DICHOTIC SPEECH DETECTION, IDENTIFICATION, AND RECOGNITION BY
CHILDREN, YOUNG ADULTS, AND OLDER ADULTS

DISSERTATION

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

By
Ursula M. Findlen, M.A.
Graduate Program in Speech and Hearing Science

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Dissertation Committee:
Dr. Christina M. Roup, Advisor
Dr. Lawrence L. Feth
Dr. Gail M. Whitelaw
Dr. Paula Rabidoux
ABSTRACT

Dichotic speech detection, identification, and recognition were evaluated using speech stimuli with varied in the amount of lexical content in order to examine lexical effects on performance characteristics measured in dichotic tasks. Data was collected for children and young adults with normal hearing, as well as older adults with mild to moderate sensorineural hearing loss for dichotic tasks administered under both free recall and directed recall response conditions in order to also examine cognitive load effects on performance. Results revealed that for dichotic speech recognition, the lexical content of the stimuli and the cognitive load of the task impacted performance measures for children, young adults, and older adults. Results from dichotic detection and identification tasks revealed young adults and older adults to perform at ceiling levels, while children demonstrated a significant difference in ability to detect versus the ability to identify target stimuli. Overall, the present study suggests that both lexical content and cognitive load impacts performance characteristics measured in dichotic tasks for children, young adults, and older adults. Clinical implications for diagnosis of auditory processing disorder are discussed.
DEDICATION

For Ben:

This dissertation would not have been possible without your love, support, and patience.
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VITA

March 7, 1980 ...................................... Born, Huntington, New York

2001 .............................................. B.S., Communication Sciences and Disorders
Syracuse University

2003 .............................................. M.A., Speech and Hearing Science
The Ohio State University

2007-Present ................................... Graduate Teaching Associate
The Ohio State University

FIELDS OF STUDY

Major Field: Speech and Hearing Science
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Auditory processing disorder (APD) has been defined as a deficiency in the perceptual processing of auditory information, typically demonstrated by poor performance in sound localization and lateralization, auditory discrimination, auditory pattern recognition, temporal processing, auditory performance in competing acoustic signals, and auditory performance in degraded acoustic signals (ASHA, 2005). A test battery approach is typically used in the assessment of APD in the pediatric population, including tests of auditory closure, temporal processing, auditory discrimination, and binaural processing. The most common binaural processing test used for assessment is dichotic speech recognition (Emanuel, 2002). Dichotic speech recognition involves listeners verbally reporting two different speech stimuli that are presented to both ears simultaneously. Performance characteristics that are measured include percent correct recognition per ear and an ear advantage that is defined as the difference between performance on materials presented to the right ear versus performance on materials presented to the left ear. When performance on materials presented to the right ear is greater than performance on materials presented to the left ear, a right ear advantage
(REA) results (Kimura, 1961b). Conversely, when performance on materials presented to the left ear is greater than performance on materials presented to the right ear, a left ear advantage (LEA) results. Although it is typical to obtain a REA for speech materials, an abnormally large REA or reduced recognition performance bilaterally are taken as indications of reduced dichotic speech recognition skills (Bellis, 2003). For children, a deficit in this area can be related to issues in higher-level language processing and learning in the typical classroom environment (Hynd, Obrzut, Weed, & Hynd, 1979; Helland & Asbjornsen, 2001; Moncrieff & Black, 2007).

Differential effects in performance in dichotic speech recognition tasks have been found secondary to: 1) the amount of lexical content introduced by the stimulus used in the task, 2) the amount of cognitive loading introduced by the test response condition, and 3) the age of the listener (Noffsinger, Martinez, & Wilson, 1994; Carter & Wilson, 2001; Hugdahl & Andersson, 1986; Hugdahl, Carlsson, & Eichele, 2001). According to the Neighborhood Activation Model (NAM), phonetic and lexical content of speech stimuli impact performance in traditional recognition tasks (Luce & Pisoni, 1998). Specifically, recognition performance is likely to be relatively high when the stimulus is familiar and has few phonetically similar words serving as competitors. Conversely, recognition performance is likely to be relatively low when the stimulus is less familiar to the listener and when the word has more phonetically similar words serving as competitors. Dichotic speech recognition studies that have included a wide range of stimuli have shown a systematic change in overall performance and ear advantage as a
function of phonetic and lexical content. Specifically, tasks using consonant-vowel (CV) stimuli reflect relatively lower levels of performance and larger ear advantages, while tasks using stimuli with more lexical content such as digits, words, and sentences, typically reflect higher performance levels and smaller ear advantages (Obrzut, Boliek, & Obrzut, 1986; Noffsinger, Martinez, & Wilson, 1994). Phonemic factors such as intelligibility, familiarity, and stimulus dominance, as well as phonemic contrast, or the difference in phonemic information present across the stimulus set, have been cited as contributing to these differences (Repp, 1977; Studdert-Kennedy & Shankweiller, 1969). Recently, the NAM was applied to the dichotic speech recognition paradigm using monosyllabic words in normal hearing young adults and older adults with hearing impairment (Carter & Wilson, 2001). Recognition performance for young adult listeners was impacted by the familiarity of the stimulus as well as the number of phonemic competitors for each stimulus, resulting in differences in overall performance per ear and ear advantage magnitudes across stimulus pairs containing different difficulties of words. Therefore, using speech stimuli with different phonetic content and different amounts of lexical content can impact performance characteristics measured in dichotic speech recognition testing.

The amount of cognitive loading introduced by the type of response condition employed in a dichotic speech recognition task has also been shown to impact the measurement of performance characteristics (Bryden, 1988; Hugdahl & Andersson, 1986; Obrzut, Boliek, & Asbjornsen, 2006). Typically, a verbal report of the stimulus is
used in dichotic speech recognition tasks, however clinical tests vary as to whether verbal report is completed under the free recall or the directed recall response condition. For free recall tests, such as the Dichotic Digits Test (Musiek, 1983), listeners are instructed to report what is presented to both ears in any order. For tests employing the directed recall response condition, such as the Competing Words Subtest of the SCAN (Keith, 1995; Keith, 2000), listeners are asked to report what they hear in the directed ear first followed by the other ear. The directed recall response condition has been used in an effort to diminish the effects of individual differences in performance and has also been used to lessen the cognitive load present in the task by providing the listener with a specific listening strategy (Hugdahl & Andersson, 1986; Obrzut, Boliek, & Asbjornsen, 2006; Jerger & Martin, 2006). Results from directed recall condition studies have shown the magnitude of the ear advantage to change systematically according to response condition (Hugdahl & Andersson, 1986). Typically, the directed recall right ear condition yields a larger REA and the directed recall left ear condition yields either a smaller REA or a LEA when compared to the free recall condition. The changes in ear advantage across response conditions, however, are stimulus dependent. Stimuli such as rhymed words have been shown to have relatively little change in magnitude of mean ear advantage across response condition, whereas CV syllables and words can show large changes in mean ear advantage magnitude across response condition (Shinn, Baran, Moncrieff & Musiek, 2005; Strouse & Wilson, 1999; Roup, Wiley, & Wilson, 2006).
The differential effects that both stimulus material and response condition have on dichotic speech recognition prompted some investigators to propose that performance characteristics derived from traditional dichotic speech recognition tasks actually reflect two different measurements: a “true” ear advantage and an “observed” ear advantage (Speaks, Niccum, & Carney, 1982). The “true” ear advantage is due to the relative transmission capacities of the auditory pathways to the dominant hemisphere for speech processing. The “observed” ear advantage may be due to a number of factors, such as the “true” ear advantage, decision variables such as attention biases and response strategies, stimulus variables such as acoustic content that may lead to a stimulus dominance, or measurement error. Speaks et al. (1982) further suggested that the use of a target detection paradigm in dichotic speech recognition that applies the theory of signal detection could potentially serve to separate these two ear advantages by separately measuring sensitivity and bias. Katsuki, Speaks, Penner, and Bilger (1984) investigated the use of a Yes/No dichotic target detection task with CV syllable stimuli in adults. A measure of ear advantage that incorporates both hit and false alarm rates and an index of criterion were calculated. Although mean data revealed a REA for the task, the ear advantage corrected for subject criterion was half of what it would have been if only calculated on hit rate alone, as typically done in verbal report dichotic speech recognition tasks. The criterion data showed that listeners had different biases depending upon the ear in which the target was presented, suggesting that listeners have response biases during dichotic speech recognition tasks that can serve to change the measured ear advantage. Clinically, it would be important to know whether a listener’s response bias...
was making a significant impact on measurement of performance criteria for dichotic speech recognition tasks, especially when attempting to differentiate between decrements in performance due to processing deficiencies in the ascending auditory pathways from response or attentional biases.

Hiscock et al. (1999) expanded the target detection dichotic speech recognition task by asking listeners to both detect the target stimulus and to identify the ear to which the target stimulus was presented using a three-alternative forced choice paradigm (right ear, left ear, or neither ear). The task was completed in both free recall and directed recall conditions to analyze the affect that biasing attention had on performance. Scoring involved calculating three sensitivity measures and one response bias measure. Detection sensitivity was calculated as the number of times the listener was successful in identifying the target was present regardless of the ear of arrival. Detection-plus-localization sensitivity was calculated as the number of times the listener was successful in correctly localizing the stimulus to the correct ear. A localization only sensitivity measure was calculated as a ratio of localization hits to detection hits. Lastly response bias was calculated for each attention condition per ear. Results revealed a consistent REA for detection hits and localization hits, however, directing the listener’s attention toward a certain ear only significantly impacted localization hits and not detection hits. Measurements of criterion suggested that listeners were using a more lax criterion for responding to left ear targets when compared to right ear targets, which was consistent with higher false alarms for the left ear. It was therefore concluded that detection of
target stimuli in a dichotic speech recognition task represents a listener’s sensitivity while the difference between detection and localization represents the attentional bias that can be manipulated by directing listeners to one ear versus the other (Hiscock et al., 1999).

Hiscock and Beckie (1993) further studied a dichotic target detection task in children with results suggesting that detection abilities develop with age. Further, results suggested that a child’s ability to both detect and identify stimuli is partially due to the application of attentional strategies children develop as they get older. Results of dichotic target detection studies in both adults and children have led to the suggestion that pairing the target detection task with a directed recall response mode can provide the examiner with a more valid measurement of binaural processing (Hiscock & Beckie, 1993; Voyer, 2004). Specifically, Voyer (2004) noted that pairing the paradigms could decrease the likelihood of individuals employing varied strategies across a testing session, as well as the likelihood of different listeners employing different strategies across tests. This, in turn, could provide a more reliable measure of dichotic speech recognition for the assessment of auditory processing disorders in children and adults.

Lastly, the age of the listener has been shown to impact both overall performance and magnitude of ear advantage measured in dichotic speech recognition tasks (Hugdahl et al., 2001; Roup et al., 2006; Noffsinger, Martinez, & Andrews, 1996). Overall, results of studies involving developmental effects in dichotic listening tasks suggest an improvement in overall performance and a decrease in REA as children get older. It has
been suggested that development and myelination of the corpus callosum is responsible for these trends (Bellis, 2003). Results from dichotic listening studies in the elderly population reveal poorer performance and larger REAs for older adults when compared to young adults. This trend has been termed a “left ear disadvantage” (LED) in this population (Martin & Jerger, 2006). Differences are accounted for by age-related changes occurring in the central auditory processing system and specifically involves the decreased conduction of the corpus callosum (Bellis & Wilbur, 2001).

Current dichotic speech recognition assessment tools for clinical diagnosis of auditory processing disorders in children use a verbal report of speech stimuli with varied amounts of lexical content and also use different response conditions (Keith, 2000; Musiek, 1983; Katz, 1962). Emanuel (2002) conducted a survey of common practices for the diagnosis of auditory processing disorders (APD) in the pediatric population. Results indicated that the Competing Words subtest of the SCAN (Keith, 2000), and the Staggered Spondaic Word (SSW) Test (Katz, 1962) are the most widely used dichotic speech recognition tasks in a practitioner’s APD test battery, followed by the Competing Sentence subtest of the SCAN and the Dichotic Digits Test (Musiek, 1983). The stimuli used in these tasks vary greatly, from familiar numbers and monosyllabic words to bisyllabic compound nouns and sentence material. These tasks also vary in terms of cognitive load in that some use the free recall response condition while others use the directed recall response condition. Due to the significant differences in stimulus material and response conditions employed in these tasks, there is a potential that conflicting
results would be obtained when using all of these tests together in a test battery to
diagnose dichotic speech recognition deficits. Further, Speaks et al. (1982) suggested
that with traditional dichotic speech recognition tasks using verbal report of stimuli, the
examiner would have no control or knowledge over how other variables such as attention
and bias may affect measurement of performance. The interaction between effects of
lexical content and cognitive load is particularly important when considering assessment
of children with coexisting diagnoses of language or cognitive deficits. Differences in
task demands introduced by varying lexical content and cognitive loading in the
assessment task could potentially interact with higher-level language or cognitive
deficits, such as attention deficit hyperactivity disorder, complicating the appropriate
diagnosis of an auditory processing deficit. Consequently, children who have coexisting
deficits could potentially perform poorly despite having typical auditory processing
skills. With reports of both cognitive and language disorders appearing simultaneously
with auditory processing problems in children (Cestnick & Jerger, 2000; Wright,
Lombardino, King, Puranik, Leonard, & Merzenich, 1997), there is a significant need to
investigate assessment tools that attempt to lessen the potential differential effects of
lexical content and cognitive loading on performance. Differential diagnosis between
children who have auditory processing deficits and those who do not is essential to
reduce the likelihood of misdiagnosis and implementation of inappropriate management
strategies.
In light of the differential effects that both lexical content and cognitive loading may have on dichotic speech recognition testing, the **specific aims** of the current project were:

1. To investigate potential recognition performance differences between stimuli with different amounts of lexical content while keeping phonetic content constant;
2. To investigate performance differences between traditional dichotic speech recognition tasks and a target detection and identification testing paradigm; and
3. To investigate performance differences across three groups of listeners, including children, young adults, and older adults.

In order to address the above specific aims for the current project, the following **hypotheses** were tested:

**Dichotic Speech Recognition Testing:**

1. Performance on stimuli with relatively more lexical content will be better than performance on stimuli with relatively less lexical content;
2. Performance characteristics will change systematically across response condition. A mean REA will be obtained for the free recall and directed right response conditions, while a mean smaller REA or LEA will be obtained for the directed left response condition;
3. Performance characteristics will change systematically across age. Overall performance will be better for young adults than for either children or older
adults. Smaller ear advantages will be obtained for young adults while larger ear advantages will be obtained for both children and older adults.

*Dichotic Target Detection and Identification Testing:*

1. Performance on stimuli with relatively more lexical content will be better than performance on stimuli with relatively less lexical content;

2. Performance characteristics will change systematically across response condition. A mean REA will be obtained for the free recall and directed right response conditions, while a mean smaller REA or LEA will be obtained for the directed left response condition;

3. Performance characteristics will change systematically across age. Overall performance will be better for young adults than for either children or older adults. Young adults will show no significant difference between detection and identification skills. Children and older adults will show better detection versus identification skills.

A significant difference in performance between groups across stimuli with different lexical content and across different testing paradigms could provide information on how dichotic speech recognition skills change as a function of lexical content, cognitive load, and age. Ultimately, understanding these differences and how they may impact performance on dichotic speech recognition tasks typically used clinically in both children and adults may provide information useful for developing assessment tools that
take into consideration how lexical content and cognitive load impacts performance measurement. This, in turn, may provide ways to differentially diagnose binaural auditory processing deficits from other higher-level language and/or cognitive deficits.
2.1 AUDITORY PROCESSING DISORDERS IN CHILDREN

The American Speech-Language-Hearing Association (ASHA) has defined auditory processing as the efficiency and effectiveness by which the central nervous system utilizes auditory information (ASHA, 2005). ASHA (2005) further defines auditory processing as encompassing mechanisms used for sound localization and lateralization, auditory discrimination, auditory pattern recognition, temporal processing, auditory performance in competing acoustic signals, and recognition performance in degraded acoustic signals. An auditory processing disorder (APD) is therefore a deficiency in the perceptual processing of auditory information as demonstrated by poor performance in one or more auditory processing skills.

Different models using different test batteries have been introduced for assessment of APD in the pediatric population (Bellis, 2003; Katz, 1962). Although having multiple models has led to confusion regarding how to most adequately assess auditory processing skills in children, each model typically recommends the assessment
of auditory processing at each level of the central auditory pathway using a test battery approach. Typically, an assessment battery includes tests that evaluate auditory figure-ground discrimination, auditory closure, temporal processing, and binaural processing such as masking level difference, localization, and dichotic speech recognition (ASHA, 2005; Jerger & Musiek, 2000; Bellis, 2003).

**Binaural Hearing**

Binaural hearing refers to how the two ears work together to process auditory information (Bellis, 2003). Processes involving combining information from both ears are mediated by brainstem structures in the central auditory nervous system as well as the auditory cortex and the corpus callosum (Musiek & Baran, 1986; Musiek, 1986). The rapid development of the brainstem during infancy and early childhood contributes to the development of binaural hearing skills, specifically localization of auditory stimuli and binaural interaction skills. Further development of the auditory cortical areas and corpus callosum during early childhood and into school-age years contributes to the development of dichotic speech recognition skills, a higher-level example of a binaural hearing process (Musiek, 1986).

**2.2 DICHOTIC SPEECH RECOGNITION**

The dichotic speech recognition task was originally developed by Broadbent (1954) to investigate the efficiency of auditory localization and the limits of memory
recall from two separate auditory channels. Kimura (1961b) used dichotic speech recognition to investigate cerebral dominance for language. Dichotic speech recognition involves the presentation of competing stimuli to the right and left ears simultaneously. Listeners are typically asked to repeat one or both stimuli presented depending upon stimulus and testing paradigm. In the free recall response condition, listeners are asked to repeat the stimuli they hear in any order. In the directed recall response condition, the listener is requested to repeat the stimulus from the directed ear first and then the other ear second. For example, in the directed recall right condition, listeners would repeat the right ear stimulus first followed by the left ear stimulus. In the directed recall left condition, listeners would repeat the left ear stimulus first followed by the right ear stimulus. When only one response is requested, the listener repeats the stimulus in the directed ear only. Performance characteristics measured via dichotic speech recognition include the recognition performance per ear expressed in terms of percent correct, and an ear advantage which is calculated by subtracting recognition performance for materials presented to the left ear from performance for materials presented to the right ear. In normal hearing adults, performance on speech materials presented to the right ear is typically better than performance on speech materials presented to the left ear (Kimura, 1961b). This phenomenon has been termed the right ear advantage (REA). There have been two models proposed to account for the observed ear advantage obtained in dichotic speech recognition tasks: the anatomical/structural model (Kimura, 1961a; Kimura, 1961b) and the attentional model (Kinsbourne, 1970).
Anatomical/Structural Model

Kimura (1961a) first proposed the anatomical/structural model to explain results obtained with dichotic listening from patients with temporal lobe damage. On a dichotic speech recognition task using multiple pairs of digits, patients with left temporal lobe lesions performed poorly when compared to patients with right temporal lobe lesions. Testing completed after temporal lobectomy revealed deficits in performance on materials presented to the ear opposite the surgical site. Consequently, Kimura (1961a) proposed that the contralateral auditory pathways were stronger than ipsilateral pathways and that the left temporal lobe was particularly important for the processing of verbal stimuli. Specifically during dichotic speech presentation in which two auditory stimuli are presented simultaneously in direct competition with each other, contralateral connections that are stronger and more numerous relay auditory information to the opposite hemisphere more efficiently than ipsilateral pathways. Therefore, when speech materials are presented simultaneously, materials presented to the right ear have a more efficient pathway to the speech processing center in the left hemisphere, whereas materials presented to the left ear are more efficiently transmitted to the right hemisphere and must cross over to the speech processing center in the left hemisphere via the corpus callosum.
To further investigate the anatomical/structural model, Kimura (1961b) studied dichotic speech recognition using digits in people whose lateralization was already determined by the sodium amytal test. The sodium amytal test was introduced by Wada and Rasmussen (1960) as a way to determine language lateralization in patients undergoing neurosurgery. This test entails injecting sodium amytal into one of the carotid arteries to temporarily disrupt neural function on that side of the brain. Language lateralization is determined by whichever injection side results in dysphasia. The main hypothesis of Kimura’s study was that listeners with known language lateralization to the right hemisphere would have better performance on materials presented to the left ear. Listeners were tested with a dichotic speech recognition task using three-pair digit stimulus materials. Results revealed that on average listeners with language lateralized to the left hemisphere had a REA on the dichotic speech recognition task while listeners with language lateralized to the right hemisphere had a left ear advantage (LEA). Results of this study were presented as evidence for the anatomical/structural model of dichotic speech recognition. Kimura (1967) further suggested that the stronger contralateral pathways occlude the weaker ipsilateral pathways and that central competition of these two pathways further enhances the contralateral advantage. Therefore, the anatomical/structural model of dichotic speech recognition is based on several assumptions: 1) contralateral auditory pathways are stronger than ipsilateral pathways, 2) the stronger contralateral pathways occlude or inhibit the weaker ipsilateral pathways, 3) the left hemisphere is the dominant hemisphere for processing speech stimuli, and 4) information presented to the non-dominant ear must travel from the non-dominant
Evidence for the anatomical/structural theory has been offered by subsequent anatomical, behavioral, and electrophysiological studies. Geschwind and Levitsky (1968) presented anatomical data supporting the structural asymmetry of the temporal lobe of the human brain. Measurements taken of the planum temporale revealed the left temporal lobe structure to be larger than the right temporal lobe structure in a majority of brains. Coupled with previous data from aphasic patients, these results suggest that the left planum temporale is the location of the speech processing center for most people (Geschwind & Levitsky, 1968).

Behavioral studies focusing on the performance of split-brain patients on dichotic speech recognition tasks have provided further support of the anatomical/structural model of dichotic speech recognition (Musiek, 1986). On dichotic speech recognition tasks using speech stimuli such as digits or CV syllables, commissurotomy patients demonstrate typical or enhanced performance for materials presented to the right ear. Performance for materials presented to the left ear, however, is typically significantly below normal and in most cases will reflect less than 10% correct recognition performance. These results further support the assumption that the left hemisphere is dominant for processing speech stimuli because in commissurotomy patients the ipsilateral ascending auditory pathways do not have access to opposite hemispheres.
through the corpus callosum. Therefore, dichotic speech recognition in this population relies almost entirely on the contralateral ascending auditory pathway and a significant REA for speech material suggests that the left hemisphere is dominant for speech processing. Results also suggest the role of the corpus callosum as the location for interhemispheric transfer of auditory information from the non-dominant ear to be processed in the dominant hemisphere (Musiek, 1986).

Studdert-Kennedy and Shankweiler (1969) also examined the role of the dominant hemisphere and the corpus callosum in dichotic speech recognition. Consonant-vowel-consonant (CVC) syllables were used in normal hearing young adults to determine which aspects of the speech signal were processed by speech-specific mechanisms in the dominant hemisphere. The authors framed this study in the context of the ear advantage necessitating two key conditions: 1) a dominant hemisphere for processing speech stimuli, and 2) loss of information as material is transferred from the non-dominant hemisphere to the dominant hemisphere for processing. Data analysis included calculating errors on initial consonants, medial vowels, and final consonants separately. Results showed that significant REAs were obtained for initial and final consonants while non-significant REAs were obtained for medial vowels. The authors interpreted these results as indicating the differential processing of consonants and vowels during dichotic speech recognition. Specifically, consonant features are independently processed as linguistic units in the left hemisphere. Two conclusions were drawn from these results: 1) although each hemisphere performs auditory pattern
recognition, only the dominant hemisphere interprets auditory patterns as a set of linguistic features, and 2) ipsilateral information undergoes a loss of information as it is transferred through the corpus callosum to the dominant hemisphere (Studdert-Kennedy & Shankweiler, 1969).

Lastly, neurophysiologic data have also supported the main assumptions of the anatomical/structural model. The contributions of the ascending auditory pathways to dichotic speech recognition performance on a CV syllable task have been investigated using magnetoencephalography (MEG; Della Penna et al., 2007). Dichotic speech recognition tasks were carried out using two sets of contrasting CV syllable pairs, those that had high spectral overlap, as in the case of /da/ and /ba/, and those that had less spectral overlap, as in the case of /da/ and /ka/. While the intensity of one of the syllables in the pair was kept constant, the intensity of the other syllable in the pair was varied between two intensities, one that matched the first and one that was 20 dB higher. Della Penna et al. (2007) reported that MEG dipole source measurements revealed a larger source intensity for the contralateral ascending auditory pathways which supported the notion that contralateral auditory pathways are dominant, more numerous, and faster conducting during dichotic processing than ipsilateral pathways. Also, a reduction in source intensity in response to dichotic pairs with different intensity levels was taken as evidence of pathway inhibition effects, suggesting that the contralateral pathways occlude or block transmission from ipsilateral pathways. Lastly, MEG source strength data
suggested that the occlusion of the ipsilateral pathway information by the contralateral pathway occurs in the primary auditory cortex (Della Penna et al., 2007).

Attentional Model

An alternate view to explain the observed REA in dichotic speech recognition was proposed by Kinsbourne (1970). The attentional model proposes that performance asymmetries found via dichotic tasks are due to a biased priming effect that occurs because of the type of stimulus used. An orientation bias is introduced into the task by the stimulus itself that primes the hemisphere responsible for processing that type of stimulus. For verbal stimuli, the left hemisphere is primed and attention is automatically shifted to the right ear. For nonverbal stimuli, the right hemisphere is primed and attention is automatically shifted to the left ear. The automatic shift in attention that is introduced by the orientation bias allows for an expectancy effect. If a specific stimulus is expected throughout the task, materials presented to the opposite ear will be preferentially processed before materials presented to the ear ipsilateral to the dominant hemisphere. Therefore, for verbal stimuli presented in a dichotic speech recognition task, a REA will result (Kinsbourne, 1970).

Hiscock et al. (1999) proposed an extension of the attentional model. In a study investigating dichotic speech recognition using a target detection task, these authors examined the ways in which attentional instructions interact with the measurement of ear advantage. Listeners were instructed to indicate if a target stimulus was present within a
dichotic pair. In the free recall condition, listeners were free to allocate their attention to both ears as they wished. In the directed recall conditions, listeners were directed to monitor one ear while ignoring the opposite ear. Results were analyzed for correct detection of the target stimulus and correct identification of the stimulus ear. Although detection performance remained relatively stable across listening conditions, identification performance changed depending upon whether listeners were instructed to monitor both ears or directed to a specific ear. Hiscock et al. (1999) suggested that the processing of dichotic stimuli could be broken up into two discrete stages: an automatic stage and a controlled stage. The automatic stage is a fixed stage of processing that is stimulus driven. The type of stimulus presented determines the orientation bias and primes the appropriate hemisphere to preferentially process materials presented to the opposite ear. The controlled stage is driven by the instructions given to the listener as to where to allocate attention. The controlled stage occurs after the automatic processing stage. The two-stage attentional model explains why the REA typically occurs with verbal stimuli and why the magnitude and direction of ear advantage can change according to instructions given for the task (Hiscock et al., 1999).

The main difference between the two models of dichotic speech recognition is that the anatomical/structural model points to static differences in the ascending auditory pathways and auditory cortices as the explanation for asymmetries in performance between ears. The attentional model proposes that an attention shift introduced by the task context and an individual’s own thought process explains the observed REA in
dichotic speech recognition. Although the anatomical/structural model and attentional model appear to be in opposition with each other, Voyer (2003) has proposed that they are actually complimentary. Voyer (2003) suggests that the attentional biases that are proposed by the attentional model can be viewed as a by-product of the anatomical/structural aspects of the auditory system. Therefore, when considering the extended attentional model proposed by Hiscock et al. (1999), the automatic stage representing the stimulus-driven stage of processing is actually in line with the anatomical/structural model while the controlled stage of processing can be viewed as resulting from the attentional model. Neurophysiological support for a combined anatomical/structural and attentional model has been provided by MEG data as discussed above as well as functional magnetic resonance imaging (fMRI) data. Jancke and Shah (2002) reported that results from fMRI dichotic listening tasks using a free recall and directed recall target detection task carried out in normal right-handed adults suggested the combined activation of both auditory and cognitive brain centers. Activation of the frontotemporal networks during the free recall response condition was taken as evidence that dichotic listening involves activation of both auditory and executive functioning areas of the brain. Additional activation of inferior frontal areas during the directed recall response condition that change depending up whether the listener engages in a directed recall right versus directed recall left response condition further suggests different executive strategies are used for processing competing auditory signals when attention is directed in a particular direction (Jancke & Shah, 2002). Therefore, results from fMRI
data suggest that the combination of the anatomical/structural and attentional models best explains the auditory and cognitive processing that is occurring during a dichotic task.

2.3 DICHOTIC SPEECH RECOGNITION CONSIDERATIONS

Typical Performance

Performance characteristics measured via dichotic speech recognition include the recognition performance per ear and the direction and magnitude of ear advantage. In normal hearing adults, performance on speech materials presented to the right ear is better than performance on speech materials presented to the left ear, resulting in a REA (Kimura, 1961b). The REA in typical listeners is taken as evidence that language is lateralized to the left hemisphere. However, there are many factors that impact performance characteristics measured via dichotic speech recognition, including cerebral dominance and handedness, the type of speech stimuli used in the task, cognitive effects including attentional strategies introduced by the use of the directed recall response condition, and the age of the listener. All of these factors need to be considered when evaluating performance on dichotic speech recognition tasks. The three factors that are the focus of the present study include the type of speech stimulus used in the task, cognitive/attention strategies introduced by the use of the directed recall response condition, and age.
Stimulus Considerations

The type of stimulus used in the dichotic speech recognition task has been shown to impact the overall performance and the magnitude of ear advantage measured. Noffsinger, Martinez, and Wilson (1994) compared stimulus types in dichotic speech recognition tasks in normal hearing young adult listeners. Stimulus materials included digits, synthetic sentences, and CV syllables. Testing was completed in a free recall closed set manner in which listeners manually checked off which two stimuli were heard on each trial on a response sheet. Results revealed a range of difficulty, with better performance on tasks using digits and synthetic sentence material when compared to tasks using CV syllable material. A ceiling effect was noted for digit stimuli. The explanation offered for the ceiling effect found with digit material was that these stimuli are a closed set of highly familiar words with acoustic parameters of both amplitude and duration that cannot be as controlled as in synthetic sentences or CV syllables (Noffsinger et al., 1994).

An effect of stimulus type on dichotic speech recognition has also been found in studies in the pediatric population. Obrzut, Boliek, and Obrzut (1986) compared the direction and magnitude of ear advantage in children ages nine to twelve years. Dichotic speech recognition testing was completed using both the free recall and directed recall response conditions. In the free recall condition, children were expected to report stimuli heard in both ears while in the directed recall response conditions children were only expected to repeat the directed ear stimulus. Stimulus types included four-pair words,
one-pair CV syllables, three-pair digits, and one-pair melodies. Results suggested that the ear advantage measured in dichotic speech recognition tasks in children is strongly affected by both stimulus material and response condition. In the free recall condition, performance on all speech stimulus types (words, CVs, and digits) yielded REAs. Digit material again showed ceiling effects, while performance on word material was similar to CV syllable material. Although word pairs are usually more easily recognized than CV syllable pairs, this particular study used four pairs of words on each trial, which increased the difficulty of the task.

When comparing performance of listeners across studies that have used a variety of stimulus types, a hierarchy of stimulus difficulty can be established. Overall, performance on digit material yields the highest performance and relatively small ear advantages (Kimura, 1961b; Noffsinger et al, 1994; Obrzut et al., 1986). Word and sentence material follow and show relatively high performance and moderate ear advantages (Noffsinger et al, 1994, Roup et al., 2006). CV syllables are the most difficult stimuli, with relatively lower levels of performance and larger ear advantages (Noffsinger et al., 1994; Wilson & Leigh, 1996; Hugdahl & Anderson, 1986; Obrzut et al., 1986).

Recent speech recognition models have proposed that phonemic and lexical content within word stimuli can have a significant impact on recognition of words in isolation (Luce & Pisoni, 1998). Speech recognition can be viewed as a two-step process, with “bottom-up” processing of sensory information, such as phonemic
discrimination, and concurrent “top-down” processing of linguistic content that leads to the selection of the appropriate response (Luce & Pisoni, 1998). The impact of phonemic content and lexical content of stimuli has been studied in relation to traditional speech recognition tasks through the Neighborhood Activation Model (NAM) of speech recognition (Luce & Pisoni, 1998). The NAM proposes that words are recognized relationally in the context of other phonetically similar words in a two-step process that involves phonetic processing and lexical selection. Three main variables that contribute to recognition of words include: 1) word frequency, 2) neighborhood density, and 3) neighborhood frequency. Word frequency refers to the number of times the word typically occurs in the language. Neighborhood density refers to the number of phonetically similar words, or neighbors, for a particular target word. Neighborhood frequency refers to the average frequency of occurrence of all the words within a neighborhood. These three factors together can define the difficulty of a specific target word as “easy” or “hard.” Easy words typically have high frequency of occurrence, sparse neighborhood densities, and occur within a neighborhood whose average frequency is relatively low. In contrast, “hard” words typically have low frequency of occurrence, a dense neighborhood, and occur within a neighborhood whose average frequency is relatively high. Words occurring in the English language have been categorized according to these three factors. Within a stimulus set, relatively “easy” and “hard” words can be identified by parsing out words falling below and above average or median scores for each of the characteristic variables (Luce & Pisoni, 1998).
Differences in speed and accuracy of word recognition across different word difficulties have been found in traditional speech recognition tasks for both normal hearing and hearing impaired listeners (Dirks, Takayanagi, Moshfegh, Noffsinger, & Fausti, 2001; Takayanagi, Dirks, & Moshfegh, 2002). Dirks et al. (2001) studied speech recognition performance on words having a continuum of difficulty according to NAM ratings in both normal hearing young adults and older adults with hearing loss. Results from the young adult normal hearing listeners revealed that performance decreased as the lexical difficulty of the word increased. Although the pattern of performance for the older listeners with hearing impairment was similar to the young adult listeners, the difference between lexically “hard” words and lexically “easy” words was larger for the older group when compared to the younger group. Although performance for the lexically “easy” words was similar for both groups, older hearing impaired listeners had more difficulty recognizing lexically “hard” words than the younger normal hearing listeners. These results were consistent with a subsequent paper examining lexical and talker effects on speech recognition (Takayanagi et al., 2002). Takayanagi et al. (2002) demonstrated that linguistic familiarity impacted word recognition performance in normal hearing and hearing impaired listeners. Specifically, listeners needed a higher sound pressure level to correctly identify lexically “hard” words 50% of the time when compared to lexically “easy” words. Takayanagi et al. (2002) concluded that lexical familiarity is a significant factor in word recognition task performance.
Recently, the NAM was applied to the dichotic speech recognition paradigm using monosyllabic words in normal hearing young adults and older adults with hearing impairment (Carter & Wilson, 2001). Words were paired according to NAM ratings to create two categories of pairings consisting of four types of stimulus pairs: same pairs consisted of easy-easy and hard-hard pairings, while mixed pairs consisted of easy-hard and hard-easy pairings. Dichotic speech recognition tasks were completed using a free recall response paradigm. Differences in recognition performance were demonstrated across group and word difficulty. For same pairs, easy words were identified correctly more often than hard words in both listening groups. Also, performance on materials presented to the right ear was better than performance on materials presented to the left ear, resulting in a REA for same pairs for both groups. However, overall performance for the older group with hearing loss was poorer than the younger group, and older listeners had a larger REA when compared to the younger group. Larger REAs in the older group were due to a decrease in performance on materials presented to the left ear, demonstrating the “left ear disadvantage” (Carter & Wilson, 2001). Results from the mixed pair stimuli revealed that easy words were identified correctly more often than hard words regardless what ear they were presented to in the younger group. However, for the older group, words presented to the right ear were identified correctly more often than words presented to the left ear regardless of word difficulty. Therefore, while the direction of ear advantage changed according to the type of word presented to each ear to the young adults, older adults had a consistent REA regardless of the difficulty of words presented to each ear. Carter and Wilson (2001) interpreted these results to suggest that
although younger listeners can partially process word stimuli in the right hemisphere, processing of speech stimuli in the right hemisphere is not efficient in older adults and therefore speech is only processed in the left hemisphere.

The above results have shown that lexical difficulty of words can impact speech recognition performance in general, and the subsequent measurement of ear advantage in a dichotic speech recognition task. The affect that speech stimulus material has on dichotic speech recognition not only complicates comparison of performance across tests that use different types of speech stimuli, but can also potentially impact performance measurement within a test using one type of stimulus. Because dichotic speech recognition tasks are scored per ear and a resulting ear advantage is calculated across ears, the combination of “easy” and “hard” words per dichotic pairing can change performance on this task accordingly. This issue could potentially impact tests using monosyllabic words or digits, as well as tests using sentence material. Therefore, when using speech stimuli in dichotic speech recognition, the nature of lexical content present in stimuli could potentially impact the outcome of the test.

Current dichotic speech recognition assessment tools for clinical diagnosis of auditory processing disorders in children use speech stimuli with various amounts of lexical content (Keith, 2000; Musiek, 1983; Katz, 1993). Emanuel (2002) conducted a survey of common practices for the diagnosis of APD in the pediatric population. Results indicated that the Competing Words subtest of the SCAN (Keith, 2000), and the
Staggered Spondaic Word (SSW) Test (Katz, 1962) are the most widely used dichotic speech recognition tasks in a practitioner’s APD test battery to assess binaural processing skills, followed by the Competing Sentence subtest of the SCAN and the Dichotic Digits Test (Musiek, 1983). These tests use familiar monosyllabic word, bisyllabic compound nouns, highly familiar numbers, and sentence material, respectively. Because performance can be impacted by the lexical content present in the speech stimulus, the incorporation of several dichotic speech recognition tasks in a test battery could potentially provide conflicting results, complicating the appropriate diagnosis of a binaural processing deficit. Moncrieff (2006) reported that within a set of children tested with several different dichotic speech recognition tests using different speech stimuli ranging from CV syllables, words, and digits, a subset of those children performed poorly on some tests while having performance within normal limits on others tests. Therefore, there is a considerable need to investigate stimuli that may potentially lessen the effects of lexical content on dichotic speech recognition.

Cognitive Considerations

The impact of cognitive processes on dichotic speech recognition performance, particularly the effect that attention has on measurement of ear advantage scores, has been significantly studied in both adults and children (Bryden, 1978; Hugdahl & Andersson, 1986; Hugdahl et al., 2001). In the free recall response condition, listeners are asked to repeat the stimuli they hear in any order. This testing paradigm allows the listener to choose how to attend to the stimuli and the order in which the stimuli are
repeated. This leaves the potential listening strategies and reporting strategies to vary across both time and listeners. Bryden (1978) reported that allowing a listener to chose how to deploy their attention and how to report the required stimuli could impact the measurement of ear advantage. For instance, a listening strategy can be introduced if a listener chooses to attend to the left ear more often than the right ear. In that case, the magnitude of the REA will decrease and may even become a LEA. Alternatively, if the listener chooses to attend to the right ear more often than the left ear, the REA for the listener may be inflated. Also, data have shown that the first stimulus reported is typically more reliable than the second stimulus reported (Inglis, 1962). Therefore, if the listener chooses to report the stimulus presented to one ear first more consistently then a reporting bias will impact the measurement of ear advantage.

Solutions for minimizing the effects of individual listening strategies and reporting bias include using a directed recall response condition or using a dichotic target detection testing paradigm. In the directed recall paradigm, the listener is requested to repeat the stimulus from the directed ear first and then the other ear second. For example, in the directed recall right ear condition, listeners would repeat the right ear stimulus first followed by the left ear stimulus. In the directed recall left ear condition, listeners would repeat the left ear stimulus first followed by the right ear stimulus. When only one response is requested, the listener repeats the stimulus in the directed ear only. The listener is therefore given a specific listening and reporting strategy to follow, whereby lessening the cognitive load of the task. The free recall condition is also typically
administered in studies using the directed recall paradigm, and measurements of ear advantages will vary in a predictable way depending upon the instructions given. Typically, right-handed young adult listeners with normal hearing will demonstrate a REA for the free recall condition, a larger REA for the directed recall right ear condition, and a LEA for the directed recall left ear condition (Asbjornsen & Hugdahl, 1995; Hugdahl & Andersson, 1986). Obrzut et al. (1986), however, reported a significant interaction between stimulus type and response condition in the pediatric population. Although all speech stimuli yielded a REA in the free recall condition, the directed recall conditions yielded variable results across stimuli. For digit and word stimuli, the directed recall right ear condition yielded REAs and the directed recall left ear condition yielded LEAs. Regardless of response condition, however, performance on CV syllable materials always yielded a REA. Therefore, in dichotic speech recognition tasks in the pediatric population, both the stimulus and response condition impacts performance and ear advantages measured.

Performance characteristics change according to the response condition employed in the test, and therefore could potentially have significant clinical implications. The most commonly used tests to assess dichotic speech recognition for diagnosis of auditory processing disorders in children use different response conditions (Emanuel, 2002). While the SCAN Competing words and Competing Sentences (Keith, 2000) subtests use a directed recall response condition, the Dichotic Digits Test (Musiek, 1983) is administered in the free recall response condition only. The Dichotic Digits Test presents
20 double pairs of digit stimulus material totaling 80 stimuli, or 40 per ear. Normative data for this task indicates that a typical eleven-year-old child should achieve performance of 90% correct in the right ear and 88% correct in the left ear. If the entire 20 double pair test is administered, each stimulus is worth 1.25 percentage points, meaning that the 2% ear advantage at this age is accounted for by only two stimuli. A child would only have to miss two additional stimuli in the right ear or one additional stimulus in the left ear to have performance be considered abnormal. It is possible that a child could miss these additional stimuli just by failing to attend to the stimuli in one ear during one of the 20 stimulus presentations or by introducing a reporting bias by choosing to preferentially report materials presented to one ear first. Therefore, if listeners are tested using only the free recall response condition, there is a potential that auditory processing abilities can be either under or over-estimated due to individual listening strategies or report bias. This in turn could potentially lead to a misdiagnosis of and auditory processing deficit when the decrement in performance could actually be due to an attentional issue.

Another proposed way to deal with subjects using individual listening strategies is the use of a dichotic target detection task. In a target detection task, a listener is prompted to monitor one or both ears for a target stimulus. Upon each trial, the listener has to make a decision as to whether the target stimulus was present in either of the ears while the competing word present acts as the “noise”. The listener can be asked to either simply indicate the presence of the target or to localize in which ear the target was
presented. Thus, on each trial, the listener decides whether one of the stimuli presented in the dichotic pair is likely to be a target or just “noise”. The signal detection model is the basis for reporting and analyzing results in a dichotic speech recognition target detection task. The utility in using a testing paradigm based in signal detection theory for a dichotic speech recognition task lies in the ability of the examiner to separate true sensory capacity for the task from response bias that may be due to a number of other factors (Katsuki, Speaks, Penner, & Bilger, 1984).

Speaks, Niccum, and Carney (1982) suggested that the ear advantage obtained in traditional dichotic speech recognition testing paradigms could reflect two different measurements: the “true” ear advantage and the “observed” ear advantage. The “true” ear advantage is due to the relative transmission capacities of the auditory pathways to the dominant hemisphere for speech processing. The “observed” ear advantage may be due to a number of factors, such as the “true” ear advantage, decision variables such as attention biases and response strategies, stimulus variables such as acoustic content that may lead to a stimulus dominance, or measurement error. With traditional dichotic speech recognition tasks using a verbal report method, the examiner would have no control or knowledge over how these other variables may affect response bias and subsequently measurement of performance. Katsuki et al. (1984) investigated the potential impact of decision variables on the measurement of ear advantage. Using a Yes/No dichotic target detection task with CV syllable stimuli in adults, a measure of ear advantage that incorporates both hit and false alarm rates and an index of criterion were
calculated. Although mean data revealed a REA for the task, the ear advantage corrected for subject criterion was half of what it would have been if only calculated on hit rate alone, as typically done in verbal report dichotic speech recognition tasks. The criterion data showed that listeners had different biases depending upon the ear in which the target was presented, suggesting that listeners have response biases during dichotic speech recognition tasks that can serve to inflate the measured ear advantage. These results also suggest a significant need to use a dichotic target detection task so that sensitivity can be separated from the observer’s bias.

More recently, dichotic target detection tasks have been directly compared to traditional verbal report dichotic speech recognition tasks to further investigate their utility (Voyer, 2003; Hiscock, Inch, & Ewing, 2005). Voyer (2003) directly compared a traditional dichotic speech recognition task using both free recall and directed recall response conditions with a Yes/No dichotic target detection task in adult listeners using the same stimuli. Performance measurements were calculated using an index of laterality, Lambda, that takes into consideration both correct and incorrect responses when calculating performance. Results revealed the dichotic target detection task yielded a more robust REA that was more consistent upon re-testing than the traditional dichotic speech recognition paradigm. Although the data analysis did not include a direct measure of listener bias, correlation data suggested that using the dichotic target detection task decreased attention deployment strategies, thereby stabilizing the measurement of ear advantage (Voyer, 2003).
The target detection paradigm has also been used to study the detection and identification of target stimuli presented in a dichotic speech recognition task (Hiscock & Beckie, 1993; Hiscock, Inch, & Kinsbourne, 1999; Hiscock, et al., 2005; Voyer, Szeligo, & Russell, 2005). Hiscock et al. (1999) studied the dichotic target detection task using both fused CVC and CV syllables in adult listeners. Listeners were asked to both detect whether or not a target stimulus was present and also identify to which ear the target was presented in a three alternative forced-choice paradigm. The task was completed in both free recall and directed recall response conditions to analyze the effect that biasing attention had on performance. Scoring involved calculating three sensitivity measures and one response bias measure. Detection sensitivity was calculated as the number of times the listener was successful in identifying if the target was present regardless of the ear of arrival. Detection-plus-localization sensitivity was calculated as the number of times the listener was successful in correctly identifying the ear to which the stimulus was presented. A localization only sensitivity measure was calculated as a ratio of localization hits to detection hits. Lastly, response bias was calculated for each response condition per ear. Results revealed a consistent REA for detection hits and localization hits for both types of stimuli. Results from the directed recall response conditions, however, revealed that directing the listener’s attention toward a certain ear only significantly impacted localization hits and not detection hits. Measurements of bias suggested that listeners were using a more lax criterion for responding to left ear targets when compared to right ear targets, which was consistent with higher false alarms for the
left ear. It was therefore concluded that detection of target stimuli in a dichotic speech recognition task represents a listener’s sensitivity while the difference between detection and localization represents the attentional bias that can be manipulated by directing listeners to one ear versus the other (Hiscock et al., 1999).

The results from detection and identification dichotic target detection task have been replicated using different stimuli (Voyer et al., 2005), as well as in the pediatric population (Hiscock & Beckie, 1993). Hiscock and Beckie (1993) used the same detection and identification dichotic speech recognition task as Hiscock et al. (1999) to assess processing abilities of children under both free recall and directed recall response conditions. Stimuli included CV syllable pairs and words presented as triple pairs. The data were analyzed according to detection hits and localization hits in the same manner as outlined above. Results suggested that detection accuracy increases with age. The increase in sensitivity, however, was partially due to the application of attentional strategies children develop as they get older. Therefore, the detection and identification dichotic target detection paradigm allowed not only the separate calculation of sensitivity from attention biases, but also provided a way to study the interaction between the development of dichotic speech recognition skills and deployment of attentional strategies as children age. By using a dichotic target detection task that involves both detection and identification of target stimuli, it is possible to separate true sensory capacity for the task from bias that may be due to response or attention biases. Therefore, there is potential in using dichotic target detection tasks that are based on signal detection
theory to differentiate between true auditory processing deficits and the effects of other
cognitive considerations, such as attention, that may impact measurement of dichotic
speech recognition skills in adults and children. To date, there is no clinically available
dichotic speech recognition task that uses a target detection paradigm.

Age- Developmental Considerations

Performance on dichotic speech recognition tasks is also impacted by the age of
the listener. There are both developmental considerations in the pediatric population and
aging considerations in the elderly population. Kimura (1963) was the first to examine
developmental considerations in the pediatric population. Right-handed children ages
four to nine years were tested using a task with single-pair, double-pair, and triple-pair
digit material. Children were asked to repeat as many digits as they could in a free recall
response condition. Results of this study indicated that as children age, individual ear
performance on the task increases. Children always exhibited a REA for the task, but the
magnitude of the REA decreased as children aged due to improved performance on
materials presented to the left ear. Kimura concluded that these results were evidence
that left cerebral dominance for speech is established by age four, and probably earlier
(Kimura, 1963).

Pohl, Grubmuller, and Grubmuller (1984) showed a similar developmental trend
in a study using monosyllabic nouns and multi-syllabic digits in the German pediatric
population. Right-handed children ages four to ten years were tested using a free recall
response condition. Results for both digit and word stimulus material showed an increase in individual ear performance as children aged. Although children again always showed a REA across age, the magnitude of REA decreased as age increased. Performance on materials presented to the left ear showed a steeper slope of development when compared to the performance on materials presented to the right ear. Therefore, the decrease in REA with increasing age appeared to be primarily due to improvement in performance on materials presented to the left ear.

Development of dichotic speech recognition skills also interacts with stimulus material and response condition considerations. Pohl et al. (1984) reported that children performed better on digit material than word material and the REA exhibited for word material was typically larger than those exhibited for digit material across ages. These results were consistent with previous studies (Obrzut et al., 1986). Lamm and Epstein (1997) also studied the effect of stimulus material type on performance of children on dichotic speech recognition tasks. Israeli kindergarten children ages five to six years were tested using a free recall response condition. The same children were tested with the same protocol one year later to examine developmental trends. Stimulus material included simple Hebrew digits and words. The authors defined the verbal workload of the stimulus according to the amount of semantic and lexical content in the stimulus, as well as the number of different phonemic combinations present in the stimulus set. Therefore, digits were considered to have relatively low verbal workload while words were considered to have relatively higher verbal workload. Lamm and Epstein (1997)
reported that overall performance on digit material was better than performance on word material. Overall performance increased from the first year to the second year for both sets of stimuli, but in different ways. Only performance on materials presented to the left ear improved for digit material, while performance on materials presented to both ears improve for word material. Although the ear advantage for the digit material decreased from the first year to the second year, the ear advantage for the word material did not change significantly. Lamm and Epstein (1997) concluded that the differences found between the stimulus material types could be attributed to the differences in verbal workload. Better performance and a smaller ear advantage magnitude for digit material was attributed to the fact that digit material were more familiar and had less semantic and lexical content than words.

The interaction between development of dichotic speech recognition skills and attention has also been studied. Hugdahl and Andersson (1986) examined performance of children ages eight to nine years versus young adults on a CV syllable dichotic speech recognition task. Testing included the free recall and directed recall response conditions, all necessitating only one response. Results for young adults revealed a REA for the free recall and directed recall right response conditions and a LEA for the directed recall left response condition. Data from child participants revealed lower overall performance across response conditions and exhibited the same pattern of ear advantage change across response conditions as adults. Results for child participants, however, revealed smaller
ear advantages in the direction conditions when compared to the adult data (Hugdahl & Andersson (1986).

Hugdahl, Carlsson, and Eichele (2001) extended the examination of dichotic speech recognition skill development and attention in a study with listeners ages seven to seventy years. CV syllables were again used to examine how attention can impact performance and measurement of ear advantage across the free recall and directed recall response conditions. Listeners were broken up into six age categories: ≤ 8 years old, 9 years old, 10-15 years old, 16-30 years old, 31-49 years old, and 50-70 years old. For the free recall response condition, all age groups exhibited a significant REA, although the magnitude of REA for the nine-year-old group did not achieve significance. For the directed recall right response condition, all groups exhibited a significant REA, with a larger magnitude of REA for the older age groups (16 and older) as compared to the younger age groups (15 and younger). For the directed recall left response condition, neither the ≤ 8 year old nor 9 year old group had a significant ear advantage while the four older age groups all exhibited LEAs. The magnitude of LEA increased as age increased except for the 50-70 year old age group. For this oldest age group, the LEA in the directed recall left response condition was relatively small, primarily due to a decrease in left ear performance for this condition (Hugdahl et al., 2001).

Overall, results of studies involving developmental effects in dichotic speech recognition tasks suggest an increase in overall performance and a decrease in REA as children get older. It has been suggested that development and myelination of the corpus
callosum is responsible for these trends (Bellis, 2003). Results consistent with this trend, however, can be impacted by stimulus type and response condition, as well as testing paradigm employed. Although Hugdahl et al. (2001) found that younger children did not show a significant change in ear advantage for CV syllables in a directed recall left response condition, results from Hiscock and Beckie (1993) revealed that even the seven-year-old children exhibited a LEA in the directed recall left response condition when tested using a dichotic target detection testing paradigm. Therefore, it appears that overall performance, as well as the direction and magnitude of ear advantage in the pediatric population can be impacted by stimulus type, response condition, and testing paradigm employed.

**Age- Considerations in the Elderly Population**

The interest in studying central auditory processing abilities in the elderly population stems from the observation that many older adults exhibit more difficulty listening in noisy situations than can be expected from the degree of peripheral hearing impairment they may have. Auditory temporal processing and dichotic speech recognition in particular have been used to examine the effects of age-related decline in cognitive function and higher-level auditory processes (Martin & Jerger, 2006).

Roup et al. (2006) examined dichotic speech recognition using word stimuli in the young adult and elderly population. Listeners included three age groups: Group I consisted of 18-30 year old normal hearing males, Group II consisted of 60-69 year old males with sensorineural hearing loss, and Group III consisted of 70-79 year old males
with sensorineural hearing loss. Stimuli included pairings of the NU-6 word lists and testing was completed in both the free recall and directed recall response conditions. Results from Roup et al. (2006) revealed significantly better performance for young listeners with normal hearing than for older listeners with hearing loss. Overall, all three groups exhibited a REA for the free recall response condition. REAs exhibited by the older listeners, however, were significantly larger that those exhibited for the younger listeners. Results of the directed recall response conditions revealed no significant differences between the free recall and directed response recall conditions for the younger listeners. In contrast, in the older groups overall performance was better in the directed recall response conditions when compared to the free recall condition. The older groups also exhibited larger ear advantages in the directed recall response conditions than the younger group. Although the presence of sensorineural hearing loss may help to explain the differences in overall dichotic word recognition performance between the younger group and older groups, hearing loss cannot fully account for differences found in ear advantages across groups. Despite having normal monaural word recognition performance in both ears in quiet using the same words, older adults exhibited significantly poorer performance on materials presented to the left ear than on materials presented to the right ear during the dichotic tasks. Therefore, results of this study suggest a dysfunction in the central auditory processing of speech stimuli during dichotic speech recognition tasks for older adult listeners (Roup et al., 2006).
Noffsinger et al. (1996) examined dichotic speech recognition abilities in elderly listeners with hearing loss between the ages of 58 and 85 years. This study compared performance on tasks using three different stimuli: digits, synthetic sentences, and nonsense CV syllables. Testing was completed in a free recall, closed set response condition. Results suggested that the type of stimulus impacted performance. Elderly listeners more easily recognized digit material than sentence material, and both digit and sentence material were recognized more easily than CV syllables. Although the hierarchy of stimulus difficulty was similar to previous results in young adults with normal hearing (Noffsinger et al., 1994), overall performance of elderly listeners was poorer than that obtained in young adults. Elderly listeners also had significantly more trouble with CV syllable material than the younger listeners. Ear advantage results from this study also revealed the trend often found in the aging literature of right ear dominance and left ear weakness.

Overall, results from dichotic speech recognition studies in the elderly population reveal poorer performance and larger REAs for older adults when compared to young adults. This trend has been termed a “left ear disadvantage” (LED) in this population (Martin & Jerger, 2006). Although hearing loss is typically present in older adults, the effects reported cannot be entirely due to the degree of hearing impairment (Roup et al., 2006). Differences are accounted for by age-related changes occurring in the central auditory processing system and specifically involves the decreased conduction of the corpus callosum (Bellis & Wilbur, 2001).
When comparing developmental consideration in the pediatric population and aging considerations in the elderly population, patterns of performance on dichotic speech recognition tasks appear to be mirror images of each other. Younger children demonstrate better performance on materials presented to the right ear when compared to the left ear. As children age, this difference becomes progressively smaller due to increased performance on materials presented to the left ear, resulting in progressively smaller REAs. Older adults demonstrate a similar pattern of performance on dichotic speech recognition tasks, but in the opposite direction. As adults age, performance on materials presented to the left ear decreases at a faster rate than performance on materials presented to the right ear, resulting in a progressively larger REA (or LED) as age increases. The maturation and myelination and subsequent demyelination and loss of conduction of the corpus callosum has been implicated as an explanation of results obtained in dichotic speech recognition tasks for pediatric and elderly populations, respectively (Bellis & Wilbur, 2001; Bellis, 2003).

2.4 CONCLUSION

Diagnosis of APD in the pediatric population is typically completed using a test battery approach with several tests to assess auditory figure-ground discrimination, auditory closure, temporal processing, and binaural processing such as masking level difference, localization, and dichotic speech recognition (Bellis, 2003). A survey of clinical practice (Emanuel, 2002) has shown that a variety of tests are being used to
assess dichotic speech recognition in the pediatric population, and more than one test is
often included in a test battery for APD assessment. Dichotic speech recognition tasks
most commonly used by clinical audiologist vary as to the type of stimulus material and
response condition used. It has been shown, however, that measurement of dichotic
speech recognition abilities is impacted by a variety of factors, including lexical content
of the speech stimulus as well as the cognitive load of the task that is introduced by the
use of different response conditions.

One of the challenges that clinical audiologists face in APD assessment is
differential diagnosis of auditory problems in children who may have higher level
cognitive and/or language deficits. Because stimulus type and response condition effects
have been document in the pediatric population, there is a potential that conflicting
results would be obtained when using multiple tests together in a test battery to diagnose
dichotic speech recognition deficits even in children who have no comorbid diagnoses.
Further, differences in task demands introduced by varying lexical content and cognitive
loading differences across response conditions could potentially interact with comorbid
higher-level language or cognitive deficits. Consequently, children who have comorbid
deficits could potentially perform poorly despite having typical auditory processing
skills. With reports of both cognitive and language disorders appearing comorbidly with
auditory processing problems in children (Cestnick & Jerger, 2000; Wright, Lombardino,
King, Puranik, Leonard, & Merzenich, 1997), there is a significant need for investigating
assessment tools that attempt to lessen the potential differential effects of lexical content
and cognitive loading on performance. Differential diagnosis between children who have auditory processing deficits and those who do not is essential to reduce the likelihood of misdiagnosis and implementation of inappropriate management strategies.

Therefore, the specific aims of the current study were to investigate differences in performance across dichotic speech recognition tasks that use speech stimuli with relatively limited lexical content versus stimuli with relatively more lexical content, and to investigate the use of a target detection testing paradigm in order to separate sensory capacity from attention and bias effects. In order to investigate changes in performance across the lifespan, children, young adults, and older adults were included in the study.
CHAPTER 3
METHODS

3.1 SUBJECTS

Three subject groups participated in this study: 12 children with normal hearing between the ages of 7 years and 7 years, 9 months (6 males, 6 females), 20 young adults with normal hearing between the ages of 19 and 32 year (10 males, 10 females), and nine older adults with mild to moderate symmetrical sensorineural hearing loss between the ages of 67 and 84 years (3 males, 6 females). Inclusion criteria for all participants included: 1) right-hand dominance based on results obtained from the Edinburgh Handedness Inventory (Oldfield, 1971), 2) otoscopic examination within normal limits, and 3) normal middle ear function as measured using a 226 Hz probe tone and normative values from Margolis and Hunter (2000).

Additional inclusion criterion for child participants included: 1) normal hearing defined as air-conduction thresholds less than 20 dB HL for octave frequencies from 250-8000 Hz with no air-bone gap greater than 10 dB, 2) normal cognitive abilities defined as performance not more than two standard deviations below the mean for age as assessed by the Kaufman Brief Intelligence Test (Kaufman & Kaufman, 1990), 3) normal
language abilities defined as performance not more than two standard deviations below the mean for age as assessed by the screening composite of the Test of Language Competence (Wiig & Secord, 1989), and 4) normal dichotic listening abilities defined as overall performance not more than two standard deviations below the mean for age and an ear advantage not more than +7 REA for the directed recall right response condition and not less than – 4 LEA for the directed recall left response condition as assessed by the SCAN-C Competing Words Subtest (Keith, 2000).

Additional inclusion criterion for young adult participants included: 1) normal hearing defined as air-conduction thresholds less than 20 dB HL for octave frequencies from 250-8000 Hz with no air-bone gap greater than 10 dB, and 2) normal dichotic listening performance defined as overall performance not more than two standard deviations below the mean and an ear advantage not more than +4 REA for the directed recall right response condition and no more negative than – 4 LEA for the directed recall left response condition as measured by the SCAN-A Competing Words Subtest (Keith, 1995).

Additional inclusion criteria for older adult participants included: 1) bilateral, symmetric mild sloping to moderately-severe sensorineural hearing loss, and 2) normal cognition defined as a score better than 25 as assessed by the Mini-Mental State Exam (Folstein, Folstein, & McHugh, 1975). Symmetric hearing loss was defined as no greater than a 10 dB difference in thresholds between the ears at any test frequency. The
inclusion criteria of normal dichotic listening abilities assessed via the SCAN-A was not included for older adults for hearing impairment because the SCAN-A does not have normative data for listeners with hearing impairment.

3.2 MATERIALS

Dichotic speech recognition materials included 100 meaningful consonant-vowel-consonant (CVC) words and 100 nonsense CVC words from Boothroyd and Nittrouer (1988). All speech materials were recorded with the same male voice via a Sennheiser PC 136 USB headset boom microphone routed through a personal desktop computer using Adobe Audition 1.5 with a 16-bit sampling rate. All stimuli amplitudes were normalized for total root mean square (RMS) value and digitally edited to reduce background recording noise via hiss reduction. For monaural and dichotic speech recognition tasks, a carrier phrase of “Say the word” was recorded separately in order to avoid coarticulation and was added to the beginning of each word in order to provide a listening cue. For dichotic target detection and identification tasks, a carrier phrase of “Listen for” was recorded separately in order to avoid coarticulation and was added to the beginning of each word in order to provide a target cue. All dichotic word pairs were temporally aligned at onset and total duration differences did not exceed 50 milliseconds.

Meaningful CVC word stimuli were rated for word frequency and neighborhood density according to the NAM (Luce & Pisoni, 1998). Ratings were taken from the English Lexicon Project (Balota et al., 2007) and each meaningful word was defined as
having high or low word frequency and high or low neighborhood density. Word frequency and neighborhood density were chosen for stimulus ratings because Dirks et al. (2001) reported that these two parameters accounted for a majority of variance for normal hearing listeners. “High” frequency words were those having a frequency rating greater than the median word frequency for this specific list of words while “low” frequency words were those words having a rating less than the median word frequency. Ratings for neighborhood density were also defined in reference to the median neighborhood density for this specific list, with “high” density words having ratings greater than the median density rating and “low” density words having ratings less than the median density rating. The “high” and “low” ratings for word frequency and neighborhood density yielded four different groups of meaningful words: high frequency-high density words, high frequency-low density words, low frequency-high density words, and high frequency-high density words. Word pairings for dichotic tasks involving meaningful CVC stimuli included only words with the same NAM ratings to ensure paired words were similar in recognition difficulty. Nonsense CVC word stimuli did not undergo the same pairing scheme, since all words are equally infrequent and density ratings for nonsense words could not be obtained.

For monaural word recognition testing, each of the stimulus types were randomly separated into two lists of 50 words to provide lists for the right and left ears, respectively. For the dichotic speech recognition and dichotic target detection and identification tasks, each of the stimulus types were separated into three lists of 50 word
pairings, with every word being presented once in each of the response conditions. The interstimulus interval (ISI) for the dichotic speech recognition tasks was five seconds whereas the ISI for the dichotic target detection and identification task was listener guided, as the next stimulus pair was not presented until the listener responded to the previous trial. Each list had novel word pairings so that no word pair was repeated across response conditions. The presentation of words was counterbalanced across both channels so that no word was presented only to one ear across response conditions.

3.3 PROCEDURES

Listeners participated in three sessions, including one initial subject criteria session that included testing to establish whether participants met the above inclusion criteria, and two experimental sessions. All audiological and experimental testing was conducted in a sound-attenuating booth (IAC, Model 403ATR). For the experimental sessions, all participants completed three tasks: 1) monaural speech recognition testing, 2) dichotic speech recognition; and 3) dichotic target detection and identification. All tasks were completed for both meaningful CVC and nonsense CVC stimuli delivered via insert earphones (ER-3A) at a presentation level of 50 dB HL for normal hearing participants and at 80 dB HL for hearing impaired participants. The stimuli in the monaural speech recognition and verbal report tasks were presented from a compact disc player routed through a Grason-Stadler Inc. (GSI) 61 clinical audiometer calibrated to the American National Standards Institute specifications for audiometers (ANSI, S 3.6-
Both channels of the audiometer were calibrated for CD materials presentation using a 1000 Hz calibration tone before each subject session.

Monaural speech recognition was completed in order to ensure that participants were familiar with all the experimental stimuli before expecting them to repeat the words for the dichotic speech recognition experimental tasks. Participants listened to and verbally repeated CVCs presented to each ear for both meaningful and nonsense stimuli. Each of the monaural tasks consisted of 50 test items. For dichotic speech recognition, participants listened to each stimulus pair and verbally repeated the two stimuli presented according to directions for each condition. In the free recall condition, participants were free to repeat the two stimuli in any order. In the directed recall response conditions, participants were instructed to repeat the word in their directed ear first and then repeat the word in their opposite ear. Each of the dichotic speech recognition tasks consisted of 50 dichotic pairs. For dichotic target detection and identification tasks, data was collected using a three-alternative forced choice testing paradigm using the computer-based data collection program APEX 3 (Francart et al., 2005). Experimental stimuli were routed from a Dell Inspiron 5150 laptop computer through a Hammerfall DSP Multiface II amplifier to a GSI-61 audiometer using Etymotic ER-3A insert earphones. The presentation level from the computer was calibrated for each subject session using a 1000 Hz calibration tone presented from the computer. Participants were asked to indicate to which ear the target CVC was present in a stimulus pair by clicking on the appropriate button (right ear, left ear, neither ear) on a separate computer monitor inside the testing
booth using a computer mouse. The three response conditions of free recall, directed recall right, and directed recall left were completed. In the free recall condition, participants were cued with the phrase “Listen for target word” binaurally and were asked to monitor both ears for the target CVC. For the directed recall conditions, participants were cued with the phrase “Listen for target word” in the directed ear only and were asked to monitor the directed ear for the target word, however, participants were instructed to click the appropriate response even if the target was not presented to the directed ear. Each of the dichotic target detection and identification tasks consisted of 50 dichotic pairs. For each response condition, the target word appeared in the right ear for 20 of the trials, in the left ear for 20 of the trials, and the target was not present in 10 of the trials. Trials were randomly presented through the APEX 3 program.

The order of presentation of nonsense and meaningful CVCs were counterbalanced across subjects for both the dichotic speech recognition and dichotic target detection and identification tasks. Participants always participated in the free recall response condition first, while the directed recall response conditions were counterbalanced across subjects. Participants never listened to the same list of stimuli for the same response condition across the dichotic speech recognition and dichotic target detection and identification tasks. Experimental testing was completed over two, one to two-hour sessions completed on separate days. Several breaks were provided for participants during each session to ameliorate fatigue and boredom. Listeners were paid via gift cards for participation in each session of the study.
CHAPTER 4

RESULTS

4.1 DATA PREPARATION

Upon initial review of the data, one of the older adults subjects was identified as an outlier due to abnormally large REAs on all dichotic speech recognition experimental tasks. That subject was therefore excluded from the following data analysis. The following results are based on 12 child participants, 20 young adults participants, and 8 older adult participants.

For all statistical analyses, raw speech percentage scores were converted using Studebaker’s (1985) Rationalized Arcsine Transform. For proportional and percent correct data, means and variances are correlated which complicates using inferential statistics. The rationalized arcsine transform produces a “rau” score that minimizes the correlation between the mean and variance. This transform makes it possible to directly compare observed differences in different parts of the performance range. For monaural speech recognition and dichotic speech recognition data, the raw number of correctly repeated stimuli was converted for statistical analysis. For the target detection and
identification data, raw hit rate scores for each sensitivity measures were used to calculate the non-parametric measure of area under the receiver-operative curve (ROC), p(Å), consistent with previous target detection studies (Hiscock & Beckie, 1993; Hiscock et al., 1999). The arcsine transformation was then applied to p(Å), similar to previous detection studies using dichotic stimuli (Grier, 1971; Pastore & Scheirer, 1974; Hiscock & Beckie, 1993; Hiscock et al., 1999). Although statistical analyses were completed using rau scores, all tables and figures for monaural and dichotic speech recognition present the percentage data and tables and figures of dichotic target detection and identification present proportion data for discussion purposes. For all statistical analyses, an a priori alpha level of 0.05 was used to evaluate significance. Bonferroni correction was used to evaluate all post-hoc comparison tests when applicable.

4.2 MONAURAL SPEECH RECOGNITION RESULTS

*Descriptive Results*

Mean monaural speech recognition scores are presented in Table 1 for both meaningful and nonsense word stimuli for the three subject groups. Overall, speech recognition performance for children and young adult listeners was at ceiling for both meaningful and nonsense words with performance ranging from 95-98 percent correct. Older adult listeners performed poorer than both children and young adults, with performance levels ranging from 80-93 percent correct. Poorer performance for older
<table>
<thead>
<tr>
<th>Subject Group</th>
<th>Meaningful Words</th>
<th></th>
<th>Nonsense Words</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Ear (%)</td>
<td>SD</td>
<td>Mean Ear (%)</td>
<td>SD</td>
</tr>
<tr>
<td>Children</td>
<td>97.09</td>
<td>2.17</td>
<td>95.45</td>
<td>2.61</td>
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<tr>
<td></td>
<td>96.55</td>
<td>2.05</td>
<td>95.64</td>
<td>2.43</td>
</tr>
<tr>
<td>Young Adults</td>
<td>98.50</td>
<td>1.57</td>
<td>97.10</td>
<td>2.86</td>
</tr>
<tr>
<td></td>
<td>98.80</td>
<td>1.36</td>
<td>96.10</td>
<td>3.52</td>
</tr>
<tr>
<td>Older Adults</td>
<td>87.75</td>
<td>5.80</td>
<td>84.00</td>
<td>11.61</td>
</tr>
<tr>
<td></td>
<td>93.75</td>
<td>3.11</td>
<td>80.00</td>
<td>20.92</td>
</tr>
</tbody>
</table>

**Table 1:** Mean monaural speech recognition performance (in percent correct) and standard deviations (SD) of meaningful and nonsense words for each subject group.
adult participants can be partially explained by the presence of peripheral hearing loss. Further, older adults had more difficulty with nonsense words versus meaningful words, and performance on nonsense words was more variable as evidenced by larger standard deviations. This suggests that even on the monaural word level in quiet, older adults rely on lexical information for speech recognition.

**Statistical Analysis**

Statistical analysis of monaural speech recognition results was completed using a two-way repeated measures analysis of variance (ANOVA) with stimulus and ear serving as within-subject factors, and group and gender serving as between-subject factors. A main effect for stimulus \( F_{(1,34)} = 21.57, p < 0.05 \) revealed that performance for meaningful words was better than performance for nonsense words. A main effect for group \( F_{(2,34)} = 48.29, p < 0.05 \) revealed that significant differences in speech recognition abilities exist among the three subject groups. Post-hoc testing revealed that all three subject groups were significantly different from each other. A main effect for gender \( F_{(1,34)} = 9.39, p < 0.05 \) revealed that females had better recognition scores when compared to males.

Several interaction effects were also noted for monaural speech recognition data. A stimulus x group interaction effect \( F_{(2,34)} = 4.01, p < 0.05 \) revealed that although all three subject groups demonstrated better recognition performance on meaningful words versus nonsense words, older adults had a larger difference in performance between meaningful and nonsense words when compared to either children or young adults. A
significant stimulus x gender interaction effect ($F_{1,34} = 5.59, p < 0.05$) revealed that the difference between performance on meaningful words and nonsense words was larger for males when compared to females. A significant stimulus x ear interaction effect ($F_{1,34} = 8.04, p < 0.05$) revealed that although recognition for materials presented to the right ear was better than performance for materials presented to the left ear, the difference in performance between the ears was larger for nonsense words when compared to meaningful words. A stimulus x ear x group interaction effect ($F_{2,34} = 4.92, p < 0.05$) revealed that although both young adults and older adults had better recognition performance for materials presented to the left ear for meaningful words and better recognition performance materials presented to the right ear for nonsense words, children had the opposite pattern of performance. Children demonstrated better recognition performance for materials presented to the right ear for meaningful words and better recognition performance for materials presented to the left ear for nonsense words. Lastly, a significant group x gender interaction effect ($F_{2,34} = 6.98, p < 0.05$) revealed that although there were no significant differences between females and males for the children and young adults, older adult females performed significantly better than older adult males on monaural speech recognition.
4.3 DICHOTIC SPEECH RECOGNITION RESULTS

Descriptive Results

Mean dichotic speech recognition scores are presented in Tables 2 and 3. Overall, performance was better and less variable for meaningful words versus nonsense words for all three subject groups. Therefore, when the listening situation is made difficult by introducing competition, children, young adults and older adults rely on lexical information for recognition. Performance, however, varied across group and response condition. Overall, young adults performed better than children and older adults.

Dichotic speech recognition performance per ear varied across response condition, resulting in ear advantages that changed as a function of response condition for both types of stimuli. As seen in Figure 1, for the free recall response condition both children and young adults demonstrated a mean REA, however older adults demonstrated a small mean LEA. For the directed recall right response condition, all three subject groups demonstrated larger REA’s when compared to the free recall condition. Lastly, for the directed recall left response condition, children demonstrated a small mean REA while young adults and older adults demonstrated a mean LEA. Overall, ear advantages for meaningful words were smaller and less variable when compared to nonsense word ear advantages.
<table>
<thead>
<tr>
<th>Meaningful Words</th>
<th>Subject Group</th>
<th>Right Ear (%)</th>
<th>Left Ear (%)</th>
<th>RE-LE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Children</td>
<td>Mean</td>
<td>79.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SD</td>
<td>6.56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Young Adults</td>
<td>Mean</td>
<td>94.10</td>
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<td></td>
<td></td>
<td></td>
<td>SD</td>
<td>3.46</td>
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<td></td>
<td></td>
<td>Older Adults</td>
<td>Mean</td>
<td>73.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SD</td>
<td>10.39</td>
</tr>
<tr>
<td>Free Recall</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Directed Right</td>
<td>Children</td>
<td>Mean</td>
<td>82.67</td>
<td>65.83</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD</td>
<td>8.84</td>
<td>9.51</td>
</tr>
<tr>
<td></td>
<td>Young Adults</td>
<td>Mean</td>
<td>96.90</td>
<td>90.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD</td>
<td>3.52</td>
<td>5.11</td>
</tr>
<tr>
<td></td>
<td>Older Adults</td>
<td>Mean</td>
<td>81.25</td>
<td>70.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD</td>
<td>8.00</td>
<td>14.01</td>
</tr>
<tr>
<td>Directed Left</td>
<td>Children</td>
<td>Mean</td>
<td>75.83</td>
<td>73.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD</td>
<td>8.59</td>
<td>12.65</td>
</tr>
<tr>
<td></td>
<td>Young Adults</td>
<td>Mean</td>
<td>94.00</td>
<td>95.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD</td>
<td>4.26</td>
<td>3.72</td>
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<td>Older Adults</td>
<td>Mean</td>
<td>70.75</td>
<td>82.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD</td>
<td>9.56</td>
<td>10.84</td>
</tr>
</tbody>
</table>

**Table 2:** Mean dichotic speech recognition performance (in percent correct) and standard deviations (SD) for meaningful word stimuli for each group for free recall, directed recall right and directed recall left response conditions.
<table>
<thead>
<tr>
<th>Nonsense Words</th>
<th>Subject Group</th>
<th>Right Ear (%)</th>
<th>Left Ear (%)</th>
<th>RE-LE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free Recall</td>
<td>Children</td>
<td>Mean 66.17</td>
<td>49.17</td>
<td>17.00</td>
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<td></td>
<td></td>
<td>SD  11.07</td>
<td>17.09</td>
<td>21.50</td>
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<td></td>
<td>Young Adults</td>
<td>Mean 83.10</td>
<td>77.20</td>
<td>5.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD   9.10</td>
<td>10.23</td>
<td>10.51</td>
</tr>
<tr>
<td></td>
<td>Older Adults</td>
<td>Mean 57.25</td>
<td>50.50</td>
<td>6.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD    5.01</td>
<td>14.25</td>
<td>16.21</td>
</tr>
<tr>
<td>Directed Right</td>
<td>Children</td>
<td>Mean 67.83</td>
<td>44.50</td>
<td>23.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD   13.89</td>
<td>14.97</td>
<td>16.43</td>
</tr>
<tr>
<td></td>
<td>Young Adults</td>
<td>Mean 89.10</td>
<td>72.40</td>
<td>16.70</td>
</tr>
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<td></td>
<td></td>
<td>SD   7.83</td>
<td>10.15</td>
<td>6.84</td>
</tr>
<tr>
<td></td>
<td>Older Adults</td>
<td>Mean 62.75</td>
<td>39.75</td>
<td>22.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD    3.96</td>
<td>16.75</td>
<td>16.75</td>
</tr>
<tr>
<td>Directed Left</td>
<td>Children</td>
<td>Mean 54.50</td>
<td>54.00</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD   7.39</td>
<td>15.75</td>
<td>16.65</td>
</tr>
<tr>
<td></td>
<td>Young Adults</td>
<td>Mean 79.60</td>
<td>85.00</td>
<td>-5.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD   7.10</td>
<td>10.23</td>
<td>10.18</td>
</tr>
<tr>
<td></td>
<td>Older Adults</td>
<td>Mean 54.50</td>
<td>62.75</td>
<td>-8.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD   12.64</td>
<td>16.80</td>
<td>22.69</td>
</tr>
</tbody>
</table>

**Table 3:** Mean dichotic speech recognition performance (in percent correct) and standard deviations (SD) for nonsense word stimuli for each group for free recall, directed recall right and directed recall left response conditions.
Figure 1: Mean ear advantage for each group across response condition for both meaningful and nonsense word stimuli.
Figures 2 and 3 depict bivariate plots for subject data across the three response conditions for meaningful and nonsense stimuli, respectively. Percent correct recognition for the right ear is plotted on the abscissa while percent correct recognition for the left ear is plotted on the ordinate. The data points that fall below the diagonal line indicate better performance on materials presented to the right ear, or a REA, whereas data points that fall above the diagonal line indicate better performance on materials presented to the left ear, or a LEA. Data points that fall directly on the diagonal indicate equal performance for materials presented to each ear. Overall, performance for young adult participants was better and more homogenous when compared to children and older adults for meaningful and nonsense stimuli. Although mean data suggest a particular pattern of performance per group across response conditions, individual data suggests ear advantages varied considerably across response conditions, especially for children and older adults.

Statistical Analysis

Statistical analysis of dichotic speech recognition results was completed for both individual ear data as well as ear advantage data. A three-way repeated measures ANOVA was completed for the individual ear data with stimulus, response condition, and ear serving as within-subject factors, and group and gender serving as between-subject factors. The ANOVA revealed a significant main effect for stimulus ($F_{1,34} = 299.63, p < 0.05$) suggesting that performance was significantly better for meaningful
Figure 2: Bivariate plot of percent correct recognition of meaningful words for the right (abscissa) and percent correct recognition for the left ear (ordinate) for all subject groups across the three response conditions.
Figure 3: Bivariate plot of percent correct recognition of nonsense words for the right (abscissa) and percent correct recognition for the left ear (ordinate) for all subject groups across the three response conditions.
words than nonsense words. A main effect for ear ($F_{1,34} = 19.64, p < 0.05$) revealed that performance on materials presented to the right ear was significantly better than performance on materials presented to the left ear. Lastly, a main effect for group ($F_{2,34} = 54.873, p < 0.05$) revealed significant differences across group. Post-hoc testing suggested that overall both children and older adults performance significantly poorer than young adults, however there was no significant difference in recognition performance between children and older adults.

Statistical analysis of individual ear data also revealed several interaction effects. An interaction effect for condition x ear ($F_{2,68} = 61.26, p < 0.05$) revealed that performance on materials presented to each ear changed as a function of response condition. Specifically, performance on materials presented to the right ear was better than performance on materials presented to the left ear resulting in a mean REA for the free recall and directed right recall response conditions, whereas performance on materials presented to the left ear was better than performance on materials presented to the right ear resulting in a LEA for the directed recall left response condition. This effect changed across group, however, as revealed by an interaction effect for condition x group ($F_{4,68} = 114.22, p < 0.05$). Specifically, although young adults followed the above pattern of performance across response condition, older adults demonstrated a small mean LEA for the free recall response condition for meaningful words and children demonstrated a small mean REA for the directed recall left response condition for both meaningful and nonsense words. Therefore, biasing attention changed performance
differentially across group. An interaction effect for ear x group ($F_{2,34} = 3.30, p < 0.05$) revealed that differences between performance on materials presented to each ear were larger in children than for either young adults or older adults, resulting in larger ear advantages overall. An interaction effect for stimulus x ear ($F_{1,34} = 301.20, p < 0.05$) revealed that differences between performance on materials presented to each ear were larger for nonsense words when compared to meaningful words, resulting in larger ear advantages for nonsense words overall. Lastly, an interaction effect for stimulus x ear x gender ($F_{1,34} = 6.24, p < 0.05$) revealed that males had better performance than females for materials presented to the left ear for nonsense words, whereas females had better performance than males for all other contrasts.

A two-way repeated measures ANOVA was completed for ear advantage data with stimulus and response condition serving as within-subject factors, and group and gender serving as between-subject factors. A main effect for stimulus ($F_{1,34} = 5.36, p < 0.05$) revealed that ear advantages for nonsense words were larger than ear advantages for meaningful words. A main effect for response condition ($F_{2,68} = 61.26, p < 0.05$) revealed that ear advantages significantly changed depending on the attention instructions. Overall, a relatively small REA was obtained for the free recall response condition, a larger REA was obtained for the directed recall right response condition, and a small LEA was obtained for the directed recall left response condition. This was group dependent, however, and a main effect for group ($F_{2,34} = 3.30, p < 0.05$) revealed significant differences in ear advantage by group when data are collapsed across response
conditions. Overall, children demonstrated relatively large ear advantages that were significantly different from the relatively smaller ear advantages demonstrated by older adults. Young adults demonstrated ear advantages that were not significantly different from either children or older adults. Lastly, an interaction effect for stimulus x gender ($F_{1,34} = 6.29, p < 0.05$) revealed that females had larger ear advantages than males for nonsense words while there was no significant difference between females and males for meaningful words. Figure 1 depicts the mean ear advantage for each group across response condition for both the meaningful and nonsense words stimuli.

4.4 DICHOTIC TARGET DETECTION AND IDENTIFICATION RESULTS

Descriptive Results

Scoring for the target detection and identification tasks used similar sensitivity measures as Hiscock and Beckie (1993) and Hiscock et al. (1999). Detection sensitivity was calculated as the number of times the listener was successful in identifying that the target was present regardless of the ear of arrival. Detection-plus-identification sensitivity was calculated as the number of times the listener was successful in correctly identifying the ear to which the stimulus was presented. An identification ratio sensitivity measure was calculated as a ratio of identification hits to detection hits. Lastly, because many participants did not have any false alarms, which complicates calculating the measure of bias beta ($\beta$), the false alarm rate itself was used as a measure of bias (Richardson, 1972). Mean hit rates for detection sensitivity and detection-plus-
identification sensitivity are presented in Tables 4 and 5, whereas identification ratio and false alarm rates are presented on Tables 6 and 7 for each subject group across response condition for meaningful and nonsense words, respectively.

Overall, performance was relatively equal for both ears and across both stimulus types. Young adults and older adults performed better than children across the three sensitivity measures. There were no differences between the ability to detect a target stimulus or identify the ear to which a target stimulus was presented for both young adults and older adults. Children, however, could detect a target stimulus more readily than they could identify to which ear a target stimulus was presented. Therefore, children demonstrated lower identification ratio scores than young adults and older adults. In terms of bias, children made more false alarms than young adults or older adults in most response conditions. False alarm data for the older adult group suggested that biasing attention, or providing a listening strategy, decreased the number of overall false alarms for meaningful word stimuli.

*Statistical Analysis*

Statistical analysis of dichotic target detection and identification data was completed via three different ANOVA analyses: one contrasting detection versus detection-plus-identification sensitivities, one comparing identification ratios, and one
### Table 4: Mean proportion of detection hits and detection-plus-identification hits and standard deviations (SD) for meaningful words for each group for the free recall, directed recall right, and directed recall left response conditions.

<table>
<thead>
<tr>
<th>Meaningful Words</th>
<th>Subject Group</th>
<th>Detection</th>
<th>Detection &amp; Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>RE</td>
<td>LE</td>
</tr>
<tr>
<td>Free Recall</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Children</td>
<td>Mean</td>
<td>0.94</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.01</td>
<td>0.08</td>
</tr>
<tr>
<td>Young Adults</td>
<td>Mean</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.00</td>
<td>0.01</td>
</tr>
<tr>
<td>Older Adults</td>
<td>Mean</td>
<td>0.98</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>Directed Right</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Children</td>
<td>Mean</td>
<td>0.93</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.05</td>
<td>0.11</td>
</tr>
<tr>
<td>Young Adults</td>
<td>Mean</td>
<td>1.00</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.00</td>
<td>0.02</td>
</tr>
<tr>
<td>Older Adults</td>
<td>Mean</td>
<td>0.99</td>
<td>0.96</td>
</tr>
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<td></td>
<td>SD</td>
<td>0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>Directed Left</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Children</td>
<td>Mean</td>
<td>0.92</td>
<td>0.96</td>
</tr>
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<td></td>
<td>SD</td>
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<td>0.05</td>
</tr>
<tr>
<td>Young Adults</td>
<td>Mean</td>
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<td>1.00</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>Older Adults</td>
<td>Mean</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>Nonsense Words</td>
<td>Subject Group</td>
<td>Detection</td>
<td>Detection &amp; Identification</td>
</tr>
<tr>
<td>---------------</td>
<td>---------------</td>
<td>-----------</td>
<td>---------------------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RE</td>
<td>LE</td>
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<tr>
<td><strong>Free Recall</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Children</td>
<td>Mean</td>
<td>0.96</td>
<td>0.90</td>
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<tr>
<td></td>
<td>SD</td>
<td>0.05</td>
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<td>Young Adults</td>
<td>Mean</td>
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<td>0.99</td>
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<td>0.05</td>
<td>0.02</td>
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<tr>
<td>Older Adults</td>
<td>Mean</td>
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<td>0.98</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td><strong>Directed Right</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Children</td>
<td>Mean</td>
<td>0.96</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.05</td>
<td>0.11</td>
</tr>
<tr>
<td>Young Adults</td>
<td>Mean</td>
<td>0.98</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.05</td>
<td>0.00</td>
</tr>
<tr>
<td>Older Adults</td>
<td>Mean</td>
<td>0.98</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>SD</td>
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<td>0.06</td>
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<tr>
<td><strong>Directed Left</strong></td>
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<td></td>
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<tr>
<td>Children</td>
<td>Mean</td>
<td>0.95</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>SD</td>
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<td>0.11</td>
</tr>
<tr>
<td>Young Adults</td>
<td>Mean</td>
<td>0.98</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>Older Adults</td>
<td>Mean</td>
<td>0.97</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.04</td>
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</table>

**Table 5:** Mean proportion of detection hits and detection-plus-identification hits and standard deviations (SD) for nonsense words for each group for the free recall, directed recall right, and directed recall left response conditions.
<table>
<thead>
<tr>
<th>Meaningful Words</th>
<th>Subject Group</th>
<th>Identification Ratio</th>
<th>False Alarm Rate</th>
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<tr>
<td></td>
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<td>RE</td>
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<tr>
<td>Free Recall</td>
<td>Children</td>
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</tr>
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<td></td>
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<td>Young Adults</td>
<td>Mean</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Older Adults</td>
<td>Mean</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD</td>
<td>0.04</td>
</tr>
<tr>
<td>Directed Right</td>
<td>Children</td>
<td>Mean</td>
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</tr>
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<td></td>
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<td>SD</td>
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</tr>
<tr>
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<td>1.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Older Adults</td>
<td>Mean</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD</td>
<td>0.02</td>
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<td>Directed Left</td>
<td>Children</td>
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<td></td>
<td></td>
<td>SD</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>Older Adults</td>
<td>Mean</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD</td>
<td>0.04</td>
</tr>
</tbody>
</table>

**Table 6:** Mean identification ratio and proportion false alarms and standard deviations (SD) for meaningful words for each group for the free recall, directed recall right, and directed recall left response conditions.
<table>
<thead>
<tr>
<th>Nonsense Words</th>
<th>Subject Group</th>
<th>Identification Ratio</th>
<th>False Alarm Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RE</td>
<td>LE</td>
</tr>
<tr>
<td><strong>Free Recall</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Children</td>
<td>Mean</td>
<td>0.92</td>
<td>0.86</td>
</tr>
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<td></td>
<td>SD</td>
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<td>Mean</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>Older Adults</td>
<td>Mean</td>
<td>1.00</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.00</td>
<td>0.02</td>
</tr>
<tr>
<td><strong>Directed Right</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Children</td>
<td>Mean</td>
<td>0.88</td>
<td>0.81</td>
</tr>
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<td></td>
<td>SD</td>
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<td>0.16</td>
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<td>Mean</td>
<td>0.97</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.04</td>
<td>0.00</td>
</tr>
<tr>
<td>Older Adults</td>
<td>Mean</td>
<td>0.99</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.02</td>
<td>0.00</td>
</tr>
<tr>
<td><strong>Directed Left</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Children</td>
<td>Mean</td>
<td>0.93</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>SD</td>
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<td>0.19</td>
</tr>
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<td>Young Adults</td>
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<td>1.00</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Older Adults</td>
<td>Mean</td>
<td>0.99</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.02</td>
<td>0.00</td>
</tr>
</tbody>
</table>

**Table 7**: Mean identification ratio and proportion false alarms and standard deviations (SD) for nonsense words for each group for the free recall, directed recall right, and directed recall left response conditions.
comparing false alarm rates. Because the identification ratio data were derived from the
detection and detection-plus-identification data, a separate analysis for identification ratio
was completed.

A four-way repeated measures ANOVA was completed to analyze detection and
detection-plus-identification sensitivities with stimulus, condition, ear, and sensitivity
measure serving as within-subject factors, and group and gender serving as between-
subject factors. A main effect for sensitivity ($F_{1,34} = 49.21$, $p < 0.05$) revealed that
detection sensitivity was significantly better than detection-plus-identification sensitivity.
This suggests that overall, listeners were better at detecting target stimuli than actually
identifying to which ear the target stimuli was presented. A main effect for group ($F_{2,34}
= 29.74$, $p < 0.05$) revealed that children had more difficulty detecting and identifying
target stimuli when compared to either young adults or older adults, suggesting that
detection and identification of dichotic stimuli is not fully developed at age seven.

A significant interaction effect for sensitivity x group ($F_{2,34} = 19.00$, $p < 0.05$)
revealed that performance for detection was significantly better than performance for
detection-plus-identification for children, whereas there was no significant difference
between sensitivities for younger adults or older adults. A significant interaction effect
for condition x group ($F_{4,68} = 2.70$, $p < 0.05$) revealed that children had overall better
performance for the free recall response condition when compared to the directed recall
right or directed recall left response conditions. Interaction effects for condition x
sensitivity ($F_{2,68} = 10.22, p < 0.05$), and condition x sensitivity x group ($F_{4,68} = 4.65, p < 0.05$) revealed that children typically had better detection-plus-identification performance for the free recall response condition versus the directed recall right and directed recall left response conditions. This suggests that biasing attention did not aid children in their ability to correctly identify the ear to which a target stimulus was presented. A ear x group x gender interaction effect ($F_{2,34} = 3.35, p < 0.05$) revealed that although there were not significant differences for young adults and older adults for performance across ear, female children had better performance for materials presented to the right ear versus performance for materials presented to the left ear whereas male children had better performance for materials presented to the left ear versus performance for materials presented to the right ear.

A three-way repeated measures ANOVA was completed to analyze the sensitivity measure of identification ratio, or the proportion of detected target stimuli that were correctly attributed to the ear to which the stimuli were presented. Stimulus, condition, and ear served as within-subject factors while gender and group served as between-subject factors. A main effect for group ($F_{2,34} = 16.19, p < 0.05$) was significant and post-hoc testing revealed that children had a lower overall identification ratio when compared to young adults and older adults. An interaction effect for condition x group ($F_{4,68} = 4.27, p < 0.05$) revealed smaller identification ratios for the directed recall right response condition when compared to the free recall response condition.
The last statistical analysis for the dichotic target detection and identification tasks was competed to compare false alarm rate which was used as a measure of bias. A three-way repeated measures ANOVA was completed with stimulus, condition, and ear serving as within-subject factors, and group and gender serving as between-subject factors. A main effect of group ($F_{2,34} = 10.98$, $p < 0.05$) suggested that false alarm rates were significantly different across groups. Post-hoc testing revealed that children had a higher false alarm rate when compared to young adults and older adults. An interaction effect for condition x group ($F_{4,68} = 4.17$, $p < 0.05$) revealed that children had a higher false alarm rate for the directed recall right and directed recall left response conditions versus the free recall response condition, whereas older adults had a lower false alarm rate for the directed recall right and directed recall left response conditions versus the free recall response condition. Therefore, although directing attention prompted children to guess more often, older adults were less apt to guess when given a specific listening strategy. An interaction effect for group x gender ($F_{2,34} = 3.54$, $p < 0.05$) revealed that for child participants, females had a higher false alarm rate than males. Lastly, an interaction effect for condition x gender ($F_{2,68} = 4.17$, $p < 0.05$) revealed that females had a higher false alarm rate and males had a lower false alarm rate in the directed recall right and directed recall left response conditions versus the free recall response condition.
Dichotic speech recognition is commonly included in a test battery to assess children for auditory processing disorder (Emanuel, 2002). One of the criticisms of auditory processing assessment is that there are lexical and cognitive factors evident in the types of testing paradigms used to diagnose APD that complicate definitive diagnosis of an auditory-specific deficit (McFarland & Cacace, 1995; Cacace & McFarland, 1998; Cacace & McFarland, 2005). Dichotic speech recognition performance specifically has been shown to change depending upon the lexical content of the stimulus used in the task (Noffsinger et al., 1994; Carter & Wilson, 2001). The effect of cognitive load, and specifically attentional biases that are examined through the use of different response conditions, have also been shown to change performance characteristics (Hugdahl & Andersson, 1986; Hugdahl et al., 2001). Because the most commonly used dichotic speech recognition tasks used to diagnose APD in children vary in terms of the lexical content present in the speech stimulus and the cognitive load introduced by the response condition employed (Musiek, 1983; Keith, 2000), there is a need to systematically investigate how lexical content and cognitive load affect the measurement of dichotic
speech recognition performance characteristics. This is especially important in light of the fact that APD often occurs comorbidly with language deficits and cognitive disorders, such as attention difficulties, which can potentially interact with lexical content and cognitive load effects (Cestnick & Jerger, 2000; Wright et al, 1997).

The specific aims of the current study were to examine performance differences in dichotic speech recognition between speech stimuli that have relatively high amounts of lexical content (meaningful words) with stimuli that have relatively low amounts of lexical content (nonsense words) while keeping phonetic content constant. In order to examine the effects of cognitive load, dichotic speech recognition was completed in three response conditions, including free recall, directed recall right, and directed recall left. The use of a dichotic target detection and identification task has been proposed to provide a way to separate differences in performance across ears possibly due to the effects of cognitive load from differences in performance across ears due to the relative transmission capabilities of the ascending auditory pathways (Speaks et al., 1982; Hiscock et al., 1999; Voyer, 2004). Therefore, a target detection and identification task was included in the present study to investigate differences in dichotic abilities across three levels of perception: detection, identification, and recognition. Lastly, dichotic speech recognition performance has been shown to change as a function of age (Hugdahl et al., 2001). Overall performance increases and a typical REA decreases as children develop dichotic skills, whereas overall performance decreases and a REA (or LED) increases in the aging population (Pohl et al., 1984; Roup et al, 2006). These
developmental and aging effects are thought to be due to the development and subsequent deterioration of the corpus callosum (Bellis & Wilbur, 2001; Bellis, 2003). Therefore, the present study sought to examine potential differences that exist in dichotic speech processing across the lifespan by including children, young adults, and older adults in the study.

Stimulus Considerations

One advantage of the stimuli used in the present study is that the stimulus materials consisted of a set of meaningful words and nonsense words that have similar phonetic content. That is, across both sets of stimuli, the same consonants and vowels appear in initial, medial, and final position with the same frequency (Boothroyd & Nittrouer, 1988). Therefore, the only variable remaining between the two lists is presence of more lexical content in the meaningful words as opposed to the nonsense words. For monaural word recognition, although there were several statistically significant findings there were very few clinically significant findings. When the results were re-analyzed using the guidelines developed by Thornton and Raffin (1978) to determine significant differences between speech recognition scores, there were no clinically significant differences in recognition performance across stimulus type or between ears for children or young adults. Also, there were no significant differences in the recognition performance of children when compared to young adults. Older adults, however, had poorer recognition performance when compared to children and young adults. This can be partially explained by the presence of peripheral hearing impairment.
in the older adult group. Additionally, there was a significant difference between
stimulus materials for the older adults group, as performance for meaningful words was
significantly better than performance for nonsense words. Because both sets of stimuli
had similar phonetic content, the decrement in performance for the older adult group for
nonsense words cannot be fully explained by the presence of peripheral hearing loss.
Therefore, it appears that the limited lexical information provided by the nonsense words
makes recognition more difficult for older adults. This suggests that older adults use
lexical content for speech recognition even in relatively easy listening situations, like
words in quiet. Dirks et al. (2001) previously reported similar findings for a set of
meaningful word stimuli that had different levels of lexical content. Specifically, older
adults listeners with hearing impairment demonstrated poorer monaural recognition
scores when compared to young adult listeners. Further, older adult listeners had better
recognition scores for lexically “easy” words than for lexically “hard” words, suggesting
that older adults appear to rely more on lexical content for monaural speech recognition
when compared to young adults. The results of the current study support that conclusion
by showing that older adults had significantly poorer monaural speech recognition for
nonsense words with relatively little lexical content than for meaningful words with
relatively more lexical content.

For dichotic speech recognition, all three subject groups demonstrated poorer
performance for nonsense words than for the meaningful words. Ear advantages obtained
for nonsense words were also larger and more variable than ear advantages obtained for
meaningful words. Therefore, when the recognition task was made more difficult by introducing competition, the results of the present study suggest that lexical content impacts recognition performance regardless of age. Carter and Wilson (2001) previously reported similar results in the young adult and older adult populations in a study that examined dichotic speech recognition of lexically hard and lexically easy words. Specifically, overall dichotic speech recognition of word pairs that consisted of two lexically hard words was significantly poorer than recognition of word pairs that consisted of two lexically easy words. Performance for lexically hard words was also more variable than performance for lexically easy words for both young adults and older adults. The results of the current study also suggest that children use lexical cues when processing speech in complex listening situations. Previously, Lamm and Epstein (1997) reported that children had better dichotic speech recognition performance for digit material when compared to word material. Lamm and Epstein (1997) partially attributed performance differences across stimulus type to the familiarity of the stimulus, with digits being a highly familiar, closed stimulus set and words being a relatively less familiar, open stimulus set. Overall, results from Lamm and Epstein (1997) suggested that the more familiar the word, the better the recognition performance in children. Results from child participants in the present study are consistent with these previous findings in that recognition performance for familiar meaningful words was better than performance for unfamiliar nonsense words.
Although the presence of sensorineural hearing loss can partially account for the overall decrease in recognition performance for older adults when compared to children and young adults, hearing loss cannot fully explain the pattern of performance demonstrated by the older adult group on dichotic speech recognition tasks. For dichotic speech recognition tasks, older adults demonstrated significant ear advantages across all three response conditions. There was no significant difference in performance between ears for monaural word recognition using the same words, however. This is consistent with previous studies that examine aging effects in dichotic speech recognition. Roup et al. (2006) measured monaural and dichotic speech recognition using the same set of stimuli and reported equal recognition performance for both ears for monaural speech recognition but significant differences between the ears on dichotic speech recognition for older adults with hearing loss. Therefore, the results of the present study further support the notion that older adult listeners demonstrate deficiencies in binaural processing during dichotic speech recognition tasks that cannot be fully accounted for by the presence of peripheral hearing loss.

In order to further examine the effect of word difficulty on dichotic recognition performance, the data were collapsed across ear and condition and then parsed according to NAM ratings. Figure 4 presents mean recognition performance for collapsed data for each difficulty category for the meaningful words and for nonsense words. The “easiest” category consisted of words with high frequency and high neighborhood density. The
Figure 4: Mean percent correct recognition for each subject group across meaningful word difficulty and for nonsense words.
“easy” category consisted of words with high frequency and low neighborhood density. The “difficult” category consisted of words with low frequency and high neighborhood density. Lastly, the “most difficult” category consisted of words with low frequency and low neighborhood density. As can be seen on Figure 4, as difficulty increased, recognition performance decreased. Lastly, nonsense words demonstrated the poorest overall performance when compared to any of the meaningful word groups.

Statistical analysis of the NAM difficulty ratings was completed via a one-way repeated measures ANOVA with difficulty serving as the within-subject factor, and group and gender serving as the between-subject factors. A main effect for difficulty ($F_{4,136} = 117.10, p < 0.05$) revealed that significant differences in dichotic recognition performance existed across word difficulty. Post-hoc testing revealed that dichotic recognition performance across all difficulties was significantly different from each other, with the exception of difficult and most difficult word categories demonstrating no significant difference in recognition performance. A main effect for group ($F_{2,34} = 65.57, p < 0.05$) revealed that performance across groups were significantly different. Post hoc testing revealed that children and older adults demonstrated significantly poorer performance overall when compared to young adults, consistent with previous findings. Lastly, an interaction effect for difficulty x group ($F_{8,136} = 2.84, p < 0.05$) revealed that older adults had better performance than children on the most difficult words despite performing similarly for each of the other word difficulties. This effect can be seen graphically in Figure 4. Because low frequency words are considered more difficult than
high frequency words, the better performance in this category for the older adults may be due to the fact that older adults have had more language experience than children. Overall, the results of dichotic recognition performance examined across difficulty suggest that even within a set of meaningful words, difficulty can have a significant impact on dichotic recognition performance, and that impact is group-specific. This is again consistent with Carter and Wilson (2001) who showed that performance on dichotic pairs consisting of two lexically easy words was better than performance on dichotic pairs consisting of two lexically hard words in both young adults and older adults. In addition, although the most difficult group of words approached performance levels similar to nonsense words, recognition of nonsense words was still significantly poorer than the most difficult meaningful word category, further supporting that limited lexical content in speech stimuli significantly impacts recognition performance in dichotic speech recognition tasks.

Lastly, for the dichotic detection and identification tasks, there were no significant differences across stimulus type. This can be partially explained, however, by the relatively high performance levels for these tasks across all three groups. Because performance was at ceiling level for the young adult and older adult groups, significant differences could not be examined. Although children did not perform at ceiling, no significant differences were found in performance between types of speech stimuli for the child participants either. High performance for these tasks was most likely due to the fact that detection and identification are easier tasks than recognition (Erber, 1982).
There are potential clinical implications for the results obtained in the present study for the diagnosis of a binaural processing deficit type of APD in children. Emanuel (2002) reported that the most commonly used dichotic speech recognition tests used to diagnose binaural processing deficits in children included the SCAN Competing Words Subtest, the SSW, and the Dichotic Digits Test (Keith, 2000; Katz, 1962; Musiek, 1983). Emanuel (2002) also reported that most clinicians use several of these tests together in a test battery to diagnose binaural processing deficits. The SCAN, SSW, and Dichotic Digits Test each use different speech stimuli that vary significantly in terms of the lexical content. The SCAN uses monosyllabic words, the SSW uses bisyllabic compound words and the Dichotic Digits test uses digits. Although there is normative data for the SCAN, SSW, and Dichotic Digits Test to which to compare performance of clinical patients, administering several tests that vary in lexical content could result in conflicting results due to the lexical content effects found to impact performance in the present study. For instance, children could perform within normal limits for a relatively easy stimulus like digits, but have performance not within normal limits for relatively hard stimulus materials such as words or compound words. In fact, Moncrieff (2006) reported that a subset of children who were tested for binaural processing deficits using a variety of dichotic speech recognition tests with different speech stimulus materials demonstrated performance within normal limits for some tests and abnormal performance on other tests. Therefore, the differences in performance obtained by several tests that use a
variety of stimuli with different lexical content that are used to diagnose APD can potentially complicate a definitive diagnosis of binaural processing deficits in children.

*Cognitive Load Considerations*

Cognitive load was examined in the present study by measuring dichotic speech recognition using different response conditions to systematically bias attention. The free recall response condition is considered to have a relatively higher cognitive load because listeners are not given a specific strategy to process the competing stimuli. The directed recall response condition, however, lessens the cognitive load of the task by providing a listening strategy that biases participants to one ear over the other. Results of the present study suggest that performance changes as a function of response condition, but that those changes are population-specific. Specifically, for both types of stimulus materials young adults demonstrated a mean REA for the free recall response condition, a larger mean REA for the directed recall right response condition, and a mean LEA for the directed recall left response condition, the pattern of performance typically found in dichotic speech recognition literature (Hugdahl et al., 2001; Roup et al., 2006). Children also demonstrated a mean REA in the free recall response condition and a larger mean REA in the directed recall right response condition, however a small mean REA was obtained for the directed recall left response condition for both types of stimuli. This is also consistent with previous findings for children. Hugdahl et al. (2001) reported the same pattern of ear advantage performance for seven-year-old children on dichotic speech recognition tasks using CV syllables. Older adults demonstrated different patterns
of performance for meaningful words versus nonsense words. For meaningful words, older adults demonstrated a small mean LEA for the free recall response condition, a REA for the directed recall right response condition, and a large LEA for the directed recall left response condition. Although a LEA for the free recall response condition is not typical for this population (Roup et al., 2006; Carter & Wilson, 2001), the magnitude of the ear advantage was relatively small (mean = -3.00) and can be partially accounted for by the significant variability in performance for the older adult group. For the nonsense words, older adults followed the same pattern of performance as the young adult listeners but had larger degrees of ear advantage, which is more typical for this population (Roup et al., 2006).

The differences in patterns of performance for the older adult group can mostly be attributed to the large variability in performance across response condition. As seen in Figures 2 and 3, young adults not only perform better than children and older adults, but the variability in the data is significantly less than what is seen for the children and older adults, as illustrated by the spread of data points across the bivariate plots. Therefore, although mean data suggests a particular pattern of performance, individual data for both children and older adults is quite variable. The results of this study not only suggest that changing cognitive load by biasing attention can change performance within and across populations, it also suggests that there is a significant amount of individual variability in performance across response condition. Significant variability across response condition for individual data has been previously reported in the older adult population. Roup et al.
(2006) showed that individual data for older adult listeners is much more variable than for young adult listeners and showed similar data trends across response condition in bivariate plots for dichotic word recognition. Significant individual variability has also been noted within the free recall condition for both older adults and children. Carter and Wilson (2001) reported that performance was more variable for older adult listeners than for young adult listeners for free recall of dichotic words ranging in lexical content. In addition, Carter and Wilson (2001) showed that individual variability increases as a function of lexical difficulty. Specifically, individual data were more variable for dichotic pairs consisting of two lexically hard words than for dichotic pairs consisting of two lexically easy words. Lastly, Moncrieff and Wilson (2009) reported changes individual variability in dichotic digit recognition as a function of age. Specifically, individual variability increased for recognition of dichotic 1-pair, 2-pair, and 3-pair digits as age decreased from young adults (19-28 years old) to children (10-12 years old). Therefore, it appears that both response condition and age of the listener can contribute to the amount of individual variability in dichotic speech recognition.

The effect of cognitive load on measurement of performance characteristics in dichotic speech recognition also has clinical implications when the tests currently used to assess APD in children are considered. The SCAN and SSW use the directed recall response condition, however the performance across the directed recall right and directed recall left response conditions are added to get one raw score. The Dichotic Digits test uses a free recall response condition in which the listener is able to direct attention as
they see fit across the test. When used together as a part of a test battery, it would be probable that different results would be obtained if several tests using different response conditions were administered, complicating definitive diagnosis of a binaural processing problem that is auditory in nature. Again, the children who reportedly had conflicting results on a variety of dichotic speech recognition tasks by Moncrieff (2006) were administered the SCAN, the Dichotic Digits Test, the SSW, and several other tests using different speech stimuli under different response conditions. Obtaining conflicting results across dichotic speech recognition tasks will complicate definitive diagnosis of a binaural processing deficit. Therefore, if multiple tests using different response conditions are used as a part of a test battery for APD, the effects of cognitive load on measurement of performance characteristics for dichotic speech recognition should be a consideration.

In addition, there is some evidence from the aging population to suggest that administering dichotic speech recognition tasks in both free recall and directed recall response conditions may help a clinician differentiate between auditory processing issues from higher level cognitive deficits (Jerger & Martin, 2006). Jerger and Martin (2006) outlined three performance patterns typically occurring in the older adult population. Normal performance in both free recall and directed recall conditions suggests normal auditory processing and cognitive abilities. As previously discussed, asking the listener to divide their attention between both right and left ears is more cognitively involved than specifically directing attention, which provides the listener with a strategy and lessens the
cognitive load of the task. Therefore, performance that is poorer in the free recall condition than directed recall conditions suggests a primarily cognitive deficit. In contrast, performance that is equally abnormal in both free recall and directed recall conditions suggests a primarily auditory deficit. In this case, providing the listener with a strategy and lessening cognitive load did not improve performance. Therefore, Jerger and Martin (2006) have suggested that dichotic listening tasks should always be carried out in both free recall and directed recall response conditions in order to differentiate between types of deficits. To date, published studies of dichotic speech recognition data collected in the pediatric population have not used this categorization scheme to differentiate between children who might have primarily auditory processing deficits from those who have issues with cognitive deficits. Currently, there are no clinical tests of dichotic listening that employ both free recall and directed recall conditions for the assessment of dichotic listening in children (Musiek, 1983; Keith, 2000). Therefore it may prove to be fruitful to further investigate the utility of applying the categorization scheme used in the aging population for use in the pediatric population in order to differentially diagnose auditory from other cognitive issues.

Dichotic Target Detection and Identification

The differential effects that lexical content and cognitive load have on performance characteristics has prompted some researchers to propose that the ear
advantage obtained during dichotic speech recognition tasks is actually due to several factors other than just the processing capabilities of the auditory pathways (Speaks et al., 1982). Several researchers have proposed that measuring dichotic processing through a target detection paradigm would allow for the separation of actual dichotic sensitivity from biases that are due to other factors, such as attentional and response biases (Speaks et al., 1982; Katsuki et al., 1984). Hiscock and Beckie (1993), Hiscock et al. (1999), Voyer (2004), and Voyer, Szeligo, and Russel (2005) further suggested that pairing a target detection and identification task with the free recall and directed recall response conditions will not only allow for the separation of sensitivity from bias, but also provide a way to examine dichotic processing as a two-stage process. This theoretical framework of dichotic processing combines the structural and attentional models of dichotic listening by proposing an “automatic” stage that is dictated by differences in processing capabilities of the auditory pathways, and a “controlled” stage that is dictated by attentional aspects of processing. Voyer et al. (2005) suggested that detection sensitivity is the correlate of the “automatic” processing stage dictated by structural asymmetries, while identification sensitivity is the correlate of “controlled” processing dictated by attentional biases. Therefore, the current study included a dichotic target detection and identification testing paradigm in order to examine how the additional information obtained through this testing paradigm can potentially further explain differences across stimulus material, response condition, and age.
As previously noted, no significant differences in performance existed on the target detection and identification tasks between meaningful and nonsense words for any of the subject groups. This is most likely because detection and identification are easier tasks than recognition, resulting in performance levels either near or at ceiling levels for both stimuli for a majority of the participants (Erber, 1982). Because of ceiling performance, there were no significant differences between detection sensitivity, detection-plus-identification sensitivity, and the identification ratio for both young adults and older adults. These findings are contrary to previous results that showed significant differences across sensitivity measures for young adults (Voyer, 2003; Hiscock et al., 1999). Previous studies, however, have purposely made tasks more difficult by either using fused stimuli, such as rhymed words, or by adding several pairs of stimuli to tax working memory. Since one of the aims of this study was to examine the effects of lexical content and cognitive loading systematically, the addition of another stimulus material with different lexical properties or adding a working memory variable was not desirable.

Children, however, did not perform at ceiling levels for the target detection and identification task. As with adults, there were no significant differences in performance across stimulus material or performance per ear, but this again may be a function of the task itself being relatively easy when compared to dichotic speech recognition tasks. Overall, children demonstrated a mean detection sensitivity that was significantly poorer than adults, suggesting that their dichotic processing at the level of detection is not yet
fully developed. This is consistent with findings from traditional dichotic speech recognition tasks that show children develop dichotic listening skills with age (Hugdahl et al., 2001). The ability for children to correctly identify the ear to which a target stimulus was presented was significantly poorer than their ability to merely detect the stimulus, resulting in lower identification ratios for children when compared to adults. These findings are also consistent with previous studies that examined similar tasks with other stimulus materials (Hiscock & Beckie, 1993; Hiscock et al., 1999). Specifically, Hiscock and Beckie (1993) reported that children demonstrated better performance for detecting a target stimulus versus identifying the ear to which the target stimulus was presented. When comparing results in children from Hiscock and Beckie (1993) with results in adults from Hiscock et al. (1999), children demonstrated lower identification ratios when compared to adults for CV syllable stimuli. The difference in detection performance versus identification performance for children can be attributed to a difference between the “automatic” processing stage and “controlled” processing stage of dichotic processing. Although children can merely detect a target stimulus correctly, their ability to selectively attend the ear to which a target stimulus was present is not fully developed when compared to adults. Clinically, for deficits in dichotic processing that are identified in children assessed using traditional dichotic speech recognition tasks, there is no way to parse out detection sensitivity from identification sensitivity. Therefore, it cannot be determined whether children are performing poorly because they have a deficit in the capability of the ascending auditory pathways to process competing signals or whether there is a selective auditory attention deficit that is contributing to
abnormal performance. The utility in assessing dichotic processing using a target detection and identification paradigm is the ability to separate a basic “automatic” processing issues from a “controlled” processing issues while also determining if bias has an impact on performance. Being able to separate these effects would be extremely helpful, especially in populations of children who may present with coexisting attention difficulties. Further research that includes examining patterns of performance for children with typical dichotic processing skills versus children with abnormal dichotic processing skills may further add to differential diagnosis of auditory-based deficits. In addition, this may allow for the differential diagnosis between children with APD versus other coexisting issues, such as language or attention issues.

Lastly, results from false alarm data suggest that children make significantly more false alarms when compared to young adults and older adults. Therefore, children are more apt to guess during dichotic task if they are unsure of the correct answer. When biased to a specific ear for the directed recall response conditions, there were no significant changes across response condition in terms of the number of false alarms made per ear. In other words, biasing attention to the right ear did not necessarily make a statistically significant difference on the amount of false alarms attributed to the right ear for any of the subject groups. This is contrary to previous dichotic target detection studies, however as discussed previously, most studies used significantly harder tasks that include fused stimuli or several pairs of stimuli presented per trial that may have contributed to the need for guessing (Hiscock & Beckie, 1993; Hiscock et al., 1999).
One interesting finding gleaned from the false alarm data is that children had a significantly higher false alarm rate for the directed recall response conditions when compared to the free recall response condition. Therefore, providing children a listening strategy by biasing attention increased children’s willingness to guess when they were unsure of the correct answer. In contrast, older adults had lower false alarm rates for the directed recall response conditions when compared to the free recall response condition. It appears that with a dichotic detection and identification task, the introduction of a listening strategy decreases the likelihood of guessing in the older adult population. This is an interesting finding considering that when older adults are provided a listening strategy with the directed response conditions in traditional dichotic speech recognition tasks, they typically have better performance for the task because it decreases the cognitive load for the task (Jerger & Martin, 2006; Roup et al., 2006). The differences in false alarms between children and young adults could possibly be explained by working memory skills. Because working memory skills are not fully developed in children, they may be more apt to guess when unsure as to whether the target word was presented. In contrast, older adult listeners who have fully developed working memory skills may be able to handle and store multiple auditory inputs more readily, decreasing the likelihood that they would need to guess on this task.

_Dichotic Detection, Identification, and Recognition across Age_

Changes in performance on dichotic speech recognition tasks across age have been previously attributed to the development of the corpus callosum in children and
subsequent deterioration of the corpus callosum in older adults (Bellis & Wilbur, 2001; Bellis, 2003). One curious finding of the present study is that although children and older adults had similar dichotic speech recognition performance, older adults did not follow the same pattern of performance for the dichotic detection and identification task when compared to children. Because it has been proposed that detection sensitivity is the correlate of the structural component of dichotic processing (Voyer et al, 2005), one would expect that older adults who have deficits in dichotic speech recognition would also have decreased detection skills. One possible explanation for this discrepancy might lie in the fact that the target detection and identification task was simply too easy for the older adult population, and despite having recognition deficits, their binaural processing is actually intact at the level of detection and identification. In contrast, children are still developing detection, identification, and recognition skills at age seven, and therefore had different levels of performance at each level of perception. More research into how patterns of performance may change with age using more difficult tasks across detection, identification, and recognition may provide ways to further investigate the mechanisms of dichotic speech processing in children, young adults, and older adults.
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