more representative of a population of middle-aged adults.

A body of literature supported that some age-related changes in the auditory system manifested during middle-age. Bellis and Wilbur (2001) revealed decreased interhemispheric transfer of auditory information in adults age 40-55 years, compared to younger adults, through measuring performance on dichotic listening tasks. Middle-aged adults with normal hearing sensitivity have been found to demonstrate poorer word recognition abilities in noise compared to younger adults with normal hearing sensitivity (Leigh-Paffenroth & Saravanan, 2011; Helfer & Vargo, 2009; Kim et al., 2006). This discrepancy between degree of hearing loss and speech understanding in noise compared to younger adults was thought to reflect age-related changes in the central auditory nervous system in middle aged-adults. The REA observed in the population of middle-aged adults in the present study may be a reflection of these age-related changes in the central auditory nervous system.

The results of this study indicated that there was no significant difference in performance on *CNC Words* or *AZ Bio Sentences* between older adults implanted in the right ear and older adults implanted in the left ear. This observation contradicted the findings of Budenz et al. (2011) that a significant REA existed in older adults on speech perception measures performed in quiet. It is possible that degradation to the central auditory nervous system is so widespread in this population that consistent or predictable ear effects are not observed.

Finally, the results of this study revealed that all subjects, regardless of age or ear of implantation, demonstrated significant improvement on speech perception measures following implantation. Further, there was no detectable difference in speech performance between younger and older adults at 6 months post-implantation when ear of implantation was not considered. This finding supported other studies that demonstrated comparable post-implantation speech perception outcomes between younger and older adults (Labadie et al., 2000; Djalilian et al., 2002; Pasanisi et al., 2003; Kelsall, Shallop, & Burnelli, 1995; Olze et al., 2012; Park et al., 2011; Herzog et al., 2003; Budenz et al., 2011; Noble et al., 2009). Similar to younger adults, older adults have also been found to demonstrate significant improvement on quality of life questionnaires following cochlear implantation (Olze et al., 2012; Djalilian et al., 2002; Kelsall et al., 1995; Di Nardo et al., 2014; Vermeire et al., 2005; Noble et al., 2009). Finally, cochlear implantation has been found to be a relatively low-risk surgery, with similar incidence of peri- and post-operative complications between younger and older adults (Kelsall et al., 1995; Lundin et al., 2013; Budenz et al., 2011; Coelho et al., 2009; Eshragi et al., 2009; Carlson et al., 2010). In summary, the literature supported that cochlear implantation is a safe and effective procedure for both younger and older adults, and that individuals should not be denied implantation based on age alone.

Limitations and Future Directions

There are several limitations inherent to studies utilizing a retrospective design (Hess, 2004; Jansen et al., 2005; Wickson-Griffiths et al., 2014). Retrospective studies analyze patient data that is not typically systematically collected for research purposes, and therefore are often limited by insufficient or missing data. Though the Oregon Health & Science University Cochlear Implant Program has an accepted clinic protocol for measuring speech perception performance in all cochlear implant patients, it is not always feasible for patients to follow this schedule for a number of reasons. Scheduling conflicts, cancelled appointments, and time constraints can limit the amount of clinical data collected for each patient. Additionally, clinicians use skilled judgment to deviate from the recommended protocol when it is warranted. One such deviation from protocol occurs when appointment time is spent making extensive changes to cochlear implant mapping, based on patient need, rather than spent administering comprehensive speech perception testing. Many of the subjects in the present study did not have data points for each diagnostic visit, which likely contributed to the large variability in performance throughout the collected time points. *See Table 3 for the number of subjects analyzed at each time point*. In order to address this limitation, performance between age groups and ear of implantation was compared at the six-month post-implantation milestone, as this was the most complete data set available. Another limitation of retrospective chart reviews is the introduction of bias due to the lack of randomization and experimenter blinding (Hess, 2004; Jansen et al., 2005; Wickson-Griffiths et al., 2014). Though the experimenter was not blinded to the hypotheses of the present study, inclusion and exclusion criteria were carefully defined and conformed in order to mitigate selection bias.

Another potential limitation to this study was that dominant handedness was not recorded for each participant. Although handedness has been found to influence language lateralization (Wilson & Leigh, 1996), the vast majority of right and left handed individuals have been found to demonstrate left-hemispheric dominance for language specialization (Rasmussen & Milner, 1977). Therefore, it was not expected the lack of these data would invalidate this study's findings.

Future research on this topic should be performed using a larger sample of adult cochlear implant recipients with more complete speech perception measure data across time points. It would be beneficial to examine ear specific differences in performance in younger adults, middle-aged adults, and older adults to determine if a REA emerges in a consistent pattern by age of implantation. Increasing the understanding of performance patterns could guide clinical decision making toward choosing the right ear for implantation in adults with symmetrical hearing loss, if all other factors (duration of deafness, use of amplification, vestibular function, pre-operative speech outcomes, anatomy, etc.) are similar between ears. If ear of implantation holds predictive value for success with cochlear implantation, this research could improve post-operative speech perception outcomes for individuals undergoing unilateral cochlear implantation.

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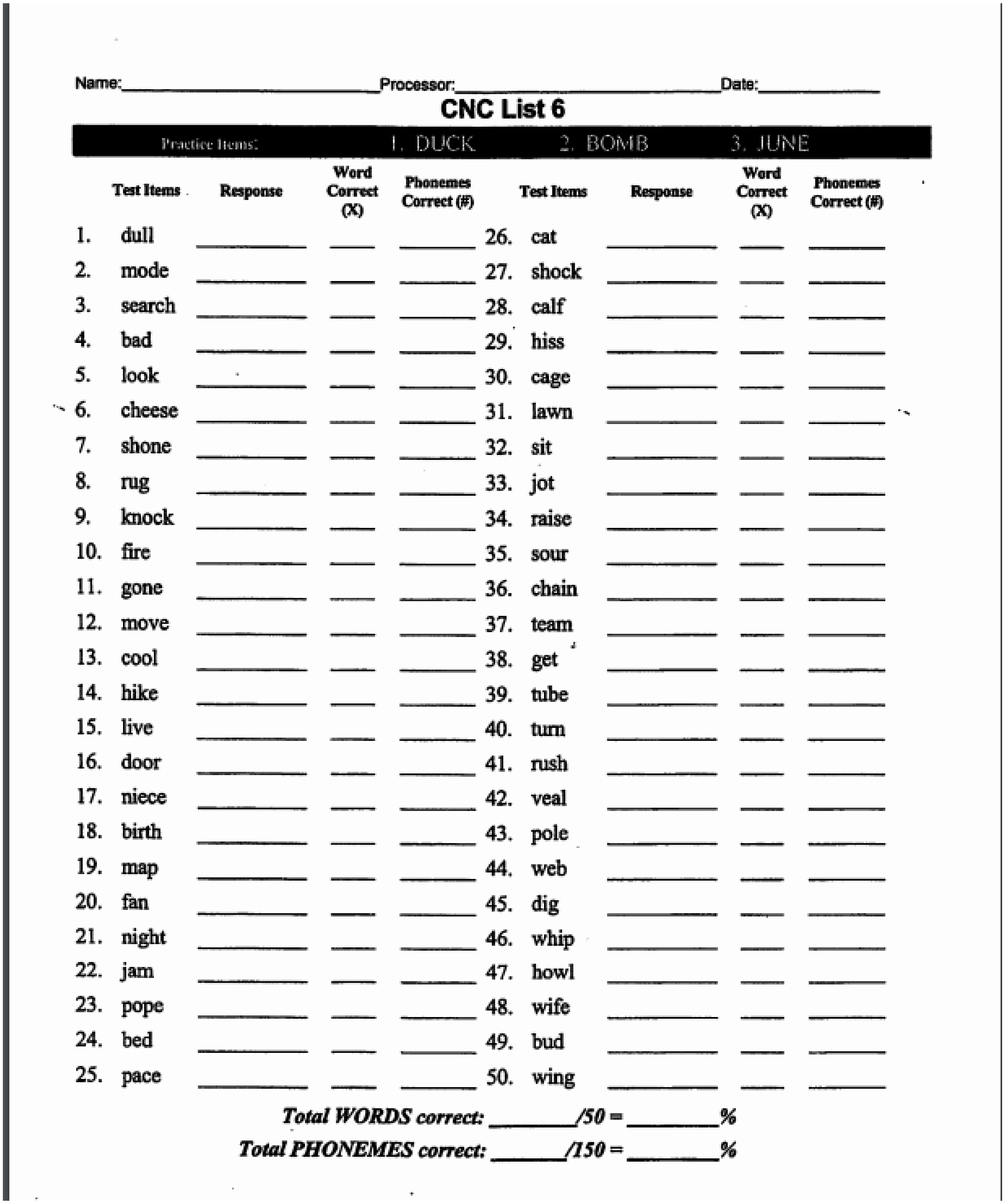
APPENDIX A



Name:____________________________Processor:______________________________Date:______________

CNC List 6

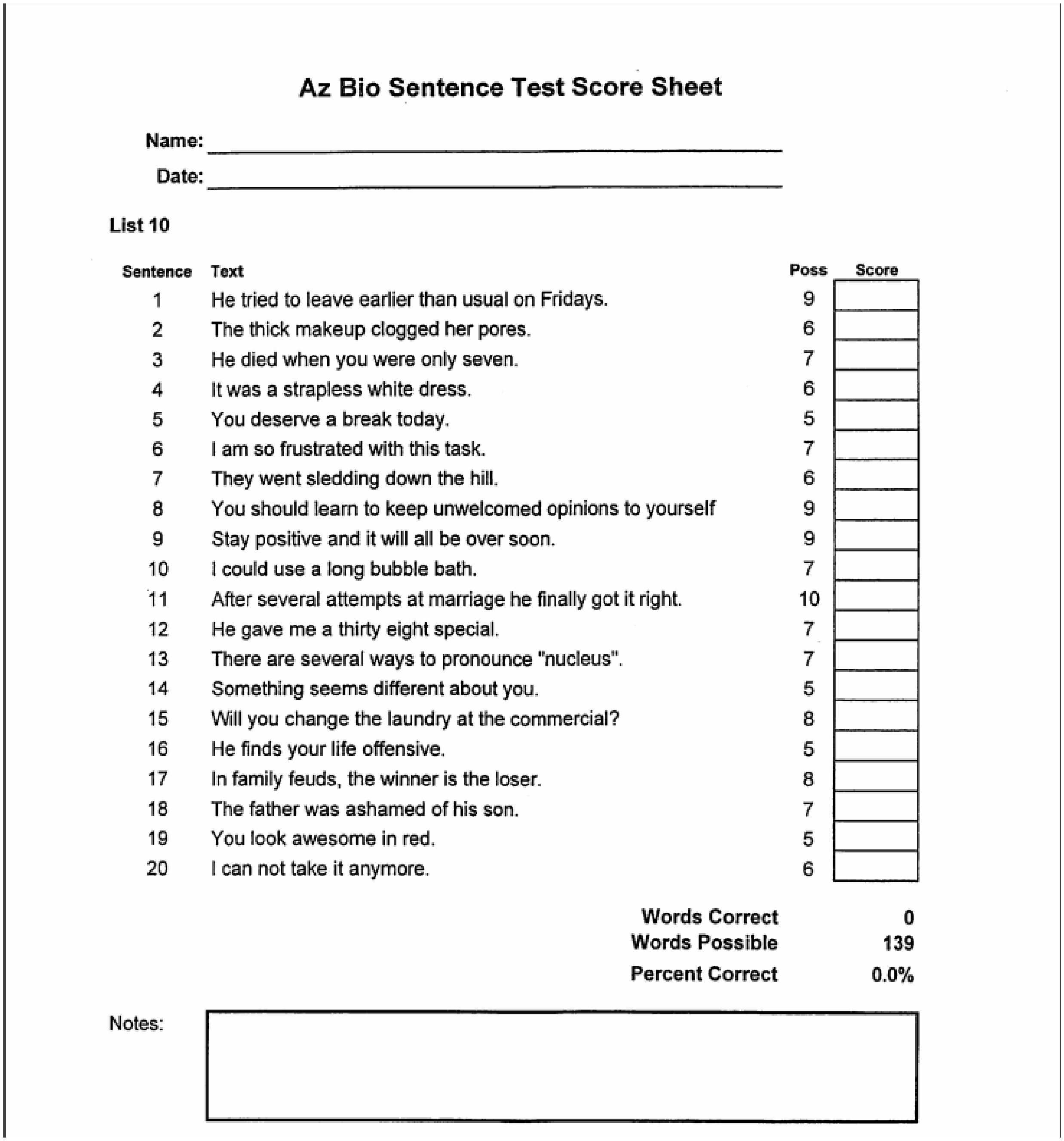
Practice Items: 1. DUCK 2. BOMB 3. JUNE

	Test Items	Response	Word Correct (X)	Phonemes Correct (#)		Test Items	Response	Word Correct (X)	Phonemes Correct (#)
1.	dull				26.	cat			
2.	mode				27.	shock			
3.	search				28.	calf			
4.	bad				29.	hiss			
5.	look				30.	cage			
6.	cheese				31.	lawn			
7.	shone				32.	sit			
8.	rug				33.	jot			
9.	knock				34.	raise			
10.	fire				35.	sour			
11.	gone				36.	chain			
12.	move				37.	team			
13.	cool				38.	get			
14.	hike				39.	tube			
15.	live				40.	turn			
16.	door				41.	rush			
17.	niece				42.	veal			
18.	birth				43.	pole			
19.	map				44.	web			
20.	fan				45.	dig			
21.	night				46.	whip			
22.	jam				47.	howl			
23.	pope				48.	wife			
24.	bed				49.	bud			
25.	pace				50.	wing			

Total WORDS correct: ________/50 = ________%

Total PHONEMES correct: _______/150 = ________%

APPENDIX B



Az Bio Sentence Test Score Sheet

Name: ______________________

Date: ______________________

List 10

Sentence	**Text**	**Poss**	**Score**
1	He tried to leave earlier than usual on Fridays.	9	
2	The thick makeup clogged her pores.	6	
3	He died when you were only seven.	7	
4	It was a strapless white dress.	6	
5	You deserve a break today.	5	
6	I am so frustrated with this task.	7	
7	They went sledding down the hill.	6	
8	You should learn to keep unwelcomed opinions to yourself	9	
9	Stay positive and it will all be over soon.	9	
10	I could use a long bubble bath.	7	
11	After several attempts at marriage he finally got it right.	10	
12	He gave me a thirty eight special.	7	
13	There are several ways to pronounce "nucleus".	7	
14	Something seems different about you.	5	
15	Will you change the laundry at the commercial?	8	
16	He finds your life offensive.	5	
17	In family feuds, the winner is the loser.	8	
18	The father was ashamed of his son.	7	
19	You look awesome in red.	5	
20	I can not take it anymore.	6	

Words Correct	**0**
Words Possible	**139**
Percent Correct	**0.0%**

Notes: