Spring 2012

The evaluation of interhemispheric transfer time (IHTT) in adults

Katherine Elise Cormier

THE EVALUATION OF INTERHEMISPHERIC

TRANSFER TIME (IHTT) IN ADULTS

by

Katherine Elise Cormier, B.A.

A Dissertation Presented in Partial Fulfillment
of the Requirements for the Degree
Doctor of Audiology

COLLEGE OF LIBERAL ARTS
LOUISIANA TECH UNIVERSITY

May 2012

LOUISIANA TECH UNIVERSITY

THE GRADUATE SCHOOL

March 12, 2012

Date

We hereby recommend that the dissertation prepared under our supervision by Katherine E. Cormier

entitled

The Evaluation of Interhemispheric Transfer Time (IHTT) in Adults

be accepted in partial fulfillment of the requirements for the Degree of

Audiology

Supervisor of Dissertation Research

Head of Department

Department of Speech

Department

Recommendation concurred in:

Advisory Committee

Approved:

Director of Graduate Studies

Dean of the College

Approved:

Dean of the Graduate School

GS Form 13a
(6/07)

ABSTRACT

The goal of the present study was to develop an objective technique to measure interhemispheric transfer time (IHTT) of linguistic stimuli using late auditory evoked potentials to develop normative data in adults. Nine participants, five females and four males (M = 25.22) were included in this study. Each participant had their hearing tested and electrodes were placed on the forehead, tip of the nose, below the right eye and several places on the scalp. The results revealed that when comparing electrode sites (CZ, C3, and C4), waves (P1-N1-P2) and ears (right ear and left ear) there was no statistically significant effect for electrode sites and ears; however, there were for waves. There also were no significant interactions when comparing electrodes to waves, waves to ears, or electrodes to waves to ears. There was also comparison to determine which waves were significantly different from the others. Analysis did not indicate any statistically significant differences between waves P1-N1-P2 when compared for the right versus the left sides. Overall results revealed consistently shorter latencies when the left ear was stimulated compared to when the right ear was stimulated. These results were unexpected and further research is needed with a larger sample size to fully understand how the human auditory system works.

APPROVAL FOR SCHOLARLY DISSEMINATION

The author grants to the Prescott Memorial Library of Louisiana Tech University the right to reproduce, by appropriate methods, upon request, any or all portions of this Dissertation. It is understood that "proper request" consists of the agreement, on the part of the requesting party, that said reproduction is for his personal use and that subsequent reproduction will not occur without written approval of the author of this Dissertation. Further, any portions of the Dissertation used in books, papers, and other works must be appropriately referenced to this Dissertation.

Finally, the author of this Dissertation reserves the right to publish freely, in the literature, at any time, any or all portions of this Dissertation.

Author Katherine E. Cormier

Date 03/12/2012

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGMENTS

I would like to thank all individuals who provided support throughout the preparation of this dissertation. A special thank you is given to the director of my dissertation committee, Sheryl S. Shoemaker, Ph.D., Au.D., CCC-A for her time, support, and commitment to this dissertation. In addition, I would like to thank, Matthew D. Bryan, Au.D., CCC-A and Melinda F. Bryan, Ph.D., CCC-A for their assistance and support throughout this process. I would also like to thank Sam Atcherson, Ph.D. for allowing us to use equipment for the electrophysiological testing. Lastly, I would like to thank Colby, my family, classmates, and friends for their support throughout these last few years.

CHAPTER I

INTRODUCTION

Language is a complex process that refers to an individual's ability to acquire a set of skills that allows for communication. Not only do humans need a peripheral auditory mechanism to detect speech, but they also depend on higher order cognitive functions to process this information. Speech is comprised of frequency, intensity, and temporal cues; each component processed at different levels in the auditory system (Scott & Wise, 2004). All auditory signals eventually arrive at the primary auditory cortex (i.e. Heschl's gyri) located in each of the cerebral hemispheres; however, once a speech signal reaches the auditory cortex, it travels the appropriate pathway to reach the language centers. As will be discussed in greater detail later, the contralateral auditory pathway, first crossing at the level of the brainstem, is found to be the strongest and fastest pathway for sound; thus the majority of sound travels to the opposite hemisphere (Fujiki, Jousmaki, & Hari, 2002; Hall & Goldstein, 1968; Mononen & Seitz, 1977). In other words, signals presented to the right ear travel to the left hemisphere and vice versa. This transfer of information from one hemisphere to the other is accomplished via a highly myelinated band of fibers called the corpus callosum. For years, it has been known that the left hemisphere of most right-handed individuals is dominant in processing verbal language-related stimuli (Bryden, 1965; Kimura, 1967; Kimura & Folb, 1968; StuddertKennedy & Shankweiler, 1970), while left-handed individuals comprise a more heterogeneous population (Dee, 1971). Behaviorally, a way to identify that the left hemisphere is dominant for language is via a right-ear advantage (REA) on dichotic test items. Dichotic testing is defined as an auditory presentation involving two different stimuli of a similar nature that are presented at the same time and require the participant to respond to both stimuli in the same manner (Mononen & Seitz, 1977).

In 1963, Kimura identified children as young as four years scored significantly better in the right ear than the left ear for dichotic listening and this has been labeled as a right ear advantage. Furthermore, this right ear advantage exists until approximately 11-12 years at which time the corpus callosum has completely myelinated and has reached adult-like functionality (Moncrieff & Musiek, 2002). This results in equivalent auditory performance in both ears on dichotic listening procedures. Therefore, one way to assess corpus callosum maturation has been through dichotic testing.

A second way in which dichotic listening has been used is through studying laterality, testing of the left and right auditory cortices separately (Bryden, 1988). With dichotic listening, Kimura (1961) found the contralateral auditory pathway to be more efficient. That is, dichotic listening tests (DLTs) that use linguistic stimuli, typically yield higher scores for the right ear over left-ear scores, reflecting left dominance for language processing (Hynd & Obrzut, 1979). Nonlingustic stimuli (e.g., dichotic cords or digits) produce a left-ear advantage (Speaks & Niccum, 1977; Keith, 2000).

While there are behavioral measures that can be used to assess maturation of the corpus callosum and both behavioral and electrophysiological data that support laterality of stimuli, data is lacking for assessing the auditory maturation of the corpus callosum in a neurophysiologic manner. One possible way of studying the maturation is by estimating interhemispheric transfer time (IHTT) through scalp-recorded late auditory evoked potentials (AEP). Interhemispheric transfer time is a measure of the speed by which information is transferred between hemispheres (Saron & Davidson, 1989). Age-related changes in the AEP latency and amplitude show that neural synchrony required for specific tasks continues to be polished through adolescence.

This study is the first in a series of studies with the ultimate goal of developing an objective technique to measure interhemispheric transfer time (IHTT) of linguistic stimuli using late auditory evoked potentials. Specifically, this study used a monaurally presented /da/ stimulus to right and left ears separately in adults to determine if latency differences existed between the two hemispheres. This, in turn, will hopefully provide researchers with an objective measure of the corpus callosum function of auditory and language processing in adults.

CHAPTER II

REVIEW OF LITERATURE

Anatomy and Physiology of the Auditory Cortex

The auditory system is comprised of the peripheral and central systems. The peripheral system encompasses the outer, middle, and inner ear systems while the central system includes the brainstem and primary auditory cortex. The brainstem is composed of the cochlear nucleus (CN), the superior olivary complex (SOC), the lateral lemniscus (LL), and the inferior colliculus (IC). The medial geniculate body (MGB) is located in the thalamus and the primary auditory cortex is located in the temporal lobe of each hemisphere of the brain.

While the peripheral auditory system is important to central auditory processing, the primary focus of this section focuses on the central auditory structures. As the eighth cranial nerve exits the internal auditory meatus it joins with the CN at the cerebello-pontine angle. Here it receives ipsilateral input sending auditory information to its three nuclei: the anterior ventral cochlear nucleus (AVCN), the posterior ventral cochlear nucleus (PVCN), and the dorsal cochlear nucleus (DCN). The AVCN and PVCN carry information to the ipsilateral and contralateral superior olivary complex (SOC) by way of the ventral acoustic stria and the intermediate acoustic stria, respectively. The SOC - first major area for contralateral crossover - contains three nuclei: the medial nucleus of the trapezoid body (MNTB), the lateral superior olive (LSO), and the medial superior olive (MSO). The MNTB transmits information to the contralateral LSO. The main function of the LSO is to use high frequencies to code for intensity differences while the MSO uses low frequencies to code for temporal differences, both of which assist in localization of a sound source (Musiek & Baran, 1986). Projections running from the SOC travel through a fiber tract called the lateral lemniscus (LL). The LL consists of dorsal and ventral nuclei and project to the inferior colliculus (IC).

The IC is the second major area where fibers cross. It also acts as the primary relay center between ascending projections from the lower portion of the brainstem and the ascending projections to the thalamus (Johnson, Nicol, Zecker & Kraus, 2008). The IC has a commisure of probst that permits neural communication between the left and right IC (Musiek & Baran, 1986). The IC is composed of the dorsal cortex, pericentral nucleus, and the central nucleus. The pericentral nucleus is in charge of auditory and somatosensory information.

Fiber projections from the IC travel via the brachium and terminate at the level of the thalamus in the medial geniculate body (MGB). The MGB has a medial, dorsal, and ventral nucleus. The medial nucleus is thought to act as an arousal to the auditory system and the dorsal nucleus is thought to function to direct attention to an auditory signal (Musiek & Baran, 1986). The ventral nucleus, which receives the majority of auditory input, is important for receiving information related to frequency, intensity, and location of sound (Musiek & Baran, 1986).

The ventral and dorsal portions of the MGB transmit fibers to the planum temporal and transverse temporal Heschl's gyri (Hackett, 2008). Heschl's gyri, considered to be the primary auditory cortices, are located in the superior temporal gyrus and ventral portions of the lateral sulcus (Hackett, 2008). Hackett (2008) describes the cortex as consisting of three areas known as the core, belt, and parabelt. Each core area projects to a bundle of adjacent belt areas and it is the core areas that are responsible for activating those specific belt areas (Kaas & Hackett, 2000). The core also has major interhemispheric connections. The belt area is a narrow two to three millimeter piece of the cortex that surrounds the core with thick interconnections with the core and has shown to receive most of its inputs coming from the dorsal and medial divisions of the MGB (Kaas & Hackett, 2000). The belt consists of eight auditory areas and each area has discrete representations as that first found in the cochlea. Although the neurons in the belt respond less vigorously to tones than the core, they can respond well enough to show tonotopic orientations (Kaas & Hackett, 2000). Neurons located in the lateral portion of the belt respond better to narrow bands of noise than pure-tones (Kaas & Hackett, 2000). Besides the belt having connections with the core, it also has connections with adjacent belt areas. More specifically, it connects with more distal belt areas, the parabelt region as well as the frontal lobe (Kaas & Hackett, 2000). The parabelt region lies laterally to the lateral belt and receives input from the dorsal and medial divisions of the MGB (Kaas & Hackett, 2000).

Once linguistic signals reach the auditory cortex, it is sent from Heschl's gryi to Wernicke's area (also known as Broadmans 22) --the receptive language center. If a motor response is required, it then spirals around by way of the arcuate fasiculus to

Broca's area. While auditory cortices are present in both hemispheres, language centers (i.e., Wernicke's and Broca's) are typically located in only one hemisphere, usually the left. An auditory signal directed to the right ear crosses at the level of the SOC has direct access to the language centers. However, an auditory signal delivered to the left ear arrives at the right hemisphere but must cross to Wernicke's area in the left temporal lobe via the corpus callosum.

Research suggests that the myelination process of cortical structures is a critical part of childhood development and the corpus callosum is one of the last pathways to fully develop (Cherbuin, 2005). The corpus callosum is the main fiber tract connecting the two cerebral hemispheres allowing for the transfer of information from the right hemisphere to the left hemisphere and vice versa. It comprises axons connecting the two cerebral hemisphere's cortices and is the principal white matter fiber bundle in the brain (Mooshagian, 2008).

The corpus callosum contains homotopic and heterotopic fiber connections. Homotopic fibers are those that connect an area in one hemisphere with the same area in the opposite hemisphere. Heterotopic fibers connect areas in one hemisphere to different areas in the opposite hemisphere (Cherbuin, 2005). The corpus callosum contains two types of fibers: larger diameter fibers and small diameter fibers (Bloom & Hynd, 2005). Large diameter fibers mediate sensory-motor coordination, whereas small diameter fibers mediate association areas (Bloom & Hynd, 2005). It is the small diameter fibers that are thought to be important in the excitation and inhibition balance between the two hemispheres (Yazgan, Wexler, Kinsbourne, Peterson, & Leckman, 1995).

The corpus callosum is divided into three portions: the splenium and isthmus; the trunk/body; and rostrum or genu. The splenium is located in the posterior portion and contains visual fibers (Funnell, Corballis, & Gazzaniga, 2000). The isthmus is located in the anterior portion of the splenium and posterior portion of the trunk. The isthmus is thought to have connections with the parasylvian regions (Aboitiz, Ide, & Olivares, 2002) and fibers from the primary and secondary auditory cortices. The trunk/ body lie in the middle of the corpus callosum and contain fibers from the occipital, parietal, and frontal lobes. The anterior portion of the corpus callosum, the rostrum and genu, contains fibers important for the sense of smell.

The corpus callosum comprises millions of fibers and the distribution of these fibers varies across the different regions (Cherbuin, 2005). The thickest portion (i.e. the portion of the corpus callosum containing the greatest number of fibers) is the isthmus (Cherbuin, 2005). According to Cherbuin 2005, it is the isthmus where information travels the fastest in turn creating a faster transfer time between hemispheres.

The myelination process during childhood is an ongoing process, which continues well beyond adolescences. Yakovlev and Lecours (1967) studied the corpus callosum and its myelination process in 200 normal infant brains from the fourth month of life until one year of age. They found that myelination begins around the fourth month of life and continues until approximately age 10. Research conducted by Yakovlev and Lecours (1967) concluded that the corpus callosum continues to mature at the same rate of human behavioral maturation.

Dichotic Listening

A way to measure maturation of the corpus callosum in the auditory domain is through dichotic testing. Dichotic testing can be defined as an auditory presentation mode involving two different stimuli of a similar nature that are presented at the same time and require the participant to respond to both stimuli in the same manner (Mononen & Seitz, 1977). In the past, dichotic testing has predominantly been used with behavioral tests to determine hemispheric lateralization; that is, studying functional laterality in which the left and right auditory cortices are tested separately (Bryden, 1988).

Lateralization is defined as the tendency for certain processes to be more developed on one side of the brain than the other (Mononen & Seitz, 1977). Behavioral studies conducted by Kimura (1961) revealed an advantage of the contralateral auditory pathway in humans. It has been established that for dichotic presentations, the contralateral pathway from the ear to the opposite hemisphere is more efficient.

Specifically, Kimura (1961) conducted a study to determine if the right ear was more strongly connected to the left temporal lobe compared to the left ear. She hypothesized that verbal material transmitted to the hemisphere that is dominant for the recognition of speech (e.g., the left hemisphere) would be more efficient when using dichotic stimuli. Also, she hypothesized that participants with the language center in the right hemisphere would show better recognition from verbal material presented to the left ear. This study included 120 patients at the Montreal Neurological Institute with lesions of different parts of the brain. A dual channel tape recorder with earphones was used for all testing. Digits were presented through earphones in groups of six with half presented simultaneously to the left ear and the other half to the right ear. After each group of digits, the subject was to report what was heard in any order. For the majority of the test, the six numbers were presented as three pairs. In other words, two different numbers were presented simultaneously to the two ears. The researcher discovered that the right ear score was consistently better than the left ear score. Kimura (1961) concluded that when speech was presented to the right ear, it apparently had a more direct route to the language hemisphere. This conclusion correctly supported her hypothesis that the contralateral auditory pathway is stronger than the ipsilateral pathway.

The main findings from dichotic listening studies such as the one above have found that participants with left-hemispheric language lateralization are faster and more accurate at reporting verbal items presented to the right ear (Kimura, 1961). However, a left ear advantage has been shown for tasks that involve musical and environmental recognition (Boucher & Bryden, 1997; Branacucci & San Martini, 1999, 2003). This is due to the fact that in the majority of humans the right hemisphere is dominant for music, spatial and visual abilities (Kimura 1961). Research has found that the binaural input of speech (i.e. same information to each ear) is represented in both hemispheres with an advantage for the contralateral pathway over the ipsilateral pathway for both the latency and amplitude of the response (Hall & Goldstein, 1968; Fujiki, Jousmaki & Hari, 2002). According to Kimura's (1967) structural theory, during dichotic listening tasks, the ipsilateral pathway is inhibited by the contralateral. In other words, when linguistic information is presented to the right ear it directly reaches the left auditory cortex. When linguistic information is presented to the left ear, it reaches the right hemisphere and has to then cross over the CC to reach the language center. The structural theory originated from studies of split-brain patients who participated dichotic listening tasks where they were required to repeat words presented monaurally to each other. However, when the words were presented dichotically, the participants had difficulty reporting words that were presented to the left ear. (Milner, Taylor, & Sperry, 1968; Sparks & Geschwind, 1968; Springer & Gazzaniga, 1975).

In a study conducted by Moncrieff and Wertz (2008), they sought to test the feasibility of an auditory training paradigm designed to remediate dichotic listening deficits in children in a two-phase clinical trial. Eight children, 7 to 13 years of age (M = 9.7 years) were included in the first trial. The goal of phase I was to establish protocol. The dichotic digits test was used to assess each child's dichotic listening performance. Two digits were presented to each ear and the child was asked to repeat both pairs of digits he or she heard. The number of correctly repeated digits were recorded and changed into a percentage. Each child was tasked with a low pass filtered speech (LPFS) and the frequency pattern test (FPT). For the LPFS test, 30 words were presented to each child and they were asked to repeat what they heard. For the LPT, each child was to listen to a pattern (e.g., high-high-low, low-high-low). If the child was unable to verbally repeat the patterns, the test was repeated and the child was asked to hum the pattern of the tones. Children were picked to participate in the phase I trial if the scores of the dichotic digit test revealed an interaural asymmetry due to poorer performance from left ear compared to the right ear.

During the training, test material was presented from the right speaker at either 0 or 10 dB HL and to the left speaker at 30 or 40 dB HL. The researchers' rationale was to suppress the right ear in order to improve the performance in the left ear. For the dichotic digits tasks, children were asked to repeat what was most easily heard; and for sentences, they were asked to repeat only what was heard from the left ear while ignoring the right ear. When performance reached between 70-100%, intensity of material presented to the right ear was increased thus making the task more difficult; however, if performance decreased, the intensity of the material presented from the left side was raised or intensity was decreased from material presented from the right side.

The researchers found that seven out of the eight children had improvements in their left ear performance from this type of training. Phase II of the clinical trial was used to determine the frequency and number of training sessions necessary to increase dichotic listening performance. Training was completed in the same manner as phase I. For phase II, the researchers found that children showed benefit in dichotic listening performance from twelve to twenty-four more training sessions for dichotic testing.

Dichotic Testing and Maturation

While using dichotic stimuli to determine lateralization of language is an important diagnostic, this stimuli has been widely used to assess the maturation of the auditory system. Since dichotic listening tests (DLTs) have been used to assess maturation of the auditory nervous system in children and adolescents, researchers Mukari, Keith, Tharpe and Johnson (2006) conducted a study for developing DLT normative data in order to make decisions about whether a child's auditory system is developing normally. Developing normative data also allows one to monitor performance over time.

Each participant (ages 6-11 years of age) was tested with single pair and double pair dichotic digits tests using free recall (repeating what they heard in no particular order), directed right-ear first (repeating what they heard in the right ear first), and directed left-ear (repeating what they heard in the left ear first). Single digits resulted only in a small right ear advantage that did not show any improvement as age increased; however, left ear scores improved up to 6-7 years of age and were stable there after. For the double-digits dichotic test, test scores revealed lower right and left-ear scores and both ears showed improvement as age increased which supported other research that right-ear scores plateau about puberty (Keith, 2000). The greater right-ear scores compared to left-ear scores also relates to the findings of the left-hemisphere dominance for language concept proposed by Kimura (1961, 1963).

Kimura (1963) conducted a study to find when the right-ear advantage (REA) began to show improvement and at which age speech becomes lateralized in the brain. Included in this study were 120 right-handed children, 4 to 9 years of age. The test material consisted of spoken digits that were presented simultaneously to the two ears. The groups of digits consisted of one pair, two pairs, or three pairs of digits and the subject was instructed to report what he/she heard in any order. Kimura found for each group of children tested, the digits that arrived at the right ear were more easily recognized than those that arrived at the left. She also found a decrease in the difference between the ears for older groups. In other words, as the individual aged, the transfer of linguistic information between hemispheres decreased. Overall, Kimura showed that as early as four years of age, spoken material arriving at the right ear is more accurately reported than spoken material arriving at the left ear. This suggested that the left cerebral hemisphere dominance for speech is established by at least four years of age and possibly earlier. Behavioral testing can be influenced by factors such as age, attention, motivation, memory, cognition etc., These factors, in turn make it difficult to rely on test results.

Therefore, an objective measure needs to be assessed in order to obtain reliable information regarding the transfer of stimuli from hemispheres. An objective measure does not need participation from the individual, which rules possible interference.

Auditory Late Responses (ALRs)

Auditory evoked potentials are used in research as a tool to measure auditory function in clinical and research populations. Auditory evoked potentials are small neuro-electric voltages of activity originating from the peripheral and/or central nervous systems in response to sound (Abrams & Kraus, 2008). Evoked potentials are an important, complex source of information, which provide information about the maturation of the central nervous system's pathways as well as structures, which are activated through auditory stimulation (Ponton, Eggermont, Kwong & Don, 2000). The response is recorded using a non-invasive approach consisting of multiple electrodes placed on the scalp including one labeled as the "common ground," which takes an average response from all other electrodes. The auditory late response (ALR) components are recorded in a time frame from about 50 to 400 ms after the onset of the acoustic stimulation. The main components of an ALR waveform consist of P1 occurring around 50 to 80 ms, N1 occurring around 100 to 150 ms and P2, which occurs around 150 to 200 ms. The N1 component receives input from primary auditory cortex and the supratemporal plane, which is found on the anterior portion of this region (Hall, 2007). It has also found that both tonal and speech stimuli elicits the N1 and P2 components which are both generated in the auditory cortex (Hall, 2007). The stimuli for an ALR can be a tone-burst as well as speech-like in nature (e.g., /da/, /ga/). The recording takes duration of 10 ms-50 ms-10 ms and a filter of .1 to 100 Hertz (Hz). Typically, the ALR is measured using an intensity of 70 dBnHL (Hall, 2007; Ponton et al., 2000). An ALR response is commonly affected by the arousal state of a patient, therefore, he/she needs to be alert (Hall, 2007). The ALR is also highly dependent on interstimulus interval or ISI (Hall, 2007; Ponton et al., 2000). The auditory late response (ALR; cortex) is mature at approximately 12 years of age (Ponton et al., 2000; Ponton, Moore & Eggermont, 1999). Previous research has shown that latencies change gradually with age; however, amplitude makes abrupt changes over time (Ponton et al., 2000)

Electrophysiological studies. Because of their behavior-independent nature, evoked potentials are ideal for examining the effects of subtle manipulations of the speech signal without relying on subjective behavioral responses (Kraus & Nicol, 2003). Researchers Kraus and Nicol (2003) stated that because evoked responses depend on synchronous activation, they are uniquely suited for examining the underlying neural bases of speech perception.

Specifically, Ponton, Eggermont, Kwong, and Don (2000) investigated the maturation of the central auditory system using multi-electrode recordings of AEPs. The purpose of this study was to provide a more in-depth description of the AEP maturation beginning from early childhood continuing through adulthood. The researchers focused on amplitude and latency changes of the AEP (specifically the P1, N1, P2 complex) due to age-related factors. Included in this study were 14 different age groups between the ages of 5 and 20 years. Thirty electrodes were placed on the scalp of each participant with the reference electrode being placed at the forehead (Fpz), the ground electrode being placed to the right of the reference as well as above and below the right eye to monitor eye blinks. The stimulus was presented to left at 65 dB and consisted of a sequence of 10 clicks. The participants were seated in a comfortable recliner in an electroacoustically shielded booth. The participants were asked to play a video game or read and to ignore the stimulus presented. Ponton and fellow researchers (2000) concluded that overall, adult-like AEP morphology begins to emerge around the age of 12. Also, a gradual decline in peak-to-peak amplitude was noticed with increasing age. Latency values were also shown to decrease with increasing age. Specifically, the peak latency decreased approximately 80-110 ms in the 5-6 year old group and 30-50 ms in the 18-20 year old group.

Ponton et al. (2000) confirmed the fact that at least some of the responses generated from the central auditory system undergo maturational changes which continue through adolescents and beyond. For auditory skills like speech recognition in noise that require cortical processes (e.g., interhemispheric transfer of information) the skills may be limited by the same immature neural processes that affect AEP latency and amplitude (Ponton et al., 2000). They also found that neural synchrony required for specific tasks continues to be polished through adolescences.

In 2005, Gilley, Sharma, Dorman, and Martin performed a study that examined the developmental pattern of changes in cortical auditory evoked potential (CAEP) as a function of age and stimulation rate. Included in this study were normal hearing children 3-12 years of age and 10 normal-hearing young adults. Subjects were seated in a comfortable chair and watched a movie or cartoon of their choice. Electrode sites were Cz (referenced to the right mastoid), ground (forehead), and above and below one eye. Evoked potentials were recorded in response to the speech syllable /uh/. The speech syllable was presented in a sequence with decreasing interstimulus intervals (ISIs) (from offset to onset of the speech sound) of 2000 ms, 1000 ms, 500 ms, and 360 ms. The waveforms were averaged for each subject and the P1 was defined as the first robust positive portion of the waveform and the N1 was defined as the first negative peak occurring after the P1 response. Also identified was P2, which was defined as the positive peak immediately, following the negative peak (N1). Latency and amplitude values were also determined for each component of the waveform (P1, N1, and P2). For the two youngest age groups (3-4 and 5-6 years) the P1 led the CAEP waveform and peaked at about 100 ms for all ISI conditions. In the 7-8 year old group the N1 became visible and for the 11-12 year old age group the N1-P2 complex was apparent in all ISI conditions. For the 24-26 year age group the N1-P2 complex was the most dominant waveform for all ISI conditions.

As previously stated, Gilley et al. (2005) used speech syllable /uh/ in a sequential pattern to examine the effects of stimulus rate and age on the CAEPs morphological development. The researchers found distinct changes in the CAEPs morphology during childhood. For the younger groups (3-4 and 5-6 years of age) their recordings showed robust positive P1 waves at all ISI conditions. The most noticeable morphological change in the CAEP was the development of the N1 in the waveform progressing from the youngest age group to the oldest age group. Overall they found that the complex maturational patterns of the components of the CAEP are best understood when the effects of age and rate waveform morphology are considered.

Abrams, Nicol, Zecker, and Kraus (2006) investigated a correspondence between brainstem encoding of speech and pattern of asymmetry at the cortex. In other words, the researchers looked to determine the accuracy of temporal (timing) encoding of speech in the auditory brainstem and cerebral asymmetry for speech sounds. Children 8 to 12 years of age were included in this study and divided into two groups, normal listeners and learning disabled (LD) children. The stimulus used was a 40 ms speech syllable /da/. The subjects were scrubbed and electrodes were placed at the vertex, over the right and left temporal lobes, the nose, which served as the reference electrode, and the forehead, which served as the ground electrode. For both brainstem and cortical recordings, the speech syllable was presented to the right ear at 80 dB sound pressure level (SPL). The researchers concluded on the notion that the contralateral pathway is stronger than the ipsilateral cortical response. This finding was independent of left hemisphere asymmetries for speech sounds. Overall, the data obtained from the study provided evidence that cortical functioning is strongly related to timing in the brainstem for speech sounds.

Late Auditory Evoked Potentials (LAEPs) using Dichotic Stimuli

There have been studies that examined laterality for speech using auditory event-related potentials (AERPs). Overall, these studies have shown greater activity of cortical areas recorded over the left hemisphere than over the right hemisphere while the subjects attended to speech like signals. Neville (1974) found asymmetries in the AERP amplitudes and latencies that supported left-hemispheric dominance for speech in normal, right-handed subjects. Later, Neville (1980) reported on unpublished results of an attempt to measure the AERP using dichotically presented word pairs by Neville, Schulman-Galambos, and Galambos. They found a strong tendency for the AERPs to be larger when recorded over the left hemisphere compared to the right hemisphere.

Mononen and Seitz (1977) conducted a study investigating the underlying mechanism of contralateral ear advantage that underlies the basis for the behavioral asymmetries revealed during dichotic presentations. A modified Ladefoged and Broadbent technique was used for this study wherein a click stimulus was temporally embedded into a sentence. The subject was asked to indicate the location of the click relative to the sentence. The click was presented in one ear and the sentence in the other ear. The sole purpose of this study was to use a dichotic method to investigate latency and amplitude differences between the ipsilateral and contralateral average electroencephalic responses. The second purpose of this study was to determine how the contralateral ear advantage might vary with the different task requirements.

Twelve adults between the ages of 18 and 30 years were included in this study. Twenty-five sentences and clicks with 20 ms duration were recorded so that one click was presented during each sentence before, within, or after the major break. Each participant was tested under both monaural click and dichotic click-sentence conditions. The order of the monaural click and dichotic conditions were counterbalanced between participants. During the dichotic presentations, the participant was required to locate the precise temporal position of the click relative to the sentence and indicate it on a response sheet provided. Next, a monaural condition was presented in which the participant passively listened to clicks. (i.e., the clicks in this condition were identical to those presented during the dichotic click-sentence task). Electroencephalogram (EEG) activity was recorded and monitored throughout all testing. Mononen and Seitz (1977) revealed that the AERs to the passive monaural presentation were faster than those to dichotic presentations and contralateral AERs were significantly faster than ipsilateral AERs.

They also revealed that the contralateral ear advantage in speed of transmission was the direct result of dichotic presentation. There was no contralateral advantage found for the passive monaural presentation.

Cranford and Martin (1991) conducted an unpublished preliminary study with dichotic stimuli that found evidence of an electrophysiological correlate of reduced attention or binaural processing in elderly patients. They found when speech competition was in the contralateral ear of participants it produced significantly greater decreases in the peak-to-peak amplitude of the N1-P2 component of the LAEP in older subjects (50 to 80 years of age) than in a younger group (20 to 49 years of age). The researchers presented with the detailed findings from previously unreported results related to the effects of contralateral speech competition on the P300 evoked related potential (Cranford & Martin, 1991). The P300 requires attention in order to process a task-related stimulus and the effects of the contralateral speech competition were thought to reflect the perception and processing of auditory information at the highest level of the auditory system. Therefore, their current study hypothesized that the presence of a contralateral competition may have a significant effect on the cognitive potential.

Four groups of female participants (20 to 34 years of age; 35 to 49 years of age; 50 to 64 years of age; and 65 to 80 years of age) were included in this study. A Nicolet Company Auditory Electro-diagnostic System was used to obtain the evoked response data. A four-talker babble tape was used during test runs involving the presentation of competing speech to the non-test ear. For the auditory brainstem response (ABR), two channels of EEG activity were obtained. The first was between the vertex (non-inverting electrode) and the ipsilateral earlobe (inverting electrode). The second recording was between the vertex and the contralateral earlobe. The middle latency response (MLR) was recorded between the vertex and the ipsilateral earlobe. One ear was tested on each patient and was alternated between subjects (i.e., half of the subjects were tested on the right ear while the other half were tested on the left ear). For the LAEP and P300 recordings an oddball stimulus presentation pattern was used. The oddball pattern consisted of the presentation of a stream of two different frequency tones; the two tones being referred to as either the rare or frequent tones. A total of four recordings were obtained for each subject. Each subject was tested in two different presentation modes: evoking stimulus (i.e., tone) to the right ear and competing speech to the left ear or evoking stimulus (i.e., tone) to the left ear and competition to the right ear. The conditions were alternated between subjects to control for any possible order effects.

The investigators found no significant latency or amplitude changes in the presence of competition from either the ABR or MLR tests in regards to age groups (20 to 34; 35 to 49; 50 to 64; and 65 to 80). The researchers did find evidence of enhanced N1-P2 amplitude, which resulted from selectively attending to the stimulus. They also found that not being able to ignore or disregard stimuli in the non-test ear was age related and resulted in reduced N1-P2 amplitude in the test ear for all age groups. Overall, the researchers concluded that there was significant effect of the speech competition on the N1-P2, which was found to be age related (65 to 80 years of age).

Barry and Sammeth (1994) conducted a dual test procedure by which both behavioral and cortical auditory event-related potentials (AERPs) were recorded in response to dichotic consonant-vowels (CVs). Sixteen right-handed, adult female participants, with normal hearing sensitivity were included in this study. The Dichotic

Consonant-Vowel (CV) Syllable Test developed at Louisiana State University Medical Center (LSUMC) (Berlin, Lowe-Belle, Cullen & Thompson, 1973) was used for all testing. A response sheet was attached to the desk and each subject was asked to check the pairs of stimuli heard. All test items were presented at 85 dB SPL. Auditory event-related potentials were recorded from electrode sites T_3 and T_4 with the nasion serving as the ground electrode.

Behavioral test results on the dichotic CVs indicated that all subjects, with the exception of one, presented with a right-ear advantage. Analysis of the electrophysiological data showed that the average amplitude of the N1-P2 complex was significantly greater over the left hemisphere than over the right hemisphere. These findings were consistent with the findings in the literature of left-hemisphere dominance for "speech-like" stimuli as well as an expected right ear advantage while engaged in a task that required identification of dichotically presented CV stimuli.

Months after the previous study was conducted, Barry and Sammeth (1994) tested an individual who showed a distinct left-ear advantage (LEA) on the dichotic task. The participant was tested in the same manner as described above. Electrodes were placed at C_3, C_4, C_5, C_6, T_3, and T_4. Initially, the participant was asked to mentally count the number of CVs that were heard without trying to identify any of them. The purpose of this run was to ensure that any asymmetries that occurred in the AERPs were attributed to the hemispheric differences in cortical processing rather than the dichotic presentation of the CV stimuli.

In contrast to earlier findings, the single participant showed a distinct left ear advantage on the dichotic CV task. Also found was an asymmetry in the AERP recordings that showed a greater amplitude, shorter latency, and clearer waveform favoring the right hemisphere. This finding was consistent for right hemisphere dominance for speech for the single female participant. The researchers believed that, overall, the results supported the hypothesis that asymmetries in cortical processing may be made known by concurrent recording of auditory event related potentials and behavioral responses to dichotic CV's.

Cranford, Rothermel, Walker, Stuart, and Elangovan (2004) conducted a study to determine if it was the difficulty level of the task and not the stimulus that plays a role in deciding which portion of the late auditory evoked potential (LAEP) is affected by opposite ear competition. Ten women (mean age = 25.5 years) served as the participants in this study. The inclusion criteria were: (1) tympanometry to rule out middle ear dysfunction and (2) pure tone testing to ensure that hearing sensitivity was normal for each of the participants. The participants were seated in a sound treated booth and were asked to focus on a visual focal point to measure eye movements. Nineteen electrodes were placed on the scalp and the face.

The participants were presented with a competing signal in the contralateral ear and were asked to ignore it while keeping a count of the number of rare tones presented. Each tone was 50 ms and had a 10 ms rise-fall time. Cranford et al. (2004) found that by adding competition to the contralateral ear and increasing the task difficulty, the P2 amplitude decreased; however the authors found no effect on the N1 amplitude. They concluded that the difference seen in the components of the late auditory evoked potential showed proof that auditory processing occurs in more central areas of the brain instead at the cochlear level.

Eichele, Nordby, Rimol, and Hugdahl (2005) conducted a study to measure the latency and amplitude of the N1 auditory-evoked potential (AEP) to onsets of repeated dichotic presentations of consonant-vowel syllables (CV). The study asked the question whether a difference in N1 latency and/or amplitude across the left and right hemispheres would be present and correspond to a perceptual difference. The N1 was used because of its sensitivity to the spectral-temporal features at the onset of a stimulus. Twelve right-handed participants were included in this study (8 males/4 females, 22-28 years of age). Different combinations of CV stimuli were presented dichotically to the ears at 65 dB HL. Dichotic presentations with two different CV syllable combinations (i.e., /ba/, /da/, /ga/, /pa/, /ta/, and /ka/) were presented simultaneously on each trial, one to the right and one to the left. There were three runs in the study; each run consisted of 3×30 trials (i.e., 90 CV pair presentations, 270 trails total). The participants were seated in a comfortable recliner in an electrically shielded and sound-attenuated room. The participants were scrubbed and the AgCI electrodes were placed at the scalp locations (i.e., FP1, FP2, F23, F7, FZ, F4, F8, FC1, FC5, FC2, FC6, T3, T4, C3, CZ, C4, CP1, CP5, CP2, CP6, P3, P7, P4, P8, O1, O2). For this particular study, dichotic listening with a natural voice CV syllable was used while the AEP was simultaneously recorded to the onset of the stimulus. After each presentation, the participants were asked to press a button on a response pad with their right finger as soon as the participant silently identified the CV. Eight hundred (800 ms) after the response, all six of the CV combinations were presented on a screen and a second button press was required to determine which CV was heard.

On a behavioral level, Eichele et al. (2005) found what they expected based on Kimura's structural model. Dichotically presented auditory input was more strongly represented contralaterally, while ipsilateral input was suppressed; therefore, correct identification of a syllable in the right ear indicated a left hemisphere perceptual advantage. Eichele and fellow researchers (2005) found that the AEP N1 showed that the latency for the left temporal lobe led by 15 ms over the right side. Overall, they concluded that under conditions of high perceptual load and the demand of the task, the N1-latency predicts perceptual preference. The authors postulated that the dichotic presentation might have been the cause of the results.

In 2006 Penna et al. attempted to identify the interactions between ipsilateral and contralateral auditory pathways during dichotic listening tasks of speech sounds which allows for lateralization of auditory input as postulated by Kimura's structural theory (1967). Penna et al. (2006) performed a study looking at the magnetic responses of the primary auditory cortices elicited by dichotic consonant-vowel syllables. Ten adult subjects (mean age = 25 years) were included in this study. Two separate sessions were conducted consisting of behavioral testing and auditory evoked potentials (AEPs). The behavioral testing consisted of a verbal dichotic listening task, which consisted of 60 dichotic CV syllables (/ba/, /ka/, /da/, /ga/, /pa/, and /ta/). The task of the subject was to indicate which CV pair he/she perceived best out of the pairs listed above. In other words, the subject was to pay attention to both ears at the same time without giving one ear more attention. The analysis was based on the number of correctly reported syllables presented to the left versus the right ear.

For the AEP recordings the dichotic stimulus consisted of three CV syllables: /da/, /ba/, /ka/, which was recorded by a female voice. The stimulus intensity was presented at two levels, 60 dBA and 80 dBA. A total of five CV syllables were used during testing (/da/ at 60 dBA, /ba/ at 60 dBA, /ka/ at 60 dBA, /ba/ at 80 dBA, and /ka/ at 80 dBA). The stimuli /da/ was always at 60 dBA while the other two stimuli, /ba/ and /ka/ were either at 60 dBA or 80 dBA. All eight of the stimuli were presented 80 times for a total of 640 presentations.

Penna et al. (2006) found inhibition of one auditory pathway by a reduction of source strength increase in response to dichotic CV-syllables presented at different intensities. It also revealed that the left ipsilateral signal was strongly inhibited by the right one. However, the right ipsilateral pathway was found to have larger inhibition when compared to the left one. The researchers also explained the idea of the right ear advantage in dichotic listening, which supported Kimura's notion that there is an advantage of the contralateral pathway when dichotic stimulation is presented to the ears.

Interhemispheric Transfer Time

Both AEP and dichotic testing have been used for measuring maturation but the two have not been used together in the auditory domain, however; they have been used in the visual domain (e.g., Hagelthorn et al 2000). One important parameter of callosal function is the speed with which information is transferred between the hemispheres referred to as interhemispheric transfer time (IHTT) (Saron & Davidson, 1989) and is primarily mediated by the corpus callosum especially under difficult task conditions (e.g., dichotic listening) (Hoptman, Davidson, Gudmundsson, Schreiber & Ershler, 1996). Behavioral and psychophysiological studies have shown that IHTT becomes more rapid with age (Hoptman et al., 1996). In other words, it takes less time for information to reach its designated hemisphere in adults compared to adolescents. For example, Brizzolara, Ferretti, Brovedani, Casalini and Sbrana (1994) found that behavioral measures of simple reaction time estimates of IHTT were slower for 7 year-olds than for 9 year-old children. Also, Salamy (1978) found that using somatosensory evoked potentials (SEPs) showed children's IHTT became faster with increasing age. This research has shown that the corpus callosum has reached "adult-like" maturation around 12 years of age (Brizzolara et al., 1994; Moncrieff & Musiek, 2002; Salamy, 1978).

Many researchers have conducted studies to estimate IHTT using visual stimuli. In the beginning, the recordings were based on a simple reaction time (RT) (Ulusoy et al., 2004). For young healthy people, the IHTTs were estimated between ranges of 2-6 ms but were later contradicted because those RTs were too fast for the majority of human callosal fibers (Davidson & Saron, 1989; Hoptman & Davidson, 1994). There are others that have used visual evoked potentials (VEPs) to estimate IHTT (Brown & Jeeves, 1993; Rugg, Lines, & Milner, 1984). Research has also shown that using electrophysiological procedures to measure IHTT, which has proven to be a more accurate measure compared to behavioral testing (Saron & Davidson, 1989). It has also been found that using a bilateral visual field shows a greater advantage and a faster IHTT in adults compared to a signal visual field (i.e., two eyes versus one eye) especially when the information is being transferred from the left hemisphere to the right hemisphere (Brown & Jeeves, 1993).

Interhemispheric transfer time studies. In 1989, Saron and Davidson performed a study measuring reaction times (RT) and electrophysiological procedures in the visual domain. Multiple experiments including both RTs and electrophysiological procedures were performed using the visual field with a checkerboard stimulus. The first experiment looked at the relationship between RT and evoked potential (EP) measures of

IHTT. The second experiment focused on measures of IHTT from medial and from lateral occipital recording sites. The purpose of the second experiment was to compare recordings from the two regions. The researchers concluded that from experiment two, EPs that came from lateral occipital sites gave more valid and longer IHTT estimates when compared to the medial occipital sites. The third experiment looked at effects of randomly presenting stimuli in the two visual fields and of blocking them to one visual field. They showed no difference between randomly presented stimuli and blocked visual stimuli. The fourth experiment looked at comparing EP estimates of IHTT from linked-ears-referenced recordings with the recordings made at the same time with a mid-frontal reference site. They also looked at the effect of decreasing stimulus eccentricity from 2.8 to 1.8 degrees. Results from experiment 4 revealed EPs from linked-ear recordings were more valid when compared to those from a mid-frontal point. They also found that small changes in the eccentricity did not control the IHTT. The researchers found that electrophysiological procedures showed better estimates for measuring IHTT when compared to behavioral measures.

In 2000, Hagelthorn, Brown, Amano, and Asarnow investigated the bilateral field advantage (BFA) and the evoked potentials (EPs) of children between the ages of 7 and 17 years. As stated by the authors, a BFA is present when there is an increase in speed or efficiency when viewing two stimuli on both visual fields than when looking at two stimuli on one visual field. Both BFA and EPs were recorded at the same time. The authors hypothesized that evoked potential interhemispheric transmission time (EP-IHTT) would be faster and that the EP's difference in amplitude would become smaller as age increased. They also hypothesized that the BFA would increase with age. Fortythree children (mean age = 15 years) served as participants in this study. Each participant was tested for behavior problems using the Child Behavior Checklist (CBCL). The participants were separated into three groups: (ages 7-9, n = 11; ages 10-12, n = 10; and ages 13-17, n = 13). The participants were tested in two different sessions. During session one the participants performed a letter matching skill where two different letters appeared on a screen for 200 ms and they had to say if they were a match or not. Responses that were measured to be longer than 200 ms were counted as incorrect. Furthermore, reaction times (RTs) were only calculated for those answers that were correct. While the participants performed the letter-matching task, evoked electroencephalogram (EEG) measurements were recorded. Electrodes were placed at midline, right and left hemispheres, and vertex. Two electrodes were also placed on the right eye to measure eye blinks. The recordings started 140 ms before the onset of the stimulus and lasted 500 ms after the stimulus. The second session consisted of the participants completing the *Edinburgh Handedness Test* and four subtests from the *Wechsler Intelligence Scale for Children-Revised (WISC-R*; Hagelthorn et al., 2005). The authors concluded that the reaction times were faster for stimuli presented bilaterally when compared to stimuli presented unilaterally for the two oldest groups. The evoked potentials showed no significant differences for the P1 or N1 complex for the three groups of children. However, the N1 latency did show a decrease as age increased.

Nowicka and Fersten (2001) performed a study estimating the IHTTs for verbal information in male and female subjects using (ERPs) method. As stated by these authors the corpus callosum's morphology shows greater numbers of fibers in the anterior commissure as well as a considerably larger splenium in females compared to males.

They also reported that larger callosal size signifies greater interhemispheric connectivity, which leads to faster interhemispheric transfer. For this study, 10 right-handed men and 10 right-handed women were chosen to participate. Event-related potentials were recorded for three letter word responses (e.g., consonant-vowel-consonant) for 30 ms. For the first half of the session the words were presented in the right visual field and the other half were presented in the left visual field. Next, three words were presented vertically (in the middle) while the participant had to determine if the word that appeared in either the left or right visual field also appeared medially. The P100, N170, and P300 as well as hemisphere and the site of recording were all taken into consideration in the results of this study. The investigators revealed that the mean latencies of the N170 recorded in the left hemisphere were shorter than those recorded in the right hemisphere. However, there was no difference found between men and women in averaged IHTTs as well as no difference between IHTTs when based on the parietal and occipital ERP recordings.

While most studies dealing with IHTT have dealt with the visual domain, one study has been found that may suggest that measuring IHTT may be possible using auditory stimuli. In 1994, Krumm and Cranford attempted to determine if there would be a decrease in the N1/P2 late auditory evoked potential amplitude using competing four-talker speech babble (i.e., using a dichotic paradigm). The children were divided into three groups: 7:6 to 9:11 years of age (M = 8.7; young group), 10:0 to 12:5 years (M = 11.3; middle group), and 12:6 to 14:11 years of age (M = 14.0; older group).

During the test, a tone burst signal was given in quiet condition and a competing speech condition. During the quiet condition, the tone burst was presented to one ear with no competing stimuli; in the competing condition or dichotic paradigm, a four-talker babble speech stimulus was presented to the non-test ear while the test ear received the tone burst signal.

Table 1 presents the findings of the N1 and P2 latencies for each of the groups. As found in other studies, latencies for the right ear are slightly shorter than the left ear; however, when the competing four talker babble stimulus was introduced, the differences between the ears were increased dramatically especially in the younger groups. Or said another way, as maturation of the auditory system occurred, the competing stimulus (i.e., four-talker babble) had less impact on the latencies of late evoked potentials and resulted in approximately equal latencies between the ears. While this was not the underpinnings of the Krumm and Cranford study and IHTT is inferred, it was apparent that the dichotic stimulus had a significant impact on the latencies of N1 and P2 especially for the younger groups.

Table 1

Means (and Standard Deviations) of N1 and P2 Latencies (Msec) Measured in Presence or Absence of Contralateral Speech Competition

		Young Group 7:6-9:1 (M = 8.7)			**Middle Group 10:0-12:5 (M = 11:3)**			**Older Group 12:6-14:11 (M = 14)**		
		LE	RE	**IHTT***	LE	RE	**IHTT***	LE	RE	**IHTT***
N1 Latency										
	Quiet	149.9	-147.2	**2.7**	123.5	-119.7	**3.8**	102.4	-99.7	**2.7**
	Speech	160	-144.3	**15.7**	124.5	-111.7	**12.8**	102.9	-102.4	**0.5**
P2 Latency										
	Quiet	243.4	-241.3	**2.1**	205.9	-201.9	**4**	198.6	-188.3	**10.3**
	Speech	255.2	-138.4	**16.8**	207.2	-192.3	**14.9**	188.5	-190.7	**-2.2**

Note. * Not in original table; Quiet = ipsilateral monotic tones; Speech = Quiet + contralateral four-talker babble; Modified from original table Adapted from "Effects of Contralateral Speech Competition on the Late Auditory Evoked Potential in Children, by Krumm and Cranford, 1994, Journal of the American Academy of Audiology, 5, p. 130.

The current study is the first in a series of studies with the ultimate goal of developing an objective technique to measure interhemispheric transfer time (IHTT) of linguistic stimuli using late auditory evoked potentials. Specifically, this study used a monaurally presented /da/ stimulus to right and left ears separately in adults to determine if latency differences existed between the two hemispheres. This, in turn, will hopefully provide researchers with an objective measure of the corpus callosum function of auditory and language processing. What is different about the proposed study is that a speech stimulus (i.e., /da/) will be used and presented monaurally (one ear at a time) instead of a tone burst.

Previous research has shown that when differently stimuli are presented dichotically, the interaction between the pathways complicates the understanding of the response (Penna et al., 2006). A monaural presentation allowed for collecting data without any interactions to determine if there any differences between electrodes (CZ, C3, and C4) and ears (right and left). Specifically, auditory evoked potentials (AEPs) have shown the contralateral pathways response to monaural stimulation begins earlier and is more constant compared to the ipsilateral one (Reite, Zimmerman & Zimmerman, 1981; Romani, Williamson & Kaufman, 1982; Papanicolaou, Baumann et al., 1990). In focusing on transfer time, it is hopeful that this will provide a valuable tool to objectively measure the transfer of speech stimuli across the corpus callosum. Currently, the only mechanism available to measure maturation of the corpus callosum is a behavioral technique called dichotic testing. Measuring IHTT of auditory regions of corpus callosum through late auditory evoked potential is innovative and holds potential. In addition, the best means of data collection and analysis will be evaluated.

CHAPTER III

METHODS AND PROCEDURES

This study is the first in a series of studies with the ultimate goal of developing an objective technique to measure interhemispheric transfer time (IHTT) using late auditory evoked potentials. Specifically, this study used a monaurally presented /da/ stimulus to each ear separately in adults to determine if electrophysiologic latency differences existed between the two hemispheres. In focusing on transfer time, it was hoped that this would provide a valuable tool to objectively measure the transfer of speech stimuli across the CC and ultimately find a measure to assess maturation. Currently, the only mechanism available to assess maturation of the auditory system is behavioral techniques in dichotic listening. Dichotic listening tests involve the presentation of CV words or sentences to one ear while simultaneously presenting a different stimulus to the opposite ear. Therefore, the goal of this project is to attempt to measure IHTT using late auditory evoked potentials and a monaurally presented /da/ stimulus.

Methods

Participants

Prior to initiation of this study, the Institutional Review Board (IRB) at Louisiana Tech University approved this project (Appendix A). Nine participants, five females and four males, ages 18-35 years, were included in this study. All participants signed a consent form (Appendix A) and were allowed to ask questions prior to initiation of data collection. All participants had normal peripheral hearing as identified by pure-tone thresholds between 0-25 dB HL for octave frequencies 250 Hz-8000 Hz. In addition, normal middle ear functioning was present in all participants as determined by peak middle ear pressure of no less than -100 da Pa and no greater than +25 da Pa with static immittance between .30 to 1.60 ml using a 226 Hz probe tone (Hall & Chandler, 1994) and acoustic reflex thresholds were between 85 and 100 dB SPL. The speech reception threshold was within $\pm$ 10 dB of the pure-tone average and word recognition scores were between 88-100%. If auditory thresholds were poorer than 25 dB HL at any of the test frequencies and/or if tympanograms were abnormal, the participant was referred for further evaluation by an audiologist or physician and was excluded or deferred from the study until normal audiological results were obtained.

None of the participants had identifiable neurological disorders, mentally handicapping conditions, auditory processing disorders, or history of closed head injury as reported by the participant. English was the primary language used by all participants. Each participant was right-handed as identified by the Edinburgh Handedness Inventory and Laterality Quotient (Appendix B). Participants were not excluded based on the diagnosis of attention deficit disorder.

Instrumentation

Otoscopy was performed using a Welch Allen otoscope. Middle ear functioning was performed using a Grason-Stadler Tympstar Version 2 Middle-Ear Analyzer (Med-Acoustics, Stone Mountain, GA) (ANSI S3.39, 1978, R2002). Pure-tone and speech testing was performed with a Grason-Stadler GSI 61 audiometer (Med-Acoustics, Stone Mountain, GA) (ANSI S3.6-1969, R-1973, R-2004). Speech testing was performed using recorded Northwestern No. 6 (NU-6) word list from Auditec of St. Louis delivered through the GSI 61 audiometer coupled to a Tascam CD-160 CD player. EARTone 3A insert earphones (Med-Acoustics, Stone Mountain, GA) were used for presentation of all audiometric testing and speech testing. All equipment received an annual electroacoustic calibration and daily biological checks to ensure consistency of performance. Preliminary testing was performed in a double-walled, double suite soundproof booth meeting the ANSI S3.1-1999 standards.

The Intelligent Hearing System (IHS) on loan from the University of Arkansas at Little Rock was used for all electrophysiological testing. The electrophysiological testing was performed on the campus of Louisiana Tech University Robinson Hall room 113. The Opti-Amp 8002 electrode box unit was used with AgAgC1 electrodes. The electrodes were linked together by jumper cables and held in place using medical tape.

Procedures

Preliminary Testing

Informed consent was received from participants prior to the initiation of testing. All adults received an audiological evaluation. The audiological evaluation included an otoscopic examination, tympanometry, acoustic reflexes, pure-tone air conduction testing, speech reception thresholds, and word recognition testing. Those individuals meeting all inclusion criteria were asked to participate in the study.

Electrophysiological testing. The following was explained verbally to each participant prior to testing:

> *I am going to wipe six areas on your head with alcohol. This will include the tip of your nose, under your right eye, center forehead, and several places on the top of your head. Then I will take a Q-tip and scrub each of these areas. The scrub I will use feels sandy but it will let me remove dirt and skin cells from these areas. Next I will use a piece of tape to attach a silver disc to each place that was scrubbed. When I am done, you will be able to relax and watch a movie of your choice. I ask that you stay awake during the testing and we will take a break and let you move around after we finish with the first ear. Do you have any questions?*

Each electrode location was cleaned thoroughly with an alcohol prep pad and mild abrasive (Nu-Prep). Six electrodes were placed on each participant's head. Electrode sites consisted of Fpz on center of the forehead, C3 over the left hemisphere, C4 over the right hemisphere, and Cz on the center of the head. Of the six electrodes, one electrode was placed on the nose as reference, one on the forehead and one below the right eye. Impedances were kept to a minimum and balanced (10 kohms or less). The continuous EEGs were amplified (fixed by IHS), sampled 200 times per second, bandpass filtered from .1 to 100 Hz with a 12dB/octave rejection rate. Each continuous EEG recordings were saved to the hard drive as EEG files for later offline processing and analysis.

Stimulus and recording parameters. The target stimulus used was a synthesized /da/ ("dah") speech sound. This 170-msec stimulus was synthetically designed to provide a clean consonant-vowel speech sound with linguistic properties to attempt to engage the language centers of the auditory system. The stimulus was presented monaurally at 70 dB SPL (peak-to-peak equivalent). The stimulus was presented in sweeps of 100 three times to each ear with interstimulus intervals (ISI) set at 1.4 sec. Thus, each ear was presented with a total of 160 speech stimuli.

Half of the participants received stimulus right testing first and the second half of participants received stimulus left testing first. The target stimulus /da/ was routed through EARTone 3A insert earphones to the test ear. Each block took approximately 2 minutes for a total recording time of approximately 8 minutes (minus short breaks of a few minutes between recordings).

The auditory late evoked potentials (P1-N1-P2) complex was evaluated off-line. Latencies for each participant's waveform recordings were marked as follows:

P1: the first prominent positive peak occurring at or after 50 ms

N1: the first prominent negative peak occurring at or after 100 ms

P2: the second prominent positive peak occurring at or after 150 ms

Recordings to the monaural /da/ stimulus were made both ipsilateral (C4R and C3L) and contralateral (C3R and C4L) to the ear stimulated. Ipsilateral recordings likely result from stimulation of both ipsilateral auditory fibers and possibly corpus callosum fibers; while contralateral recordings are more likely the result of auditory stimulation of the more numerous anatomical pathways crossing at the level of the SOC reaching Heschl's gyri at the hemisphere opposite to the ear being stimulated.

CHAPTER IV

RESULTS

As mentioned before, this study was the first in a series of studies using late auditory evoked potentials to measure interhemispheric transfer time (IHTT). The /da/ stimulus was presented monaurally to the each ear separately and then the recordings compared. Two factors—maturation and competing stimulus—can make interpretation of late auditory evoked stimuli difficult. Therefore, a preliminary study was necessary to determine what type of results would be obtained using a /da/ stimulus and the paradigm selected (i.e., stimulus rate, filter settings, etc.).

Data from nine adult participants (mean age = 25.22; range = 18 to 35) with normal peripheral hearing was used to collect the P1-N1-P2 complex. Maturation of auditory structures was not considered to be a factor in the analysis since research suggests that these structures are fully mature at 10-14 years of age (Moncrieff & Musiek, 2002; Yakovlev & Lecours, 1967). Prior to data analysis, data for female participant 002 revealed absent P1-N1-P2 waveforms for electrode site C4 for the right ear. Therefore, data for all other participants was averaged together for those electrodes, and that data was used for the missing data points.

A 3×3×2 repeated measures analysis of variance (RM-ANOVA) was performed with electrode (CZ, C3, C4), waves (P1, N1, N2), and ear (Right ear, Left ear) being the main effects. Partial eta squared (partial η^2) values were included to evaluate effect size and clinical significance. A Bonferroni correction was used to correct for the multiple comparisons used. Effects sizes (Large = > .138; Medium = .059-.137; Small = .01-.058) were reported for each variable and revealed magnitude of the observed effect or the level of clinical significance (Nolan & Heinzen, 2007). The main effects were not significant for electrode site, F (2, 16) = .683, p = .504, partial η^2 = .079, or for ears, F (1, 8) = 1.775, p = .219), partial η^2 = .182. However, main effects were significant for waves, F (2, 16) = 417.721, p = < .001, partial η^2 = .182. See Table 2 for mean latencies and standard deviations for all variables.

Although the main effect for electrode site was not found to be statistically significant, a medium effect size (partial η^2 = .079) was found suggesting clinical significance. As noted previously in Chapter III, recordings to the monaural /da/ stimulus were made both ipsilaterally (C4R and C3L) and contralaterally (C3R and C4L) to the ear stimulated. Specifically as seen in Figure 1 and Table 2, when the left ear was stimulated, shorter latencies were measured over the right hemisphere (C4) for P1; as shown in Figure 2 and Table 2, shorter latencies were obtained for N1 for the left ear and electrode site, and as seen in Figure 3, latencies for P2 were shorter for CZ for both the right and left ears as compared to electrode sites of C3 and C4.

A large partial eta squared (partial η^2 = .182) was identified for the main effect of ears although statistical significance was not found. In reviewing Figures 1, 2 and 3, when the left ear was stimulated, shorter latencies were consistently measured irrespective of electrode site, wave, or ipsilateral/contralateral site of stimulation.

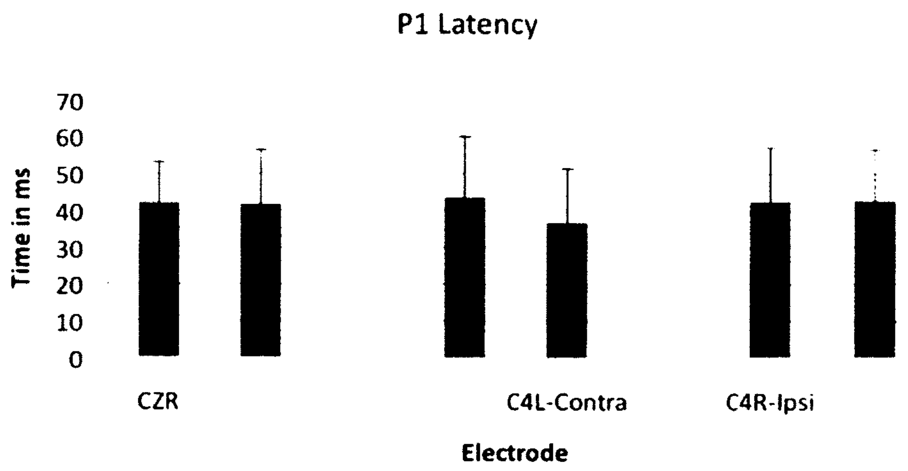
Although statistical significance and a large effect size were found for waves, a post hoc analysis was not necessary on the main effects of waves. Latency differences of P1, N1, and P2 of approximately 50, 100, and 200 ms respectively are to be expected.

Table 2 Means and Standard Deviations

Variables	M	SD
CZRP1	42.22	10.92
CZLP1	41.89	14.59
CZRN1	89.44	6.64
CZLN1	88.22	9.44
CZRP2	143.55	12.73
CZLP2	143.33	14.76
C3RP1	43.67	16.32
C4LP1	36.78	14.54
C3RN1	88.33	15.98
C4LN1	83.00	14.67
C3RP2	148.89	20.90
C4LP2	144.00	14.81
C4RP1	42.56	14.58
C3LP1	42.78	13.87
C4RN1	84.11	10.69
C3LN1	82.56	9.52
C4RP2	149.00	16.02
C3LP2	145.89	10.95

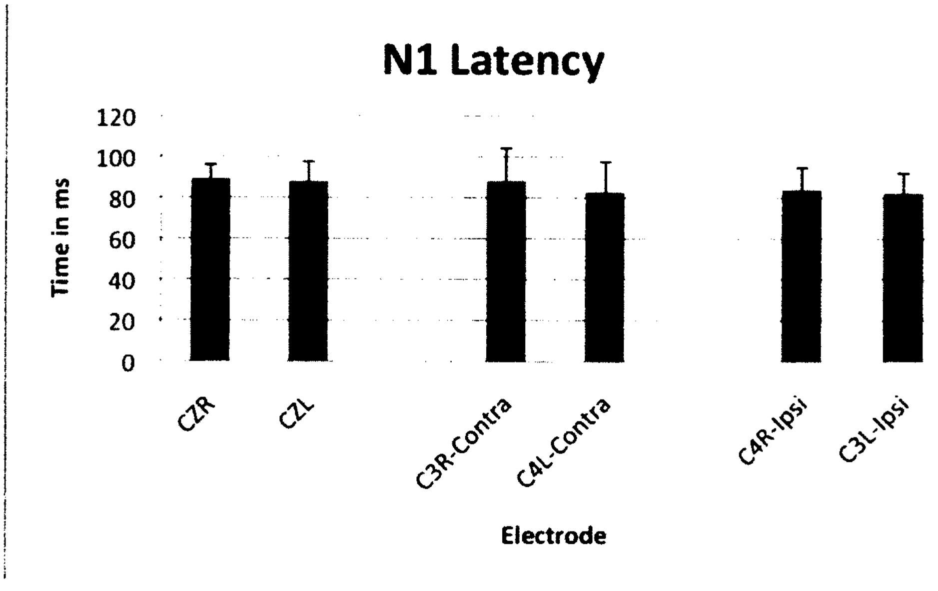
CZ = Center Head
C3 = Right Hemisphere
C4 = Left Hemisphere
R = Right ear stimulated
L = Left ear stimulated

P1 = 1st positive peak
N1 = 1st negative trough
P2 = 2nd positive peak



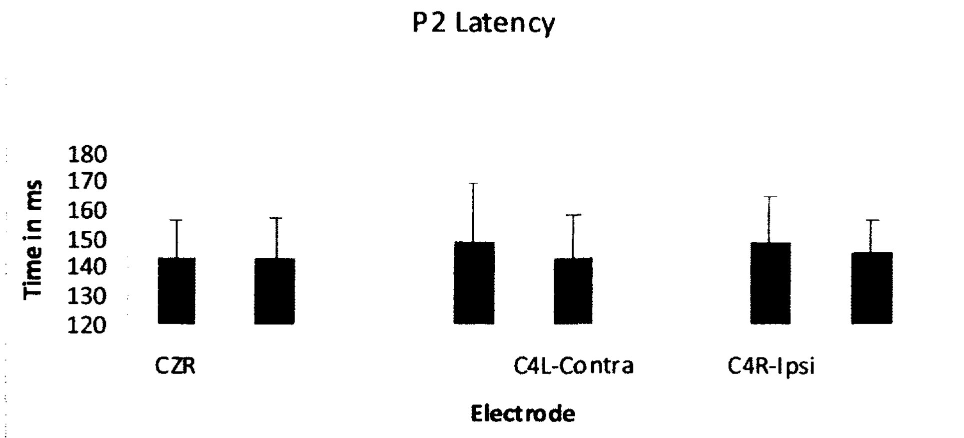
CZ Center Head, C3 Right hemisphere, C4 Left hemisphere

Figure 1. P1 latency.



CZ Center Head, C3 Right hemisphere, C4 Left Hemisphere

Figure 2. N1 Latency.



CZ Center Head, C3 Right Hemisphere, C4 Left Hemisphere

Figure 3. P2 Latency.

There were no significant interactions when comparing electrodes to waves, F (4, 32) = 1.591, p = .222, partial η^2 = .166, electrodes to ears, F (2, 16) = .157, p = .773, partial η^2 = .019, waves to ears, F (2, 16) = .004, p = .994, partial η^2 = .001, or for electrodes, waves, and ears, F (4, 32) = .426, p = .700, partial η^2 = .05.A large partial eta squared (partial η^2 = .166) was identified for the interaction of electrodes to waves. In review of Figure 4, a clinically significant interaction can be seen for electrode locations of C3 and C4 deviating from the electrode location of CZ specifically for the wave P2. In addition, when reviewing Figure 3 and Table 2, latencies for C3 and C4 can be visualized and tabulated as being longer than for the electrode location of CZ.

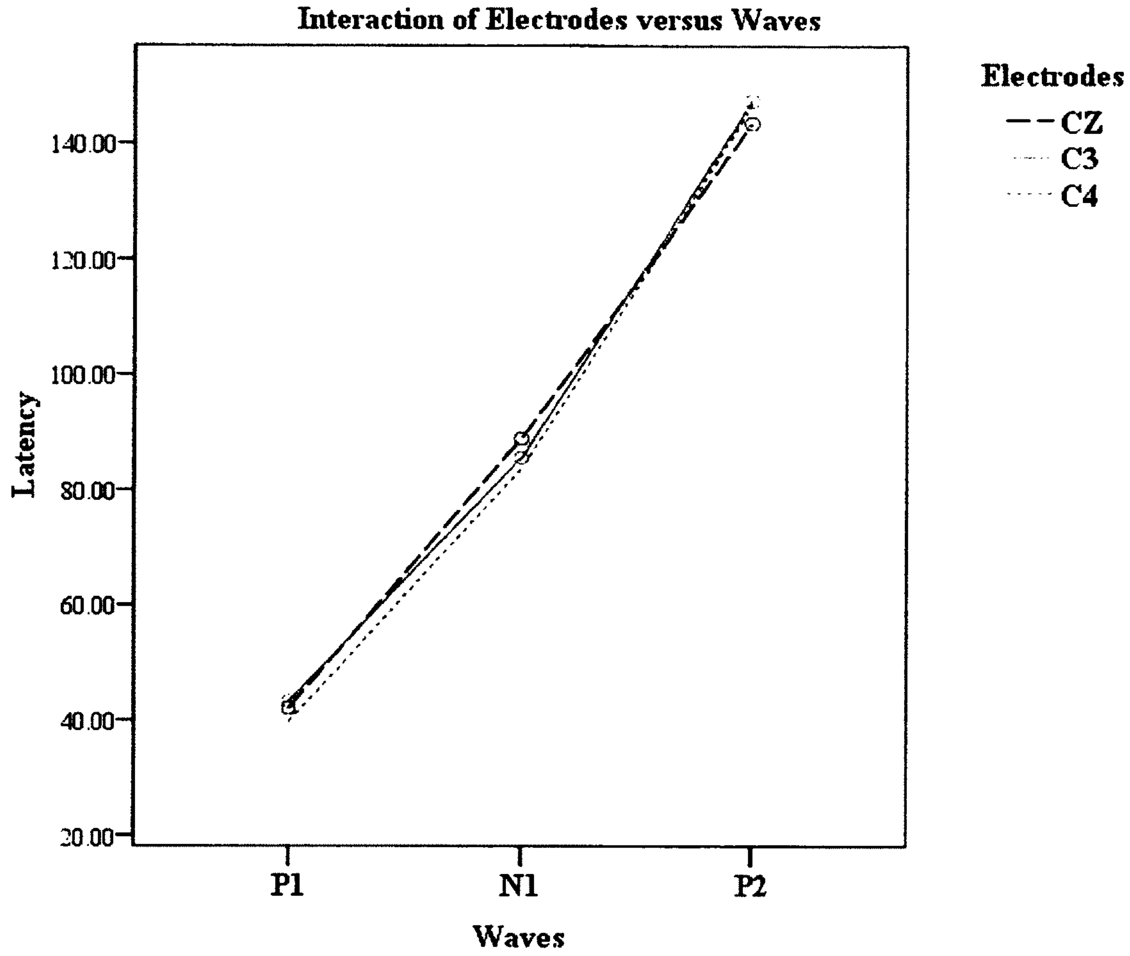


Figure 4. Interaction of Electrodes Versus Waves.

A RM-ANOVA was used to further investigate the relationship between the ears and latencies. The means for each the right and left ear were compared for differences. See Table 3 for F-Statistics, Mean Differences, P-Value and Effect Size. The post-hoc analysis did not indicate any statistically significant differences between waves P1-N1-P2 when comparing the right versus the left ear.

Table 3. Repeated Measures ANOVA comparison of electrode (CZ, C3, C4) sites to ears (Right ear, Left ear)

RM-ANOVA Mean Differences, F-Statistics, P-Values and Effect Sizes

	Mean Differences	F	*p*	Partial η^2
CZRP1-CZLP1	0.33	0.009	0.927	0.001
CZRN1-CZLN1	1.22	0.116	0.742	0.014
CZRP2-CZLP2	0.22	0.001	0.973	0.000
C3RP1-C4LP1Contra	6.89	2.826	0.131	0.261
C3RN1-C4LN1Contra	5.33	0.656	0.441	0.076
C3RP2-C4LP2Contra	4.89	0.796	0.398	0.091
C4RP1-C3LP1Ipsi	0.22	0.001	0.972	0.000
C4RN1-C3LN1Ipsi	1.56	0.228	0.646	0.028
C4RP2-C3LP2Ipsi	4.11	0.648	0.444	0.075

CZ=Center Head
C3=R Hemisphere
C4= Left Hemisphere

R=Right Ear
L= Left Ear

P1 = 1st positive peak
N1 = 1st negative trough
P2 = 2nd positive peak

A small effect size (partial η^2 = .014) was identified for CZRN1-CZLN1 indicating a slight clinical significance where the left ear latency for N1 for the left ear was slightly shorter than the right ear. A large partial eta squared (partial η^2 =.261) was found for C3RP1-C4LP1Contra (i.e., when the hemisphere contralateral to the stimulus was measured) and a medium effect size was identified for both C3RN1-C4LN1Contra (partial η^2 = .076) and C3RP2-C4LP2Contra (partial η^2 = .091), all suggesting a shorter latency for the left ear in comparison to the right ear for waves P1, N1, and P2. A small partial η^2 (.028) was found for C4RN1-C3LN1Ipsi (i.e. when the hemisphere ipsilateral to the stimulus was measured) and a medium partial η^2 (.075) was found for C4RP2-C3LP2Ipsi, in both cases the latencies for waves N1 and P2 were shorter for the left than the right ear.

CHAPTER V

DISCUSSION

This study was the first in a series of studies attempting to develop an objective technique to measure IHTT. However, it was found that the use of this particular /da/ stimulus and recording paradigm did not support the underlying notion of measuring maturation or IHTT. While these results were not statistically significant, a clinically significant finding revealed an unexpected observation. When the left ear was stimulated, shorter latencies were consistently measured irrespective of electrode site, wave, or ipsilateral/contralateral site of stimulation. In other words, it did not matter what electrode site was measured (i.e. CZ, C3, or C4), wave (P1-N1-P2), or if it was an ipsilateral to the side of stimulation or a contralateral to the side of stimulation, the left ear consistently revealed shorter latencies than right ear.

The results were contradictory of what was expected and refuted what many other researchers have found. For example, Hornickel, Skoe, and Kraus (2009) found that when the right ear was stimulated, speech stimuli traveled faster when compared to the left ear. This is also supported by Kimura's notion that the left hemisphere is dominant for language. As stated earlier it was Kimura's (1963) study that established children as young as four years of age presented with a right-ear advantage. Specifically, they scored better in the right ear compared to the left.

Data in this study also refutes other researchers who found that the contralateral pathway transmitted information faster than the ipsilateral pathway (Kimura 1967; Kraus et al, 1993; Johnsrude, Zatorre, Milner, & Evans, 1997; & Sebastion & Yasin, 2008) and those who revealed that the strongest and fastest pathway for sound in one ear to the opposite hemisphere is the contralateral pathway (Fujiki, Jousmai, & Hari, 2002; Hall & Goldstein, 1968; Mononen & Seitz, 1977). Also, behavioral studies conducted by Kimura (1961) revealed an advantage of the contralateral auditory pathway in humans and it has been established that for dichotic presentations, the contralateral pathway from the ear to the opposite hemisphere is more efficient. Due to the /da/ stimulus in this study being a monaural presentation, the faster ipsilateral pathway may have prevailed in this study.

One can speculate that the /da/ stimulus used in the present research may have not been speech-like enough to elicit the language center of the brain. Typically speech is lateralized to the left hemisphere wherein the right hemisphere is more sensitive for temporal processing (Zatorre, Belin, & Penhune, 2002). For example, Sandmann and his colleagues (2007) investigated hemispheric asymmetries in processing temporal acoustic cues of voiced and voiceless consonant-vowels. The investigators found that ear advantage was affected by voiced and voiceless consonant vowels with stronger leftward lateralization for voiced as compared to voiceless CV syllables. It may be possible that the /da/ stimulus used in the present study may not have been voiced enough to engage that left hemisphere language center.

As noted, all data from the present research revealed that when stimuli presented to the left ear, transmission was consistently faster compared to the right ear as supported by effect sizes. It should be noted that males and females were averaged together and a small sample size was used; therefore the results of this study should be viewed cautiously. Additional research should be conducted to include a larger sample size and males and females should be averaged separately to account for latency differences between the genders. In addition, a different stimulus should be selected to attempt to elicit a quicker response from the left hemisphere/right ear advantage. Eichele, Nordby, Rimol and Hugdahl (2005) recorded auditory-evoked potentials with consonant vowel speech sounds and found shorter latencies when recorded from the scalp overlying the left hemisphere. The findings that the investigators observed supported the REA explained by Kimura's model. Investigators Mononen and Seitz's (1977) findings also supported Kimura's notion that the contralateral pathway is faster and more efficient and has an advantage over the ipsilateral pathway.

Since this present research is the first in a series of studies, one of the long-term goals is to use the data collected and protocol that has been developed to compare it with children that have been diagnosed with an auditory processing disorder or a disorder associated with auditory processing. One way of doing that is by attempting to replicate the 2004 Krumm and Cranford study. The researchers used a tonal stimulus and found that measuring IHTT was possible.

Auditory processing disorder, along with other associated disorders, has been extremely controversial for many years. They have drawn much attention from both research and clinical aspects and further research is needed in order to develop an objective technique measuring IHTT of information across the corpus callosum. Both auditory processing and its associated disorders, typically, are diagnosed using behavioral tests, which are influenced by things such as age, cognition, attention etc. Much data is lacking in the understanding of normal auditory processes and the lack of information halts in the diagnoses and treatment of children and/or adults with auditory processing abnormalities. Being that the data from this research was consistently opposite from what all other researchers have found, it is possible that the /da/ stimulus used was not speech-like enough to stimulate the language centers of the brain. It is also speculated that it may have been stimulating more of a non-linguistic area. It is also possible that the parameters (e.g., filter settings, stimulus rate, etc.) may have not been appropriate and further research is needed to better understanding normal and abnormal auditory processing abilities.

APPENDIX A

IRB APPROVAL MEMORANDUM

LOUISIANA TECH
UNIVERSITY

OFFICE OF UNIVERSITY RESEARCH

MEMORANDUM

TO: Ms. Katherine Cormier and Dr. Sheryl Shoemaker

FROM: Barbara Talbot, University Research

SUBJECT: HUMAN USE COMMITTEE REVIEW

DATE: October 27, 2009

In order to facilitate your project, an EXPEDITED REVIEW has been done for your proposed study entitled:

"Use of Auditory-late Evoked Potentials as a Measure of Inter-hemispheric Transfer Time"

HUC 704

The proposed study's revised procedures were found to provide reasonable and adequate safeguards against possible risks involving human subjects. The information to be collected may be personal in nature or implication. Therefore, diligent care needs to be taken to protect the privacy of the participants and to assure that the data are kept confidential. Informed consent is a critical part of the research process. The subjects must be informed that their participation is voluntary. It is important that consent materials be presented in a language understandable to every participant. If you have participants in your study whose first language is not English, be sure that informed consent materials are adequately explained or translated. Since your reviewed project appears to do no damage to the participants, the Human Use Committee grants approval of the involvement of human subjects as outlined.

Projects should be renewed annually. ***This approval was finalized on October 22, 2009 and this project will need to receive a continuation review by the IRB if the project, including data analysis, continues beyond October 22, 2012.*** Any discrepancies in procedure or changes that have been made including approved changes should be noted in the review application. Projects involving NIH funds require annual education training to be documented. For more information regarding this, contact the Office of University Research.

You are requested to maintain written records of your procedures, data collected, and subjects involved. These records will need to be available upon request during the conduct of the study and retained by the university for three years after the conclusion of the study. If changes occur in recruiting of subjects, informed consent process or in your research protocol, or if unanticipated problems should arise it is the Researchers responsibility to notify the Office of Research or IRB in writing. The project should be discontinued until modifications can be reviewed and approved.

If you have any questions, please contact Dr. Mary Livingston at 257-4315.

A MEMBER OF THE UNIVERSITY OF LOUISIANA SYSTEM

P.O. BOX 3092 • RUSTON, LA 71272 • TELEPHONE (318) 257-5075 • FAX (318) 257-5079
AN EQUAL OPPORTUNITY UNIVERSITY

APPENDIX B

HUMAN SUBJECTS CONSENT FORM

HUMAN SUBJECTS CONSENT FORM

The following is a brief summary of the project in which you have been asked to participate. Please read this information before signing below:

TITLE: Use of Auditory-Late Evoked Potentials as a Measure of Inter-Hemispheric Transfer Time

PURPOSE OF STUDY/PROJECT: The purpose of this project is an attempt to measure inter-hemispheric transfer time in adults using a **non-invasive** procedure.

PROCEDURE: Prior to inclusion in this study, each participant will receive a standard audiometric battery (otoscopic examination, tympanometry, acoustic reflexes, pure tone testing, speech reception threshold, word recognition testing), and the Edinburgh Handedness Inventory. If meeting inclusion criteria, each participant will receive an auditory late evoked response. The auditory late evoked response will require the placement of surface electrodes and listening to sounds at a comfortable level.

INSTRUMENTS: The participant's identity will not be used in any form in the analysis or representation of the data. Only numerical data will be used in the presentation of the results.

RISKS/ALTERNATIVE TREATMENTS: There are no known risks to participants. These procedures do not vary from routine audiometric measures. Participation is voluntary. The participant understands that Louisiana Tech is not able to offer financial compensation nor to absorb the costs of medical treatment should you be injured as a result of participating in this research.

BENEFITS/COMPENSATION: None.

I, ______________________________, attest with my signature that I have read and understood the following description of the study, "Use of Auditory-Late Evoked Potentials as a Measure of Inter-Hemispheric Transfer Time", and its purposes and methods. I understand that my participation in this research is strictly voluntary and my participation or refusal to participate in this study will not affect my relationship with Louisiana Tech University and the Louisiana Tech University Speech and Hearing Center. Further, I understand that I may withdraw at any time or refuse to answer any questions without penalty. Upon completion of the study, I understand that the results will be freely available to me upon request. I understand that the results will be confidential, accessible only to the project director, principal experimenters, myself, or a legally appointed representative. I have not been requested to waive nor do I waive any of my rights related to participating in this study.

______________________________ ______________________________

Signature of Participant Date

CONTACT INFORMATION: The principal experimenter listed below may be reached to answer questions about the research, subject's rights, or related matters.

Sheryl S. Shoemaker, Ph.D., Au.D. CCC-A Department of Speech (318) 257-4764
Associate Professor and Head,
Department of Speech

Sam Atcherson, Ph.D., CCC-A
Assistant Professor of Audiology Department of Audiology and Speech Pathology (501) 683-7178

Members of the Human Use Committee of Louisiana Tech University may also be contacted if a problem cannot be discussed with the experimenters: Dr. Les Guice (257-3056) or Dr. Mary Livingston (257-2292 or 257-4315).

APPENDIX C

EDINBURGH HANDEDNESS INVENTORY

Edinburgh Handedness Inventory

Developed by R.C. Oldfield, Edinburgh University,
Edinburgh, Scotland (1971)

Last Name/First
Name/M.I.____
Date of Birth____________________
Sex__________________________

Please indicate your preferences in the use of hands in the following activities by putting + in the appropriate column. Where the preference is strong that you would never try to use the other hand unless absolutely forced to, put ++. If in any case you are really indifferent put + in both columns.

Some of the activities require both hands. In these cases the part of the task, or object, for which hand preference is wanted in brackets.

Please try to answer all the questions, and only leave a blank if you have no experience at all of the object or task.

	LEFT	RIGHT	
1. WRITING			
2. DRAWING			
3. THROWING			
4. SCISSORS			
5. TOOTHBRUSH			
6. KNIFE (without fork)			
7. SPOON			
8. BROOM (upper hand)			
9. STRIKING MATCH (match)			
10. OPENING BOX (lid)			

TOTAL number in each column L_______ R_______

Laterality quotient (LQ) is defined as (R-L) / (R+L) x 100 = _______.

McMeekan & Lishman (1975) defines right-handed as +30 to +100 and left-handed as -30 to -100. Handedness of -29 to +29 is indifference (or ambidexterity).

REFERENCES

Aboitz, F., Ide, A., & Olivares, R. (2002). Corpus callosum morphology in relation to cerebral asymmetries in the postmortem humans. In E. Zaidel & M. Iacoboni (Eds), *The Parallel Brain: The Cognitive Neuroscience of the Corpus Callosum* (33-46). Cambridge, Massachusetts: The MIT Press.

Abrams, D., Nicol, T., Zecker, S., & Kraus, N. (2006). Auditory brainstem timing predicts cerebral asymmetry for speech. *The Journal of Neuroscience*, *26*(4), 11131-11137.

Abrams, D., & Kraus, N. (2008). Right-hemisphere auditory cortex is dominant for coding syllable patterns in speech. *The Journal of Neuroscience, 28* (15), 3958-3965.

Barry, S., & Sammeth, C. (1994). Concurrently recorded auditory event-related potentials and behavioral responses to dichotic cv stimuli. *The American Academy of Audiology, 5*, 70-75.

Berlin, C., Lowe-Bell, S., Cullen, J., & Thompson, C. (1973). Dichotic speech perception: An interpretation of right-ear advantage and temporal offset effects. *The Journal of the Acoustical Society of America, 53*(3), 699-708.

Bloom, J., & Hynd, G. (2005). The role of the corpus callosum in interhemispheric transfer of information: Excitation or inhibition? *Neuropsychology Review*, *15*(2), 59-71.

Boucher, R., & Bryden, M. (1997). Laterality effects in the processing of melody and timbre. *Neuropsychologia, 35*, 1467-1473.

Brancucci, A., & San Martini, P. (1999). Laterality in the perception of temporal cues of musical timbre. *Neuropsychologia. 37*(13), 1445-1451.

Brancucci, A., & San Martini, P. (2003). Hemispheric asymmetries in the perception of rapid (timbral) and slow (nontimbral) amplitude fluctuations of complex tones. *Neuropsychology, 17*(3), 451-457.

Brizzolara, D., Ferretti, G., Brovedani, P., Casalini, P., & Sbrana, B. (1994). Is interhemispheric transfer time related to age? A developmental study. *Behavioural Brain Research, 64*, 179-184.

Brown, W.S., & Jeeves, M.A. (1993). Bilateral visual field processing and evoked potential interhemispheric transmission time. *Neuropsychologia, 31*(12), 1267-1281.

Bryden, M. (1965). Tachistoscopic recognition, handedness, and cerebral dominance. *Neuropsychologica, 3*, 1-8.

Bryden, M. (1988). An overview of the dichotic listening procedure and its relation to cerebral organization. Handbook of Dichotic Listening Theory, Methods, and Research.New York: Wiley and Sons, 1-44.

Cherbuin, N. (2005). Hemispheric interaction: When and why is yours better than mine? A thesis submitted for the degree of doctor of philosophy of the Australian National University, Canberra, Australia.

Cranford, J., & Martin, D. (1991). Age-related changes in binaural processing: Evoked potential findings. *The American Journal of Otology, 12*(5), 357-364.

Cranford, J., Rothermel, A., Walker, L., Stuart, A., & Elangovan, S. (2004). Effects of discrimination task difficulty on N1 and P2 components of late auditory evoked potential. *Journal of the American Academy of Audiology, 15*, 456-461.

Davidson, R., & Saron, C. (1992). Evoked potential measures of interhemispheric transfer time in reading disabled and normal boys. *Developmental Neurophysiology, 22*, 353-364.

Dee, H. (1971). Auditory asymmetry and strength of manual preference. *Cortex, 7*(3), 236-245.

Eichele, T., Nordby, H., Rimol, L., & Hygdahl, K. (2005). Asymmetry of evoked potential latency to speech sounds predicts the ear advantage in dichotic listening. *Cognitive Brain Research, 24*, 405-412.

Funnell, M., Corballis, P., & Gazzaniga, M. (2000). Insights into the functional specificity of the human corpus callosum. *Brain, 123*, 920-926.

Fujiki, N., Jousmaki, V., & Hari, R. (2002). Neuromagentic responses to frequency-tagged sounds: A new method to follow inputs from each ear to the human auditory cortex during binaural hearing. *Journal of Neuroscience, 22*(3), RC205.

Gilley, P., Sharma, A., Dorman, M., & Martin, K. (2005). Developmental changes in refractoriness of the cortical auditory evoked potential. *Clinical Neurophysiology, 116*, 648-657.

Hackett, T. (2008). Anatomical organization of the auditory cortex. *Journal of American Academy of Audiology, 19*, 774-779.

Hagelthorn, K., Brown, W., Amano, S., & Asarnow, R. (2000). Normal development of bilateral field advantage and evoked potential interhemispheric transmission time. *Development Neuropsychology*, *18*(1), 11-31.

Hall, J., & Goldstein, M. (1968). Representation of binaural stimuli by single units in primary auditory cortex of unanaesthetized cats. *The Journal of Acoustical Society of America, 43*(3), 456-461.

Hall, J. (1992). Handbook of auditory evoked responses. Boston, Allyn and Bacon.

Hall, J.W., & Chandler, D. (1994). Tympanometry in clinical audiology. In J. Katz (Ed.), Handbook of Clinical Audiology (pp. 284-299). Baltimore: Williams & Wilkins.

Hall, J. (2007). New handbook of auditory evoked responses. Boston: Pearson Education, Inc.

Hoptman, M., & Davidson, R. (1994). How and why do two cerebral hemispheres interact? *Psychology Bulletin, 116*, 195-219.

Hoptman, M., Davidson, R., Gudmundsson, A., Schreiber, R., & Ershler, W. (1996). Age differences in visual evoked potential estimates of interhemispheric transfer. *Neuropsychology*, *10*(2), 263-271.

Hornickel, J., Skoe, E., & Kraus, N. (2009). Subcortical laterality of speech encoding. *Audiology and Neurotology, 14*(3), 198-207.

Hynd, G.W., & Obrzut, J.E. (1979). Development of cerebral dominance: Dichotic listening asymmetry in normal and learning-disabled children. Journal of Experimental Child Psychology, *28*, 445-454.

Johnson, K., Nicol, T., Zecker, S., & Kraus, N. (2008). Development plasticity in the human auditory brainstem. *The Journal of Neuroscience*, *28*(15), 4000-4007.

Johnsrude, I., Zatorre, R., Milner, B., & Evans, A. (1997). Left hemisphere specialization for processing of acoustic transients. *Cognitive Neuroscience and Neuropsychology, 8*, 1761-1765.

Kaas, J., & Hackett, T. (2000). Subdivisions of auditory cortex and processing streams in primates. *Psychology and Hearing and Speech Sciences, 97*(22), 11793-11799.

Keith, R.W. (2000). Diagnosing central auditory processing disorders in children. In R.J. Roeser, M. Valente & H. Hosford-Dun (eds.) Audiology: Diagnosis. New York: Thieme Medical Publishers, pp. 337-353.

Kimura, D. (1961). Cerebral dominance and the perception of verbal stimuli. *Journal of Canadian Psychology, 15*(3), 166-171.

Kimura, D. (1963). Speech lateralization in young children as determined by an auditory test. *Journal of Comparative and Physiological Psychology, 56*(5), 899-902.

Kimura, D. (1967). Functional asymmetry of the brain in dichotic listening. *Cortex, 3*, 1-8.

Kimura, D., & Folb S. (1968). Neural processing of backwards speech sounds. *Science, 161*, 395-396.

Kraus, N., McGee, T., Carrell, T., Sharma, A., Micco, A., & Nicol, T. (1993). Speech-evoked cortical potentials in children. *Journal of the American Academy of Audiology, 4*, 238-248.

Kraus, N., & Nicol, T. (2003). Aggregate neural responses to speech sounds in the central auditory system. *Speech Communication, 41*, 35-47.

Krumm, M., & Cranford, J. (1994). Effects of contralateral speech competition on the late auditory evoked potential in children. *The Journal of the American Academy of Audiology, 5,* 127-132.

Ladefoged, P., & Broadbent, D. E. (1960). Perception of sequence in auditory events. *Journal of psychology, 12*, 162-170.

Milner, B., Taylor, L., & Sperry R.W. (1968). Lateralized suppression of dichotically presented digits after commissural section in man. *Science, 161*, 184-186.

Moncrieff, D., & Musiek, F. (2002). Interaural asymmetries revealed by dichotic listening tests in normal and dyslexic children. *Journal of the American Academy of Audiology, 13*, 428-437.

Moncrieff, D., & Wertz, D. (2008). Auditory rehabilitation for interaural asymmetry: Preliminary evidence of improved dichotic listening performance following intensive training. *International Journal of Audiology*, *47*, 84-97.

Mononen, L.J., & Seitz, M. R. (1977). An AER analysis of contralateral advantage in the transmission of auditory information. *Neuropsychologia, 15*, 165-173.

Mooshagian, E. (2008). Anatomy of the corpus callosum reveals its function. *Journal of Neuroscience, 28*(7), 1535-1536.

Mukari, S., Keith, R., Tharpe, A., & Johnson, C. (2006). Development and standardization of single and double dichotic digit tests in Malay language. *International Journal of Audiology*, *45*, 344-352.

Musiek, F., & Baran, J. (1986) Neuroanatomy, neurophysiology, and central auditory assessment. Part 1: Brainstem. *Ear and Hearing, 7*(4), 207-219.

Neville, H. (1974). Electrographic correlates of lateral asymmetry in the processing of verbal and nonverbal auditory stimuli. *Journal of Psycholinguist Research, 3*, 151-163.

Neville, H. (1980). Event-related potentials in neuropsychological studies of language. *Brain Language, 11*, 300-318.

Nolan, S. A., & Heinzen, T. E. (2007). *Statistics for the Behavioral Sciences*. New York: Worth Publishers.

Nowkicka, A., & Fersten, E. (2001). Sex-related differences in interhemispheric transmission time in the human brain. *Cognitive Neuroscience and Neuropsychology*, *12*(18), 4171-4175.

Papanicolaou, A., Baumann, S., Rogers, R., Saydjari, C., Amparo, E., & Eisenberg, H. (1990). Localization of auditory response sources using magnetoencephalography and magnetic resonance imaging, *Archives of Neurology, 47*(1), 33-37.

Penna, S., Brancucci, A., Babiloni, C., Franciotti, R., Pizzella, V., Rossi, D., Torquati, K., Rossini, P., & Romani, G. (2006). Lateralization of dichotic speech stimuli is based on specific auditory pathway interactions: Neuromagnetic evidence. *Cerebral Cortex*, 1-9.

Ponton, C.W., Moore, J.K., & Eggermont, J.J. (1999). Prolonged deafness limits auditory system developmental plasticity: Evidence from an evoked potentials study in children with cochlear implants. *Scandinavian Audiology*, *51*, 13-22.

Ponton, C.W., Eggermont, J.J., Kwong, B., & Don, M. (2000). Maturation of human central auditory system activity: Evidence from multi-channel evoked potentials. *Clinical Neurophysiology, 111*, 220-236.

Reite, M., Zimmerman, J.T., & Zimmerman, J.E. (1981). Magnetic auditory evoked fields: Interhemispehric asymmetry. *Electroencephalography Clinical Neurophysiologica, 51*(4), 388-392.

Romani, G., Williamson, S., & Kaufman, L. (1982). Tonotopic organization of the human auditory cortex. *Science, 216*(4552), 1339-1340.

Rugg, M., Lines, C., & Milner, A. (1984). Visual evoked potentials to lateralized stimuli and the measurement of interhemispheric transmission time. *Neuropsychologia, 22,* 215-225.

Salamy, A. (1978). Commissural transmission: Maturational changes in humans. *Science, 22*, 1409-1411.

Sandmann, P., Eichele, T., Specht, K., Jancke, L., Rimol, L., Nordby, H., & Hugdahl, K. (2007). Hemispheric asymmetries in the processing of temporal acoustic cues in consonant-vowel syllables. *Restorative Neurology and Neuroscience, 25*, 227-240.

Saron, S.K., & Davidson, R.J. (1989). Visual evoked potential measures of interhemispheric transfer time in humans. *Behavioral Neuroscience, 103*(5), 1115-1138.

Scott, S., & Wise, R. (2004). The functional neuroanatomy of prelexical processing in speech perception. *Cognition, 92*, 13-45.

Sebastian, C., & Yasin, I. (2008). Speech versus tone processing in compensated dyslexia: Discrimination and lateralization with dichotic mismatch negativity (MMN) paradigm. *International Journal of Psychophysiology, 70*(2), 115-126.

Sparks, R., & Geschwind, N. (1968). Dichotic listening after section of neocortical commissures, *Cortex, 4*, 3-16.

Speaks, C., & Niccum, N. (1977). Variability of the ear advantage in dichotic listening. *Journal of the American Audiology Society, 3*(1), 52-57.

Springer, S., & Gazzaniga, M. (1975). Dichotic testing of partial and complete slit-brain subjects. *Neuropsychologia, 13*(3), 341-346.

Studdert-Kennedy, M., & Shankweiler, D. (1970). Hemispheric specialization for speech perception. *The Journal of Acoustical Society of America, 48*(2), 579-594.

Ulusoy, I., Halici, U., Nalcai, E., Anac, I., Leblebicioglu, K., & Basar-Eroglu, C. (2004). Time-frequency analysis of visual evoked potentials for interhemispheric transfer time and proportion in callosal fibers of different diameters. Biological Cybernetics, http://www.eee.metu.edu/tr/~ilkay/biolcyber.pdf.

Yakovlev, P.I., & Lecours, A.R. (1967). The myelogenetic cycles of regional maturation of the brain. In A. Minkowski (Ed.), *Regional Development of the Brain in Early Life* (3-70). Oxford, England:Blackwell.

Yazgan, M., Wexler, B., Kinsbourne, M., Peterson, B., and Leckman, J. (1995). Functional significance of individual variations in callosal area. *Neuropsychology, 33*(6), 769-779.

Zatorre, R.J., Belin, P., & Penhune, V.B. (2002). Structure and function of auditory cortex: Music and speech. *Trends in Cognitive Sciences, 6*(1), 37-46.