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# The Right Ear Advantage in Response to Levels of Linguistic Complexity: A Functional Magnetic Resonance Imaging Study

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The Right Ear Advantage in Response to Levels of Linguistic  
Complexity: A Functional Magnetic  
Resonance Imaging Study

Elizabeth Hyatt

A thesis submitted to the faculty of  
Brigham Young University  
in partial fulfillment of the requirements for the degree of  
Master of Science

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## ABSTRACT

### The Right Ear Advantage in Response to Levels of Linguistic Complexity: A Functional Magnetic Resonance Imaging Study

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The right ear advantage (REA) phenomenon has been utilized in clinical and research settings to study auditory processing disorders and linguistic lateralization. Previous research has established that the REA is not reliable in its measures within or between individuals. This is likely due to the influence of other variables, such as neuromaturation and attention. One variable that has not been studied in depth in this context is linguistic complexity. It was hypothesized that stimulus conditions with levels of linguistic complexity would elicit corresponding levels of temporal lobe activity. Understanding and controlling the variables that affect the REA will increase the reliability of the measure. Twenty right handed, neurotypical individuals aged 18-29 participated in a functional magnetic resonance imaging (fMRI) study that identified the regions and the extent of activation involved in listening to dichotic syllables, words, and sentences. Three durations of speech babble corresponding to the mean duration of the syllables, words, and sentences were used as control stimuli. Participants listened to dichotic stimuli and reported the stimulus they heard best during an fMRI scan. Reaction time (RT), ear preference, and fMRI data were recorded simultaneously and analyzed post hoc. Behavioral results showed that words had the shortest RTs and the greatest REA; syllables and sentences were similar to each other for both measures. Significant main effects were found in brain regions known to be involved in cognitive control of attention and linguistic processing. Words were associated with significant activation differences for ear preferences and minimal frontal lobe involvement for right ear preference. Syllables caused the least activity in the frontal lobe regions and less voxel activity in the temporal lobes than syllable-length babble. Sentences had the greatest voxel activity in the frontal and temporal lobe regions. It was concluded that words would best reflect the REA in clinical and experimental designs. Words had minimal involvement of frontal lobe regions indicating minimal cognitive control of attention and the largest discrepancies in activation patterns between right and left ear preferences that showed less cognitive power to process right ear stimuli in a dichotic listening situation.

Keywords: Functional magnetic resonance imaging, right ear advantage; linguistic laterality; linguistic processing; linguistic complexity; mid-frontal gyrus

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## TABLE OF CONTENTS

LIST OF TABLES .....	vi
LIST OF FIGURES .....	vii
LIST OF APPENDICES.....	viii
DESCRIPTION OF STRUCTURE AND CONTENT.....	ix
Introduction.....	1
Structural Model .....	2
Hemispheric lateralization.....	2
Contralateral innervation.....	3
Corpus callosum.....	5
Contributing Variables.....	6
Neuromaturation .....	7
Attention .....	8
Linguistic complexity .....	9
Measurement of Ear Advantage.....	10
Behavioral data.....	11
Neuroimaging.....	11
Statement of the Problem.....	12
Method .....	12
Participants.....	12
Stimuli.....	13
Instrumentation .....	13
Consonant-vowel syllable recording instrumentation.....	13
Auditory screening.....	14
Functional magnetic resonance imaging.....	14

Procedures.....	14
Stimuli preparation.....	14
Data presentation .....	15
Data Analysis .....	17
Results.....	18
Behavioral Data .....	18
Ear advantage.....	18
Reaction time.....	19
Neuroimaging Data.....	21
Whole brain analysis.....	21
Region of interest analysis.....	25
Right versus left ear preference.....	41
Discussion.....	42
Behavioral Discussion .....	43
Neuroimaging Discussion.....	44
Conclusions.....	47
Summary of Findings.....	47
Limitations and Further Research.....	48
References.....	50

## LIST OF TABLES

1. Descriptive Statistics of Ear Laterality .....	19
2. Descriptive Statistics for Reaction Time (RT) in ms for All Conditions .....	20
3. Descriptive Statistics of All Variables for fMRI Beta Activity for Each ROI in the Main Effect of Complexity.....	25
4. ANOVA of the Regions of Interest for Main Effect of Condition .....	27
5. Descriptive Statistics of Linguistic Processing for fMRI Beta Activity in Each ROI.....	28
6. ANOVA of the Regions of Interest for Main Effect of Linguistic Processing.....	41

## LIST OF FIGURES

1. Percent of participants for each ear preference in all conditions .....	19
2. Mean reaction time in ms for syllables, words, and sentences. ....	21
3. Axial view: main effect of condition and ear preference.....	22
4. Coronal view: main effect of condition and ear preference.....	23
5. Sagittal view: main effect of condition and ear preference. ....	24
6. Syllables minus babble brain slices. ....	30
7. Words minus babble brain slices. ....	31
8. Sentences minus babble brain slices. ....	32
9. Linguistic processing: right mid-frontal gyrus. ....	33
10. Linguistic processing: right mid-frontal gyrus. ....	34
11. Linguistic processing: right temporal region. ....	35
12. Linguistic processing: left temporal region. ....	36
13. Linguistic processing: left mid-frontal gyrus - posterior. ....	37
14. Linguistic processing: left medial frontal region. ....	38
15. Linguistic processing: left orbital frontal region. ....	39
16. Linguistic processing: left cerebellum. ....	40
17. Post hoc analysis of the linguistic effect. ....	41
18. Words <sub>Right</sub> minus Words <sub>Left</sub> brain slices. ....	42



## LIST OF APPENDICES

Informed Consent to Act as a Human Research Subject .....	55
Preliminary Questionnaire .....	58
Annotated Bibliography.....	59

## DESCRIPTION OF STRUCTURE AND CONTENT

The body of this thesis was written as a manuscript suitable for submission to a peer-reviewed journal in speech-language pathology. This thesis is part of a larger collaborative project, portions of which may be submitted for publication, with the thesis author being one of multiple co-authors. Appendix A includes the consent form for participants. Appendix B includes a preliminary questionnaire filled out by participants. Appendix C includes an annotated bibliography. Level of evidence in the annotated bibliography was determined by the following guidelines; Level I: Evidence obtained from a systematic review of the majority (more than one) of relevant randomized control trials (meta-analysis). Level II: Evidence obtained from at least one well-designed randomized control trial. Level III (a): Evidence obtained from well-designed controlled trials without randomization. Level III (b): Evidenced from well-designed cohort or case-controlled analytic studies, preferably from multiple clinical programs or research centers. Level III (c): Evidence from multiple time series, with or without intervention, showing dramatic results from uncontrolled research. Level IV: Opinions of respected authorities, based on clinical experience, descriptive studies or reports of expert committees.

## Introduction

The classic paper on the central auditory processing system using a dichotic listening (DL) task was first published by Kimura in 1967. In a dichotic listening task, the listener is simultaneously presented with two different stimuli to the two ears (i.e., “dog” presented to the right ear and “house” presented to the left ear). This type of presentation stresses the auditory processing system with competing stimuli thus showing slight advantages in processing between the pathways of the two ears (Bellis, 2003; Kimura, 1967).

Studies by Kimura and others have shown that when listeners are presented with a DL task, they are able to report the information presented to the right ear (RE) more accurately and faster than the information presented to the left ear (LE; Bayazıt, Öñiz, Hahn, Güntürkün, & Özgören, 2009; Eichele, Nordby, Rimol, & Hugdahl, 2005; Hugdahl et al., 2003; Jerger & Martin, 2005; Kimura, 1961a; Kompus et al., 2012; Kraus & Cheour, 2000; Narain et al., 2003; Rimol, Specht, & Hugdahl, 2006; Roup, 2011; Yasin, 2007; Yurgil & Golob, 2010). This preferential processing of linguistic information presented to the RE is known as the right ear advantage (REA). Studies of the REA provide experimental and clinical information on hemispheric lateralization of speech and auditory pathway efficiency and integrity (Bayazıt et al., 2009; Eichele et al., 2005; Hugdahl et al., 2003; Iliadou, Kaprinis, Kandyliş, & Kaprinis, 2010; Jerger & Martin, 2004; Kimura, 1961a; Kimura, 1961b; Narain et al., 2003; Roup, 2011; Yasin, 2007; Yurgil & Golob, 2010). Although used frequently in clinical and experimental settings as a measure of speech laterality to the left hemisphere, the REA has poor validity and reliability. Retesting participants' ear advantage shows changes in degree of ear advantage and even ear dominance; normative measures of the REA in the neurotypical population do not match clinical measures of left hemisphere dominance (Hiscock & Kinsbourne, 2011). Unknown and

unaccounted for variables are a likely cause for the poor validity and reliability of the REA. This study attempts to identify the effect that one such variable, level of linguistic complexity, has on the REA.

### **Structural Model**

Kimura (1967) was the first to interpret the REA in relation to auditory processing, and the author proposed the structural model to explain the phenomenon. The structural model proposed by Kimura (1961a) identifies a number of factors that combine to cause the REA. These include lateralization of linguistic stimuli, more efficient contralateral pathways, and the role of the corpus callosum in DL auditory processing (Bellis, 2003; Kimura, 1961a; Kimura, 1961b; Kimura, 1967). Kimura's model has been supported by a number of brain imaging and behavioral studies.

**Hemispheric lateralization.** Clinical observations, as well as research findings, support the claim that the hemispheres are specialized. Approximately 95% of the right-handed population and 59-70% of the left handed population is left hemisphere dominant for speech (Bellis, 2003; Hermann, 1998). An invasive but effective method of determining the laterality of speech is the Wada test. In this procedure, sodium amytal is injected into the carotid artery and causes a temporary "paralysis" of the targeted hemisphere. Individuals participating in this test are then asked to perform a number of tasks. Abilities that remain are ascribed to the function of the non-target hemisphere. Studies using this technique have found that speech is strongly associated with the left hemisphere (Hermann, 1998; Kimura, 1961a).

Results from other studies have also found that the left hemisphere is specialized in linguistic processing. Kimura (1961b) behaviorally tested the auditory pathway by presenting listeners with frontal lobe, right temporal lobe, or left temporal lobe lesions with sets of three

dichotic digits, six digits presented with half a second delay alternating between ears, and six digits presented to only one ear. The listeners were asked to report all the digits that they heard. Kimura found that the group with left temporal lobe lesions was significantly less accurate at reporting dichotic digits and rapidly alternating digits than the group with right temporal lobe lesions. The damage of the left temporal lobe decreased accuracy in reporting the linguistic material more than damage to the right hemisphere or frontal lobe indicating that the left hemisphere is most involved in DL tasks. It is important to note that the right hemisphere can process some linguistic stimuli. In the study referenced above, the listeners with the left temporal lobe removed were still able to report some of the digits, but were much less accurate than the group with the right temporal lobe removed. The participants who had a frontal lobe lesion were significantly more accurate at reporting digits than both of the groups with temporal lobe lesions. Although the left temporal lobe is most important for language processing, the right temporal lobe also plays a role in linguistic processing (Eichele et al., 2005; Hiscock & Kinsbourne, 2011; Kimura, 1961b).

The Wada test and behavioral studies indicate that the left temporal lobe is more involved in processing linguistic stimuli than the right temporal lobe, but they do not address the presence of processing differences for levels of linguistic stimuli. The current study reexamines locations recruited to process dichotic linguistic stimuli as well as differences elicited by different levels of linguistic complexity.

**Contralateral innervation.** Another component of the structural model is that the contralateral processing pathway is stronger than the ipsilateral pathway in DL. Kimura (1967) reported that there is both a contralateral and an ipsilateral pathway to the auditory cortex and auditory association areas from the cochlea, and human studies have shown that the contralateral

pathway is denser than the ipsilateral pathway (Jäncke, Wüstenberg, Schulze, & Heinze, 2002; Kimura, 1961b; Stefanatos, Joe, Aguirre, Detre, & Wetmore, 2008). The RE, then, has a strong contralateral pathway to the specialized linguistic processing centers of the left hemisphere. Kimura's (1961b) study of listeners with temporal lobe lesions provides evidence for these strong contralateral pathways. Listeners were significantly more accurate in reporting digits presented to the ear contralateral to the intact hemisphere in a DL task.

The relative strength of the contralateral pathways is evident in studies that report the temporal aspects of left hemisphere and right hemisphere processing. These studies reported an overall REA along with temporal advantages in processing DL tasks. Eichele et al. (2005) presented dichotic syllables to listeners and measured timing differences in electrical activity between hemispheres in an EEG study; they found that the N1 wave of the right hemisphere occurred 15 ms after the N1 wave occurred in the left hemisphere. The authors hypothesized that the latency in activation of the right hemisphere was a result of greater myelination of the pathway from the RE to the left hemisphere allowing the signal presented to the RE to travel to the cortex more rapidly than the signal presented to the right hemisphere. Another EEG study also found a temporal advantage in left hemisphere processing. Listeners were asked to attend to both ears at different times during the study; latencies were shortest when listeners attended to the RE than when they attended to the LE (Jerger & Martin, 2005). A diffusion tensor imaging study found that fiber tracts of the left temporal lobe were denser than the same fiber tracts in the right hemisphere (Ocklenburg, Schlaffke, Hugdahl, & Westerhausen, 2014).

Not only is the contralateral pathway stronger than the ipsilateral pathway, but the contralateral pathway also inhibits the ipsilateral pathway. Kimura (1967) examined the interaction of the ipsilateral and contralateral pathways by studying the REA in listeners with a

severed corpus callosum. Kimura presented dichotic digits and found that the listeners were unable to report LE stimuli but were able to report RE stimuli. The ipsilateral pathway from LE to the left hemisphere was not injured, yet the listeners could not report the stimuli. This finding was explained with the hypothesis that in auditory processing the contralateral pathway is inhibited by the ipsilateral pathway.

Because the left hemisphere is specialized in linguistic processing and contralateral pathways are stronger than the ipsilateral pathways, the RE has an advantage in linguistic processing. Theoretically, as more linguistically complex stimuli are presented, this difference will increase. The linguistic processing power of the left hemisphere will be increasingly utilized as linguistic complexity increases. As the demands for linguistic processing exceed the right hemisphere's capabilities, there will be fewer correct responses to the LE resulting in an increase in the REA.

**Corpus callosum.** The corpus callosum is the pathway for communication between the hemispheres. The left hemisphere is the language processing region, so the right hemisphere transfers complex linguistic stimuli via the corpus callosum to process speech. Strong support for the importance of the corpus callosum is found in studies of individuals who have had a corpus callosotomy. They are able to report stimuli from either ear when presented monaurally but have a very strong REA in dichotic presentation (Hiscock & Kinsbourne, 2011; Kimura, 1967). The ipsilateral pathway is inhibited by the stronger contralateral pathway in the DL situation, but the ipsilateral pathway of the LE allows the word to be identified in a monotic listening situation. Listeners with both hemispheres intact are still able to report the LE stimulus because the signal can be transferred through the corpus callosum to the left hemisphere. This deficit in reporting the LE stimulus in a dichotic paradigm verifies that the fibers between the hemispheres must

communicate for identification of verbal stimuli presented to the LE in listening situations that stress the auditory processing system. In a magnetic resonance imaging (MRI) diffusion tensor imaging study, dichotic stimuli were presented to listeners, and researchers observed the correlation between involvement of the corpus callosum and a RE or LE response. It was found that involvement of the corpus callosum was positively correlated to LE responses and negatively correlated to RE responses (Westerhausen et al., 2006). In order to respond to the signal presented to the LE, the signal was passed through the corpus callosum to the left hemisphere. The signal presented to the RE did not involve the corpus callosum because it has a strong contralateral pathway to the left hemisphere. The corpus callosum is an integral component of the structural model in explaining how the stimulus presented to the RE has the advantage and also how linguistically complex stimuli presented to the LE can still be identified.

### **Contributing Variables**

Measures of the REA have low reliability and poor validity because variables that affect the REA are not fully understood. Hiscock and Kinsbourne (2011) reviewed studies of the REA and discussed the inconsistency of DL results; uncontrolled and unknown variables decrease the reliability and validity of the REA. Retesting listeners showed that the ear advantage fluctuated within the same listener and even switched ears in some listeners. Additionally, normative data of linguistic lateralization to the left hemisphere using the REA does not match clinical measures of speech lateralization. Understanding and controlling variables that affect the REA would increase the reliability and validity of the task.

Two variables affecting the REA that have been studied include a listener's neuromaturation and attention (Hugdahl et al., 2003; Jerger & Martin, 2005; Kompus et al., 2012; Roup, 2011; Takio et al., 2009; Westerhausen et al., 2006). A variable that has not



received the same attention but would theoretically affect the REA is the linguistic complexity of the stimuli presented in a DL task. Based on the structural model of the REA, increasing levels of linguistic complexity would require a corresponding increase in involvement of the left hemisphere. The RE has a direct connection through the contralateral pathway to the left hemisphere so that it would have the advantage in DL tasks with linguistically complex stimuli. These known and unknown variables alter the REA observed and reduce the task's validity and reliability when not controlled.

**Neuromaturation.** The REA is affected by the age of the listener. Studies show that the ear advantage in young children and older adults is more lateralized to the RE than in older children and younger adults. Kimura (1963) examined the REA in children and found that the REA may be identified as early as four years of age. Although it was not the focus of the study, numbers reported indicate that younger children had a greater difference between correctly identified RE and LE stimuli than the older children. A more recent study examining the change in ear advantage over a lifetime showed that children aged 5-9 and older adults aged 59-79 have a strong REA and are unable to alter their ear advantage even when directed to attend to the LE. Adults aged 19-32 also demonstrated a REA but were able to change to a left ear advantage (LEA) when directed to attend to the LE (Takio et al., 2009). Roup (2011) examined the relationship of age-related hearing loss and ear advantage to determine if hearing-loss in older adults was the source of the stronger REA. Word recognition scores were obtained from all listeners, and younger adults' word recognition scores were made to match the word recognition scores of the older group by presenting stimuli to the younger group in noise. Listeners then participated in a DL task: older adults listened in quiet, and younger adults listened in the same level of noise as was used in matching word recognition scores. Although the word recognition

scores were made to be equivalent for both groups, the REA continued to be significantly greater in the older adult group than the young adult group. There is an age-related change in the linguistic processing system that causes stimuli at the RE to be more salient than stimuli at the LE. The neurological changes that occur with neuromaturation and aging effect auditory processing are unknown. Hypotheses explaining the stronger REA in typical children and older adults include reduced myelination, decreased integrity of the auditory pathway, and less ability to control attention (Bellis, 2003; Jerger & Martin, 2005; Kimura, 1963; Roup, 2011; Takio et al., 2009). Because it is known that neuromaturation and aging alter the REA, age is taken into account in the current study by including participants within the young adult population (ages 18-29).

**Attention.** Another variable that has a strong effect on ear advantage is attention. Kinsbourne (1982) hypothesized that attention is the cause of the REA and proposed the attentional model of the REA. It was postulated that the brain is not parsed into discreet systems with hemispheres that function independently. Rather, all areas of the brain have some degree of interaction. The attentional model proposes that many variables can predispose an ear advantage in either direction and include verbal instructions or methods of response, tilting the head, or attention to prosodic features (Hiscock & Kinsbourne, 2011; Kinsbourne, 1982). A number of studies demonstrate that controlling the response has an effect on ear advantage (Hiscock & Kinsbourne, 2011; Kompus et al., 2012; Sætrevik & Hugdahl, 2007; Westerhausen et al., 2006). For example, the REA is very strong when attention is directed to the RE, and listeners demonstrate a LEA when attention is directed to the LE (Hiscock & Kinsbourne, 2011; Kompus et al., 2012; Westerhausen et al., 2006). The current study controls for attention by asking

participants to report the stimulus heard best (Hugdahl et al., 2003; Ocklenburg et al., 2014; Rimol et al., 2006; Sætrevik & Hugdahl, 2007).

**Linguistic complexity.** Another variable that would theoretically affect the REA is the linguistic load of the stimulus presented to a listener. Because the left hemisphere is responsible for processing linguistic information, it will be involved to a greater degree as more linguistically complex stimuli are included. According to the current body of literature, the effect of linguistic complexity has not been directly investigated, but some existing studies provide preliminary support for the hypothesis that the REA is directly affected by the linguistic complexity of the signal.

Jerger and Martin (2004) reported on a two-part electroencephalography study in which adult listeners were presented with continuous speech with different response conditions in the two parts of the study. Listeners identified the number of times a target word was said in the first segment (i.e., “I’ll give you a break, *Pam* said.”) and the number of semantically and/or morphologically incorrect sentences present in the other (i.e., “and you shall *door* the ball”). Analysis of the data supported the theory that the linguistic demand of the signal alters the degree of ear advantage. Both parts of the study had an overall REA, but the advantage seen in the more linguistically demanding condition in which listeners identified incorrect morphological or semantic sentences was greater than the target word identification. This study tested the REA and hemispheric specialization while listeners identified components of a stimulus rather than simply listening to stimuli, but the results still suggest that levels of complexity cause a corresponding hierarchy of cortical response. The authors hypothesized that the signal and the response task were complex enough that the right hemisphere was not capable of processing the signal independently, so the signal was sent via the corpus callosum from the right hemisphere to

the left hemisphere to assist in processing the linguistic components which increases the REA. In the current study, participants listen to levels of linguistically complex stimuli and report what is heard in order to test only the auditory processing of a signal.

A study reported by Speaks, Niccum, and Van Tasell (1985) compared the REA elicited by dichotic presentation of digits, words, and CV syllables in the sensorineural hearing loss population to find the condition that identified the sensorineural hearing loss population with the greatest accuracy. The authors found that the REA increased as the difficulty of the stimuli increased (greatest REA for CV syllables and least for digits). The stimulus condition that elicits the greatest REA differs across populations as discussed by Speaks and colleagues. The current study will provide data on a neurotypical population.

Two unpublished studies from the Speech-Language-Hearing clinic at University of South Dakota found that the REA in 7 year-old children is 15% for dichotically presented digits and 50% for dichotic sentences (Bellis, 2003). As discussed previously, this age group has a stronger REA than adults, but it is expected that adults would show the same trend. It is hypothesized that the REA will be greater for the stimuli with greater linguistic complexity. The current study will provide objective data to compare behavioral and imaging data obtained from a hierarchy of linguistic stimuli in a DL task.

### **Measurement of Ear Advantage**

Since Kimura (1961b) first observed the REA in the 1960s, DL has been the method of obtaining behavioral data on the REA in both research and clinical settings. With the advancement of technology, behavioral and neuroimaging data have been combined to provide a more complete understanding of how the dichotic stimuli are processed.

**Behavioral data.** To obtain a measure of ear laterality, listeners are presented with a different stimulus to the ears; responses are recorded and a percentage reflecting extent of laterality is calculated with the formula  $[(RE - LE)/(RE + LE)] * 100$  (Ocklenburg et al., 2014; Rimol et al., 2006). Results can range from -100% to 100% where positive percentages indicate a REA and negative percentages indicate a LEA.

A number of response methods have been utilized in previous studies. Many procedures have listeners verbally report stimuli presented to both ears (Iliadou et al., 2010; Kimura, 1961a; Roup, 2011; Schmithorst, Farah, & Keith, 2013), report the stimulus heard best (Hugdahl et al., 2003; Ocklenburg et al., 2014; Rimol et al., 2006; Sætrevik & Hugdahl, 2007), report stimuli presented to a specific ear (Eichele et al., 2005; Hugdahl et al., 2003; Iliadou et al., 2010; Kompus et al., 2012; Westerhausen et al., 2006), or answer visually presented questions to report which ear had the advantage in specific trials (Bayazit et al., 2009; Yurgil & Golob, 2010). These response methods are often selected based on the procedure of the study. Studies that are observing the effect of attention to the two ears often control attention by asking listeners to report the stimuli presented to a target ear. Study designs, such as the current study's, that use imaging software sensitive to movement have listeners report the presence/absence of a specific target sound (Jerger & Martin, 2004; Stefanatos et al., 2008; Yasin, 2007) or report what is heard best with the use of a button press (Yurgil & Golob, 2010). The current study will utilize a button press to obtain behavioral data to reduce movement.

**Neuroimaging.** Behavioral tests used with objective neuroimaging techniques allow for the further study of the cause of the REA both when the REA is observed and when ear advantage switches. Functional magnetic resonance imaging (fMRI) applies the imaging capabilities of MRI to identify specific regions that have heightened blood flow while an

individual completes a task. Because increased blood flow is provided to active neurons, fMRI has high location resolution. Unfortunately, it cannot show which areas are inhibitory and which are excitatory, and it has poor temporal resolution. The high location resolution of fMRI affords the ability to learn the function of brain regions. Functional MRI studies of the REA are useful in identifying regions involved in auditory processing (Narain et al., 2003; Rimol et al., 2006), variables that alter ear advantage (Kompus et al., 2012), and disordered brain activation patterns (Schmithorst et al., 2013). The current study will use fMRI to examine the cortical regions activated when processing levels of linguistic stimuli both with intra- and inter-hemispheric activation.

### **Statement of the Problem**

The aim of the present study is to investigate behavioral and cortical activation differences in response to levels of linguistic stimuli (i.e., babble, syllables, words, and sentences). Behavioral data collected will include ear advantage and reaction time both between ear preferences and across stimulus conditions. Functional MRI will identify the presence of functional differences in location and extent of voxel activity in response to auditory processing of dichotic stimuli with levels of linguistic complexity.

### **Method**

#### **Participants**

The study included 20 right-handed participants, 11 male and 9 female, between the ages of 18 and 29 years who spoke English as a first language. Each participant read and signed an informed consent document approved by the Institutional Review Board at Brigham Young University (see Appendix A) and completed a preliminary questionnaire to verify that they met inclusion criteria: MRI compatibility, no history of psychiatric or neurologic diagnoses, and no

history of hearing loss (see Appendix B). Each participant received \$20 for participating in the study.

### **Stimuli**

Stimulus conditions included four levels of linguistic complexity: multi-speaker babble, consonant-vowel (CV) syllables, words, and sentences. All stimuli were calibrated to the SCAN 3 (Keith, 2009) calibration tone. Stimuli were presented dichotically at a comfortable listening level to the participants. Three durations of multi-speaker babble were included that corresponded to the average duration of the syllables, words, and sentences which were 0.59 s, 0.63 s, and 1.46 s, respectively. Syllables included /ba/, /da/, /ga/, /pa/, /ta/, and /ka/ and were combined in all non-matching pairs for a total of 30 CV syllable pairs. Syllables were pseudo-randomized so that the same syllable was not consecutively presented to the same ear twice in a row and a stimulus pair did not switch ears (/ba/-/da/ pair followed by /da/-/ba/). Dichotic words and sentences were obtained from the Competing Words-Free Recall and Competing Sentences subtests from the SCAN 3 for Adolescents and Adults (Keith, 2009). To isolate word and sentence pairs into individual WAV files with simultaneous onset times, the recording and editing software Audacity version 2.0.5 (Audacity, 2013) was used.

### **Instrumentation**

**Consonant-vowel syllable recording instrumentation.** Syllables were digitally recorded by an adult, female, Native speaker of English. The signal was recorded in a sound treated room using a Larson Davis (Provo, UT) model 1.27 cm model 2541 microphone attached to a Larson Davis model 900 microphone preamplifier. A 7.62 cm foam windscreen was used on the microphone at 0 degrees azimuth. The microphone preamplifier was attached to a Larson Davis model 2200 preamplifier power supply. The audio signal was then digitized with 24-bit

quantization and a 44.1 kHz sample rate using a Benchmark ADC1 analog-to-digital converter (Benchmark Media Systems). The digital output of the Benchmark ADC1 (Benchmark Media Systems) was routed to the digital input of a SADiE (Studio Audio & Video Limited, 2004) digital editing station using version 5.5.4 software. Files were then saved as 24-bit wav files.

**Auditory screening.** Participants were required to pass an initial hearing screening. Otoscopy was conducted with a Welch Allyn otoscope (Welch Allyn), and otoscopic examination revealed clear ear canals and normal appearing tympanic membranes bilaterally. Participants passed a hearing threshold screening test bilaterally with pure tone thresholds of  $\leq$  20 dB HL for octave frequencies between 250 Hz and 8000 Hz. Noise levels were within the limits as specified by ANSI S3.1-1999 R2008. A Grason-Stadler model GSI-1761 audiometer was used for auditory screening stimuli presentation.

**Functional magnetic resonance imaging.** Magnetic resonance imaging was performed with a Siemens TIM-TRIO 3.0T MRI scanner using a 32-channel head coil at the Brigham Young University MRI Research Facility. Before echo-planar image (EPI) acquisition, a T1-weighted magnetization-prepared rapid acquisition with gradient echo sequence (MP-RAGE, echo time = 2.08 ms, flip angle =  $8^\circ$ ) was used to acquire an image formed from 156 slices (1.0 mm thick, matrix size = 256 x 256, field of view 256 x 256 mm, voxel size = 1x1x1 mm). Functional data was collected in 4 EPI scan runs that ranged from 446 s to 506 s (echo time = 28 ms, flip angle =  $90^\circ$ , repetition time = 2000 ms) with 39 slices (3 mm thick, 64 x 64 matrix size, field of view 218 x 218 mm, voxel size = 3.4 x 3.4 x 3 mm).

## **Procedures**

**Stimuli preparation.** Stimuli were presented in 33 pseudo-randomized blocks using e-prime (Schneider, Eschman, & Zuccolotto, 2012). Eight blocks each of syllables, words, and



sentences and three blocks each of the syllable-length babble, word-length babble, and sentence length-babble were pseudo-randomly presented. Blocks of syllables, words, and their corresponding babble blocks each consisted of 20 dichotic stimuli while the sentences and sentence length babble blocks had 12 dichotic presentations each. Order of stimulus presentation in each block was pseudorandomized such that there was no repetition of a stimulus in the same block (except for in syllable blocks). There was a total of 160 word presentations, 160 syllable presentations, 96 sentence presentations, 60 syllable-length babble presentations, 60 word-length babble presentations, and 36 sentence-length babble presentations.

**Data presentation.** Just prior to MR scanning, each participant completed an MRI safety screening form and reviewed safety information with a trained operator. Before beginning the test, they were read the following script:

You will hear many pairs of speech sounds including noise, syllables, words, and sentences. You will simultaneously hear one sound in your right ear and another sound in your left ear. You will then see a screen with the two sounds you heard. Indicate which sound you heard best by pressing the corresponding button. If you wish to discontinue the test at any time, you may say, "I want to stop now" or squeeze the panic ball. Do you have any questions? Okay, we will start the test.

Participants were then situated in the MRI scanner with headphones. They were given the participant alarm bulb, the response pad, and fitted with an array of mirrors to allow them to comfortably view a screen that allowed participants to view instructions and the response options on a screen. Participants were instructed to hold the response pad in the right hand such that the index finger was placed on button one and the middle finger on button two. While the

localization scan and structural scan were being completed, a practice block was presented to familiarize participants with the task. First, a screen appeared that read as follows:

Welcome to the experiment. You will hear two different speech sounds simultaneously in each of your ears. After listening to a pair of sounds, you will see the two sounds written on the screen. Please press the button corresponding to the sound you heard best. Let's practice.

The practice block consisted of a syllable block with the same presentation procedure as the rest of the task. Half of the participants had button 1 corresponding to the stimulus presented to the RE and button 2 corresponding to the stimulus presented to the LE and half had the opposite button configuration. After completing the practice block, a screen appeared that said, "Great job. You will hear noise, syllables, words, and sentences during the test. We will begin shortly." Participants continued to the rest of the study tasks after the structural scans were completed.

Before each block was presented, a screen was shown for 10 s that informed the participant what stimulus type would be presented next. Baseline hemodynamic activation data was collected during this time. A run in the MRI scanner included eight blocks followed by a screen that said "End of block." After each run, the operator checked on the participant's comfort level and gave them an opportunity to relax.

Stimuli within syllable blocks, word blocks, syllable-length babble blocks, and word-length babble blocks were presented in a 1500 ms time window and stimuli in sentence blocks and sentence-length babble blocks were presented in a 2500 ms time window. A fixation cross was shown in the center of the screen during stimulus presentation. Response options were then presented for 1000 ms. Response options were pseudo-randomized so that button 1 would

represent the stimulus presented to the RE in some blocks and the stimulus presented to the LE in other blocks. After babble presentations, half of the participants were asked to press button 1 and the other half were asked to press button 2.

### **Data Analysis**

Reaction time (RT) and ear preference were recorded for all responses. The mean of RT to each condition and ear preference was analyzed using a repeated measures ANOVA.

Behavioral ear advantage was calculated first by finding the percentage of overall REA and LEA for the participants. A more precise measure of ear laterality was calculated by taking the correct responses from both ears and calculating  $[(RE - LE)/(RE + LE)] * 100$ . Negative numbers indicate a LEA; positive numbers indicate a REA.

Functional MRI data were subjected to standard post-processing procedures to identify regions of interest (ROI). The program Analysis of Functional NeuroImages (Cox, 1996) was used to process all fMRI data and SPSS was used to generate statistical reports.

Functional scans were slice time corrected to account for acquisition time differences between slices within a single TR. TRs containing significant motion events were excluded from the analysis, and movement across runs were accounted for. To achieve spatial normalization, the structural scans from all participants were fit to a standard brain mask. Single subject regression analyses were conducted by creating six motion regressors (coding for three translations and three rotations) and six behavioral regressors coding for RE and LE preferences for each of the three linguistic conditions. Functional data were then subjected to an ANOVA using SPSS software. ROIs in group analysis for main effect of condition met the criteria of 40 voxel clusters with  $p \leq .001$ . ROIs were selected in analysis of the effect of ear preference for the different conditions and the effect of condition and ear preference minus babble met the criteria

of 20 voxel clusters with  $p \leq .05$ . It was expected that activation in the left STG and Heschl's gyrus would demonstrate greater voxel activation than the right STG and Heschl's gyrus and that the activation of the left STG would become increasingly greater as the linguistic complexity of the stimuli increased.

Behavioral and neuroimaging results of the study were analyzed for statistical significance. Gender differences were not taken into account as previous studies do not show a difference in ear advantage between males and females in the young adult age group (Kimura, 1963; Kimura, 1967; Takio et al., 2009).

## Results

### Behavioral Data

We examined ear advantage, laterality of linguistic processing, RT for ear preferences, and duration of linguistic processing.

**Ear advantage.** Participants demonstrated an overall REA as is seen in Figure 1. According to previous studies, 95% of the right handed population is left hemisphere dominant for speech, and if the REA is reflective of this similar numbers should be observed in the DL task. Results showed that words had the strongest REA with 75% of the participants showing an overall REA. To reflect the degree of REA elicited for each level of complexity, the laterality of ear advantage was calculated using the formula  $[(\text{Right} - \text{Left})/(\text{Right} + \text{Left}) * 100]$  for each participant in each condition. Group descriptive statistics are reported in Table 1. Again, all conditions demonstrated a laterality towards the RE; sentences had the smallest REA, closely followed by syllables, and words had the greatest REA. A Chi-Square test found that although there is a trend for a REA for each of the three stimulus types, only the words reached significance ( $\chi^2(1, 20) = 5.0, p \leq .025$ ).

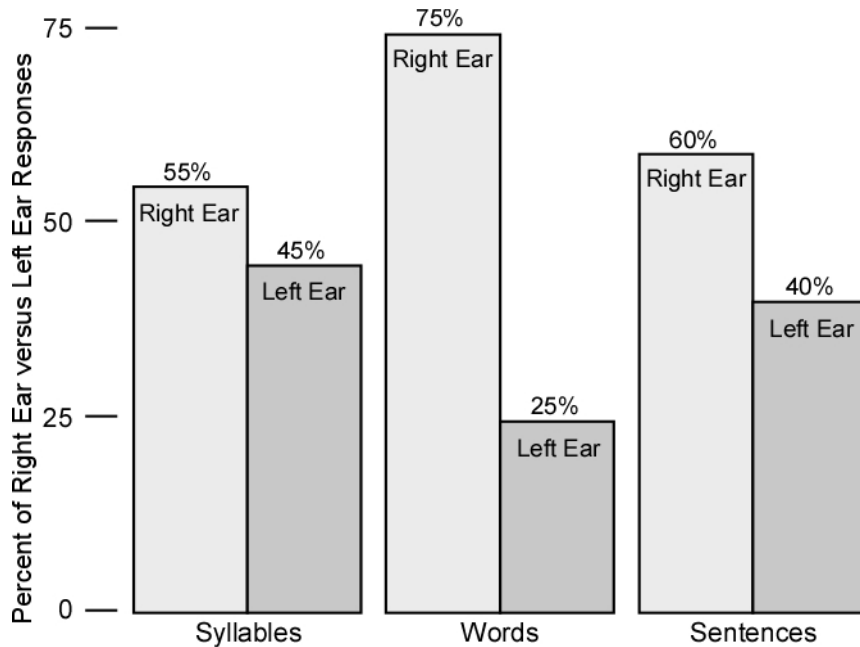


Figure 1. Percent of participants for each ear preference in all conditions

Table 1

*Descriptive Statistics of Ear Laterality*

Stimulus	<i>n</i>	<i>M</i>	<i>SEM</i>	<i>SD</i>	Minimum	Maximum	Range
Syllable	20	12.058	7.585	33.921	-57.962	85.333	143.295
Word	20	16.776	7.561	33.812	-52.201	70.667	122.868
Sentence	20	11.888	8.022	35.875	-48.936	72.414	121.350

Note. Laterality was calculated with the formula  $[(\text{Right} - \text{Left})/(\text{Right} + \text{Left}) * 100]$ . Negative ear advantage numbers indicate a LEA, and positive numbers indicate a REA.

**Reaction time.** Descriptive statistics for RTs are reported in Table 2. The RTs to the three babble durations were shortest followed by words, syllables, then sentences. The differences between the three babble durations and differences between RE and LE preferences for each condition were minimal. Duration of linguistic processing was calculated by subtracting the average RT of the corresponding babble duration from the average RT for the specific condition. These results showed that processing words takes the least amount of time, followed by syllables, and then sentences with the longest processing time.

Table 2

*Descriptive Statistics for Reaction Time (RT) in ms for All Conditions*

Stimulus	<i>n</i>	<i>M</i>	<i>SEM</i>	<i>SD</i>	Minimum	Maximum
Syllable	40	544.783	8.215	51.957	408.600	632.000
Right Ear	20	538.629	11.168	49.943	408.605	615.477
Left Ear	20	550.937	12.180	54.471	453.774	632.000
Word	40	493.121	9.546	60.374	325.340	610.090
Right Ear	20	494.180	13.095	58.562	325.341	556.396
Left Ear	20	492.060	14.230	63.639	331.647	610.085
Sentence	40	589.086	14.812	93.682	358.260	744.980
Right Ear	20	589.764	20.237	90.501	380.564	744.980
Left Ear	20	588.408	22.162	99.112	358.256	725.619
Babble Lengths						
Syllable	19	321.793	10.500	45.768	236.931	389.810
Word	19	312.965	6.981	30.431	260.407	373.117
Sentence	20	320.505	7.230	32.334	266.806	374.830
Linguistic Processing						
Syllable	19	220.923	14.158	61.714	111.520	338.690
Word	19	177.418	13.877	60.488	68.090	271.190
Sentence	20	268.582	21.104	94.380	70.140	432.510

*Note.* Linguistic processing time was acquired by calculating the formula  $[(RT_{\text{Right}} + RT_{\text{Left}})/2 - RT_{\text{Babble}}]$  for each linguistic condition. Only 19 subjects were included in syllable and word length babble because there was an error recording the data for one subject.

A repeated measures ANOVA was completed for the RT to the three speech categories separated into RE and LE preferences. Within subjects analysis revealed a significant F ratio ( $F(5,95) = 22.188, p < .001$ ) showing a significant ( $p < .001$ ) main effect for stimulus type . Likewise, between subject analysis revealed a significant F ratio ( $F(1,19) = 1564.090, p < .001$ ) showing a significant ( $p < .001$ ) main effect for stimulus type. This would suggest that there are RT differences for the ear preferences across the three speech categories for both individual processing times as well as differences between the participants. Further analysis showed that ANOVAs for repeated measures failed to show differences in RT between the three speech babble lengths or between RE and LE preferences for the three linguistic conditions ( $p \geq .05$ ). This is in contrast to significant differences ( $F(1,18) = 8.730, p \leq .008$ ) between the three speech

categories. Linguistic processing RTs showed significant differences were not seen in the RTs for syllables versus words; however, significant differences ( $p \leq .05$ ) in RTs were seen for words versus sentences. This is illustrated in Figure 2, which shows the smallest RT for word stimuli and the greatest RT for sentences.

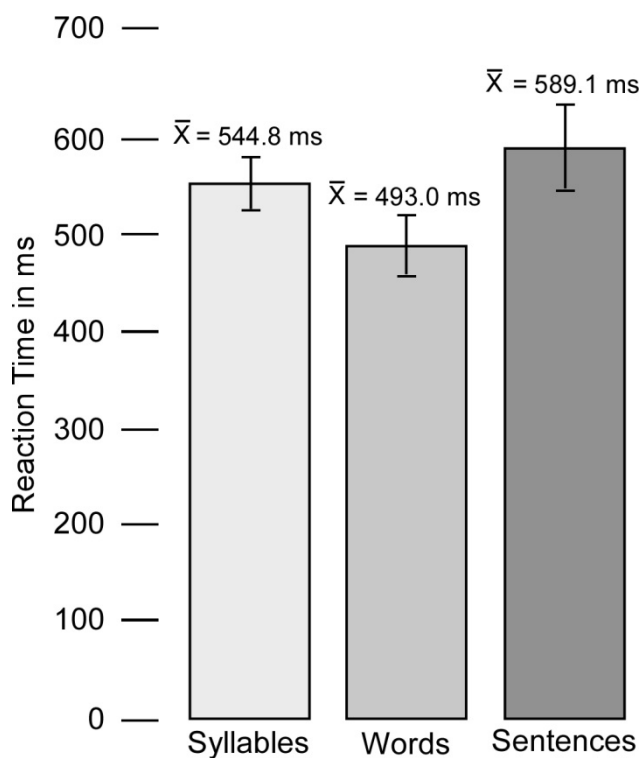
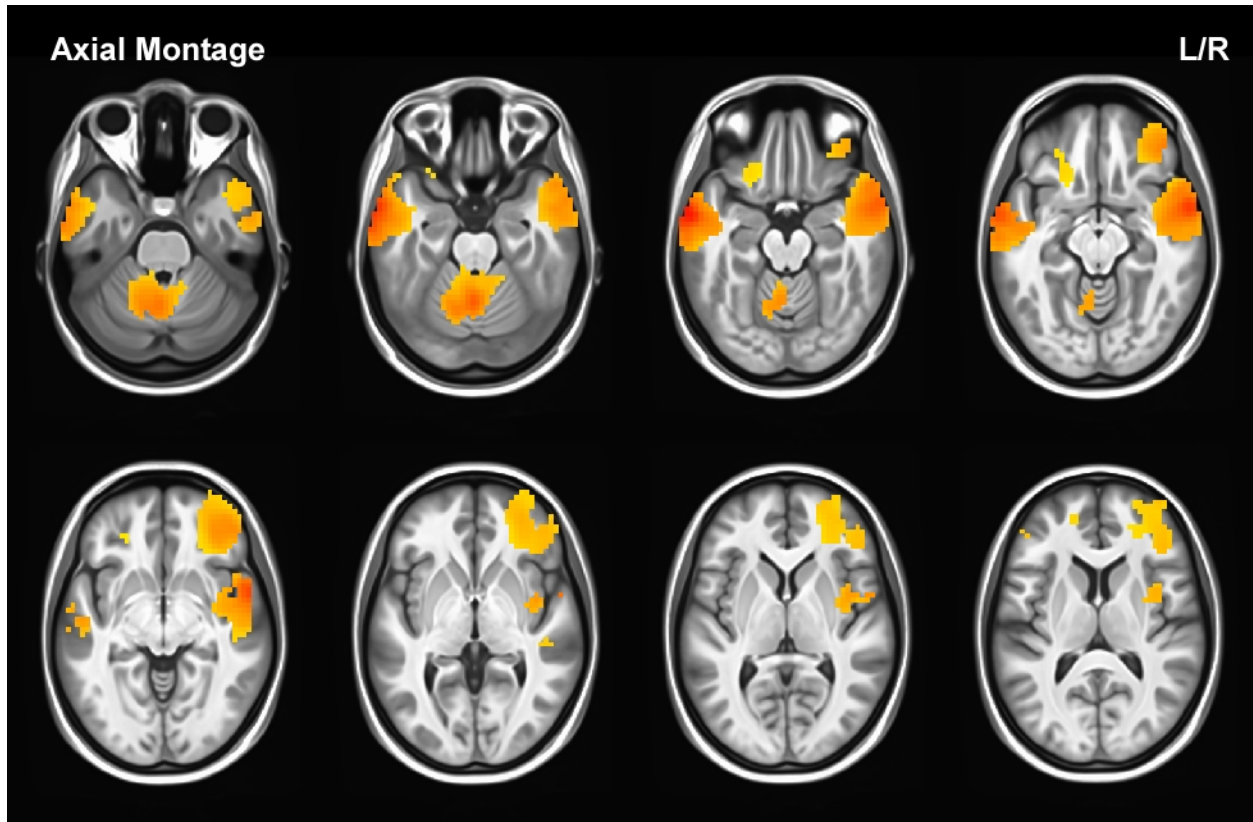


Figure 2. Mean reaction time in ms for syllables, words, and sentences. Error bars represent the *SD*.

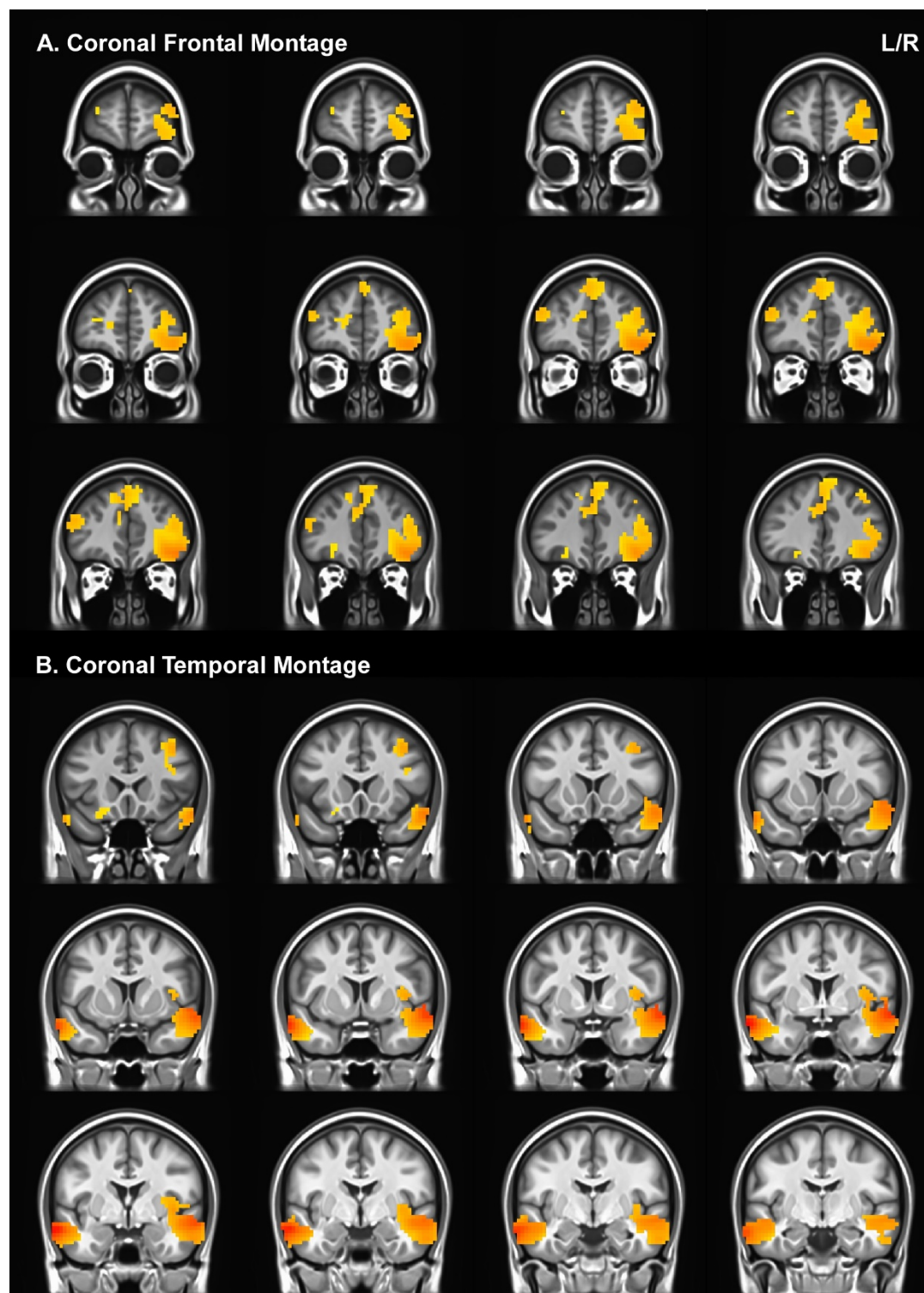
### Neuroimaging Data

**Whole brain analysis.** The GLM voxel-based analysis revealed eight clusters with a significant main effect of condition and ear preference. Regions of interest ( $p \leq .001$ ; 40 voxel cluster) included the right mid-frontal gyrus (MFG), left MFG, right MFG-posterior, left medial frontal, left orbital frontal, right temporal, left temporal, and left cerebellum. Figures 3-5 show the whole brain analysis for the main effect of stimulus complexity in different views.

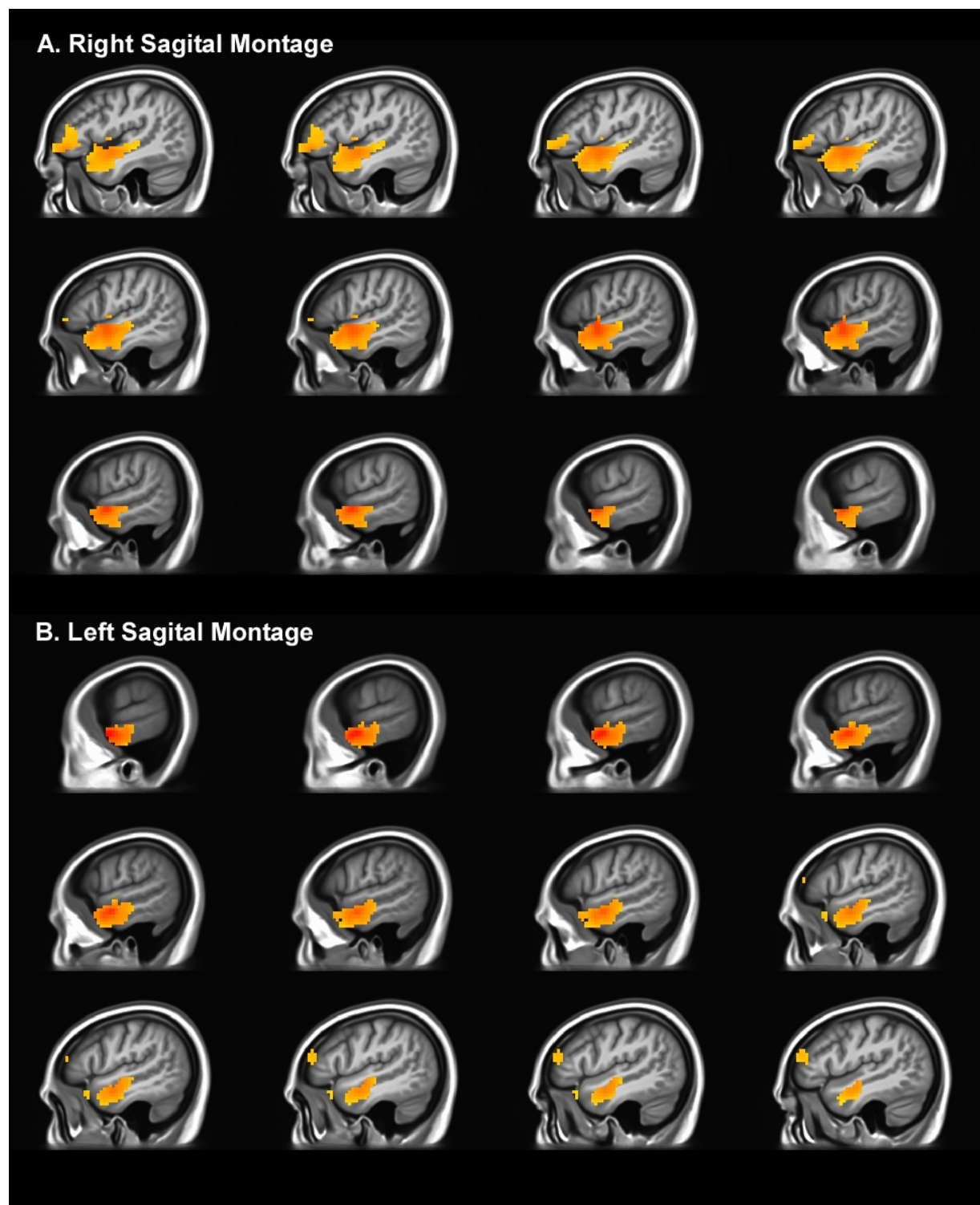


*Figure 3.* Axial view: main effect of condition and ear preference. Axial slices show ROIs for whole brain fMRI analysis. Significant main effects were found in the right and left-mid frontal gyrus, the right and left temporal regions, the posterior right mid-frontal gyrus, the left medial frontal region, the left orbital frontal region, and the left cerebellum.





*Figure 4.* Coronal view: main effect of condition and ear preference. Coronal slices show ROIs for whole brain fMRI analysis. Significant main effects were found in the right and left mid-frontal gyrus, the right and left temporal regions, the posterior right mid-frontal gyrus, the left medial frontal region, the left orbital frontal region, and the left cerebellum. Figure A depicts frontal regions, and Figure B depicts temporal regions.



*Figure 5.* Sagittal view: main effect of condition and ear preference. Sagittal slices show ROIs for whole brain fMRI analysis. Significant main effects were found in the right and left mid-frontal gyrus, the right and left temporal regions, the posterior right mid-frontal gyrus, the left medial frontal region, the left orbital frontal region, and the left cerebellum. Figure A depicts the right hemisphere, and Figure B depicts the left hemisphere.

**Region of interest analysis.** Descriptive statistics for mean beta activity of voxels for each condition and ear preference were calculated in all ROIs; results are reported in Table 3. This analysis showed a trend of increasing activity with increasing linguistic complexity, greater left hemisphere activity than right hemisphere activity in ROI hemispheric pairs, and greater activity for LE preferences than for RE preferences. Repeated measure ANOVAs on the ROIs for condition and ear preference revealed significance for within subject analyses for all ROIs, and between subject analyses revealed significance for all ROIs except the left orbital frontal region. This suggests that there are significant differences for mean voxel beta activation both for individuals and the group. Results are reported in Table 4.

Table 3

*Descriptive Statistics of All Variables for fMRI Beta Activity for Each ROI in the Main Effect of Complexity*

Stimulus	<i>n</i>	<i>M</i>	<i>SEM</i>	<i>SD</i>	Minimum	Maximum
Right Mid Frontal Gyrus						
Syllable RE	20	0.110	0.109	0.489	-0.839	1.445
Syllable LE	20	0.244	0.119	0.534	-1.069	1.020
Word RE	20	0.364	0.092	0.410	-0.352	1.080
Word LE	20	0.759	0.127	0.568	-0.072	2.365
Sentence RE	20	0.885	0.155	0.694	-0.110	2.378
Sentence LE	20	0.935	0.167	0.746	-0.277	3.125
Babble Syllable	20	0.127	0.144	0.645	-1.013	1.396
Babble Word	20	-0.151	0.168	0.750	-1.863	1.164
Babble Sentence	20	0.238	0.172	0.769	-0.992	2.396
Left Mid-Frontal Gyrus						
Syllable RE	20	0.251	0.178	0.798	-2.316	1.350
Syllable LE	20	0.434	0.246	1.099	-1.320	3.657
Word RE	20	0.447	0.211	0.945	-1.727	2.914
Word LE	20	0.902	0.227	1.017	-0.842	2.893
Sentence RE	20	0.909	0.303	1.355	-1.304	4.197
Sentence LE	20	1.189	0.275	1.231	-1.557	3.352
Babble Syllable	20	-0.024	0.164	0.732	-1.641	1.839
Babble Word	20	-0.074	0.178	0.797	-1.488	1.292
Babble Sentence	20	0.252	0.178	0.796	-1.644	2.091

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Right Temporal						
Syllable RE	20	0.290	0.081	0.363	-0.177	0.905
Syllable LE	20	0.297	0.129	0.578	-1.052	1.217
Word RE	20	0.500	0.117	0.523	-0.238	1.492
Word LE	20	0.725	0.114	0.510	0.071	2.124
Sentence RE	20	1.287	0.200	0.892	0.003	3.137
Sentence LE	20	1.271	0.209	0.934	0.045	3.713
Babble Syllable	20	0.725	0.142	0.636	-0.609	1.727
Babble Word	20	0.647	0.153	0.685	-0.492	2.495
Babble Sentence	20	1.207	0.217	0.971	-0.640	3.062
Left Temporal						
Syllable RE	20	0.531	0.154	0.690	-0.397	2.272
Syllable LE	20	0.475	0.163	0.729	-0.565	2.786
Word RE	20	0.688	0.201	0.901	-0.428	3.062
Word LE	20	0.861	0.230	1.029	-0.492	3.451
Sentence RE	20	1.627	0.351	1.571	-0.629	4.972
Sentence LE	20	1.554	0.363	1.622	-0.419	5.398
Babble Syllable	20	0.674	0.200	0.895	-1.003	3.242
Babble Word	20	0.656	0.205	0.917	-0.457	2.794
Babble Sentence	20	1.152	0.327	1.461	-1.058	4.418
Right Mid-Frontal Gyrus - Posterior						
Syllable RE	20	0.133	0.122	0.544	-0.915	1.259
Syllable LE	20	0.168	0.184	0.823	-1.383	2.786
Word RE	20	0.327	0.135	0.602	-0.314	2.174
Word LE	20	0.535	0.141	0.630	-0.244	2.107
Sentence RE	20	0.751	0.269	1.201	-0.769	4.496
Sentence LE	20	0.919	0.251	1.121	-0.341	3.727
Babble Syllable	20	0.166	0.124	0.553	-0.456	2.020
Babble Word	20	-0.087	0.170	0.759	-1.087	2.189
Babble Sentence	20	0.653	0.270	1.209	-0.436	5.146
Left Medial Frontal						
Syllable RE	20	0.060	0.093	0.416	-0.547	1.203
Syllable LE	20	0.125	0.160	0.715	-1.214	2.115
Word RE	20	0.252	0.114	0.511	-0.533	1.018
Word LE	20	0.487	0.152	0.678	-0.503	2.179
Sentence RE	20	0.584	0.147	0.657	-0.240	3.315
Sentence LE	20	0.756	0.212	0.948	-0.724	3.315
Babble Syllable	20	0.083	0.103	0.459	-0.547	0.986
Babble Word	20	-0.008	0.122	0.547	-1.133	1.250
Babble Sentence	20	0.353	0.174	0.779	-0.745	2.848
Left Orbital Frontal						
Syllable RE	20	-0.007	0.083	0.373	-0.809	0.552
Syllable LE	20	-0.136	0.106	0.473	-1.013	0.874

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Word RE	20	0.140	0.097	0.432	-0.496	1.088
Word LE	20	0.247	0.102	0.455	-0.465	1.299
Sentence RE	20	0.282	0.114	0.508	-0.624	1.226
Sentence LE	20	0.373	0.133	0.594	-0.890	1.762
Babble Syllable	20	0.052	0.149	0.668	-1.813	1.347
Babble Word	20	0.173	0.157	0.700	-1.336	1.755
Babble Sentence	20	0.199	0.166	0.743	-0.748	2.655
Left Cerebellum						
Syllable RE	20	-1.657	0.267	1.192	-3.980	0.336
Syllable LE	20	-1.724	0.314	1.404	-4.691	0.916
Word RE	20	-1.395	0.298	1.332	-3.773	0.818
Word LE	20	-1.617	0.323	1.445	-4.868	1.209
Sentence RE	20	-0.751	0.324	1.448	-3.023	2.873
Sentence LE	20	-0.858	0.241	1.080	-2.604	1.549
Babble Syllable	20	-1.372	0.304	1.358	-5.480	0.417
Babble Word	20	-1.298	0.270	1.206	-3.323	1.233
Babble Sentence	20	-1.463	0.391	1.749	-6.078	3.053

Table 4

*ANOVA of the Regions of Interest for Main Effect of Condition*

Region of Interest	Within Subjects			Between Subjects		
	<i>df, error</i>	<i>F</i>	<i>p</i>	<i>df, error</i>	<i>F</i>	<i>p</i>
Right Mid-Frontal Gyrus	8, 152	10.283	.000	1, 19	20.191	.000
Right Temporal	8, 152	11.641	.000	1, 19	46.078	.000
Left Cerebellum	8, 152	3.842	.000	1, 19	27.102	.000
Left Temporal	8, 152	9.638	.000	1, 19	17.332	.001
Left Medial Frontal	8, 152	4.816	.000	1, 19	10.503	.004
Right Mid-Frontal Gyrus	8, 152	5.909	.000	1, 19	7.562	.013
Left Orbital Frontal	8, 152	2.242	.027	1, 19	3.498	.077
Left Mid-frontal Gyrus	8, 152	5.694	.000	1, 19	11.526	.003

The data sets reported above provide information on overall activation related to the different conditions, but do not report the effect of linguistic processing. To determine the processing that reflected only the linguistic complexity of the signal, the mean voxel beta activity of babble durations was subtracted from the mean voxel beta activity of corresponding linguistic conditions. The remaining mean voxel beta activity was due to linguistic processing of the stimuli. Descriptive statistics are reported in Table 5. Activation patterns of linguistic processing

according to condition are shown in Figures 6-8, and extent of beta activity for all conditions in each ROI are depicted in Figures 9-16. General trends in the data included greater mean beta activity for occurrences of LE preference than RE preference, increasing mean beta activity with increasing linguistic complexity in the temporal lobes, negative mean beta activity values when processing syllables, and greater activity in left hemisphere ROIs than right hemisphere ROIs in bilateral pairs (i.e., right and left temporal regions). An ANOVA for within subjects found that there were significant differences between conditions in all ROIs except the left orbital region. This suggests that individual participant responses demonstrated significant differences in all regions except the left orbital. A between subject ANOVA found significant differences between conditions in the right and left MFG. Between and within subject ANOVA results are shown in Table 6. Pairwise comparisons identified significant differences between syllables and sentences, and syllables and LE preference for words (see Figure 17).

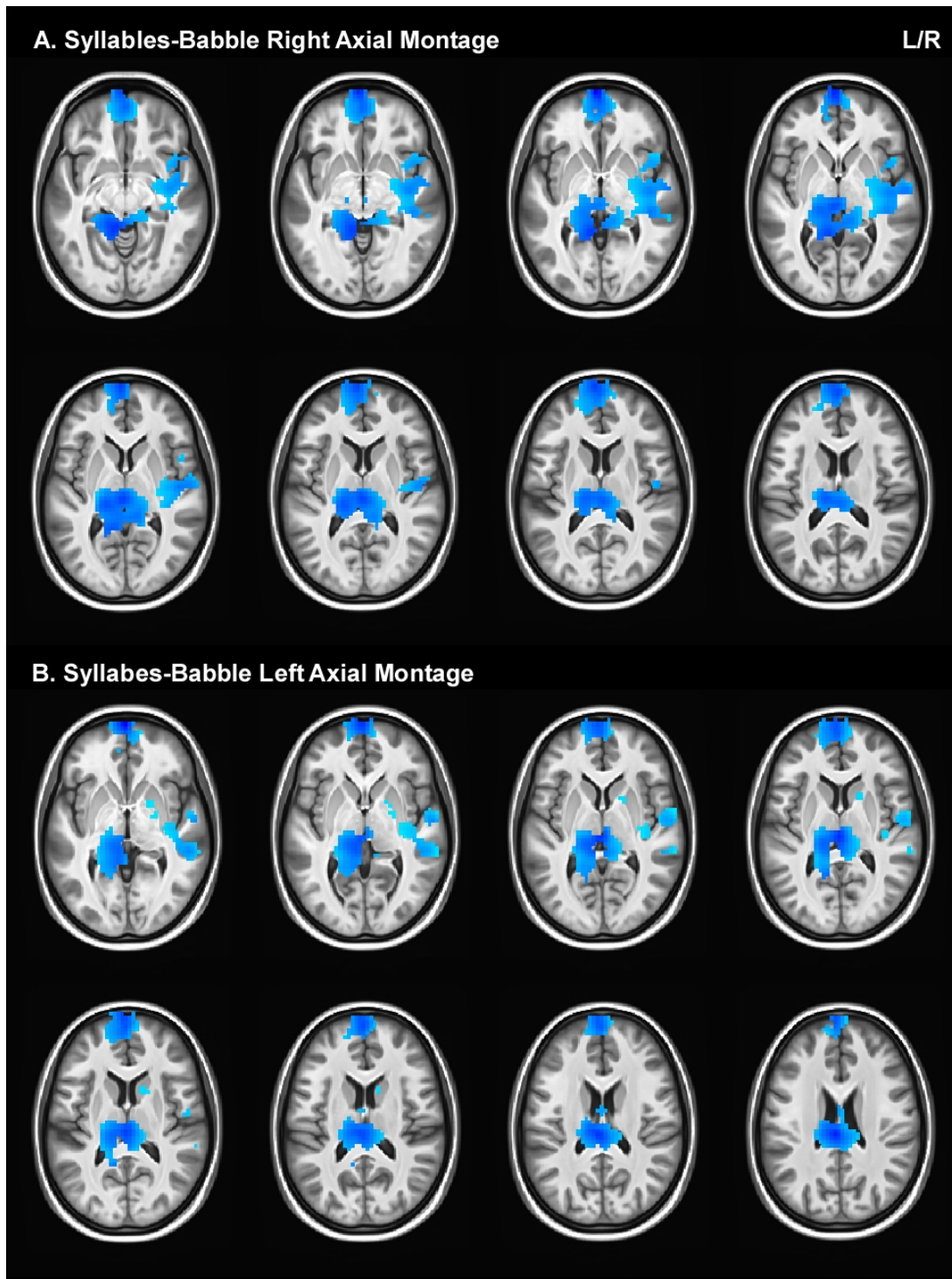
Table 5

*Descriptive Statistics of Linguistic Processing for fMRI Beta Activity in Each ROI*

ROI	<i>n</i>	<i>M</i>	<i>SEM</i>	<i>SD</i>	Minimum	Maximum
Right Mid-Frontal Gyrus						
Syllable LE	20	0.117	0.147	0.658	-1.085	1.694
Syllable RE	20	-0.017	0.180	0.805	-1.747	1.507
Word LE	20	0.910	0.222	0.991	-0.415	4.228
Word RE	20	0.514	0.155	0.695	-0.434	2.351
Sentence LE	20	0.698	0.217	0.969	-1.088	3.243
Sentence RE	20	0.648	0.123	0.551	-0.199	1.596
Left Mid-Frontal Gyrus						
Syllable LE	20	0.459	0.303	1.355	-2.084	3.625
Syllable RE	20	0.275	0.246	1.101	-2.427	2.097
Word LE	20	0.976	0.341	1.523	-2.134	4.382
Word RE	20	0.520	0.311	1.390	-3.019	3.707
Sentence LE	20	0.937	0.315	1.409	-1.015	4.996
Sentence RE	20	0.656	0.256	1.146	-1.907	2.661
Right Temporal						
Syllable LE	20	-0.428	0.142	0.637	-2.076	0.483

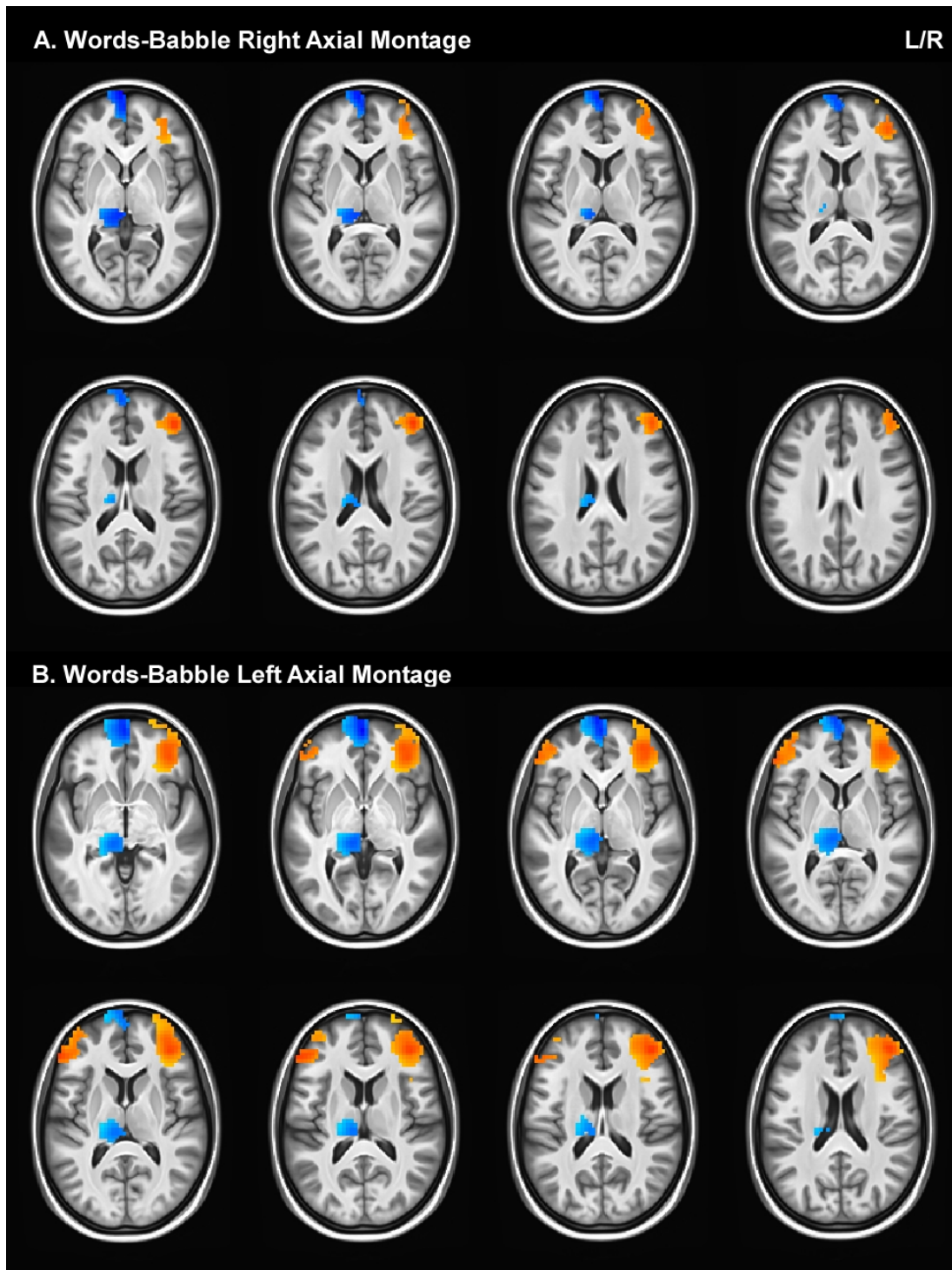
Syllable RE	20	-0.434	0.143	0.641	-1.806	0.846
Word LE	20	0.078	0.185	0.829	-1.627	2.616
Word RE	20	-0.148	0.152	0.681	-1.430	1.614
Sentence LE	20	0.064	0.146	0.655	-1.013	1.157
Sentence RE	20	0.080	0.122	0.547	-1.407	0.937
Left Temporal						
Syllable LE	20	-0.199	0.136	0.607	-1.440	1.318
Syllable RE	20	-0.143	0.159	0.711	-1.158	1.366
Word LE	20	0.205	0.196	0.876	-1.415	3.232
Word RE	20	0.031	0.164	0.731	-1.294	1.750
Sentence LE	20	0.402	0.195	0.870	-1.067	2.304
Sentence RE	20	0.476	0.178	0.794	-0.986	2.429
Right Mid-Frontal Gyrus - posterior						
Syllable LE	20	0.002	0.158	0.706	-1.599	1.391
Syllable RE	20	-0.032	0.176	0.788	-1.510	1.394
Word LE	20	0.622	0.206	0.919	-0.885	2.853
Word RE	20	0.414	0.179	0.802	-0.655	2.285
Sentence LE	20	0.266	0.279	1.249	-2.531	3.157
Sentence RE	20	0.098	0.151	0.673	-1.126	1.768
Left Medial Frontal						
Syllable LE	20	0.042	0.178	0.797	-1.346	2.489
Syllable RE	20	-0.023	0.157	0.703	-1.317	1.528
Word LE	20	0.496	0.206	0.922	-0.661	3.312
Word RE	20	0.260	0.163	0.728	-0.484	2.037
Sentence LE	20	0.403	0.222	0.993	-1.942	2.998
Sentence RE	20	0.231	0.138	0.617	-0.750	1.281
Left Orbital Frontal						
Syllable LE	20	-0.187	0.140	0.627	-1.472	0.800
Syllable RE	20	-0.059	0.168	0.751	-2.156	1.494
Word LE	20	0.074	0.189	0.844	-1.035	2.635
Word RE	20	-0.033	0.175	0.783	-1.242	1.953
Sentence LE	20	0.174	0.188	0.839	-1.898	1.626
Sentence RE	20	0.082	0.156	0.698	-1.550	1.051
Left Cerebellum						
Syllable LE	20	-0.352	0.248	1.108	-2.147	2.198
Syllable RE	20	-0.285	0.220	0.983	-2.013	2.606
Word LE	20	-0.319	0.242	1.082	-2.700	1.412
Word RE	20	-0.097	0.228	1.019	-1.593	2.650
Sentence LE	20	0.605	0.346	1.549	-2.359	5.411
Sentence RE	20	0.711	0.262	1.172	-0.920	3.054

*Note.* Values for conditions were identified by taking the mean voxel beta activity for each condition in each ROI and subtracting the corresponding babble mean beta activity

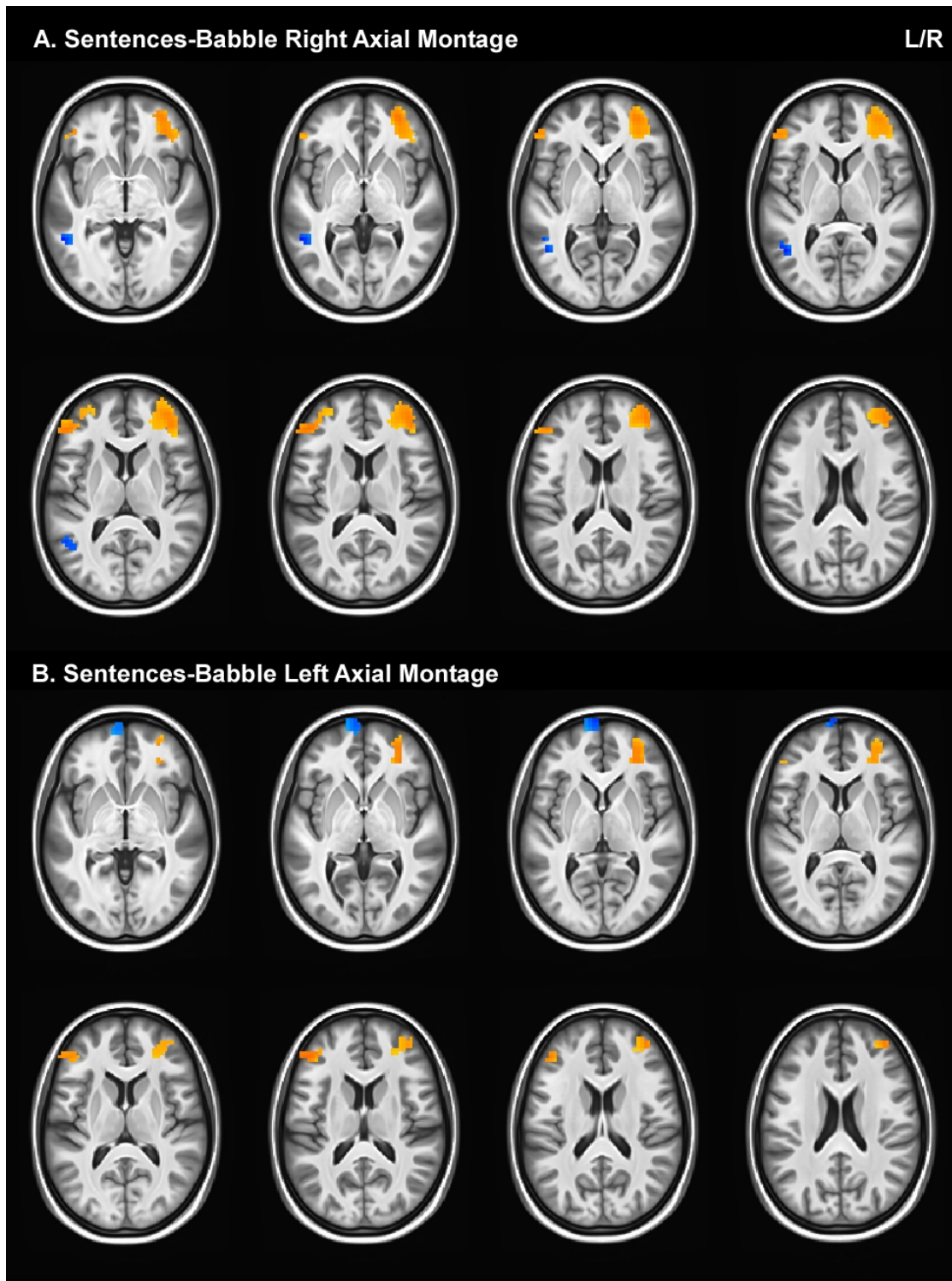


*Figure 6.* Syllables minus babble brain slices. Blue colors indicate voxel activity during dichotic syllable-length babble presentation that did not occur during dichotic syllable presentation. Orange colors would indicate voxel activity during syllable presentation that does not occur during syllable-length babble presentation. Figure A depicts the activation that occurs when the syllable presented to the right ear was heard better, and Figure B depicts the activation that occurs when the syllable presented to the left ear was heard better.

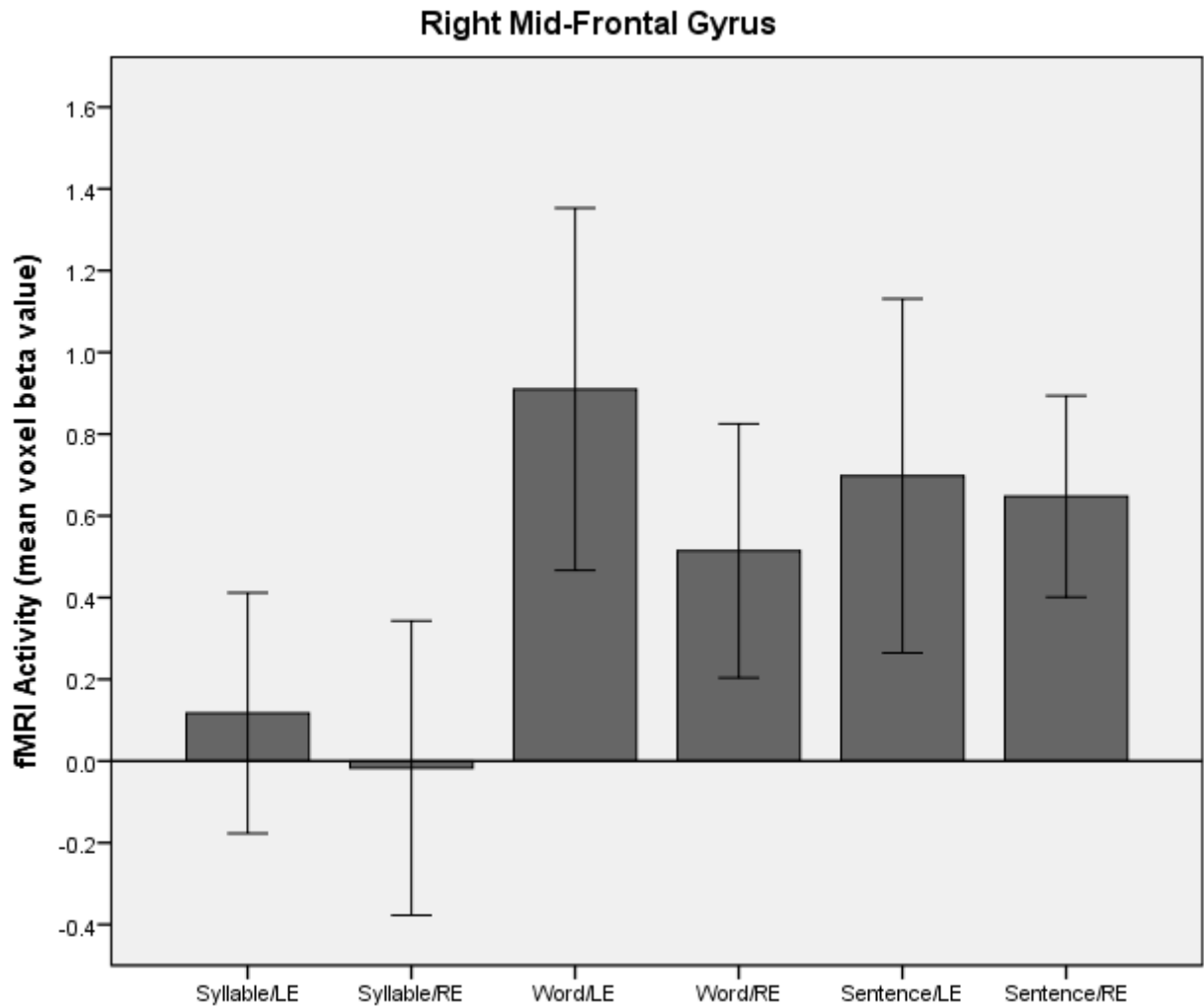




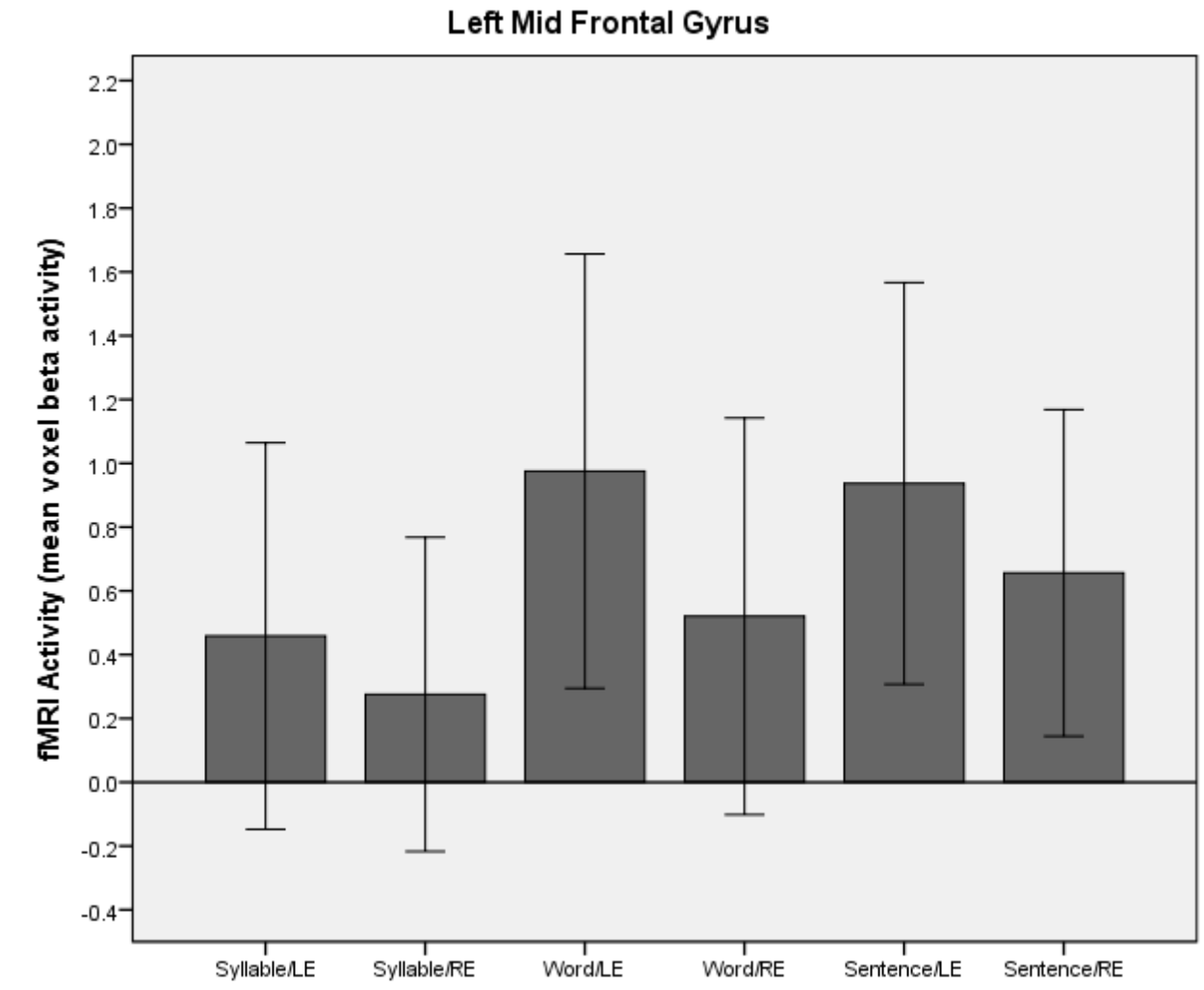
*Figure 7.* Words minus babble brain slices. Blue colors indicate voxel activity during dichotic word-length babble presentation that does not occur during dichotic word presentation. Orange colors indicate voxel activity during word presentation that does not occur during word-length babble presentation. Figure A depicts the activation that occurs when the word presented to the right ear was heard better. Figure B depicts the activation that occurs when the word presented to the left ear was heard better.



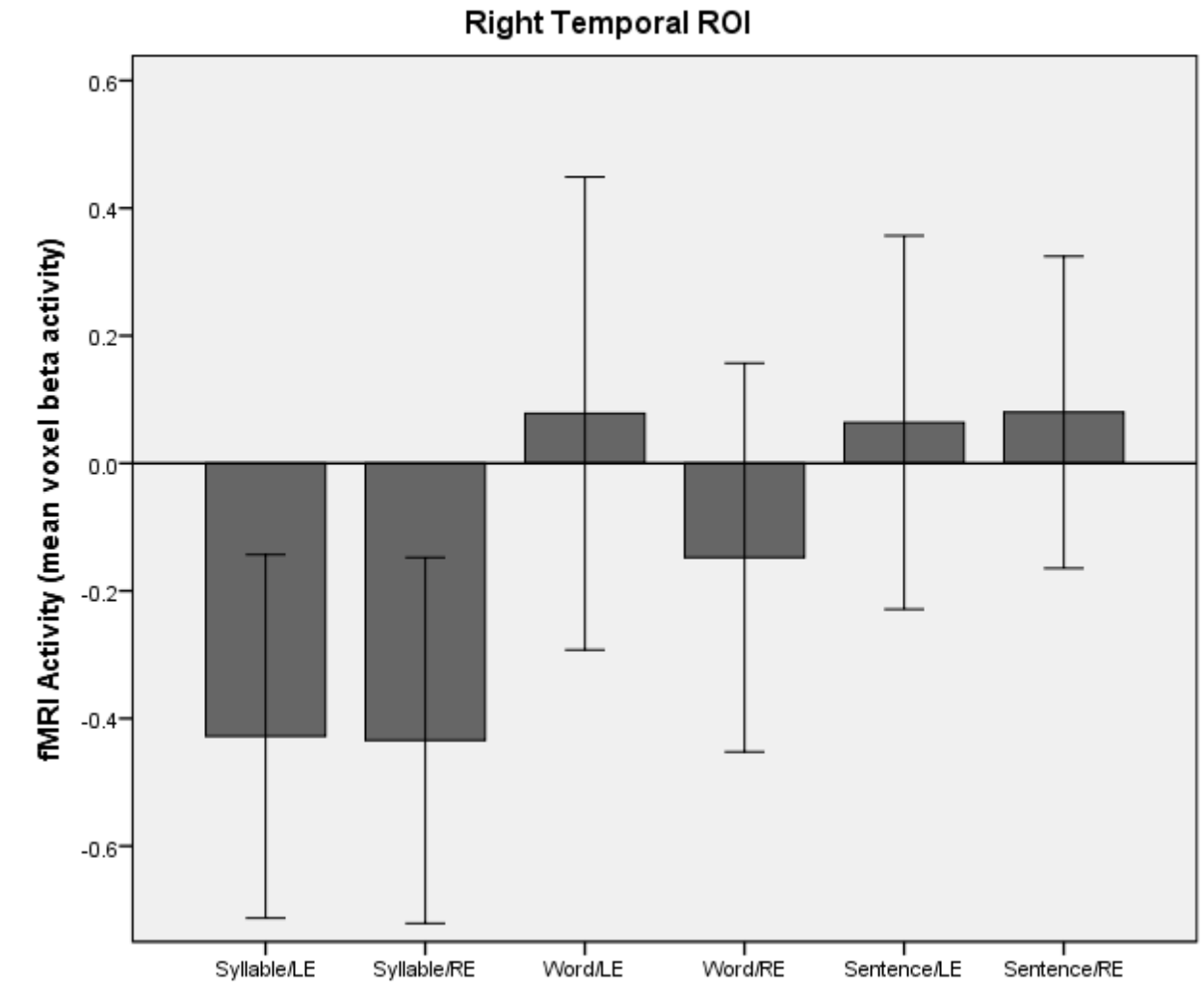
*Figure 8.* Sentences minus babble brain slices. Blue colors indicate voxel activity during sentence-length babble presentation that does not occur during dichotic word presentation. Orange colors indicate voxel activity during dichotic word presentation that does not occur during dichotic word-length babble presentation. Figure A depicts the activation that occurs when the word presented to the right ear was heard better. Figure B depicts the activation that occurs when the word presented to the LE was heard better.



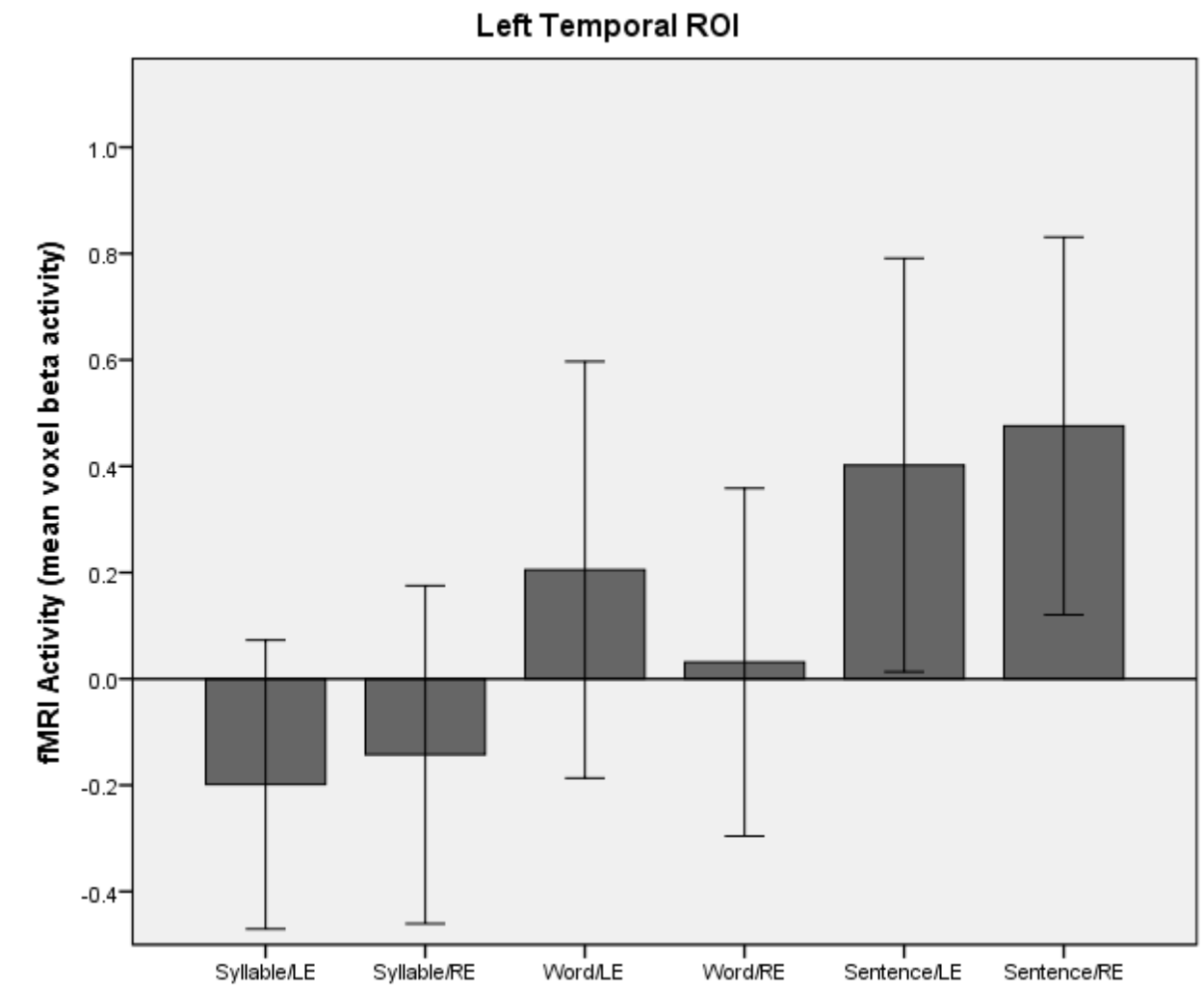
*Figure 9.* Linguistic processing: right mid-frontal gyrus. Beta activity in the right mid-frontal gyrus for babble conditions was subtracted from the corresponding beta activity for condition and ear preferences. Error bars represent the *SEM*.  $p \leq .05$ .



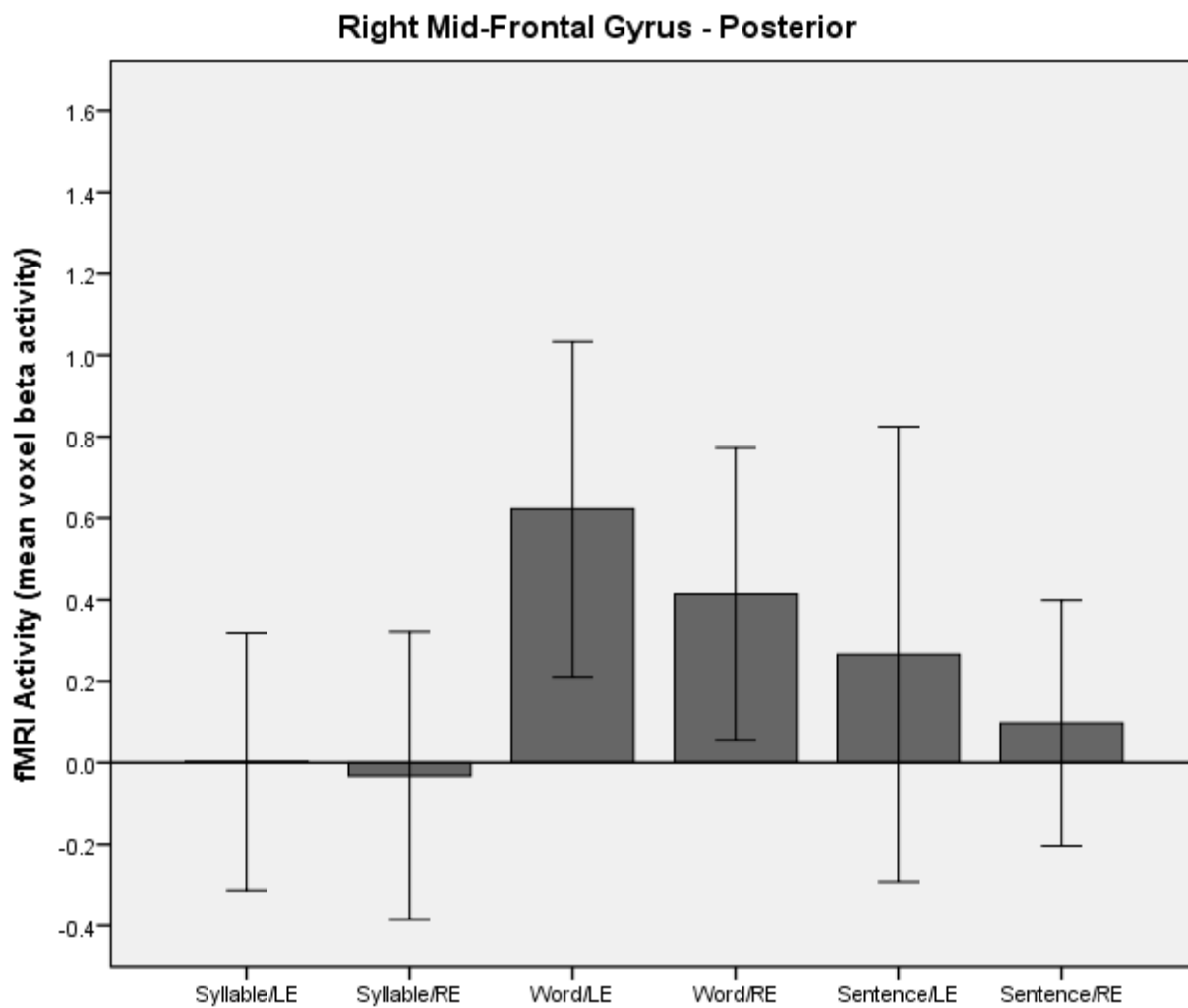
*Figure 10.* Linguistic processing: left mid-frontal gyrus. Beta activity in the left mid-frontal gyrus for babble conditions was subtracted from the corresponding beta activity for condition and ear preferences. Error bars represent the *SEM*.  $p \leq .05$ .



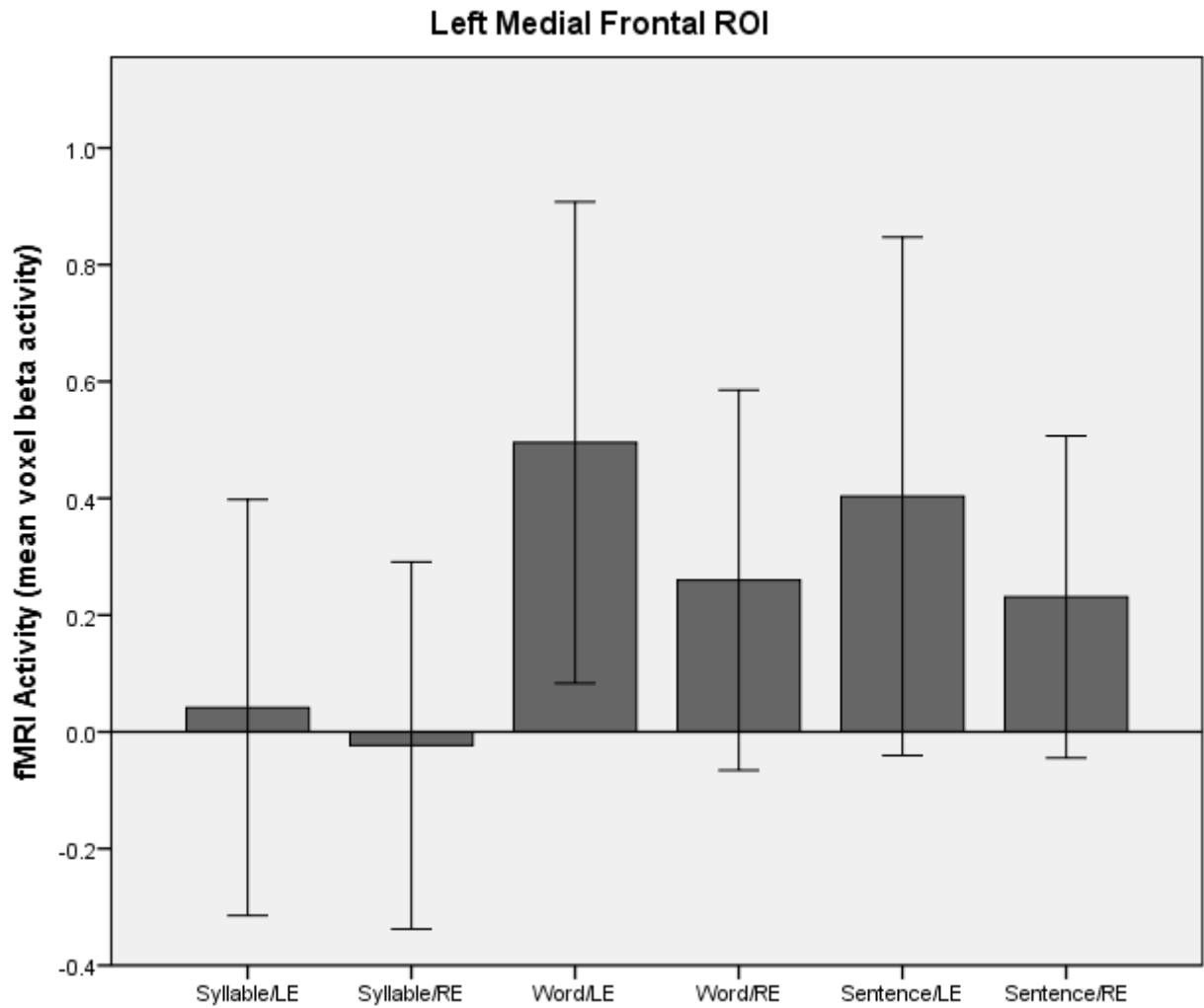
*Figure 11.* Linguistic processing: right temporal region. Beta activity in the right temporal regions for babble conditions was subtracted from the corresponding beta activity for condition. Error bars represent the *SEM*.  $p \leq 0.05$ .



*Figure 12.* Linguistic processing: left temporal region. Beta activity in the temporal region for babble conditions was subtracted from the corresponding beta activity for condition and ear preferences. Error bars represent the *SEM*.  $p \leq .05$ .

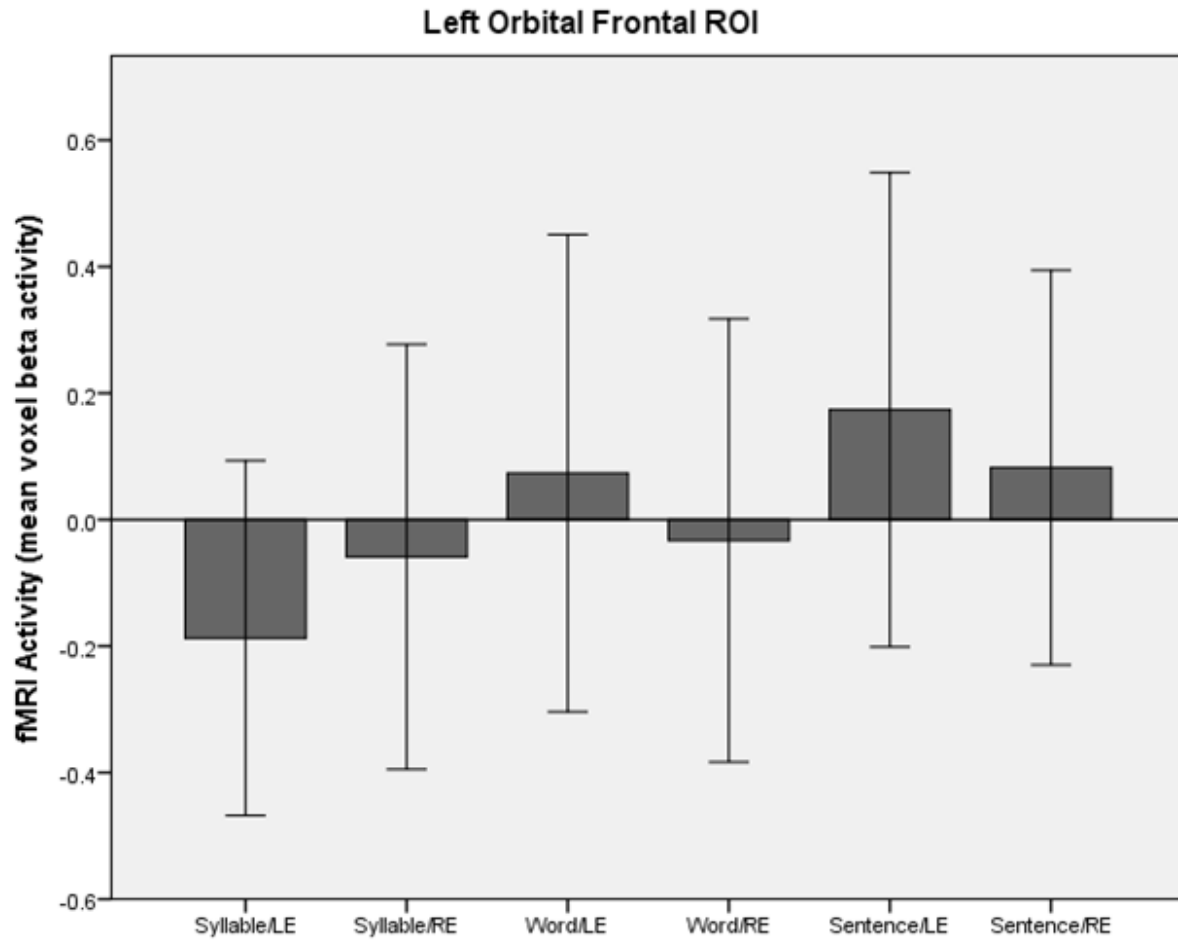


*Figure 13.* Linguistic processing: right mid-frontal gyrus - posterior. Beta activity in the right mid-frontal gyrus - posterior for babble conditions was subtracted from the corresponding beta activity for condition and ear preferences. Error bars represent the *SEM*.  $p \leq .05$ .

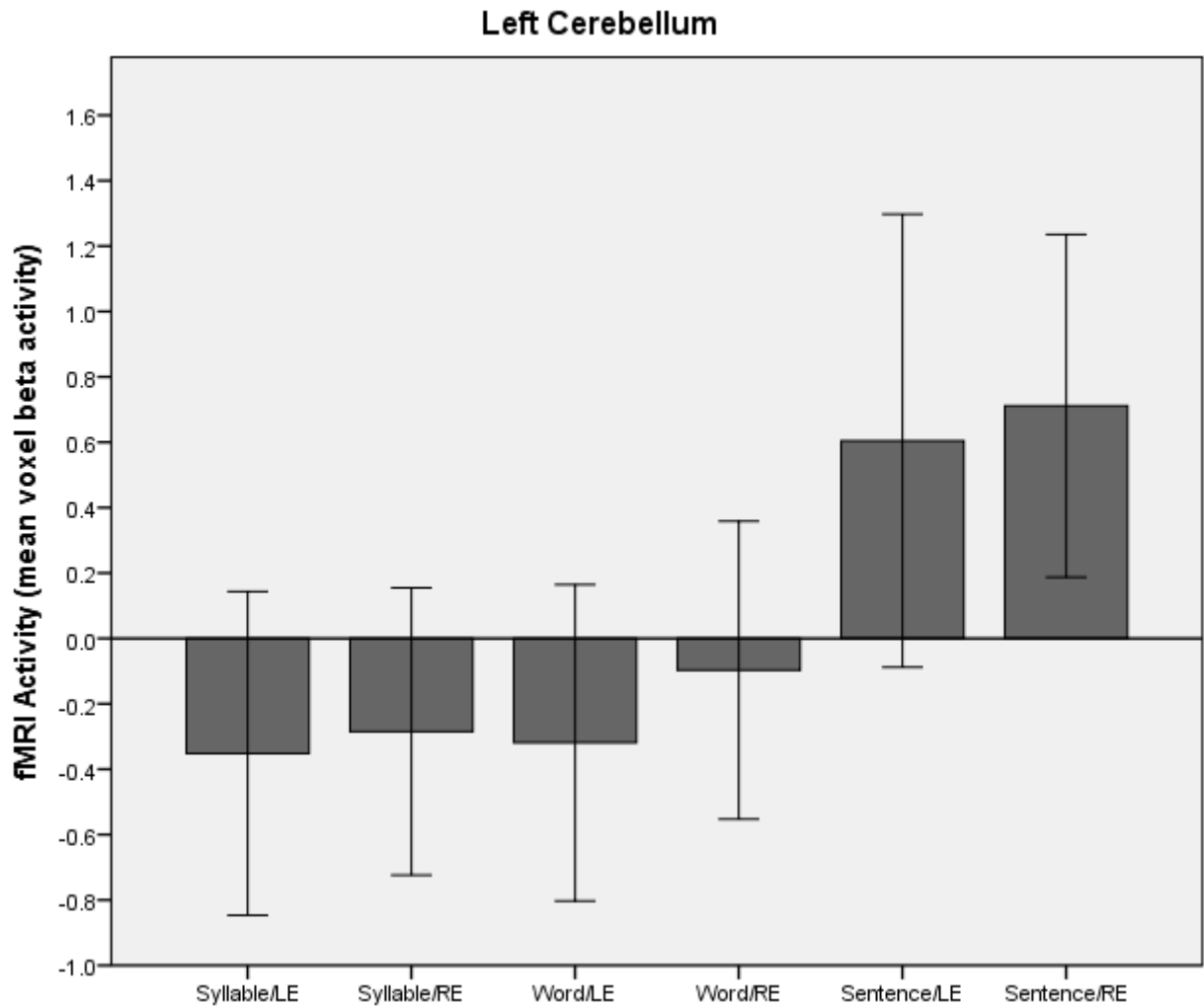


*Figure 14.* Linguistic processing: left medial frontal region. Beta activity in the left mid-frontal gyrus for babble conditions was subtracted from the corresponding beta activity for condition and ear preferences. Error bars represent the *SEM*.  $p \leq .05$ .





*Figure 15.* Linguistic processing: left orbital frontal region. Beta activity in the left mid-frontal gyrus for babble conditions was subtracted from the corresponding beta activity for condition and ear preferences. Error bars represent the *SEM*.  $p \leq .05$ .

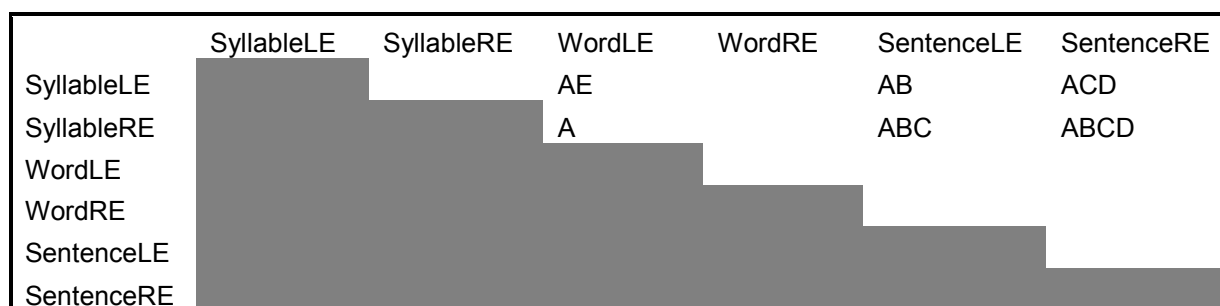


*Figure 16.* Linguistic processing: left cerebellum. Beta activity in the left mid-frontal gyrus for babble conditions was subtracted from the corresponding beta activity for condition and ear preferences. Error bars represent the *SEM*.  $p \leq .05$ .

Table 6

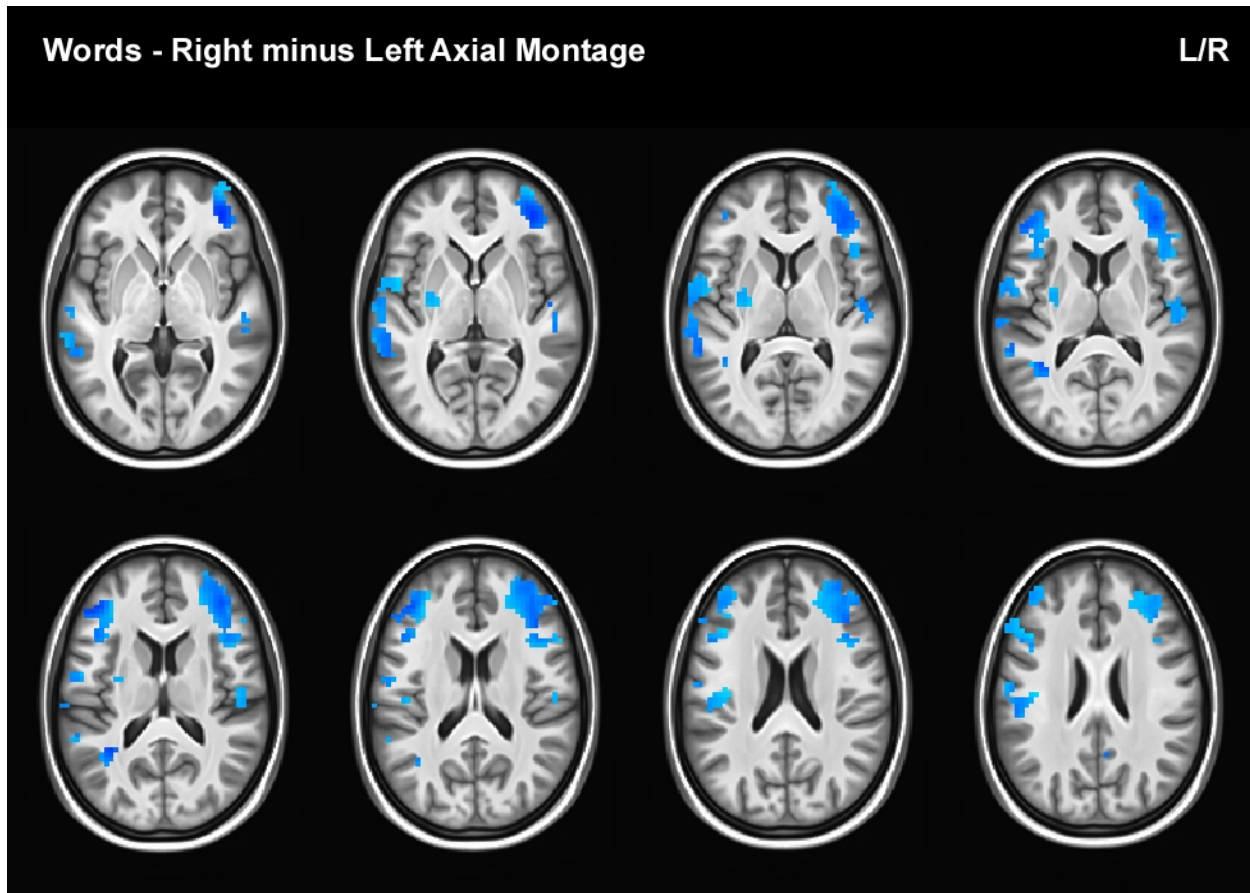
*ANOVA of the Regions of Interest for Main Effect of Linguistic Processing*

Region of Interest	Within Subjects			Between Subjects		
	<i>df, error</i>	<i>F</i>	<i>p</i>	<i>df, error</i>	<i>F</i>	<i>p</i>
Right Mid-Frontal Gyrus	5, 95	8.161	.000	1, 19	12.362	.002
Left Mid-Frontal Gyrus	5, 95	2.572	.032	1, 19	6.384	.021
Right Temporal	5, 95	4.719	.001	1, 19	1.483	.238
Left Temporal	5, 95	5.665	.000	1, 19	.913	.351
Right Mid-Frontal Gyrus-Posterior	5, 95	3.578	.005	1, 19	2.240	.151
Left Medial Frontal	5, 95	2.577	.031	1, 19	2.854	.107
Left Orbital Frontal	5, 95	.773	.571	1, 19	.006	.938
Left Cerebellum	5, 95	5.609	.000	1, 19	.058	.812



*Figure 17.* Post hoc analysis of the linguistic effect. Conditions that were identified as statistically different in mean voxel beta activation ( $p \leq .05$ ) for each of the regions of interest are coded by the letters A through E. A: Right mid-frontal gyrus; B: Right temporal; C: Left cerebellum; D: Left temporal; E: Right mid-frontal gyrus-posterior

**Right versus left ear preference.** The LE and RE preferences for each linguistic stimulus type were compared. There were no differences in the syllables and sentences conditions, but there was a significant difference in RE and LE preferences for words as can be seen in Figure 18. Left ear preferences were correlated to greater activation in multiple regions than was observed in the pattern of activation for RE preferences.



*Figure 18.* Words<sub>Right</sub> minus Words<sub>Left</sub> brain slices. Blue colors indicate voxel activity during left ear preferences that does not occur during right ear preference presentation. Orange colors would indicate voxel activity during right ear preference that does not occur during left ear preference.

### Discussion

The aim of the current study was to determine the effect of linguistic complexity on the behavioral and cortical activation patterns in DL. Poor validity and reliability of DL tasks are likely caused by poor control of the many variables that affect this measure. If contributing variables are identified and controlled, the clinical and experimental value of DL tasks will increase. The variable of linguistic complexity examined in the current study appears to affect both behavioral responses and the extent of neural activation, although variability of participant responses was high in all three linguistic conditions.

## **Behavioral Discussion**

Results from behavioral measures of overall ear advantage, laterality, and RT suggest that words are the best indicator of the REA in neuro-typical young adults. The prosodic processing involved in sentences, and the low linguistic complexity of syllables, reduces the ear advantage for the other stimuli such that words show the expected REA more closely than the other stimuli.

Behavioral results from the study identified percentages of REA for the different conditions (see Table 1). The syllables and sentences conditions did not meet expected values to demonstrate a REA, but the results from the words were significant with 75% of participants showing a REA. Because attention and other variables were not completely controlled, none of the conditions meet the expected left hemisphere/RE dominance of 95% in the population (Hermann, 1998), but the words were nearest the expected values.

Behavioral analysis of the RT also points to words as the stimulus condition that best reflects the left hemisphere's advantage in speech processing. The RT reflects the difficulty of the processing; in this study words were easiest to process followed by syllables, and sentences were the most difficult to process. A possible explanation for these findings that words have a stronger REA and a shorter RT is due to how well the stimuli match the specializations of the hemisphere. Sentences and words are both identified as linguistic material and are processed as such in the left hemisphere. There is more linguistic information to process in sentences than words, so sentences require longer processing time. Syllables do not have as much linguistic content as words, yet the syllables have a longer RT than words. A possible explanation is that the temporal aspects characteristic of speech cue the brain to analyze the signal for linguistic content, but there is no linguistic information in these stimuli. This processing for linguistic information that is not there requires additional time to process.

If these trends are reflected in future studies, clinicians and researchers should consider selecting diagnostic and research stimuli accordingly. Words elicit the strongest REA and require the least time to process. Based solely on behavioral measurements of RT and ear laterality, attention has the least effect on words.

### **Neuroimaging Discussion**

Significant differences between some conditions in linguistic processing were identified in neuroimaging results, but the trends that did not reach significance are informative and will be addressed as well. General trends and specific ROI differences in the neuroimaging data support the structural model of the REA and suggest possible uses of the types of stimuli. Dichotic words appear to provide measures of the expected REA most accurately, syllables have the least interference of brain regions associated with cognitive control of attention, and sentences demonstrated the strongest overall hemodynamic response of regions associated with cognitive control of attention and auditory processing.

The first observation was that bilaterally activated regions (the MFG and temporal regions) demonstrated greater mean beta voxel activity in the left hemisphere than in the right hemisphere. In occurrences of LE preference, contralateral pathways would direct the signal to the right hemisphere for processing, but the right hemisphere is not specialized in linguistic processing. The specialization of the left hemisphere resulted in increased recruitment of the left hemisphere in occurrences of LE preference to process data in the challenging DL tasks (Bellis, 2003; Eichele et al., 2005; Hiscock & Kinsbourne, 2011; Kimura, 1961b). When processing the three babble durations, activity was very similar between the hemispheres. It can be concluded, then, that the differences in activation in the linguistic processing analysis are the result of linguistic processing demands. Regardless of ear advantage, the left hemisphere was more

involved in processing than the right hemisphere. The specialization of the left hemisphere leads to the routing of linguistic signals from the right hemisphere to the left hemisphere.

Another trend across ROIs was that occurrences of LE preference demonstrated greater activity than occurrences of RE preference for all stimulus conditions suggesting increased processing demands. This finding is validated by another study that found forced left attention caused greater activation in the left prefrontal cortex, which has been associated with cognitive control of attention and decision making tasks, than it did in the right prefrontal cortex (Kompus et al., 2012). Forced left attention had greater activation in prefrontal areas than forced right or non-forced listening conditions (Kompus et al., 2012). This consistent activation difference combined with ear preference suggests that LE preference requires greater enlistment of cognitive attention than RE preference which corresponds to the structural model of processing. The contralateral pathway to the left hemisphere is specialized in processing linguistic material making the RE stimulus more salient (Eichele et al., 2005; Jerger & Martin, 2005; Kimura, 1961b; Ocklenburg et al., 2014). The physiological causes of the REA reduce the need for cognitive control of attention in occurrences of RE preference. Neuroimaging results suggest that occurrences of LEA required increased control of attention evident in increased MFG activity (Bayazit et al., 2009; Farah, Schmithorst, Keith, & Holland, 2014; Jemel, Oades, Oknina, Achenbach, & Röpcke, 2003). When increased attention was appropriated to identify the signal to the LE, greater activity in the left temporal lobe was seen as well. In situations of LE preference, the contralateral pathway directs the signal to the right hemisphere for processing, but more processing power is required, so the signal is sent to the left hemisphere for linguistic processing (Hermann, 1998; Kimura, 1961a).

In the investigation of trends within ROIs, the statistically significant differences observed in post hoc analysis identified the extremes of the pattern of increasing activity with increasing linguistic complexity. Inclusion of the trends that did not reach significance provides a more complete understanding of the processing of linguistic complexity. The stimulus conditions each had different levels of activation in the ROIs and can be used to interpret DL results to interpret the function of the brain.

Syllables demonstrated the least activation in the various temporal and frontal ROIs suggesting that they are lowest in the hierarchy of linguistic complexity and also lowest in the required cognitive control of attention. Assuming that the involvement of frontal regions demonstrates increased attention, syllables are the stimulus most accurate in distinguishing between the influence of attention and linguistic processing, but there is minimal linguistic processing required. Syllables had less temporal lobe voxel activity than syllable length babble, which is likely due to the spectral complexity of the syllable-length babble (Belin et al., 1998; Eichele et al., 2005). Less linguistic processing demands reduce the effectiveness of syllables to identify the REA. Dichotic syllables appear to be a fairly good indicator of ear advantage without confounding the effect of attention.

Dichotic sentences caused the greatest activation in the temporal and frontal ROIs, so these stimuli have the greatest interference of attention and the greatest linguistic complexity. In a review of literature on the REA, Hiscock and Kinsbourne (2011) emphasized that the structural model alone cannot account for the variability of the REA; attention and other variables cause the variability in ear advantage. When performing tests with sentences, greater care should be given to controlling attention than may be necessary with the other two conditions. Because of the level of activation in the temporal regions which are strongly associated to auditory



processing, sentences may be more useful in analyzing linguistic processing if attention is more controlled in the experimental design.

Dichotic words appeared to be the most promising stimulus condition to differentiate between linguistic processing and attention. Dichotic words showed a significant REA unlike the other stimuli, had the shortest RT, had significant differences between ear preferences in frontal regions, and showed differences in temporal region activity. The REA and RT results for words were discussed in the behavioral results; the neuroimaging results support the finding that words best reflect the expected REA.

### **Conclusions**

Additional research on the effect of linguistic complexity on the REA should be pursued. This is the first study that has examined the effect of this variable, and results are promising. Studying all variables that affect the REA will advance the understanding of DL tasks in clinical and experimental use.

### **Summary of Findings**

Although all three stimulus conditions demonstrated a trend for the REA, behavioral and neuroimaging results suggest that dichotic words most accurately reflect the REA. The overall ear advantage was closest to population values, the RT to respond to words was fastest, ROIs associated with attention had minimal involvement in occurrences of RE preference, and temporal regions were more active in the left hemisphere than the right hemisphere. Dichotic words have enough linguistic complexity to activate the REA, not enough prosodic cues to require right hemisphere involvement, and minimal involvement of the MFG for RE preference, but the most involvement of the MFT for LE preference. Syllables and sentences provide additional information on the contribution of attention in processing and a combination of all

three conditions in a diagnostic or research setting would allow greater precision in differentiating the REA from attention when analyzing results.

The many variables that affect the laterality of ear advantage are still under investigation. Previously identified and researched variables include attention and neuromaturation. The results from this study suggest that linguistic complexity also affect ear advantage. Words appear to have enough linguistic complexity and little enough interference of other variables to be the most predictive of population values of left hemisphere dominance.

### **Limitations and Further Research**

This study has provided initial findings on the effect of levels of linguistic processing on behavioral and neurological responses. Limitations to this study include the impact of attention, threshold differences between ears within the same participant, possible inequalities in words and sentences, and the effect of the fMRI noise on the behavioral and neurological response. Future research should examine the effect of linguistic complexity on different age groups.

Controlling attention with greater consistency within and between participants would reduce the confounding of the two variables. Multiple participants reported that they noticed during the study that they could very easily alter their attention to one ear or the other. Reducing the random alterations in attention would have given the results greater validity.

Participants' specific hearing thresholds were not tested, and could have skewed results toward one ear or the other. Greater sensitivity to an ear will increase that ear's advantage; this study was aiming to analyze central auditory pathways but may not reflect the central pathway because the peripheral hearing was not tested beyond meeting a threshold of at least 20 dB HL.

A final limiting factor of this study is that the background fMRI noise may have changed the REA observed. A previous study found that the REA is decreased when there is background

noise during the DL task (Sequeira, Specht, Hamalainen, & Hugdahl, 2008). Roup (2011) reported that a control young adult group that listened in noise and in quiet did not have a change in REA, so the effect of noise is likely not very strong.

Further research in this area should examine the interaction of age and linguistic complexity on the REA. It is known that the REA is stronger in children and older adults, but the effect of linguistic complexity on these populations has not been studied and would add to the understanding of both the REA in general as well as the effects of aging.

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## Appendix A

### Informed Consent to Act as a Human Research Subject

David L. McPherson, Ph.D.  
Communication Science and Disorders  
Brigham Young University  
(801) 422-6458

Name of Participant: \_\_\_\_\_

#### **Purpose of Study**

This research is being conducted by Dr. David McPherson, Dr. Brock Kirwan, and Elizabeth Hyatt at Brigham Young University to identify differences in neural activation between the two sides of the brain in response to a variety of stimuli. This will be accomplished by measuring brain activity while listening to noise syllables, words, and sentences presented and reporting what information is heard best. Before you decide to participate in the study, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether you want to volunteer or take part in this study. You were invited to participate because you indicated your interest and that you are a good match for the group that we would like to study. We anticipate about 10 people will participate in this study.

#### **Procedures**

This study will involve one to three visits, which will last approximately an hour and 45 minutes to 3 hours in total. This will occur at the BYU MRI research facility and in the TLRB. If you agree to be in this study, the following will happen:

- You will fill out a magnetic resonance imaging (MRI) screening questionnaire which will determine if it is safe for you to undergo MRI scanning.
- Next, an MRI will be done of your head. MRI detects the magnetic properties of fluids and tissues and allows researchers to obtain high resolution images of your brain. This will involve your lying quietly inside the center of a large doughnut-shaped magnet for up to an hour. Your head will be positioned with cushions to keep your head in the proper position within the scanner. While in the scanner, you will complete a computerized task during which you will be presented with sounds and words to both ears simultaneously. You will be asked to respond by pressing buttons on a hand-held response box to indicate which sound you hear best (first, more clearly).

#### **Risks/Discomforts**

Participation in this study may involve some additional risks or discomforts. There are no known adverse effects from exposure to magnetic fields (MRI). However, if you are pregnant or believe

you may be pregnant, you should not take part in this research. The MRI may be harmful to an unborn baby. The scanner makes a loud banging noise while it is taking pictures. You will be given a set of earplugs to help with the noise. Some people undergoing this procedure become acutely anxious, or get claustrophobic. If this happens to you, you can tell us and we will stop the procedure immediately. You may experience some muscular aches and fatigue from lying still on your back in a confined space during the imaging. If you have any metal clips or plates in your body, or a pacemaker, you should tell the investigator about it immediately. MRI may not be appropriate under some of the following conditions: a cardiac pacemaker; metal fragments in eyes, skin, body; heart valve replacement; brain clips; venous umbrella; being a metal worker or welder; aneurysm surger; intracranial bypass; renal or aortic clips; prosthetic devices such as middle ear, eye, joint, or penile implants; joint replacements; hearing aid; neuro-stimulator; insulin pump; IUD; shunts/stents; metal mesh/coil implants; metal plates, pins, screws, or wires or any other metal implant; permanent eye liner or eyebrows.

### **Benefits**

There will be no direct benefits to you from these procedures. However, your participation may contribute to the scientific community's understanding on how language is processed in the brain which will be beneficial to professionals in the corresponding field.

### **Incidental Findings**

The MRI scans being performed are for research purposes and are not of clinical quality. If the research team observes any abnormalities on your scans, they will be forwarded to be read by a qualified medical professional, who will contact you with any possible concerns. It will be your responsibility to arrange any clinical scans with your primary care physician.

### **Confidentiality**

All information obtained from testing is confidential and is protected under the laws governing privacy. All identifying references will be removed and replaced by control numbers. Data collected in this study will be stored in a secured area accessible only to personnel associated with the study. Data will be reported without individual identifying information.

### **Compensation**

You will be given \$20 compensation at the completion of this portion of the study. If you do not complete the study session because you ask to be let out of the scanner before the study is complete or because the researcher terminates the study, you will be compensated \$10 for your participation.

### **Participation**

Participation in this research study is voluntary. You have the right to withdraw at any time or refuse to participate entirely without affecting your standing with the University.

### **Questions about the Research**

If there are any further questions or concerns regarding this study, you may ask the investigator or contact David McPherson, Ph.D., Communication Science and Disorders, at (801) 422-6458; Taylor Building Room 129, Brigham Young University, Provo, Utah 84602; e-mail: david\_mcpherson@byu.edu.

**Questions about your Rights as a Research Participant**

If you have questions regarding your rights as a research participant, you may contact the BYU IRB Administrator at (801) 422-1461; A-285 ASB, Brigham Young University, Provo, UT 84602; e-mail: [irb@byu.edu](mailto:irb@byu.edu).

**Statement of consent**

I have read and understand the above consent and desire of my own free will to participate in this study.

Printed Name: \_\_\_\_\_

Signature: \_\_\_\_\_

Date: \_\_\_\_\_

**Appendix B****Preliminary Questionnaire**

David L. McPherson, Ph.D.  
Communication Science and Disorders  
Brigham Young University  
(801) 422-6458

Name of Participant: \_\_\_\_\_

Phone number: \_\_\_\_\_

Email: \_\_\_\_\_

1. Gender

Male  Female

2. Age

\_\_\_\_\_

3. Right or left hand?

Right  Left

4. Do you currently have a documented hearing loss in one or both ears?

Yes  No

5. Do you have a history of neurological deficits/disorders (e.g. epilepsy, stroke)?

Yes  No

6. Have you ever been diagnosed with psychological deficits/disorders (e.g. anxiety, depression)?

Yes  No

I certify that the information given above is correct.

Printed Name: \_\_\_\_\_

Signature: \_\_\_\_\_

Date: \_\_\_\_\_

## Appendix C

### Annotated Bibliography

Bayazit, O., Öniz, A., Hahn, C., Güntürkün, O., & Özgören, M. (2009). Dichotic listening revisited: Trial-by-trial ERP analyses reveal intra- and interhemispheric differences. *Neuropsychologia*, 47, 536-545. doi: 10.1016/j.neuropsychologia.2008.10.002

*Objective:* Results from dichotic listening tasks usually show a REA with some responses in which the LE signal is responded to. The goal of the study is to study the systems that change the laterality during the dichotic listening task. *Study Sample:* Sixty participants were included in the study with a subgroup for the EEG participants of 20. All were classified according to handedness and brain laterality in dichotic listening. No history of neurologic or psychological illnesses or hearing loss was reported. *Method:* Participants were scanned with an EEG while they listened to dichotic and diotic syllables. Electrodes were used to determine the region with the greatest electrode activation. Left ear and RE responses in the DL condition and responses in the diotic condition were evaluated individually. *Results:* A REA was observed in both left-handed and right-handed participants. Responses to the LE and RE in the DL condition and responses in the diotic condition all showed a higher N1P2 event-related potential at central locations rather than temporal, frontal, or parietal. Laterality at this point in processing favored the right hemisphere. N2P3 values had highest amplitudes in the left hemisphere, but did not have significant differences between the regions. A comparison of late negativity event related potentials (ERP) showed higher frontal amplitudes for dichotic stimuli than for diotic. Specifically, late negativity responses were greatest in frontal lobe locations and further analysis showed that the right frontal lobe was more activated than the left. The latency of event-related potentials was longest for presentations resulting in a LE response with processing a RE response next and diotically presented sounds being processed the most rapidly. *Conclusions:* The high level of electrode activation of the frontal lobe during dichotic presentation suggests the inclusion of top-down processing for the processing of dichotic stimuli. Future studies could show more accurately the regions of activation with a combined fMRI and EEG design. *Relevance to current work:* Analysis of individual responses showed the same pattern of activation. This suggests that the brain processes auditory stimuli presented to the two ears in similar ways but more quickly in the left hemisphere resulting in an overall REA. More dense fiber tracts may be the cause of this difference. *Level of Evidence:* Level IIIa

Bellis, T. J. (2003). *Assessment and management of central auditory processing disorders in the educational setting: From science to practice (2nd ed.)*. Clifton Park, NY: Delmar Learning.

Bellis explains the general functioning of the central auditory system, models of the REA, and assessment methods of auditory procession disorder (APD). There are a few key components of the neural system integral to understanding the structural model of the REA. In 96-98.3% of the population, the left hemisphere is specialized in processing linguistic components while the right hemisphere is specialized in processing non-linguistic stimuli. The author points out that there are regions of the left hemisphere, the planum temporale and Heschl's gyrus for example, that are larger than their counterparts in the right hemisphere. These structural asymmetries may be a part of the cause of the left-hemisphere's advantage for linguistic processing. In order to be

processed for both components, the information must traverse the corpus callosum. This makes that structure key in processing stimuli originally presented to the right hemisphere for linguistic properties. The central auditory system is frequently studied using the dichotic listening test. Kimura was the first to use the test for central auditory assessment. The author found that the stimulus from the RE is processed faster and with greater accuracy than the stimulus presented to the LE. To explain the phenomenon, the structural model was developed. This explanation suggests that the REA in auditory processing is caused by the left hemisphere's specialization in linguistic processing, the stronger and more numerous contralateral pathways of the central auditory pathway, and the inhibition of the ipsilateral pathway in dichotic stimulation. These components acting together provide a processing advantage to the stimulus presented at the RE. Support for the theory has been provided in a number of types of studies. When the corpus callosum is severed, the listener in dichotic stimulation is unable to report the stimulus at the LE. Because the connection between hemispheres is broken, the information sent to the right hemisphere cannot be sent for linguistic processing at the left hemisphere. Electrophysiological studies have shown that there is greater activation in the left hemisphere in dichotic phonemic stimulation and in the right hemisphere when music is presented dichotically. Evidence from a sensorineural hearing loss study showed that as the test stimuli became more difficult (digits, concrete non-words, and CV nonsense syllables), the REA increased. More linguistic processing was required leading to greater demand for the left hemisphere. The RE has a more direct pathway so the more complex stimuli coming from the right hemisphere could not be processed as well. Other studies reviewed in the text explain other characteristics of the auditory pathway learned through DL tasks. Myelination of the auditory system occurs with age and the effects of that are seen in the REA of typically developing children. As children age and the myelination of the auditory system increases, the REA decreases until it reaches adult levels at the age of 11. When children are presented with dichotic sentences, they have a 15% REA at the age of 7 years which decreases to 2% by age 11. The myelination that occurs at the corpus callosum as the child ages likely causes the decrease in REA. Even with all of this evidence, new research continues to find results that show that the simple encoding of stimuli in a strict structural model interpretation is insufficient to explain the manner that auditory stimuli are processed.

Cherry, E. C. (1953). Some experiments on the recognition of speech, with one and two ears. *The Journal of the Acoustical Society of America*, 25, 975-979.

*Objective:* People are able to determine the content of messages that are presented simultaneously. The author studies different situations of multiple signals to observe how the auditory system copes with difficult auditory stimuli. *Method:* The author reviews studies already completed on the participants. All recordings were created with the same speaker's voice. *Results:* When a stimulus is composed of two separate signals the listener required multiple repetitions of the stimulus to understand the messages. In another method, stimuli were presented to each ear, and the listener was asked to report the stimulus from one ear or another. This task was much easier for the participant to complete. It was noted that the participant could not report the stimulus from the unattended ear. *Relevance to current study:* The article provides background to the research question. *Level of evidence:* Level I

Eichele, T., Nordby, H., Rimol, L. M., & Hugdahl, K. (2005). Asymmetry of evoked potential latency to speech sounds predicts the ear advantage in dichotic listening. *Cognitive Brain Research*, 24, 405-412. doi: 10.1016/j.cogbrainres.2005.02.017

*Objective:* Many studies have shown a REA when stimuli are words, but other studies have shown that brain lateralization may be due to factors other than cognition of speech; there is evidence that the right hemisphere analyzes spectral content while the left hemisphere analyzes rapidly changing formant signals. Studying hemisphere activation with syllable stimuli will reveal more on the specializations of the hemispheres. *Study Sample:* The study included 12 participants with normal hearing. *Method:* Stimuli consisted of 6 CV syllables: /da/, /ta/, /ga/, /ka/, /ba/, and /pa/ presented dichotically. The syllables were presented in 3 blocks of 90 pairs for a total of 270 dichotic syllable presentations. Event related potentials were collected from electrodes located on the scalp above the left temporal lobe, the longitudinal fissure, and right temporal lobe. *Results:* The participants had more correct responses for the RE than the LE indicating a REA, but the reaction time was not significantly different for RE, LE, or incorrect responses. Amplitude and latency measures at N1 were analyzed at the regions of interest and showed that the central region amplitude was greater than either of the temporal lobes. A comparison of the electrode activation at the hemispheres for N1 showed that the right hemisphere was 15 ms delayed compared to the left hemisphere. *Conclusions:* The latency of the N1 measurement for the hemispheres corresponds to the degree of RE advantage that was observed in the behavioral results. The authors hypothesize that increased myelination and size of cortical columns in the left hemisphere are the source of the greater temporal resolution and conduction of neural signals as seen by the N1 latency differences and behavioral responses. *Relevance to current work:* The results show that the REA is at least partially due to a time advantage in processing which is often caused by density and myelination of white matter fiber tracts. *Level of Evidence:* Level IIIa

Farah, R., Schmithorst, V. J., Keith, R. W., & Holland, S. K. (2014). Altered white matter microstructure underlies listening difficulties in children suspected of auditory processing disorders: A DTI study. *Brain and Behavior, 4*, 531-543. doi:10.1002/brb3.237

*Objective:* Auditory processing disorders are difficult to diagnose because of the interaction with other co-occurring disorders. Behavioral measures and reports along with dichotic listening tests are the main measures in the diagnosis of APD. Behavioral measures have low reliability due to a similar profile between APD and other disorders. Dichotic listening is not a reliable measure as many studies have shown. The authors use DTI to observe the rate of firing and density of white fibers in frontal white matter. *Study Sample:* Information from 24 children was included. Ten male and two female children ages 7-14 (M = 10.9) with complaints of APD and a LEA and 12 matched peers according to age, sex, and handedness (all were right-handed) participated in the study. Parents of children in the first group reported that their child had normal hearing but difficulty following oral directions, listening to directions, made frequent requests for clarification of oral material, etc. All participants had normal hearing thresholds <20 dB HL. *Method:* Dichotic, monosyllabic words were presented at 50 dB HL to determine ear advantage. Diffuser tensor echo planar images were collected during the study of all participants. Twenty-four of the 34 datasets were analyzed due to gross artifacts in the other participants. Fractional anisotropy, mean diffusivity, axial diffusivity, and radial diffusivity maps were collected and analyzed. Voxels were only included for analysis if fractional anisotropy was greater than 0.25 and white matter probability of >0.9 in clusters of 100 voxels or more. *Results:* Children with a LEA showed reduced fractional anisotropy in white matter of the frontal region—specifically the right inferior frontal gyrus (BA47), the left middle frontal gyrus (BA9 and BA10), left anterior cingulate (BA32). Analysis of mean diffusivity revealed that the LEA group had an increase of

mean diffusivity close to the transverse temporal gyrus, but these areas did not correspond to the fractional anisotropy regions that were statistically different. Radial and axial diffusivity were further analyzed in regions that showed great fractional anisotropy and mean diffusivity differences. The LEA group had a significant decrease in fractional anisotropy paired with a significant increase in right hemisphere dominance in almost all clusters. In the left medial frontal gyrus and the left anterior cingulate, a decrease in fractional anisotropy was paired with an increase in axial diffusivity but no change in the radial diffusivity. In all other regions in which fractional anisotropy decreased significantly, axial diffusivity also decreased.

*Conclusions:* The main differences between the REA and LEA groups was that the LEA group showed decreased frontal lobe fractional anisotropy. Decreased fractional anisotropy suggests reduced myelination. The regions this lower fractional anisotropy was found appear to control attention and cognitive control. It appears from the results of the study that structural connectivity differences are correlated to APD. *Relevance to current study:* This article reports findings from one of the few studies utilizing DTI and DL. Differences between the white matter connections were observed between the LEA and REA group. It is the differences in frontal lobe white matter that differentiated the data from the LEA and the REA groups. The ability to attend to auditory stimuli is, in part, caused by structure. *Level of evidence:* Level IIIa

Hermann, G. S. (1998). Handedness, footedness, and language laterality: Evidence from Wada testing. *Laterality*, 3, 323-330. doi:10.1080/135765098397188

*Objective:* The commonly used DL task has low reliability. The development of the sodium amytal test allows for more accurate measures of the relationship handedness, footedness, and language laterality. The current study compares the results on a laterality test which includes both handedness and footedness to results on the sodium amytal test. *Study Sample:* 37 individuals who were candidates for temporal lobectomy participated. Ages ranged from 16-58 years. Participants were excluded if IQ scores were lower than 70 or if the patient already had cerebral lesions. 19 were right handed and footed, 6 were right footed and left handed, 11 were left footed and handed, and 1 was left footed and right handed. Twenty-nine participants were left speech dominant, 1 participant had mixed hemisphere language dominance, and 7 were right hemisphere language dominant. *Method:* Participants participated in a lateral dominance test in which handedness and footedness were assessed. Results were compared to a sodium amytal test. *Results:* A regression analysis found that there was a .64 probability that a left footed and left handed would have right hemisphere dominance for speech, .58 probability that a left footed person would have language lateralized to the left hemisphere, and a .41 probability that a left handed person would be right hemisphere language dominant. The study found that 95% of right handed participants and 59% of left handed participants were left hemisphere dominant for speech. This was compared to a similar study by Rasmussen and Miller which found that 96% of right handed participants were left hemisphere dominant while 70% of left handers were left hemisphere, 15% were right hemisphere, and 15% were mixed speech dominant. *Conclusions:* Handedness and footedness are both predictive of speech dominance; footedness is the strongest prediction of speech dominance. *Relevance to the current study:* The study shows that handedness and footedness are related to laterality of language. The current study uses right-handedness as inclusion criteria because approximately 95% of right handed individuals are left hemisphere language dominant according to this study. *Level of Evidence:* Level IIIa



Hiscock, M., & Kinsbourne, M. (2011). Attention and the right-ear advantage: What is the connection? *Brain and Cognition*, 76, 263-275. doi: 10.1016/j.bandc.2011.03.016

*Objective:* Classic dichotic listening test studies have yielded two schools of thought in explanation to the REA—Kimura’s structural model and Kinsbourne’s attentional model. Both have support in the literature; this study attempts to reconcile the two theories. *Method:* The authors reviewed the literature of dichotic listening studies to understand the connection of the REA and attention. *Results:* A review of many studies showed that there is much more influencing ear advantage than simply a structural advantage as Kimura suggested. Studies that support Kimura’s structural model include studies of individuals with a severed corpus callosum; these individuals exhibit the inability to identify stimuli presented to the LE in a dichotic listening situation yet have the ability preserved in monotic left presentation. This shows that the fibers do cross hemispheres and that the right hemisphere has the more direct route. A similar model, Ivry and Robertson’s double filtering by frequency model, also supports Kimura’s structural advantage theory. They found that higher frequency stimuli are directed to the left hemisphere and lower frequencies to the right hemisphere. This suggests that high frequency phonemic stimuli are automatically directed to the left hemisphere due to a structural advantage in processing that material. The structural model is called into question because the test-retest reliability and concurrent validity measures for the DL test are low; ear-advantage switches for individuals between dichotic listening tests and the expected percentage of left-hemisphere dominant participants is significantly lower than what has been seen in clinical measures. Attentional models have attempted to compensate for the short-comings of the structural model. In this model, it is claimed that the left hemisphere is more activated at the onset of testing due to verbal input and a verbal mental set. Thus the brain is already biased to the RE. Studies have shown that priming to one side or the other, directed attention, concurrent visual presentation, response type used, body movements and individual differences between participants alter the REA to neutral and sometimes LEA. The altered methods and the different results suggest that the structural model does not fully explain the phenomenon of the REA. *Conclusions:* A review of literature both supporting and opposing the structural model resulted in the conclusion that the structural model alone is not fully correct. A possible explanation suggested is that the attentional model overlays the structural model to answer why the REA is usually present but can be overcome by attention, stimulus characteristics, and priming. *Relevance to current study:* The current study looks for other variables that cause the low reliability and poor validity of the REA. *Level of Evidence:* Level I

Hugdahl, K., Rund, B. j. R., Lund, A., Asbjørnsen, A., Egeland, J., Landrø, N. I., . . . Sundet, K. (2003). Attentional and executive dysfunctions in schizophrenia and depression: Evidence from dichotic listening performance. *Biological Psychiatry*, 53, 609-616. doi: 10.1016/S0006-3223(02)01598-6

*Objective:* Patients suffering from schizophrenia or depression frequently have attention and executive functioning deficits in the auditory modality. A hypothesis for this with some support in the literature is that the prefrontal regions have reduced activation. Imaging studies have also shown that the planum temporale and white fiber tracts are abnormal in schizophrenic patients. The authors used a CV dichotic listening paradigm with conditions of non-directed, forced right, and forced left attention conditions to test attention and executive functioning. If the participants have attention deficits, they will not have a strong REA in a forced RE attention condition. If the

participants have executive functioning deficits, they will demonstrate difficulties overcoming the structural REA and identifying stimuli presented to the LE. *Study sample*: Participants included 51 individuals diagnosed with schizophrenia, 49 diagnosed with depression, and 49 control participants. Participants with a history of meningitis, brain tumors, drug or alcohol abuse, seizures, or hemorrhages were excluded from the study. Ages of the participants ranged from 19 to 51 years. *Method*: Participants were presented with a dichotic listening task through headphones with the test administrator wearing a second set of headphones to hear as the stimuli were presented. The stimuli were the CV syllables /ba/, /da/, /ga/, /pa/, /ta/, and /ka/ combined to form 30 dichotic pairs and 6 diotic pairs. The stimuli were randomized and presented to the participants once in each of three conditions: non-directed attention, forced right attention, and forced left attention. In the control condition the participant reported the syllable heard best, and in the directed attention conditions the participant was told to only report the syllable of the specified ear. *Results*: Analysis showed an overall REA. All three groups demonstrated a REA in the control and forced right conditions. During the forced left condition, the schizophrenic group continued to have a REA while the other two groups showed a LEA. *Conclusions*: The authors suggest that attending to the LE stimulus requires a different cognitive process than attending to the RE; this ability is impaired in the schizophrenic population which is why the group continued to show a REA while the other two groups did not. *Relevance to current study*: Attention has a strong effect on ear advantage and must be controlled for. *Level of evidence*: Level IIIa

Iliadou, V., Kaprinis, S., Kandyliis, D., & Kaprinis, G. S. (2010). Hemispheric laterality assessment with dichotic digits testing in dyslexia and auditory processing disorder. *International Journal of Audiology, 49*, 247-252. doi:10.3109/14992020903397820

*Objective*: Individuals with various neurological abnormalities demonstrated abnormal DL results. Studies that compare DL scores in APD, dyslexia, and neurotypical children are present, but there are not studies comparing the adults in the groups. *Study sample*: 120 adults were included in the study sample: 30 with dyslexia, 30 with APD, 30 with both dyslexia and APD, and 30 neurotypical participants. Exclusion criteria included higher order cognitive deficits, attention and memory deficits, low IQ, hearing thresholds  $\leq 20$  dB, and other neurological or psychological disorders. *Method*: A handedness test was administered and groups included consistent right handed, left handed, and mixed-handed. Participants listened to dichotic digits in a sound proof booth with digits presented at 60 dB. Participants were asked to repeat all of the words that they could recall; if they were not positive they could guess. The test was administered again a week later to check for reliability. Laterality was measured with the following formula:  $[(\text{correct RE results} - \text{correct LE results}) / (\text{correct RE results} + \text{correct LE results})] * 100$ . Results range from -100 to +100; REA is shown by positive numbers and LEA by negative numbers. *Results*: Statistical analysis revealed a difference in ear advantage between groups. Overall, the control and APD groups were left hemisphere dominant, the dyslexia group had no ear dominance, and mixed APD/dyslexia group had right hemisphere dominance. *Conclusions*: The results indicate that ear advantage is more variable in patients with dyslexia and/or APD. Dyslexia has a greater occurrence of LEA than APD. The different disorders alter laterality of language. Understanding auditory processing in these groups will assist in providing more specific treatment to patients with these disorders. *Relevance to current study*: The study provides further background information on the REA. *Level of evidence*: Level IIIa.

Jäncke, L., Wüstenberg, T., Schulze, K., & Heinze, H. J. (2002). Asymmetric hemodynamic responses of the human auditory cortex to monaural and binaural stimulation. *Hearing Research, 170*, 166-178. doi: 10.1016/S0378-5955(02)00488-4

*Objective:* The differences in activation for monaural and binaural activation are unknown for pure tones and phonetic stimuli. Observing the activation of different regions to different stimuli and ear activation will show the specific functions of various regions more accurately. *Study Sample:* Participants included 11 right-handed, neuro-typical individuals. *Method:* Stimuli consisted of pure tones and the CV syllables /pa/, /ba/, /ta/, /da/, /ka/, and /ga/ presented binaurally and monaurally; patients were scanned with fMRI technology. The hemodynamic responses of the participants were recorded during stimuli presentations and during the presence of machine noise alone. *Results:* Analysis of the fMRI images showed greater hemodynamic response bilaterally for phonetic stimuli compared to tones; bilateral hemodynamic response was also greater in response to binaural tones than to monaural tones. Monaural presentation resulted in greater hemodynamic response in the contralateral hemisphere. When combining the average activation for monaural RE and LE activation, it was found that the sum of the monaural presentation summation was greater than was seen in the binaural presentation. Stimuli type had a significant effect in region of hemodynamic response; CV stimuli were associated with the posterior STG and the tones showed a greater response in the anterior STG. *Conclusions:* The contralateral hemodynamic response seen in the monaural activation supports the structural theory presented by Kimura that the auditory fibers are more concentrated to the contralateral hemisphere. The results did not show a REA; the processing followed the easiest pathway—dense contralateral fibers—and was a simple enough signal that additional processing did not need to be transferred through the corpus callosum to the left hemisphere. *Relevance to current study:* The current study takes a structural advantage approach; the finding that monaural stimulation results in stronger hemodynamic response in the contralateral hemisphere supports the structural model. *Level of Evidence:* Level IIIa

Jerger, J., & Martin, J. (2004). Hemispheric asymmetry of the right ear advantage in dichotic listening. *Hearing Research, 198*, 125-136. doi: 10.1016/j.heares.2004.07.019

*Objective:* Hemisphere asymmetries in dichotic listening are well documented, and attention is known to affect the laterality of speech processing. The present study used directed attention to observe the structural and attentional processes of the REA. *Study Sample:* Participants included 24 right-handed, English speaking adults with normal hearing. *Method:* Two methods were used to study the REA. One experiment involved a phonemic target, the other a series of morpho-syntactic anomalies. The stimuli for both parts of the study were presented from loudspeakers in a sound-treated room. The phonemic-features experiment presented a story about a character named Pam (which was the target word). The signal from one of the loudspeakers was delayed 60 s relative to the other loudspeaker. Participants were instructed to keep a mental count of the number of times they heard the target word from the target side. In the morpho-syntactic experiment, stimuli consisted of segments of fairy tales with anomalous words in the sentences (e.g. “and you shall *door* the ball”). The stories were cut into 200 segments, 50 with anomalies in the RE, 50 with anomalies in the LE, and 100 normal segments. Epoch data was collected from -200 to 1800 ms relative to the target word from electrodes placed on the scalp. *Results:* Analysis of late positive component of the ERP data showed greatest activation of the leftmost electrode with decreasing intensity as electrodes moved towards the right for both experiments. At all

electrode locations the morpho-syntactic experiment showed greater activation and had a stronger REA than the phonemic-features experiment. *Conclusions:* The late positive component shows the language processing in the left hemisphere. The authors theorize that the right hemisphere is not involved in the phonetic-features experiment because the signal was simple enough that the left hemisphere could complete the task following the attention theory of REA. The authors theorize that the morpho-syntactic task was more difficult, so the signal traveled through the corpus callosum to the right hemisphere to help with stimulus decoding. Structure is responsible for the REA, but attention and complexity alters the degree of REA. *Relevance to current study:* The current study attempts to identify the relationship between linguistic complexity and the REA. This study showed that the more linguistically complex task caused a greater electrical response. *Level of Evidence:* Level IIIa

Jerger, J., & Martin, J. (2005). Some effects of aging on event-related potentials during a linguistic monitoring task. *International Journal of Audiology, 44*, 321-330.  
doi:10.1080/14992020500146450

*Objective:* Studies have noted that the latency of auditory processing increases with age. There have been few ERP studies targeting language processing. The study examines the effect aging has on ERP components in linguistic processing. *Study Sample:* Two groups were included in the study: young adults and seniors. Participants were right handed and spoke English as a second language. The younger adult group had normal hearing and the older adult group presented with presbycusis. *Method:* Participants were presented with dichotic, continuous speech and asked to attend to one ear at a time. Stimuli were presented to the young adult group at 60 dB SPL and at a comfortable level to the senior group. Participants were asked to track the number of semantic and grammatical anomalies. As participants listened, ERP data was collected with 30 EEG electrodes. *Results:* Both groups demonstrated a late-positive component (LPC) component beginning at 400 ms and ending at 1400 ms. Onset of the LPC was slightly earlier for the senior group than the young adult group in the RE. There was a processing negativity at 200-500 ms in the younger group but not in the senior group that was most present when attention was directed to the LE. The peak amplitudes of the two groups were compared and the senior group had a slightly smaller LPC amplitude than the young adult group. The latency between hemispheres was significantly greater in the senior group (greater latency over the right hemisphere). Other findings included shorter latency when participants were instructed to attend to the RE for both groups and lowest peak amplitudes over the right hemisphere for both conditions and for both groups. *Discussion:* The difference between LPC between hemispheres observed in both groups supports the structural model of the REA. The signal is processed earlier in the left hemisphere than in the right hemisphere. The negativity observed in the younger group at 200-500 ms could be support for the attentional model proposed by Kinsbourne. The activation observed at this earlier time could be the control of attention to the specified ears. Another possible explanation is that the wave observed is part of the LPC wave which would make the senior group's LPC different from the young adult group's LPC. *Conclusions:* Results from previous studies have shown later latencies of P300 in older adults compared to younger adults when presented with simple auditory tasks. The similar latencies of the LPC between the two groups taken with previous findings suggests that older adults can compensate for slowed auditory processing by taking advantage of prosodic and contextual cues. *Relevance to current study:* This study supports the structural model and indicates that the REA is altered with aging. The current study includes adults aged 18-29 years. *Level of evidence:* Level IIIa

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

*Objective:* The author's previous studies suggest that dense crossed neural pathways and the left hemisphere's specialization in auditory processing of speech signals cause the REA for the DL digits test. The author hypothesizes that individuals with a right hemisphere specialization in speech signals would have a LEA rather than a REA which this study investigates. *Study Sample:* One hundred and twenty patients were recruited from the Montreal Neurological Institute. All had epileptogenic lesions in various regions of the brain. One hundred and seven participants were left hemisphere dominant and 13 were right hemisphere dominant for language as found by the sodium amytal test. *Method:* The participants were presented with 3 dichotic digit pairs. The participant reported the digits heard in any order. *Results:* Regardless of the location of lesion, a REA advantage was observed. As was expected, the left hemisphere speech dominance group demonstrated a REA while the right hemisphere dominant group showed a LEA. The author determined with the use of ANOVA comparing handedness and hemispheric laterality that handedness did not have an effect on laterality of language. The author further analyzed the data by looking at a subgroup including both right and left hemisphere dominant participants that all had severe left hemisphere damage. Despite the damage to the brain, the opposite ear still showed the advantage. *Conclusions:* The ear opposite the hemisphere dominant in processing language has the advantage. Therefore, the author's hypothesis that the crossed pathway is superior to the ipsilateral pathway is supported. This phenomenon has not been recognized previously because the ears receive the same information in the usual listening environment. *Relevance to current study:* This study supports the theory that the REA is due to structural differences rather than attention. *Level of evidence:* Level IIIa

Kimura, D. (1961b). Some effects of temporal-lobe damage on auditory perception. *Canadian Journal of Psychology*, 15, 156-165.

*Objective:* Lesions of the left temporal lobe result in auditory deficits. Stimuli presented to the ear contralateral to the lesion are not processed. Additionally, specific deficits differ depending on the hemisphere that is affected. Lesions in the right hemisphere result in difficulties identifying tone quality and discrimination of patterns whereas lesions in the left hemisphere reduce the ability to recall stories presented orally. The current study examines the relationship of these two findings. *Study Sample:* Seventy-one participants were recruited from the Montreal Neurologic Institute who presented with epilepsy. *Method:* Participants were tested both before and after partial lobectomy. Three test conditions were used: dichotic presentation of 3 pairs of digits, six digits presented one after another with  $\frac{1}{2}$  second between the numbers alternating between the ears, and all six digits presented to one ear or the other to serve as the control. After presentation of all six digits the participant was asked to report all the digits that were heard. Participants were excluded from analysis if Heschl's gyrus was removed or post-operative aphasia was observed. *Results:* The group with left temporal lobe lesions was significantly less accurate at reporting digits presented dichotically and alternating rapidly between the ears. Unilateral temporal lobectomy reduced recognition of contralateral ear stimuli. *Discussion:* Individuals with a left temporal lobectomy were not as accurate at reporting dichotic or rapidly alternating digits. The author determined that this difficulty was not due to attention deficits because these participants showed good attention in other tests. As the result was only seen when there was competition between pathways, the author concludes that the pathways overlap as they

are processed and the contralateral has the preference in processing. The left temporal lobe lesion group scored higher on non-linguistic auditory asks than the right temporal lobectomy group. Both right and left lobectomy groups are less accurate than the frontal lobectomy group which suggests that both temporal lobes are used in processing of speech. *Relevance to current study:* This study demonstrates that although the left hemisphere is more specialized in speech processing, the right hemisphere also contributes to speech processing. This is due to structure and not to attention. The current study uses these findings to design the study paradigm and in analysis of results. *Level of Evidence:* Level IIIa

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

*Objective:* Ear advantage in a dichotic listening condition is a result of the organization of the brain. Studies have shown that adults with a left hemisphere advantage in linguistic processing have a REA and adults with a right hemisphere advantage in linguistic processing have a LEA. This study looks at ear advantages in children to observe when linguistic processing becomes specialized. *Study Sample:* Approximately the same number of girls and boys participated for a total of 145 children between 4 and 9 years of age in the study. Children were grouped according to age. Children with hearing loss were excluded. Most of the analysis excluded 25 of the listeners because they were left handed which is correlated to right hemisphere speech dominance and a LEA. *Method:* Children listened to digits presented in 1, 2, or 3 pairs and reported what was heard. A total of 60 pairs were presented. *Results:* Each age group demonstrated a REA. Younger children had a stronger REA than older children. There was a significant difference between boys and girls in reporting digits in the 5 and 6 year-old age groups. *Conclusions:* Results from the study suggest that there is a difference in ear advantage between the sexes. Children as young as 4 have hemispheric lateralization of speech processing. *Relevance to current study:* The current study looks for variables that affect the REA. This study shows that age affects the degree of ear advantage: younger children have a stronger ear advantage than older children. *Level of evidence:* Level IIIa

Kimura, D. (1967). Functional asymmetry of the brain in dichotic listening. *Cortex*, 3, 163–178.

*Objective:* A functional difference between the hemispheres of the brain has previously been established. The author proposes that dichotic listening tests accurately reflect the specific specialization of each hemisphere. *Method:* The author reviewed studies previously published as support for the structural theory presented in the article. *Results:* Various studies were presented supporting the hypothesis that DL tests can be used to show hemispheric laterality for auditory stimuli. The author reported that the ear advantage of patients with left and right temporal lobe lesions was compared and showed that left temporal lobe lesions had more DL errors. Animal and human electrophysiology studies show that the auditory pathway has slightly more fibers coursing contralaterally than ipsilaterally. Contralateral fibers inhibit the signal being transmitted by the ipsilateral pathway. Individuals with right hemisphere dominance for speech as determined by the sodium amytal test showed that the LE has the advantage in a dichotic digits test as would be expected. Another method used in studying the REA was to dichotically present 4 CVC words that matched in the vowel, but not the consonants on either end. The participants were asked to report the words from either ear; those that reported RE stimuli had much more accuracy than participants who reported LE stimuli. The advantage of verbal stimuli was then

compared to advantages in non-verbal stimuli. In this non-verbal situation, a LEA was observed. *Conclusions:* Kimura hypothesized that the advantage of the contralateral white matter pathway paired with the left hemisphere's language specialization would give the RE an advantage in processing language. The pathways to the brain and the specialization of the hemispheres are behaviorally observed with the DL test. *Relevance to current study:* Kimura's work on DL has been fundamental in developing theories of REA. The author proposed that the REA is due to the structural advantage of the brain which the current study is studying with MR technology. *Level of evidence:* Level II

Kinsbourne, M. (1982). Hemispheric specialization and the growth of human understanding. *American Psychologist*, 37, 411-420. doi:10.1037/0003-066X.37.4.411

*Objective:* The author explains the attentional model of hemispheric specialization. Brain organization models do not take into account the network of the brain. The author questions the idea that the ability to perform two tasks at the same time depends on the relative locations of the brain that are specialized in that skill. *Method:* The author reviewed neural principles to explain neural processing. *Results:* The brain is a network between all of the different processes rather than discreet systems. This incorporation of all the systems must be taken into account when analyzing neural responses. There are specialized regions of the brain, but this is not necessarily due to discreet systems that feed directly to that area. It is not known how regions interact for processing. When analyzing behavior, it is important to note that behaviors with physically close processing areas interfere with each other. The performance of both of the tasks will be affected because of the interaction. When the main processing systems are located in opposite hemispheres, the organism can process material with more success; this is the cause of lateralization of skills. Even still, both hemispheres have the capability to perform the various tasks of the opposite hemisphere. With split brain and hemispherectomy patients, the ability to perform a function supposedly located in the removed hemisphere is not completely destroyed. The brain is not two separate brains that communicate via the corpus callosum, but a whole with the corpus callosum being an integral part of the system. *Conclusions:* A study of the inhibition of parts of the brain would provide valuable information as to behavior rather than a study of function of brain regions. *Relevance to current study:* The attentional model of ear advantage proposed by Kinsbourne helps explain why the REA has poor validity and reliability. *Level of evidence:* Level IV

Kompus, K., Specht, K., Ersland, L., Juvodden, H. T., van Wagneningen, H., Hugdahl, K., & Westerhausen, R. (2012). A forced-attention dichotic listening fMRI study on 113 subjects. *Brain and Language*, 121, 240-247. doi:10.1016/j.bandl.2012.03.004

*Objective:* Forced-attention tasks have been used to simulate the effect of selective attention on ear advantage. An underlying assumption that this approach has is that the forced attention model activates the same neural pathways as natural selective attention which may not be accurate. Studies have illustrated that in certain disorders such as schizophrenia, aging in normal adults, Alzheimer's disease, and attention deficit/hyperactivity, reduce the ability to attend to LE stimuli whereas there is no change in attention to the RE. This observation indicates that there are differences in the processing systems stimuli from the RE and LE. It was hypothesized that attention directed to the LE involves more frontal regions responsible for cognitive control in order to overcome the structurally preferred RE. This study was intended to test the hypothesis

that the forced left condition requires more frontal lobe (lateral prefrontal cortex and striatum) involvement. *Study Sample*: Participants included 113 (62 males, 51 females) volunteers with normal hearing of whom all but 6 are right-handed. None of the participants had a history of psychiatric or neurologic disorders. *Method*: Participants listened to dichotic presentation of randomized syllables /pa/, /ba/, /ta/, /da/, /ka/, /ga/. Stimuli were presented in 9 blocks of 10 syllable pairs—3 blocks of no directed attention in which participants reported the syllable they heard best followed by 6 blocks in which attention was randomly directed to the right or left. Data was collected with fMRI technology. *Results*: The ANOVA revealed a REA for the non-directed attention and forced right conditions. Attention directed to the LE did not show a REA or LEA. An analysis of clusters of brain activity during the different conditions showed that clusters of voxels in the left inferior frontal gyrus and the parieto-occipital sulcus had an increase in activation in the forced left condition compared to the control. The control and forced right condition did not differ in the level of activation of the inferior frontal gyrus and the parieto-occipital sulcus was less activated for the forced right condition and the control had the least activation in this region. The two forced conditions both showed more voxel activation in the right inferior frontal sulcus and the right superior parietal lobule than was found in the control condition. *Conclusions*: Behavioral data demonstrated a REA as was expected, and the increase in right stimuli responses during forced right was greater than the decrease observed during the forced left condition. This supports the hypothesis that directing attention to the two ears requires different cognitive processes. Also, regions that were activated during the forced left condition are regions that have previously been shown to be activated in tasks that require cognitive attention. *Relevance to current study*: The current study is modeled after this study. The results show that attention does not overcome structural advantages. *Level of Evidence*: Level IIIa

Kraus, N., & Cheour, M. (2000). Speech sound representation in the brain. *Audiology & Neuro-Otology*, 5, 140-150.

*Objective*: The article reviewed the literature at the time of publication concerning what has been learned about the auditory pathway specifically addressing how stimulus type is related to brain regions activated, how auditory processing differences can cause learning disorders, and how training of stimuli can alter how the brain processes that signal. *Method*: A review of the literature was completed to create a description of the specific areas of study. *Results*: A number of mismatch negativity (MMN) studies of the auditory pathway have shown that speech signals are processed in the midbrain, thalamus, and cortex in both hemispheres. Auditory processing occurs in many different locations of the brain, and also has different processing patterns according to the stimulus. Tones show a stronger MMN in the right hemisphere, while various studies show symmetric or left hemisphere activation for speech stimuli. Listeners trained in identifying foreign language syllables have an especially strong MMN measure when listening to the foreign language. Studies of individuals with auditory processing disorders suggest that different sounds have different processing pathways; some sounds are more vulnerable to disruption than others in this population. In one specific study, a participant with a left hemisphere lesion could identify tonal differences between presentations of /da/, but was not as accurate identifying the phonetic difference of /ga/ and /da/. Supporting this finding was another study that showed that /ba/ and /wa/ differences were picked up in the auditory thalamus, but /da/ and /ga/ processing differences only varied in the cortex. Studies of how the brain changes with development and training showed that MMN measures for foreign and native languages had different hemisphere lateralities. The vowels of the listeners' native tongue had a greater left



hemisphere activation whereas the vowel of the foreign vowel showed equal hemisphere involvement and less overall activation. When listeners were trained to identify the vowels of the foreign language, the left hemisphere became more involved. Studies on the development of infants mirror the findings of the ability to train auditory discrimination. The MMN amplitude in infants decreases for non-native vowels and increases for native vowels as seen in studies observing children ages 6 months and 1 year old. *Conclusions:* The MMN has been very useful in learning about the auditory pathway in research. The variability of the MMN amplitude between participants precludes it from clinical use at the present time. *Relevance to current study:* This study provides background knowledge on the auditory processing system. *Level of Evidence:* Level I

Kraus, N., McGee, T., Sharma, A., Carrell, T., & Nicol, T. (1991). Mismatch negativity event-related potential elicited by speech stimuli. *Ear and Hearing, 13*, 158-164.

*Objective:* MMN is a measure of the perception of a change in a steady stimulus. As it has not been observed in the visual EEG studies, it has been assumed that is specific to the auditory system. It may be useful in studying the central auditory system. The study looks at the possibility of using MMN as a diagnostic tool. *Study Sample:* Ten healthy young adults (ages 17-29) and 10 children (age 7-11) with normal hearing thresholds. *Method:* Computerized variants of /da/ and /ga/ that were made to be more similar in the second and third formants were used as non-standard stimuli, and /da/ and /ga/ without a change in formants were used as the standard stimuli. Participants watched a movie with volumes kept below 40 dB HL while auditory stimuli were presented to the patients. *Results:* The MMN was observed in all participants; the difference in latency and amplitude between children and adults was not statistically significant. Averages of the waves elicited in the oddball paradigm and syllable alone were compared showing a clear presence of the MMN. *Conclusions:* The study clearly shows the presence of a MMN response in the participants. It is assumed that the absence of a MMN would be considered abnormal and can reasonably be used in diagnostic procedures. Using the standard minus the deviant wave measurement would be more accurate because amplitudes vary among individuals, but the difference is relatively intact. There is not yet a practical application for MMN, but areas that potentially could utilize MMN measurements include auditory discrimination and memory, ability to attend to stimuli in presence of background distractors, and function of cochlear implants. *Relevance to current study:* the study provides background information on the auditory system. *Level of Evidence:* Level IIIa

Narain, C., Scott, S. K., Wise, R. J. S., Rosen, S., Leff, A., Iversen, S. D., & Matthews, P. M. (2003). Defining a left-lateralized response specific to intelligible speech using fMRI. *Cerebral Cortex, 13*, 1362-1368. doi:10.1093/cercor/bhg083

*Objective:* Results from previous imaging studies show bilateral processing of speech which does not correspond to clinical evidence in aphasic patients. These studies have not fully accounted for the complexities of speech in their control measures. The authors hypothesize that the activation in the right hemisphere observed by other studies is a result of processing temporal complexity of the signal not the speech. Controlling for the temporal complexity of speech will result in more accurate images of speech processing. *Study Sample:* Data was collected from 11 English speaking participants (2 females, 9 males). *Method:* Stimuli consisted of two intelligible forms of speech—recorded speech and 6-channel noise-vocoded speech—and two unintelligible

signals—spectrally rotated normal speech and spectrally rotated noise-vocoded speech. The types of signals were presented in 10 blocks each of 5 sentences. Participants were told not to try to repeat the sentences but to pay close attention. After the presentation of each block, the fMRI scanner would take images. Rather than using a cognitive subtraction method, researchers used statistical parametric mapping (SPM). *Results*: Areas of significant voxel activation were all in the left temporal lobe and included the dorsal posterior margin (Wernicke’s area), the mid superior sulcus, and the anterior superior sulcus. *Conclusions*: Controlling for the complexity of speech showed the clear left lateralization of speech processing that would be expected based on clinical research. Activation of the Wernicke’s area has been seen in other studies to relate to short-term memory for language; the results from this study support the hypothesis. If this is the function of Wernicke’s area, it would be more active when listening to narratives. *Relevance to current study*: This article shows that by accounting for variables, as the current study attempts to identify, the REA more closely matches clinically expected values. *Level of evidence*: Level IIIa.

Ocklenburg, S., Schlaffke, L., Hugdahl, K., & Westerhausen, R. (2014). From structure to function in the lateralized brain: How structural properties of the arcuate and uncinate fasciculus are associated with dichotic listening performance. *Neuroscience Letters*, 580, 32-36. doi:<http://dx.doi.org/10.1016/j.neulet.2014.07.044>

*Objective*: Hemispheric laterality is frequently measured using the dichotic listening test, but the neurological basis of this laterality of the hemispheres is still not entirely understood. Studies have shown that the grey matter activation is part of the reason for RE and left hemisphere advantage for auditory stimuli, but the differences are not present in all participants. White matter underlying the grey matter has not been explored as another contributing factor for hemispheric laterality. This study observes fractional anisotropy in the arcuate fasciculus and the uncinate fasciculus to increase the understanding of the cause of the REA. *Study Sample*: Twenty-nine adults, 15 females and 14 males, participated in the study. All had hearing thresholds within normal limits and were right handed. *Method*: Participants completed a dichotic listening task in which they identified the syllable they heard best (/ba/, /da/, /ga/, /pa/, /ta/, or /ka/). While participants did this task their brain was scanned to identify the arcuate and uncinate fasciculi. *Results*: The left uncinate fasciculus was larger than the right for tract volume with statistical significance but not for fractional anisotropy (FA). For the arcuate fasciculus, the tract volume was larger in the left hemisphere, but the FA was greater in the right hemisphere. *Conclusions*: The results of this study showed that increased FA co-occurred with stronger functional laterality in the DL task. FA was interpreted as a measure of a tract’s integrity, indicating that the integrity of the left hemisphere is stronger than the right, which supports the structural model. *Relevance to the current study*: The study supports the structural model of the REA. Fibers in the left hemisphere were more numerous than fibers in the right hemisphere. The current study takes the structural model as the main source of the REA with fiber tract sizes in the left hemisphere being one part of the structural model. *Level of evidence*: Level IIIa

Rimol, L. M., Specht, K., & Hugdahl, K. (2006). Controlling for individual differences in fMRI brain activation to tones, syllables, and words. *Neuroimage*, *30*, 554-562. doi:10.1016/j.neuroimage.2005.10.021

*Objective:* Inter-subject differences in laterality of auditory perception could cause previous studies to report equal activation of the right and left hemispheres in response of speech. Given behavioral support for the REA, imaging studies could show equal activation because researchers average results without controlling for ear advantage in the participants. By controlling for ear advantage, laterality can be better observed. *Study sample:* The study included 18 right-handed males with normal hearing and no history of psychiatric illness. All were screened for auditory laterality using a DL task. Each participant had a REA that fit normal ranges of the population. *Method:* Stimuli included sine waves, CV syllables and CVC words randomly presented monaurally in 24 blocks of approximately 20 stimuli each. Participants listened to stimuli in the MR scanner. *Results:* Main results showed presentation of tones led to greater activation in the right hemisphere than the left. Statistical analysis showed that there was greater voxel activation in the left Superior Temporal Gyrus for words and syllables compared to tones. *Conclusions:* According to the results of this study and others in the literature, Wernicke's area is not as important for speech processing as the structures surrounding it. Although the voxels of the superior temporal sulcus of both hemispheres were recorded as active, it is believed that left hemisphere, not both, is responsible for speech processing. The authors' rationale is that tones, the control subtracted from the speech trials, do not represent the full temporal complexity, so it is likely that some portion of the activation in the right hemisphere was due to a control that did not fit the variable. *Relevance to current study:* The current study will also test the REA using a variety of stimuli. Instead of using tones, the current study will use speech babble to include the full temporal and spectral complexity. *Level of evidence:* level IIIa.

Roup, C. M. (2011). Dichotic word recognition in noise and the right-ear advantage. *Journal of Speech, Language & Hearing Research*, *54*, 292-297. doi:10.1044/1092-4388(2010/09-0230)

*Objective:* Studies of dichotic word recognition in older adult populations with sensorineural hearing loss have shown that they have not only reduced recognition of words but also an increased REA. It has been hypothesized that this increased REA is due to an age-related change to the auditory pathway. To learn about the differences of the auditory pathway in the two populations, the hearing of the older adult population with sensorineural hearing loss was compared to the results of dichotic listening in noise of young adults with normal hearing. *Study Sample:* The participants were 32 young adults in the age range of 18-30; 17 participants were female and 15 male. All participants were right-handed and had normal hearing. *Method:* Dichotic stimuli were presented with noise to match the word recognition thresholds of older adults with sensorineural hearing loss. Two trials of 25 dichotic word pairs were presented to the participants in noise and another two trials of 25 words were presented in quiet. Participants were instructed to say the words presented to both ears. *Results:* The results from the present study were compared to a previous study with older adult participants with sensorineural hearing loss. In the young adult population, statistical analysis revealed that the RE was significantly more accurate than the LE and that the word recognition was significantly better in quiet than in noise. Although the word recognition scores decreased with the introduction of noise to match scores of the older adults, a correlating increase in the REA was not seen in the young adult population.

The older adults had a significantly larger REA compared to the younger adults listening in noise. *Conclusions*: The higher REA of the older adults despite the equivalent word recognition scores of young adults listening in noise indicates a change in the auditory pathway in older adults. Rather than simply having reduced hearing thresholds, older adults have impaired auditory processing. *Relevance to current study*: The study demonstrates that the REA and LEA stimuli identification changes with age. This supports the current study's assumption that the REA is due to structural differences between the pathways of the two ears. *Level of evidence*: Level IIIa.

Sætrevik, B., & Hugdahl, K. (2007). Priming inhibits the right ear advantage in dichotic listening: Implications for auditory laterality. *Neuropsychologia*, 45, 282-287.  
doi:10.1016/j.neuropsychologia.2006.07.005

*Objectives*: The REA, as seen in many dichotic listening studies, is controlled by attention; when participants are instructed to report the word or vowel in the LE there is a LEA. This shows that the REA can be controlled by top-down processing. The interaction of the REA and attention is often studied using forced attention, but this does not reflect how attention alters the REA in auditory situations where other stimuli direct attention. By modifying the study design to use priming of different hemispheres, it can be seen how attention affects degree of ear advantage. *Study sample*: The sample for the first half of the experiment with an aural prime included 15 right-handed individuals with normal hearing and no history of brain trauma. The second half of the experiment which used visual prime syllables included 23 participants that fit the same criteria used for the participants in the first half of the experiment. *Method*: The participants were presented first with a prime syllable followed by the probe dichotic presentation of syllables. The prime could have been different from the probe or matched one of the ears. Half of the prime syllables were presented monaurally and half were presented visually. Participants reported the prime syllable and the probe syllable that they heard best. *Results*: Statistical analysis showed that there was a significant REA when auditory prime syllables were different from dichotic probe syllables and also when the prime syllable matched the LE probe. Prime syllables that matched the RE presentation showed a significant LEA. The second half of the experiment with visual presentation of prime stimuli showed a significant REA for all presentation conditions; the condition where the prime matched the LE had the smallest degree of REA following the direction of results in the first half of the experiment. *Conclusions*: The top-down processing of the brain focuses on novel stimuli thus reducing the degree of the REA when the prime syllable matches one of the probe syllables. Control of attention alters the degree of the REA. *Relevance to current study*: Attention is one of the variables that affects the REA. This study shows that the situation affects the way that auditory stimuli are processed. *Level of evidence*: Level IIIa

Schmithorst, V. J., Farah, R., & Keith, R. W. (2013). Left ear advantage in speech-related dichotic listening is not specific to auditory processing disorder in children: A machine-learning fMRI and DTI study. *NeuroImage: Clinical*, 3, 8-17.  
doi:http://dx.doi.org/10.1016/j.nicl.2013.06.016

*Objective*: Auditory processing disorder is difficult to diagnose due to similarities to other syndromes that cause cognitive, attention, or memory deficits. Clinical audiologists frequently use the dichotic listening test to determine ear advantage and use a LEA as an indication of APD. This study is intended to make objective observations of the neurological differences in children

with APD compared to typically developing children. *Study sample*: Thirteen English speaking children ages 7-14 were included in the study. None had been previously diagnosed with neurological pathologies or hearing loss but did have listening/hearing complaints. Parents reported deficits congruent with APD. Twenty typically developing children participated as controls. All participants had a hearing threshold of  $\leq 15$  dB HL. *Method*: Outside of the MR scanner, the patients participated in the SCAN 3 test. Patients listened to dichotic words in the MR scanner and repeated the words heard. As a control, words were presented diotically. Functional magnetic resonance imaging and DTI analysis were used. Machine learning was also used which allows a discussion of the sensitivity and selectivity of a test battery. *Results*: There was no difference observed between the groups for the auditory figure ground, competing sentences, or competing words directed ear; a difference between groups was observed in the filtered words subtest. Analysis showed that results were not a function of participant motion. Children with a REA had greater activation in the left frontal area during diotic presentation than dichotic. There was not a similar finding in children with a LEA. Children with a LEA had greater activity in the posterior limb of the internal capsule than children with a REA. *Conclusions*: Although axial diffusivity is not fully understood, the study interprets increased axial diffusivity representative of increased organization of the white matter. Activation of the left frontal eye fields suggests that the REA is not due to structure alone but that attention plays a role. *Relevance to current study*: The current study looks at white matter as well but only in neuro-typical individuals to identify any differences in processing of stimuli with various levels of linguistic complexity. *Level of evidence*: Level IIIa

Speaks, C. (1985). Effects of stimulus material on the dichotic listening performance of patients with sensorineural hearing loss. *Journal of Speech, Language, and Hearing Research*, 28, 16-17-25.

*Objective*: Previous studies have examined how scores on DL tasks with various stimuli types are related to lateralization of speech and sites of lesion in disorders. This study examines the effect of hearing loss on the REA. Previous studies suggest that the size and direction of ear advantage may be effected by peripheral hearing loss. *Study Sample*: Twenty-seven individuals with sensorineural hearing loss in which there was no reason to suspect a central auditory system component were included. *Method*: Stimuli consisted of dichotic digits, vowel words, consonant words, and CV syllables. The stimuli were presented in four blocks of 30 pairs of items. Stimuli were presented in an increasing level of difficulty as was found by another study: digits, vowel words, consonant words, and CV syllables. *Results*: The number of correct RE and LE responses, the ear advantage ( $EA=RE-LE$ ), the performance level ( $P=(RE+LE)/2$ ), and the laterality index were calculated. Scores were also compared to the results of another study that tested individuals with aphasia using the same stimuli. The dichotic digits test was the most similar to previous results, both word tests were next most similar, and CV syllables were most different. *Discussion*: The digits test results were most similar to results from another study that tested a group with aphasia indicating that the dichotic digits test is relatively insensitive to peripheral hearing loss. The CV syllables were most different from the aphasia group, so CV syllables appear are most sensitive to peripheral hearing loss. *Conclusions*: It is difficult to definitively report which test is most insensitive to peripheral hearing loss because there are no age-matched norms to compare. The similarity of the dichotic digits scores between the aphasic group and the peripheral hearing loss group suggests that dichotic digits would be the most effective. *Relevance to current study*: The current study also uses levels of linguistic stimuli to observe the REA but

in a neurotypical population which would have been useful in the analysis of the current study.  
*Level of evidence:* Level IIIa

Stefanatos, G. A., Joe, W. Q., Aguirre, G. K., Detre, J. A., & Wetmore, G. (2008). Activation of human auditory cortex during speech perception: Effects of monaural, binaural, and dichotic presentation. *Neuropsychologia*, *46*, 301-315.  
 doi:http://dx.doi.org/10.1016/j.neuropsychologia.2007.07.008

*Objective:* Few studies have been completed to observe hemodynamic responses in the different hemispheres in response to monaural stimulation. The design of the experiments could be the cause for not seeing the expected brain laterality. The use of random presentation would better reflect the structural advantage of the ear because directed attention to one ear or the other activates other brain regions that direct spatial attention. *Study Sample:* Data was included from 10 right-handed adults with normal hearing and no history of neurologic or psychiatric disorders. All participants showed a strong REA in a dichotic listening test of syllables. *Method:* Stimuli consisted of the CV syllables /ba/, /ka/, and /da/. The syllables were presented binaurally, monaurally, dichotically, or with noise in the opposite ear while the participants were in the MR scanner. To maintain attention, participants were asked to push one button if /da/ was heard and another if it was not. To have more accurate measurements, the primary auditory cortex was not defined based on macro-structural but microstructural landmarks. Laterality was determined using a weighted laterality index and the activation differences within the hemispheres were calculated. *Results:* Behavioral results showed no differences between the two ears in the monaural and noise conditions. Hemodynamic responses showed a stronger contralateral hemisphere response than ipsilateral for both ears. Subtracting the voxels activated in the right hemisphere from the voxels activated in the left hemisphere resulted in no remaining voxels in the right hemisphere and two regions remaining in the left hemisphere—the rolandic operculum and the posterior STG. Binaural and dichotic presentation of stimuli slightly favored the left hemisphere, RE CV with LE noise favored the left hemisphere, and the LE CV with RE noise had no statistically significant differences between the two hemispheres. *Conclusions:* Fewer voxels above threshold in the right hemisphere in identifying syllables supports the laterality for language in the left hemisphere. Although both hemispheres are involved, the structures of the primary and non-primary auditory cortices of the left hemisphere have an advantage over the right hemisphere in decoding rapidly changing temporal signals. *Relevance to the current study:* The study shows a structural advantage with the condition of presentation randomized supporting the structural model that is also the model used in the current study. *Level of evidence:* Level IIIa

Takio, F., Koivisto, M., Jokiranta, L., Rashid, F., Kallio, J., Tuominen, T., Laukka, S. J., Hamalainen, H. (2009). The effect of age on attentional modulation in dichotic listening. *Developmental Neuropsychology*, *34*, 225-239. doi:10.1080/87565640902805669

*Objective:* Studies have shown that the ability to control attention to the LE changes with age: older adults and young children have difficulty directing attention. The current study presents dichotic stimuli to listeners of all age groups to specifically identify how top-down processing abilities change with age. The study also examined how linguistic skills are related to language lateralization and to selectively attend to the LE in DL. *Study sample:* Participants included 186 individuals separated into five different groups. The age of 5-7 included 30 children, 41 participants in the 8-9 group, 25 children aged 10-11, 50 young adults (aged 19-32), and 40

adults in the age group of 59-79. All participants were right handed. *Method*: Stimuli included dichotic presentation of the syllables /ba/, /da/, /ga/, /pa/, /ta/, and /ka/. Participants were asked to report which of the syllables were heard in a non-forced attention condition, in a forced right condition, and a forced left condition. Data was statistically analyzed with the ANOVA. The formula  $[(\text{Correct}_{\text{Forced}} - \text{Correct}_{\text{Nonforced}}) / (\text{Correct}_{\text{Forced}} + \text{Correct}_{\text{Nonforced}})] * 100$  was used to identify changes in performance between the two forced conditions and the non-forced condition. Laterality of ear advantage was calculated with the formula  $[(\text{RE} - \text{LE}) / (\text{RE} + \text{LE}) * 100]$ . Children aged 5-9 also participated in the Rhyme Task, Alliteration Task, and Phoneme Isolation Task subtests from the Finnish Phonological Awareness Test. *Results*: Main effects found with the ANOVA suggest that there was an overall REA, an interaction of ear advantage with sex and age. The 5-7, 8-9, and 59-69 year-old groups demonstrated a REA that did not have an attention component. The laterality of ear response was significantly affected by attention condition in the 10-11 and 19-32 year-old groups. Both groups showed the strongest REA in the forced right condition, but the 10-11 year-old group still was unable to change the REA to a LEA while the 19-32 year-old group could do so. Regarding the interaction of sex and ear advantage, the results for the different age groups differed with females having the stronger REA in one group while males had a stronger REA in another. The 19-32 year-old group had no significant difference between the sexes. Reading ability did not correlate with the laterality indices while the alliteration task did. Another measure, grade in English, showed a correlation between a stronger REA in the forced right condition and higher grades in English. *Discussion*: Asymmetry of language processing is present among all age groups tested, but the activation patterns changed with age (the youngest group did not alter the REA with the change in attention conditions) which suggests structural-developmental changes of the auditory system and that top-down processing is not yet mature. The 19-69 year-old adults had the least accurate performance of any group supporting the hypothesis that there are aging changes the auditory pathway. *Conclusions*: Laterality of language processing is present from age 5-69, but the ability to control the auditory pathway changes with development and aging. Ability of children ages 5-9 in the area of alliterations is positively related to correct responses in any attention condition. *Relevance to current study*: The study shows that sex does not have an effect on REA in the age group of 19-32 and that the REA changes with age. *Level of evidence*: Level IIIa

Van der Haegen, L., Westerhausen, R., Hugdahl, K., & Brysbaert, M. (2013). Speech dominance is a better predictor of functional brain asymmetry than handedness: A combined fMRI word generation and behavioral dichotic listening study. *Neuropsychologia*, 51, 91-97. doi:<http://dx.doi.org/10.1016/j.neuropsychologia.2012.11.002>

*Objective*: Handedness has frequently been used as a measure of brain laterality. This study examines why both right and left handed individuals exhibit a REA. *Study sample*: A total of 63 participants—including 41 left-handed and 22 right-handed individuals—were separated into three groups to study the relationship between handedness and brain laterality. The groups consisted of 25 left-hand and left hemisphere dominant individuals, 16 left hand and right hemisphere dominant, and 22 right hand and left hemisphere dominant participants. *Method*: Participants were presented with consonants while in the MRI scanner and asked to mentally rehearse as many words that began with that letter as possible. During the control block, the participants rehearsed a given non-word. Participants also participated in a dichotic listening task which consisted of syllables. *Results*: Statistical analysis showed that the left hemisphere dominant groups exhibited a REA and the right hemisphere dominant group a LEA. Handedness

did not alter degree of REA in the left-handed left hemisphere dominant group. *Conclusions:* When researchers select participants, hemisphere dominance rather than handedness should be considered as the study showed that handedness did not equate to a specific laterality of speech. Also, the degree of laterality is not consistent between the hand/hemisphere groups. For example, the variability of the REA in individual participants varied much more in left-handed participants with a dominant left hemisphere than the right-handed left hemisphere dominant. Researchers should select participants carefully when forming study parameters. *Relevance to current study:* The current study will take the results of this study into account during analysis of data. *Level of evidence:* Level IIIa

Westerhausen, R., Woerner, W., Kreuder, F., Schweiger, E., Hugdahl, K., & Wittling, W. (2006). The role of the corpus callosum in dichotic listening: A combined morphological and diffusion tensor imaging study. *Neuropsychology, 20*, 272-279. doi:10.1037/0894-4105.20.3.272

*Objective:* The corpus callosum is recognized as being an important component of the REA caused by a structural advantage and also pivotal in cognitively directing attention. This study observes, with the use of DTI, the relationship of the REA and microstructural differences as well as the effect of directed attention on the corpus callosum. *Study Sample:* Forty, right-handed male participants were included. Participants did not have a history of psychiatric, neurologic, or hearing disorders. All participants also showed a REA in a non-forced dichotic listening test. *Method:* The Bergen Dichotic Listening Test was used; in this test CV syllables /ba/, /da/, /ga/, /pa/, /ta/, and /ka/ are randomly paired for a total of 36 different combinations. Each pair was presented once in each of three blocks for a total of 108 trials while the participant was in the MR scanner. Each block had a different listening condition: no listening instructions, forced right, and forced left attention. Participants reported the syllables heard, when both were heard the syllable heard best was also reported. The percent correct for each condition was calculated as well as the reduction in correct answers that resulted from attending to the other ear. *Results:* The effect of attention in the different conditions on the REA was measured with an ANOVA. Participants identified significantly more syllables in forced attention conditions than the control. Between the two forced conditions, there were more correct responses for forced right. A REA was observed in the forced right and no forced attention, but no ear advantage was observed for the forced left. A positive correlation was observed between the posterior third of the corpus callosum and correct LE responses. Correct RE responses were inversely correlated to the area of the corpus callosum. In the forced left condition, there were no significant correlations to regions of the corpus callosum, but the correct right responses were negatively correlated and the reduction in correct RE response due to attention to the LE were positively correlated to the mean diffusivity in the posterior third of the corpus callosum. *Conclusions:* The study found that as more of the corpus callosum was involved, there was less laterality of speech. This finding can be explained with the structural model. A correlation between the area of the corpus callosum involved and the percent of LE responses was observed. Despite the same instructions (except for direction) given in the forced right and forced left conditions, the activation of the corpus callosum was vastly different between the two conditions. This supports a combination of the structural and attentional models. *Relevance to current study:* The current study takes the approach outlined in the structural model with the attentional model overlaying it. Similar to this study, it attempts to identify other variables that affect the REA. *Level of evidence:* Level IIIa



Yasin, I. (2007). Hemispheric differences in processing dichotic meaningful and non-meaningful words. *Neuropsychologia*, 45, 2718-2729. doi:10.1016/j.neuropsychologia.2007.04.009

*Objective:* The REA has been observed in many behavioral situations and has been interpreted to indicate a left hemispheric dominance for speech. Objective methods of brain activity such as the EEG have not shown the same clear hemispheric asymmetry. It was hypothesized that dichotic presentation of meaningful and non-meaningful words would yield a stronger MMN response in the left hemisphere. The authors also compared the late negativity to the MMN because they believed that the LN would show more left hemisphere lateralization than the MMN. *Study Sample:* The study included 18 right-handed participants, 10 female and 8 male. All had normal hearing thresholds and indicated English as the dominant language. *Method:* Participants were fitted with an electrode cap and headphones; they watched a silent movie and were asked not to attend to the auditory stimuli presented to them. Stimuli consisted of two standard, non-meaningful words (/beIgi/ and /leIgi), two deviant meaningful words (/beIbi/ and /leIdi/), and two deviant non-meaningful words (/beIdi/ and /leIbi/). The stimuli were presented in four blocks; each block included a standard word and a deviant word; both words had the same first syllable (i.e., /beIgi/ and /beIbi/ would be paired). The blocks had 400 presentations of the standard word diotically, dichotic presentation of 50 deviant words to the LE, and 50 deviant words to the RE with the standard word in the opposite ear. *Results:* Data analysis showed that the greatest amplitude of MMNs occurred when deviant words with /bi/ as the second syllable were presented. The MMN amplitude was much greater when the word was presented to the RE than to the LE. Meaningful words presented to the RE caused a greater response than any other condition. As expected, the LN measurements showed much greater left hemisphere dipole strength than the right hemisphere for both meaningful and non-meaningful stimuli. *Conclusions:* Objective data results of the EEG are reflective of the behavioral REA previously seen in the normal population. Meaningful words presented to the RE caused greater activation in the left hemisphere than the LE created in the right hemisphere. With regards to the left lateralization of meaningful words in LN measures, dipole strength results do not show an increase compared to the MMN. *Relevance to current study:* The analysis of REA in this study support the assumption that the current study functions on that REA is due primarily to a structural advantage which is then affected by attention. *Level of evidence:* Level IIIa

Yurgil, K. A., & Golob, E. J. (2010). Neural activity before and after conscious perception in dichotic listening. *Neuropsychologia*, 48, 2952-2958. doi:10.1016/j.neuropsychologia.2010.06.004

*Objective:* Previous studies have found that dichotic listening tasks do not show a 100% advantage in one ear or the other; top-down processing interacts with the auditory pathways to alter ear advantage. The researchers observed the effect of pre-stimulus brain activation on the REA. *Study sample:* The study included 20 participants with normal hearing thresholds. *Method:* Participants were fitted with an EEG cap. Two control blocks and 4 test blocks of 60 CV pairs were presented to the participants. In the test condition, the participants were presented with dichotic CV pair and given visual options to select the CV that they heard the most clearly. The control presented squares—one red and three white—in which the participant was to select the red square. The control task identified regions responsible for processing perceptual decision making using a visual selection question (identifying the square that is a different color). Participants selected what was heard or seen for the dichotic listening and control trials by

pushing a button that corresponded to the target as was viewed on a computer screen. Brain activity was measured by EEG; event related potentials were collected between -200 to 1000 s relative to the stimulus presentation. *Results*: The proportion of correct syllables identified from the RE and LE indicated a REA for 17/18 participants. There was a LEA in 35% of the trials and a REA in 54% of the trials. Analysis of EEG power before the presentation of the stimulus showed that higher power was correlated to LE identification. Analysis of the difference between the pre and post neural activity in the beta band showed that a LEA occurred when there was an increased beta band pre-stimulus and reduced P50 amplitudes post-stimulus. *Conclusions*: The increased Beta band activity observed just previous to dichotic presentation in which the LE syllable was selected indicates that top-down processing does effect ear advantage. *Relevance to current study*: The study shows evidence supporting the assumption that ear advantage is a result first of a structural advantage which can be altered by alterations in attention. The article pointed out that there is a REA in the majority of the dichotic listening samples, but as the article discussed in relation to beta bands, certain neural activity conditions result in a LEA. *Level of evidence*: Level IIIa