Event-Related Potential and Reaction Time Differences in Processing of Words Acquired in Early and Late Childhood

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Abstract

Previous research has demonstrated that the left hemisphere specializes in language processing, while the right hemisphere specializes in emotional and visuospatial processing (Purves, 2007). However, a recent study found that words acquired in early childhood (3-4 years) are processed faster by the right hemisphere whereas, words acquired in late childhood (7-8 years), are processed faster by the left hemisphere (Bowers, Bradley, & Kennison, 2013). In addition, there was an overall difference with early-acquired words processed faster than late-acquired words. The present research obtained reaction times and even-related potential (ERP) recordings to investigate processing differences between words with different ages of acquisition (AoA). Participants included 35 undergraduates (17 males, 18 females) enrolled in psychology, science, and statistics courses at Bethel College. Reaction time results indicated that overall, early AoA words were processed faster than late AoA words by both the left and right hemisphere, $F(1,32) = 37.55, p < .0001$. When examining ERP results, late AoA words presented on the left produced a significantly more positive ERP ($p < .05$, corrected for multiple comparisons) than those presented on the right for all left hemisphere electrodes, while such differences were not found in early AoA words. Furthermore, when looking at early and late AoA words presented to the left visual field, late AoA words had more positive ERPs than early AoA words for electrodes throughout the brain. Overall, this study suggests that early AoA words are processed bilaterally whereas late AoA words are processed in the left hemisphere. Furthermore, there are no ERP asymmetries between the left and right hemispheres when processing early- and late-acquired words. Future research should examine different age groups to further investigate age differences in word processing.

Introduction

I. Cerebral Lateralization and Language Processing

One of the most important neuropsychological findings is that the cerebral hemispheres are specialized for different processes. It is normally believed that the left hemisphere is important for language processing, while the right hemisphere is important for emotional and visuospatial processing (Purves, 2007). How cerebral lateralization differs during language processing has been an extensive area of research throughout the years. Although there has been much research on hemispheric differences in language processing, a clear consensus has not been reached on how hemispheric processing differs from childhood to adulthood. Some evidence indicates that hemispheric activation during language processing in childhood is similar to that in adulthood (Boles, Rogers, & Wymer, 1982; Travis et al., 2011). Other evidence indicates that in childhood, bilateral language processing occurs while in adulthood, there is a left-lateralized language processing (Holland et al., 2007; Perani et al., 2011). Yet, other evidence indicates that hemispheric activation during language processing is different in childhood compared to adulthood and that somewhat different areas of the brain are used in language processing (May, Byers-Heinlein, Gervain, & Werker, 2011; McNealy, Mazziotta, & Dapretto, 2011). Additionally, studies have indicated that during instances in which the left hemisphere is damaged, the right perisylvian areas can take over language processing (G. Dehaene-Lambertz, Pena, Christophe, & Landrieu, 2004). This evidence provides support for the idea that the right hemisphere plays an important role in language processing. Growing evidence seems to indicate that language processing during childhood is different from language processing in adulthood, and that these differences diminish as individuals become older and gain more language experience (McNealy et al., 2011). Overall, research indicates that the left hemisphere is not the only hemisphere involved in language processing in adulthood; there is also an involvement of the right hemisphere (Atchley & Kwasny, 2003; Bowers, Bradley, & Kennison, 2013).

II. Early Studies on Hemispheric Differences

Although research on language processing in adults has indicated that there is a left hemisphere dominance, studies have shown that different types of words are processed differently in the brain (Atchley & Kwasny, 2003; Bowers, Bradley, & Kennison, 2013; Mohr, Rowe, & Crawford, 2008). Research continues to focus on whether hemispheric differences in language processing are due to brain differences present at birth and throughout childhood (May, Byers-Heinlein, Gervain, & Werker, 2011; McNealy, Mazziotta, & Dapretto, 2011). Gazzaniga (1974) was one of the first researchers to propose that different types of words are processed differently by the hemispheres. Gazzaniga hypothesized that because the corpus callosum is not completely myelinated until after two years of age, there is a weak connection between the left and right hemispheres. As a result, the two hemispheres are unable to communicate effectively. Gazzaniga stated that at this age children are functionally split and that cognitive abilities acquired during this time are represented in both hemispheres. When applying this hypothesis to language, it suggests that words learned early in childhood would be represented in both hemispheres while words learned later in childhood would be represented in the left hemisphere.

In order to test Gazzaniga's hypothesis, Boles, Rogers, and Wymer (1982), conducted a study. Their goal was to determine whether words with different ages of acquisition (AoA) were processed differently in the adult brain. In this case, the authors used words from the corpus of Nelson (1973) and categorized them depending on the number of children (1 to 2 years old) that knew each word. The words were split into three categories: early-acquisition words, or words acquired by the majority of children; middle-acquisition words, or words acquired by some of the children; and late-acquisition words, or words that had not been acquired by any of the children. Overall, no evidence for right hemisphere processing of early AoA words was found. The three groups of words showed the same asymmetry, indicating that perhaps there are no differences in language processing from childhood to adulthood. However, it is important to note that a small set of words, only eight words per category, were used. The low number of words used for each category may have not been enough to produce asymmetries during processing, thus affecting the results.

III. Divided Visual Field Techniques and Language Processing

Throughout the years, a common method for studying hemispheric differences in language processing has been the divided visual field (DVF) technique. In this technique, individuals are presented with a word on either the right visual field (RVF) or the left visual field (LVF). The basic idea is that words presented in the RVF will go to the left hemisphere (LH) for processing; while words presented in the LVF will go to the right hemisphere (RH) for processing. The DVF technique makes it possible for researchers to gather behavioral data for the study of hemispheric processing. More specifically, scientists have used this technique to analyze language processing differences between the left and right hemisphere (Atchley & Kwasny, 2003; Boles, Rogers, & Wymer, 1982; Bowers, Bradley, & Kennison, 2013; Mohr, Rowe, & Crawford, 2008). For example, if a participant has a faster reaction time to a word presented in the LVF/RH compared to the word being presented in the RVF/LH, it is believed that the RH processes the word faster than the LH.

At the same time, recent technological advancements have facilitated the study of hemispheric differences in language acquisition and processing by allowing the incorporation of brain imaging techniques. As a result, researchers are able to obtain not only behavioral data but also brain electrical activity data through the use of event-related potentials (ERPs); functional magnetic resonance imaging (fMRI); magnetoencephalography (MEG); and more recently, near-infrared spectroscopy (NSRI) (Atchley & Kwasny, 2003; Bortfeld, Fava, & Boas, 2009; Ghislaine Dehaene-Lambertz, Hertz-Pannier, & Dubois, 2006; Holland et al., 2007). Language processing studies using DVF techniques along with brain imaging techniques have become quite popular because they allow individuals to obtain both behavioral data, i.e., reaction times, and brain data, i.e., brain electrical activity. For example, DVF and ERP measurements have been used to study adult processing of lexically ambiguous words in the left and right hemispheres (Atchley & Kwasny, 2003). In this study, the N400 component, which is seen as an indicator of semantic processing, was measured in ERP responses. Results indicated that ERPs were different for the left and right hemispheres over the posterior areas around 400-600 ms after the presentation of a word in either the LVF or RVF. Words presented in the LVF/RH did not show an N400; while words presented in the RVF/LH showed significant differences in N400 amplitude. The authors interpreted these findings as an indication that the right hemisphere does not generate any semantic expectations when it comes to word processing, thus showing no N400. Meanwhile, the left hemisphere seems to generate semantic expectations (Atchley & Kwasny, 2003).

Other studies have used the DVF technique to look at lexical processing of negative and positive words (Mohr et al., 2008). Mohr et al., found that right-handed female students had faster responses and higher accuracy when making lexical decisions to words presented in the RVF/LH (2008). This finding suggests that there is a left hemisphere dominance during language processing. Results also indicated that positive words were recognized more quickly than negative words for both the RVF/LH and LVF/RH. Meanwhile, responses to negative words were faster when presented to the RVF/LH than when presented to the LVF/RH. Responses to negative words were also slower and less accurate in the LVF/RH. In general, there was a LVF/RH advantage for overall word recognition. The study by Mohr et al., (2008), suggests that hemispheric differences in language processing could also be attributed to emotional valence; positive words may induce faster reaction times and higher accuracy than negative words.

IV. Brain Imaging Techniques and Language Processing

As previously mentioned, technological advancements in recent years have made the study of language acquisition and processing in newborns and children possible. These studies yielded mixed results. For example, a study by Travis et al., used magnetoencephalography (MEG) and high-resolution structural magnetic resonance imaging (MRI) to investigate lexico-semantic information processing in 12- to 18-month-old infants. Brain activity in response to spoken words was recorded from adults and infants. The dynamic statistical parametric mapping (dSPM) technique was used to compare word processing between the adults and children who were in early stages of language acquisition. Results showed increased activity in the left frontotemporal area of the brain when processing words, similar to the activity found in adults (Travis et al., 2011).

Other studies have found similar results (G. Dehaene-Lambertz et al., 2004; Ghislaine Dehaene-Lambertz, Dehaene, & Hertz-Pannier, 2002; Ghislaine Dehaene-Lambertz et al., 2006); in a study by Dehaene-Lambertz et al., brain responses to forward and backward speech were recorded in three-month-old infants (2002). Findings showed an activation of the superior temporal gyrus, including Heschl's gyrus, and the superior temporal sulcus and pole. Findings also showed a difference in activation between the left and right planum temporale with a higher activation of the left planum temporale during forward speech. The authors also found that the angular gyrus and precuneus showed a higher activation during forward speech compared to backwards speech. Additionally, activation in the right dorsolateral prefrontal cortex during forward speech of awake infants was observed (Ghislaine Dehaene-Lambertz et al., 2002). The authors concluded that because some of the same areas during language processing are activated in infants and adults, language processing during infancy is similar to that in adulthood. That is, the angular gyrus has been associated with lexical storage in adults, while the dorsolateral prefrontal cortex has been associated with memory retrieval in adults (Ghislaine Dehaene-Lambertz et al., 2006). The authors also mentioned that the activation of a variety of areas in the brain during speech processing indicates that language processing is not a simple process that occurs in one area. Language processing involves the recruitment of many areas throughout the brain. Although the study found similar results and activation of areas in the left hemisphere of 3-month-olds, the authors also found activation of areas in the right hemisphere, indicating that perhaps there is less left hemisphere lateralization in infants compared to adults. The authors noted that activation of certain brain areas indicated a strong bias for those specific areas during speech processing.

In order to assess language processing during childhood, Bortfeld, Fava, and Boas (2009) conducted a study with older infants (6- to 9-month-olds). In this study, near-infrared spectroscopy (NIRS) was used to measure hemoglobin concentration changes in the brain (2009). Higher hemoglobin concentrations indicate greater blood flow to the brain area which is interpreted as a sign of greater brain activation. In this study, older infants were shown audiovisual and visual stimuli while measuring changes in oxygenated blood. The auditory stimuli consisted of a female speaker telling children's stories. Meanwhile, visual stimuli consisted of rotating three-dimensional objects on a colored background. Overall, results indicated that during the audiovisual condition there were greater hemoglobin concentration changes in the left temporal cortex compared to the right temporal cortex. The authors interpreted the results as further support for the idea that the left hemisphere is involved in language processing in older infants (Bortfeld et al., 2009).

A different study focused not only on brain activation but also on brain pathways in infants and adults (Perani et al., 2011). Perani and colleagues (2011) found that brain connectivities in newborns somewhat differ from those of adults. In this study, 2-day-old infants were studied in order to investigate how speech is processed at birth. The authors tested the degree of activation of different brain regions in newborns while they listened to three types of speech: normal speech, hummed speech, and flattened speech. The authors found that brain regions that aid in processing auditory information for adults and infants, are also activated in newborns (Perani et al., 2011). An overall decreased lateralization of the left and right hemispheres was found in newborns. fMRI data indicated that the right primary and secondary auditory cortex were involved in the newborns' processing of normal speech. These areas were strongly activated during normal speech, less activated during hummed speech, and they were not activated during flattened speech. More specifically, a greater activation of the right auditory cortex than the left auditory cortex was found when processing normal speech. When looking at the whole brain, activation of both hemispheres was shown but the right auditory cortex was more strongly activated.

Analyses of brain connections also indicated that there was strong connectivity of the left and right hemispheres especially in the left and right temporal and frontal regions. The authors emphasized the importance of this pathway because it allows proper communication between the two hemispheres at birth. However, unlike adults, results indicated that connections within the hemispheres were not fully developed. The authors did not find a left hemisphere pathway from the temporal cortex to Broca's area. This dorsal pathway is found in adults and is thought to aid in “sensory-to-motor mappings” which are needed for language acquisition that occurs later in life (p. 16060). The authors concluded that although newborns have pathways that connect both hemispheres, the absence of the intrahemispheric pathway in the left hemisphere indicates that newborns are unable to have a “highly specialized language system” like the one found in adults (p. 16060). Overall, these results suggest that similarities between the brains of newborns and adults can be seen in the pathways that connect the two hemispheres. However, newborns differ from adults because they do not have the left hemisphere pathway that connects Broca's area to the temporal cortex. Perhaps the differences in connectivities between the brains of newborns and adults can explain activation differences. In this case, newborns have greater bilateral brain activation during speech processing while adults have a more lateralized brain activation during speech processing.

Other studies have also examined newborns; for example, May and colleagues (2011) investigated the brain responses of newborns to speech in their native language. Results indicated that newborns who listened to a familiar language had an increase in oxygenated hemoglobin across both hemispheres. On the other hand, listening to an unfamiliar language caused a decrease in oxygenated hemoglobin. It is important to emphasize that no differences in oxygenated hemoglobin distribution were found between the left and right hemispheres (May et al., 2011). Once again, these findings suggest that bilateral language processing occurs in newborns in contrast with the typical left hemisphere lateralization found in adults during language processing.

V. Developmental Changes in Language Processing

The fact that infant and children studies have yielded mixed results regarding language processing mechanisms, has led to a growing interest in the study of developmental changes in hemispheric lateralization during language processing (McNealy et al., 2011). McNealy et al. (2011), aimed to investigate how language processing changes throughout development. This study is one of the few studies that has examined children with different ages along with adults, and compared their blood-oxygenation level dependent (BOLD) signal increases during a variety of speech listening tasks. The study looked at a group of 6-, 10-, and 13-year-old children as well as adults. Main findings included changes in laterality of BOLD signal increases in temporal cortices throughout development. In 6-year-old children, there was a greater activation of the right hemisphere. This result contrasts that found in adults in which there was a greater activation of the left hemisphere (McNealy, Mazziotta, & Dapretto, 2006). Meanwhile, 10- and 13-year-old children showed bilateral brain activation during the speech listening tasks (McNealy, Mazziotta, & Dapretto, 2010). The findings indicate that during early childhood, the right temporal cortex is involved in speech processing; meanwhile, in late childhood there is involvement of both the right and left temporal cortices; in adulthood, the left temporal cortex is involved. These findings are important because they indicate that there are developmental changes in the activation of the left and right temporal cortices during speech processing.

VI. Recent Findings on Hemispheric Differences

Recently, a study by Bowers, Bradley, and Kennison (2013), found that AoA affects word processing. In this case, adults gave age of acquisition ratings for different words. Words classified as early AoA words corresponded to an age of approximately 3 to 4 years while words classified as late AoA words corresponded to an age of approximately 7 to 8 years. In this study, individuals had faster reaction times to early AoA words than to late AoA words. More specifically, early AoA words presented in the LVF/RH were processed faster than early AoA words presented in the RVF/LH. On the other hand, late AoA words presented in the RVF/LH were processed faster than late words presented in the LVF/RH. These results indicated that AoA affects word processing, early AoA words are processed by the right hemisphere while late AoA words are processed by the left hemisphere. The authors indicated that the results supported other findings regarding hemispheric lateralization differences between adults and children, where a right hemisphere dominance was found during childhood, and a left hemisphere dominance was present during adulthood.

Other studies have focused on lateralization differences in the hippocampus between children and adults (Hopf et al., 2013). A study by Hopf et al. (2013), found that children had a right hemisphere hippocampal lateralization when performing a relational memory task. This study examined three groups of individuals: younger children (11- to 14-years-old); older children (15- to 18-years-old); and adults. Magnetoencephalography (MEG) was used to investigate whether activation of the hippocampus during a memory task in children was similar to hippocampal activation found in adults. Results indicated that children's hippocampal lateralization during the memory task was similar to that found in adults. For all three groups, greater right-lateralized hippocampal activation was associated with increased accuracy in the memory task. A trend was also found regarding an increase in activation strength of the right hippocampus with age. More specifically, in younger children (11- to 14-years-old) greater accuracy was seen with greater right hippocampal lateralization. These findings support the hypothesis that increased right hippocampal lateralization in children is similar to those in adults and that this greater lateralization leads to better performance in memory tasks. Overall, the authors concluded that an adult-like pattern of hippocampal lateralization was associated with increased relational memory performance. The authors also emphasized that during certain time frames, younger children showed different activation patterns compared to older children and adults; suggesting that brain lateralization may increase as individuals get older (Hopf et al., 2013).

VII. Summary

Throughout the years there has been a great interest in language processing and the brain mechanisms that facilitate this process. Although the left hemisphere is usually associated with language processing, recent studies seem to indicate that the right hemisphere also plays a crucial role in language processing (Bowers, Bradley, & Kennison, 2013; McNealy et al., 2011). Studies regarding the role of the right hemisphere in language processing throughout development have not been very conclusive. However, the literature seems to suggest that at birth, there is greater involvement of the right hemisphere in language processing. As children get older and language acquisition improves, there is a switch to bilateral language processing and in adulthood, the usual left-lateralized language processing is observed. More importantly, hemispheric differences in language processing may also be apparent in adulthood which could have important implications for current understandings of language acquisition.

Overall, when examining the current research on language processing a few problems stand out. First, the language processing tasks used across studies are inconsistent. When looking at brain imaging studies, some studies use forward and backward speech (Dehaene-Lambertz et al., 2002) while others use normal and hummed speech (Perani et al., 2011). Additionally, the passages used differed among studies. On the other hand, the DVF technique used to examine hemispheric language processing has typically been used in studies with adults as opposed to studies with children (Bowers, Bradley, & Kennison, 2013; Boles, Rogers, & Wymer, 1982). Perhaps this difference in the ages of participants used is due to the fact that it is difficult for children to perform this task. The fact that children are not used for studies that use the DVF technique makes it more difficult to pinpoint what is going on during language processing in childhood. More importantly, a clear consensus has not yet been reached regarding which words are learned in early and late childhood. At the same time, different techniques have been used to categorize words as early- or late-acquired. For example, Boles, Rogers, and Wymer (1982) observed the frequency of word use in children and categorized early- and late-acquired words based on these findings. Meanwhile, Bowers, Bradley, and Kennison (2013) had adults categorize words depending on the age they believed they acquired the words. Additionally, there is still debate on what "early-acquired" and "late-acquired" words mean. Boles and colleagues (1982) categorized words as early-acquired if they were learned before the age of two while Bowers and colleagues (2013) categorized words as early if they were learned around the age of three to four.

Perhaps one of the most important challenges in the previous studies is that the types of words used have differed. Some studies have focused on only nouns while others have not made this distinction (Bowers, Bradley, & Kennison, 2013; McNealy et al., 2011; Perani et al., 2011). Differences in types of words used are important because it has been suggested that lateralization differences during word processing may simply be due to differences in concreteness or ambiguity of words rather than the age in which they were acquired (Fassbinder & Tompkins, 2006). For example, since the right hemisphere is associated with the process of imagery, the right hemisphere may process words that are more highly imaginable. Overall, it is important to mention these methodological discrepancies in order to understand why findings regarding word processing are so inconsistent. At the same time, it is also important to recognize that hemispheric differences during language processing may be due to other factors besides age of acquisition.

VII. Current Study

Based on previous research, the present study investigated whether hemispheric differences exist when adults process early and late AoA words. In this study, four major questions were asked. First, does AoA have an effect on word processing in the brain? Secondly, are early AoA words processed mainly by the right hemisphere? Third, are late AoA words processed mainly by the right hemisphere? Finally, can processing differences between early-acquired and late-acquired words be observed through asymmetries in event-related potentials (ERPs)? The goal of these questions was to further investigate findings that suggest that the right hemisphere is more dominant during early childhood (Bowers, Bradley, & Kennison, 2013; Ghislaine Dehaene-Lambertz et al., 2002; Perani et al., 2011). If previous studies suggesting that the right hemisphere is more dominant during early childhood are correct, then words acquired during this time should be learned and processed by the right hemisphere. That is, there should be faster reaction times for early AoA words presented to the right hemisphere. However, if Gazzaniga's hypothesis is correct, early AoA words should be processed by both hemispheres. This would result in faster reaction times to early AoA words compared to late AoA words when presented to both hemispheres. To investigate hemispheric differences in processing early and late AoA words, reaction times and ERPs were analyzed.

Methods

Participants

Participants included 38 Bethel College students enrolled in psychology, science and statistics courses at Bethel College. Participants were right-handed, native English speakers. Three participants were excluded from data analysis because two were ambidextrous, one was left-handed, and one had data recording problems. Of the 35 participants left, 18 were females and 16 were males. The age range was 18-23 years with an average age of 19.6 years. Participants received extra credit in exchange for their participation.

Design

This experiment consisted of two within-subjects variables: AoA (early and late) and visual field (RVF and LVF). A between-subjects variable used was the counterbalancing list (list 1 or 2). Two counterbalancing lists were used in order to ensure that stimuli were shown on the LVF and RVF an equal amount of times. Stimuli were randomly presented and were only presented once for each participant. An additional control variable included was the button (red or purple) used to respond “YES” or “NO.” The “YES” or “NO” buttons were alternated from the left (red) or right (purple) side in order to keep this factor from influencing ERP asymmetries. The two dependent variables were reaction times and ERPs.

Random assignment was used to assign participants to one of four conditions. Condition 1 included counterbalancing list 1 (L1) with the red button (R) as the “YES” response and the purple button (P) as the “NO” response. Condition 2 consisted of L1, with the R button as the “NO” response and the P button as the “YES” response. Condition 3 consisted of L2, with the R button as the “YES” response and the P button as the “NO” response. Finally, condition 4 included L2 with the R button as the “NO” response and the P button as the “YES” response. A random order of the numbers 1, 2, 3, and 4, was generated using the website: http://www.random.org/. For every four participants that signed up to participate in the experiment, the number 1, 2, 3, or 4 was randomly assigned to each participant. Random assignment was used to control for individual differences and experimental bias.

Materials

SurveyMonkey was used to create a survey that required participants to provide handedness and demographic information. A PsyScope script (Cohen, MacWhinney, Flatt, & Provost, 1993) running on an iMac computer (MacOS 10.6.8) was used to present participants with a lexical decision task. In this case, stimuli was presented in either the LVF or RVF. Participants began by completing a practice block in which they were presented with 40 trials of 20 non-words, 10 early AoA words and 10 late AoA words. For the experimental block, 240 trials were presented consisting of 60 non-words, 90 early AoA words, and 90 late AoA words. Stimuli were obtained from Bowers, Bradley, and Kennison (2013) and are provided in Appendix A. For early and late AoA words, factors such as word length, syllables, and imageability were matched. As trial items were presented, signals were sent to an EEG recording box. EEG data was recorded using ActiVIEW software, running on LabVIEW (version 8.6.1) on an iMac computer (MacOS 10.6.8). The software also allowed the recording of an event channel with signals provided by the PsyScope script. EEG recording was completed using a Biosemi 32-channel biopotential measurement system with eight auxiliary channels (http://www.biosemi.com/products.htm). Four auxiliary channels were used as left and right mastoid reference electrodes, and vertical and horizontal eye movement electrodes. A chin rest was also used so that individuals would be in a stable position approximately 60 cm from the computer screen.

Procedure

Participants were assigned a time slot in which they came into lab to complete the experiment. Participants began the experiment by completing the online survey via

SurveyMonkey (https://www.surveymonkey.com). After this, an electrode cap was placed on the participant's head to obtain EEG recordings which measured electrical brain activity during the experiment. Four other electrodes were placed on the participant. Two reference electrodes were placed on the left and right mastoids. The other two electrodes were placed in the left eye to measure vertical and horizontal movements. Once the cap and electrodes were placed, participants moved to a different room to begin the experiment on a computer. The electrode cap was connected to a device that sent the EEG signals to a second computer.

Before beginning the lexical decision task, the experimenter instructed participants to place their chin on the chin rest, to sit as still as possible, and to keep eye movements to a minimum. Individuals then began the lexical decision task. First, participants were presented with a screen giving them instructions on how to complete the task. Participants were informed that they would be presented with strings of words to the LVF or RVF. During the task, participants were instructed to keep their eyes on a fixation cross in the middle of the screen at all times and to not move their eyes to either visual field during stimulus presentation. Part of the instructions stated, *"You will use the BUTTONBOX to respond. The 'red' and 'purple' buttons will be used to respond 'yes' it is a word and 'no' it is not a word."* The instructions were adapted from the instructions provided in the experiment by Bowers, Bradley, and Kennison (2013). Stimuli were presented for 250 milliseconds using the DVF technique. Participants were first presented with a practice block that was composed of 40 trials including 20 non-words and 20 words (10 early AoA, 10 late AoA). No EEG data recording was done during the practice block because it was used to familiarize participants with the experiment. After individuals were done with the practice block, the experimenter entered the room to answer any questions that individuals had. Once questions were answered, a second experimenter started the EEG recording in the other room. The lexical decision task consisted of 240 trials that took individuals about 25 to 30 minutes. Once individuals completed the lexical decision task, EEG recording stopped and individuals were allowed to leave after experimenters answered any questions they had.

Data Analysis

PsyScope data was entered into a spreadsheet for data analysis. Data analysis for the reaction time data was completed using R statistical software. Non-word trials were excluded from data analysis. Trials in which participants did not answer correctly were also excluded from data analysis. Average reaction times were calculated for early AoA words presented in the LVF/RH; late AoA words presented in the LVF/RH; early AoA words presented in the RVF/LH; late AoA words presented in the RVF/LH. Finally, responses in which reaction times exceeded three standard deviations from participants' mean reaction time were excluded. Averages were compiled in a spreadsheet and imported into R statistical software. The averages for the reaction time data were analyzed using R statistical software.

EEG data was analyzed using MATLAB (version 8.0.0.783, The Mathworks, Natick, MA) to run EEGLab (version 13.1.1b, http://sccn.ucsd.edu/eeglab/). First, data was imported into EEGLab. After data was imported, 32 EEG channels for the cap electrodes and the third and fourth EXG channels representing the eye movement channels were selected. After this, event code 34559 was removed because it interfered with data analysis for the other event codes. After removing the event code, channel locations were edited to ensure that they were in the right location. A band pass filter was used to remove frequencies above 30 Hz and below 0.1 Hz and to remove 60 Hz frequencies generated by electrical devices. Responses were binned according to correct answers and early versus late AoA words presented to either the LVF/RH or the

RVF/LH. Incorrect answers and non-word trials were extracted from EEG data. Response-locked epochs from -200 ms before stimulus onset to 1500 ms after stimulus onset were extracted. Independent eye components analysis (ICA) was used to control for eye movements. Eye movement artifacts were then identified and extracted from the data. After removing eye movements, ERPLab was used to average ERP data across trials for each participant. ERPLab is an open source plugin for EEGLab (http://erpinfo.org/erplab). Data was averaged across all participants. After computing a grand average, statistical analyses were performed using ERPLab.

Results

Figure 1 shows the reaction times for early- and late-acquired words according to visual field. An analysis of variance (ANOVA) with two within-subjects variables (AoA, visual field) and one between-subjects variable (counterbalancing list) indicated that there was a main effect of AoA on reaction times $F(1,32) = 37.55, p < .0001$. However, no interaction effect between AoA and visual field was found $F(1,32) = 0.480, p > .1$. Indicating that the visual field in which words were presented did not have an effect on reaction times. Additional paired t-tests were conducted to examine differences in reaction times more closely. Results indicated that although AoA had an effect on reaction times for both visual fields, differences between early AoA and late AoA words were greater, or more statistically significant, when presented to the LVF/RH $t(33) = -6.1945, p < 0.0001$, than when presented to the RVF/LH $t(33) = -4.2224, p < 0.001$. Indicating that processing differences were greater when early and late AoA words were presented to the LVF/RH.

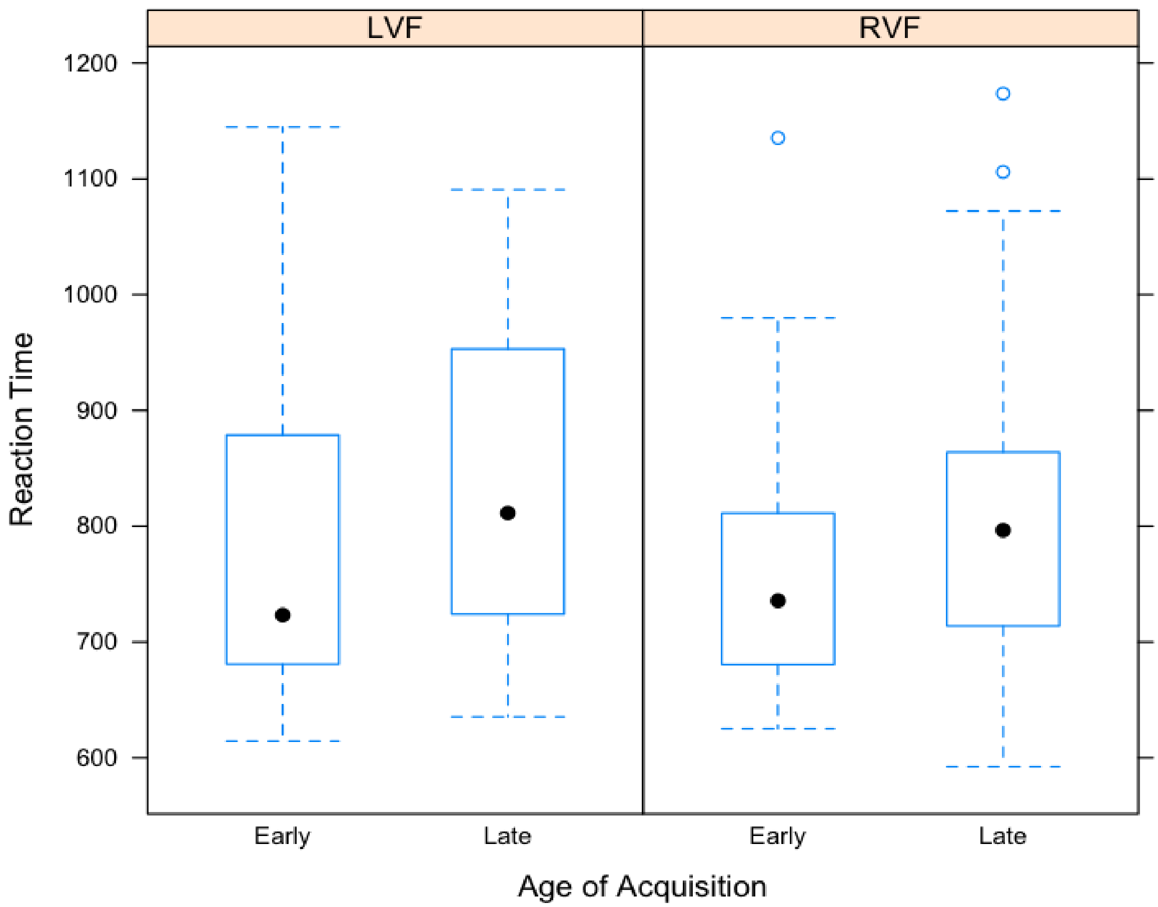

Fig. 1 Boxplot showing reaction times for early and late AoA words according to visual field

Figure 2 shows a topographic map for early and late AoA words presented to the LVF/RH and RVF/LH from 0 to 400 ms. False discovery rate ($p < .05$) was used to ensure that the statistically significant differences that were found were due to differences in conditions and not chance alone. No statistically significant differences were found between early AoA words presented to the LVF/RH and early AoA words presented to the RVF/LH. However, statistically significant differences were found between late AoA words presented to the LVF/RH and late AoA words presented to the RVF/LH. Late AoA words presented to the LVF/RH showed greater positivity while late AoA words presented to the RVF/LH showed greater negativity. These differences in potential were statistically significant in almost all left hemisphere electrodes.

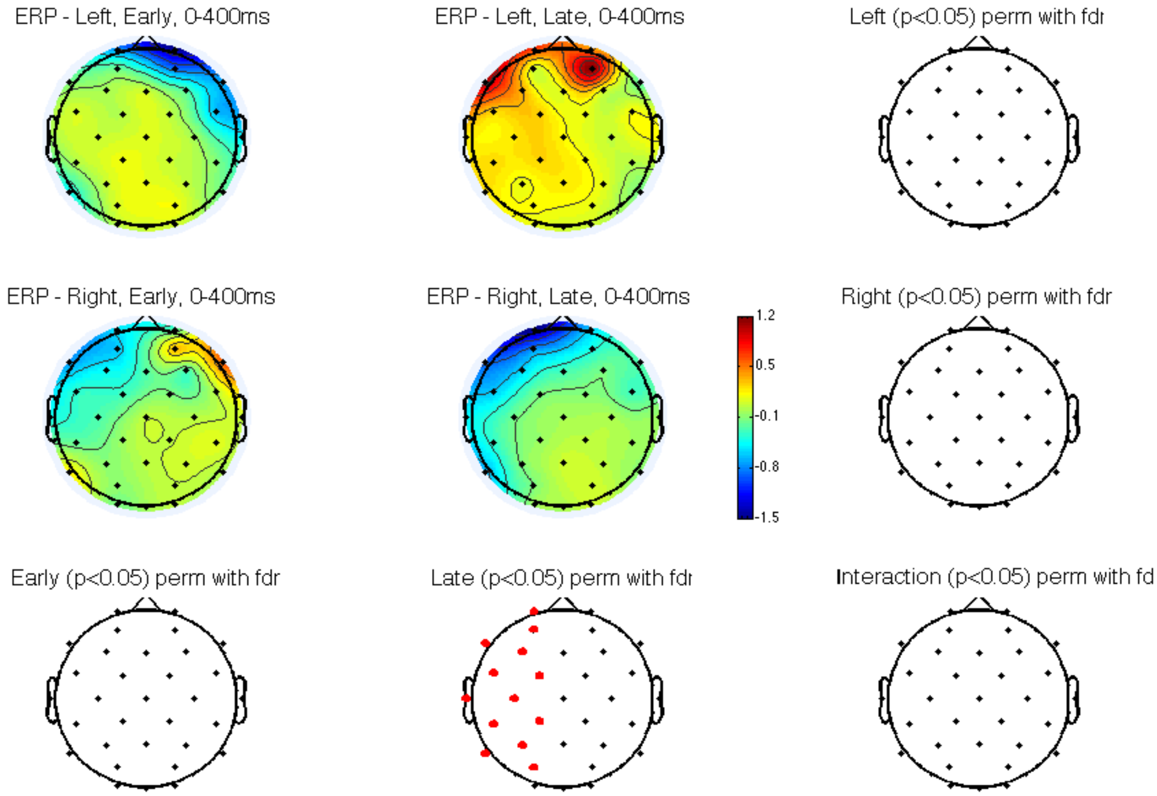

Fig. 2 Topographic map for early and late AoA words presented to the LVF/RH or RVF/LH (0 – 400 ms)

Figure 3 shows a topographic map for early and late AoA words presented to the LVF/RH and RVF/LH from 0 to 600 ms. Once again, false discovery rate was used in order to ensure that the statistically significant differences that were found were due to differences in conditions and not chance alone. In this case, no statistically significant differences were found between early AoA words presented to the LVF/RH and early AoA words presented to the RVF/LH. However, in this case, statistically significant differences were found between early AoA and late AoA words presented to the LVF/RH. When presented to the LVF/RH, early AoA words showed a negative potential while late AoA words showed a positive potential. These differences in potential for early and late AoA words were seen throughout the brain and were not limited to a specific hemisphere. These differences indicate that there are processing differences in the right hemisphere between early and late AoA words. Once again, statistically significant differences were found between late AoA words presented to the LVF/RH and late AoA words presented to the RVF/LH. With late AoA words presented to the LVF/RH showing a positive potential and late AoA words showing a negative potential. These differences in potential were statistically significant in left hemisphere electrodes.

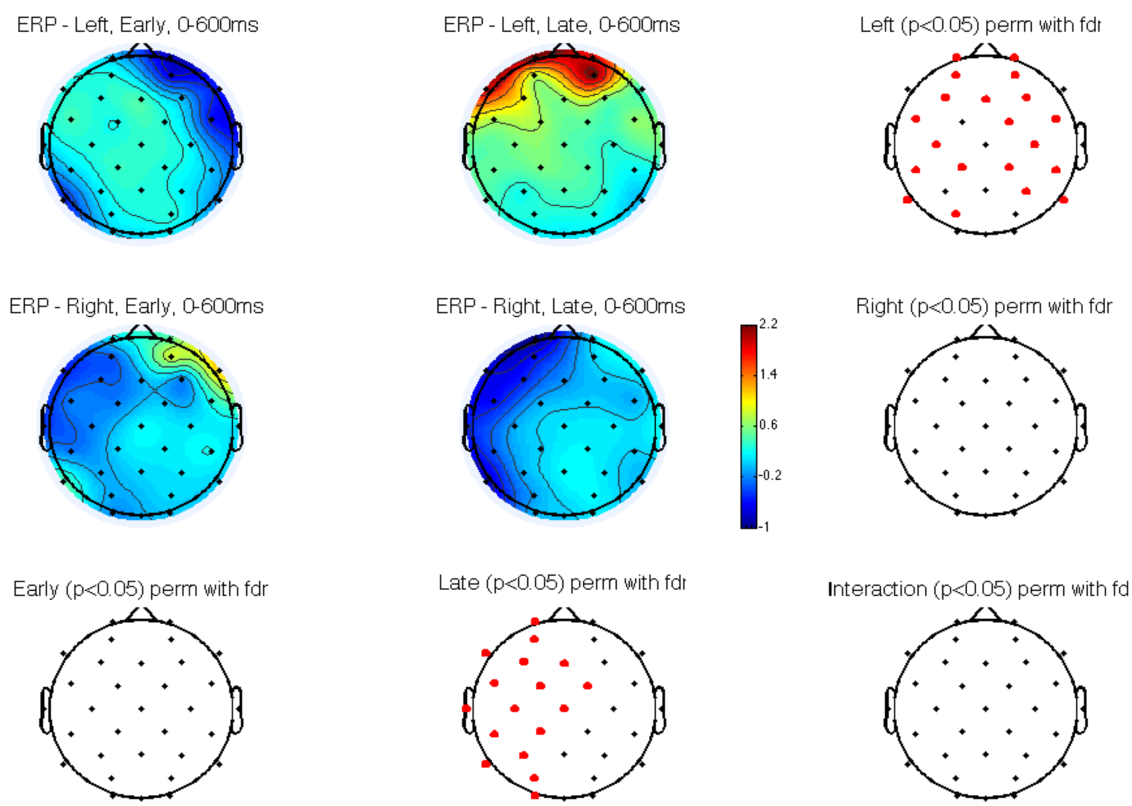

Fig. 3 Topographic map for early and late AoA words presented to the LVF/RH or RVF/LH (0 – 600 ms)

Figure 4 shows the waveforms for early and late AoA words presented in the LVF/RH for the C3 electrode. The waveforms shown are from -200 to 600 ms. The figure indicates that there was a statistically significant difference in potentials for early and late AoA words between 540 ms to 600 ms. Late AoA words had a greater positive potential when compared to early AoA words.

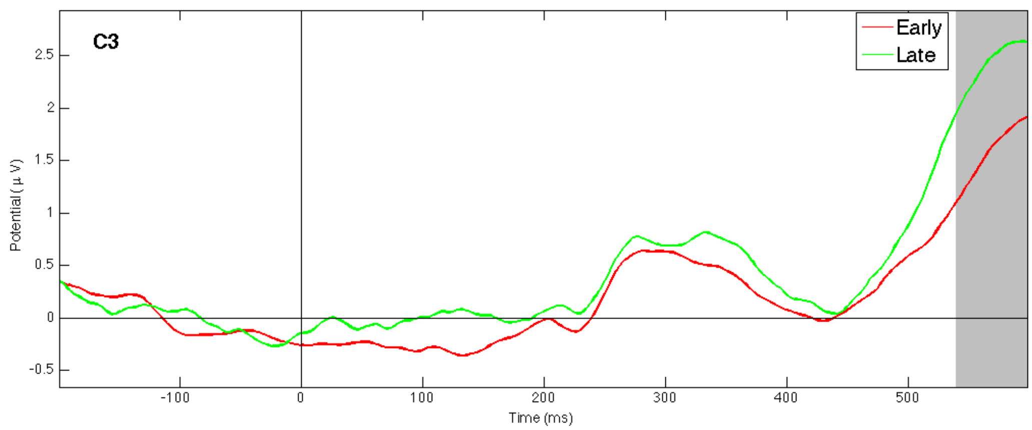

Fig. 4 C3 electrode waveforms for early and late AoA words presented to the LVF/RH (-200 – 600 ms)

Figure 5 shows the waveforms for early and late AoA words presented in the RVF/LH for the C3 electrode. The waveforms shown are from -200 to 600 ms. The figure indicates that there were no statistically significant differences in potential for early and late AoA words presented to the LVF/RH.

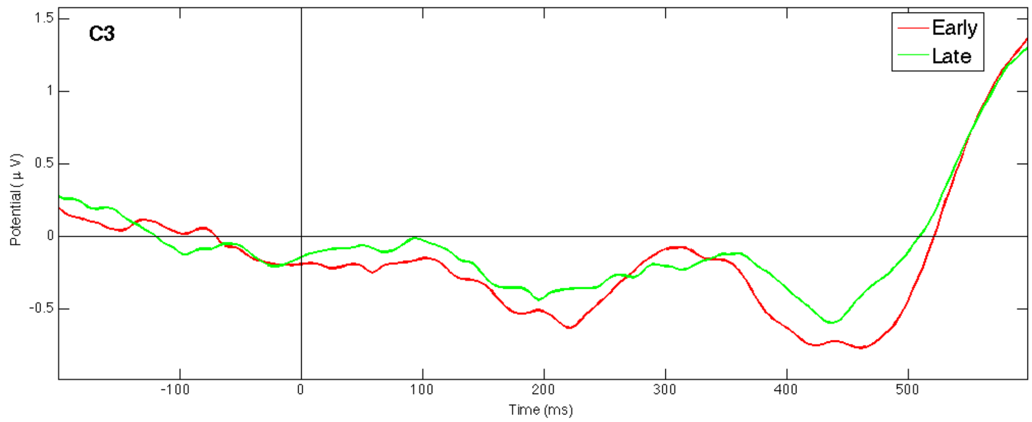

Fig. 5 C3 electrode waveforms for early and late AoA words presented to the RVF/LH (-200 – 600 ms)

When comparing the waveforms for late AoA words in figures 4 and 5 there is a difference in potential between 250 ms to 450 ms. In this case, late AoA words presented to the LVF/RH (fig. 4) show a more positive potential while late AoA words presented to the RVF/LH (fig. 5) show a more negative potential. These differences in potential correspond to the differences seen in the topographic maps in figures 2 and 3.

Discussion

This study is among one of the first to use behavioral and ERP data to investigate the effects of AoA on word processing in the brain. The first question investigated whether differences in processing early and late AoA words existed. Overall, results indicated that early and late AoA words are processed differently by the brain. Participants had faster reaction times when processing early AoA words than when processing late AoA words. The second question investigated whether early AoA words are processed mainly by the right hemisphere. In this case, reaction time differences between early AoA words presented to the LVF/RH or RVF/LH were not found. However, paired t-tests indicated that there was a slight processing advantage for early AoA words when presented to the LVF/RH. Regarding the third question investigating whether late AoA words are processed mainly by the left hemisphere; results indicated that late AoA words were processed mainly by the left hemisphere.

The fourth and final question investigated whether processing differences between early and late AoA words could be observed through ERP asymmetries. In this case, ERP asymmetries were not found. More specifically, no processing differences between the LVF/RH and the RVF/LH during early AoA word processing were observed. These findings provided further support for the idea that there is bilateral processing of early AoA words. However, when examining ERP data for late AoA words, processing differences between the LVF/RH and RVF/LH were found between 0 to 600 ms. Late AoA words presented to the LVF/RH showed a positive potential while late AoA words presented to the RVF/LH showed a negative potential. These differences were evident in almost all of the left hemisphere electrodes indicating that late AoA word processing occurs in the left hemisphere.

The finding that early AoA words are processed differently by the brain has important implications. First, these findings suggest that the typical left lateralization observed during language processing in adulthood is not present at birth. Instead, in early childhood there seems to be a decreased lateralization. Furthermore, results indicate that language processing in the brain changes from childhood to adulthood. Perhaps during language processing in early childhood there is greater involvement of the right hemisphere while in late childhood there is bilateral language processing. Finally, in adulthood there is greater involvement of the left hemisphere. This view is supported by the study conducted by McNealy, Mazziotta, and Dapretto (2011), which found that hemispheric lateralization differed during speech processing from early childhood to adulthood. McNealy and colleagues found that during early childhood the right temporal cortex showed a greater activation during speech processing; in late childhood there was activation of both the right and left temporal cortices; and in adulthood there was a greater activation of the left temporal cortex.

Additionally, this research supports the idea that acquiring a second language during adulthood may be more difficult. Since bilateral language processing does not occur for words acquired later in life, adults are at a disadvantage during language acquisition. In this case, individuals are unable to use the left and right hemispheres to learn a second language. The fact that adults can only use the left hemisphere during language acquisition may make the process more difficult since fewer brain areas are involved. In this case, if individuals learn a second language later in life, the right hemisphere is unable to play a significant role in language acquisition. As a result, adults would be unable to store the words they acquire in the right hemisphere. Fewer storage areas in the brain would lead to fewer words acquired because bilinguals who learned a second language in adulthood would not have extra storage space in the right hemisphere; compared to their monolingual counterparts who learned the language early in childhood. Furthermore, this research also has important implications for individuals with learning disabilities such as dyslexia. Understanding what is occurring in the brain during early word processing may help researchers develop better interventions for individuals who suffer from learning disabilities.

The present research supports the idea that language processing is not solely a left hemisphere process; the right hemisphere also plays a role in word processing especially during early childhood. The involvement of the two hemispheres during language processing also has important implications for the ability of children to improve their language acquisition skills. Language teaching methods for children in early stages of childhood could be more effective by taking advantage of bilateral language processing. Knowing that language processing is different in early childhood could also lead to the development of different techniques to improve children's language acquisition skills.

The present results do not fully support the study conducted by Bowers, Bradley, and Kennison (2013). Although AoA had an effect on word processing, early AoA words were processed faster by both hemispheres. At the same time, ERP results indicated a bilateral processing of early AoA words. This finding is consistent with Gazzaniga's hypothesis that early AoA words are represented bilaterally due to late myelination of the corpus callosum (1974). Based on the current findings, future research should examine whether AoA plays a role in processing verbs. The present study used only nouns to investigate AoA effects on word processing. Other studies should focus on other types of words such as verbs to investigate if the present results can be generalized across other types of words. Secondly, researchers could also examine whether AoA affects processing for auditory stimuli. This study only examined processing of written words but in future studies participants could perform a similar task in which they listen to spoken words. The research would aid in determining whether auditory stimuli are processed differently than written stimuli. Finally, a more extensive study could include participants of different ages such as children. Examining language processing among different age groups would lead to a better understanding of how word processing changes from childhood to adulthood. Results from different age groups could be compared to better understand the role of the right hemisphere during early language processing.

References

Atchley, R. A., & Kwasny, K. M. (2003). Using event-related potentials to examine hemispheric differences in semantic processing. *Brain & Cognition*, *53*(2), 133. doi:10.1016/S0278-2626(03)00095-2

Boles, D. B., Rogers, S., & Wymer, W. (1982). Age of acquisition and visual field asymmetry in word recognition. *Perception & Psychophysics*, *32*(5), 486–490. doi:10.3758/BF03202780

Bortfeld, H., Fava, E., & Boas, D. A. (2009). Identifying cortical lateralization of speech processing in infants using near-infrared spectroscopy. *Developmental Neuropsychology*, *34*(1), 52–65. doi:10.1080/87565640802564481

Bowers, J. M., Bradley, K. I., & Kennison, S. M. (2013). Hemispheric differences in the processing of words learned early versus later in childhood. *Journal of General Psychology*, *140*(3), 174. doi:10.1080/00221309.2013.783779

Cohen J.D., MacWhinney B., Flatt M., and Provost J. (1993). PsyScope: A new graphic interactive\environment for designing psychology experiments. *Behavioral Research Methods, Instruments, and Computers, 25*(2), 257-271.

Dehaene-Lambertz, G., Pena, M., Christophe, A., & Landrieu, P. (2004). Phoneme perception in a neonate with a left sylvian infarct. *Brain and Language*, *88*(1), 26–38.

Dehaene-Lambertz, G., Dehaene, S., & Hertz-Pannier, L. (2002). Functional neuroimaging of speech perception in infants. *Science (New York, N.Y.)*, *298*(5600), 2013–2015.

Dehaene-Lambertz, G., Hertz-Pannier, L., & Dubois, J. (2006). Nature and nurture in language acquisition: anatomical and functional brain-imaging studies in infants. *Trends in Neurosciences*, *29*(7), 367–373.

Delorme, A. & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEGdynamics *Journal of Neuroscience Methods* 134:9-21

ERPLAB (http://erpinfo.org/erplab) is an open source plugin for EEGLAB that facilitates ERP data processing, visualization, and analysis.

Fassbinder, W., Tompkins C. A., (2006). Hemispheric differences in word-meaning processing: alternative interpretations of current evidence. *Aphasiology, 20,* 110-122. doi: 10.1080/02687030500472397

Gazzaniga, M. (1974). Cerebral dominance viewed as a decisions system. In S. Dimond & J. Beaumont (eds.) *Hemisphere function in the human brain*. (pp. 367-382) New York, NY: John Wiley & Sons.

Holland, S. K., Vannest, J., Mecoli, M., Jacola, L. M., Tillema, J.-M., Karunanayaka, P. R., … Byars, A. W. (2007). Functional MRI of language lateralization during development in children. *International Journal of Audiology*, *46*(9), 533–551. doi:10.1080/14992020701448994

LabVIEW (National Instruments, Austin, TX).

May, L., Byers-Heinlein, K., Gervain, J., & Werker, J. F. (2011). Language and the newborn brain: does prenatal language experience shape the neonate neural response to speech? *Frontiers in Psychology*, *2*. doi:10.3389/fpsyg.2011.00222

McNealy, K., Mazziotta, J. C., & Dapretto, M. (2006). Cracking the language code: neural mechanisms underlying speech parsing. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *26*(29), 7629–7639. doi:10.1523/JNEUROSCI.5501-05.2006

McNealy, K., Mazziotta, J. C., & Dapretto, M. (2010). The neural basis of speech parsing in children and adults. *Developmental Science*, *13*(2), 385–406. doi:10.1111/j.1467-7687.2009.00895.x

McNealy, K., Mazziotta, J. C., & Dapretto, M. (2011). Age and experience shape developmental changes in the neural basis of language-related learning. *Developmental Science*, *14*(6), 1261–1282. doi:10.1111/j.1467-7687.2011.01075.x

Mohr, C., Rowe, A. C., & Crawford, M. T. (2008). Hemispheric differences in the processing of attachment words. *Journal of Clinical & Experimental Neuropsychology*, *30*(4), 471–480. doi:10.1080/13803390701550110

MATLAB (The Mathworks, Natick, MA).

Nelson, C. (1973). Structure and strategy in learning to talk. *Monographs of the Society for Research in Child Development*, *38*(1/2), 1-137.

Perani, D., Saccuman, M. C., Scifo, P., Anwander, A., Spada, D., Baldoli, C., … Friederici, A. D. (2011). Neural language networks at birth. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(38), 16056–16061. doi:10.1073/pnas.1102991108

Purves, D., Brannon, E.M., Cabeza, R., Huettel, S.A., LaBar, K.S., Platt, M.L., & Woldorff, M. (2007). *Principles of cognitive neuroscience*. (pp. 537-540) Sunderland, MA: Sinauer Associates, Inc.

R Development Core Team (2008). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0

Travis, K. E., Leonard, M. K., Brown, T. T., Hagler, D. J., Curran, M., Dale, A. M., … Halgren, E. (2011). Spatiotemporal neural dynamics of word understanding in 12- to 18-month-old-infants. *Cerebral Cortex (New York, NY)*, *21*(8), 1832–1839.

doi:10.1093/cercor/bhq259

Appendix A

Early AoA Words

1. Apple
2. banana
3. barn
4. bear
5. belt
6. bib
7. blanket
8. boots
9. button
10. cat
11. cheese
12. circle
13. cookie
14. corn
15. diaper
16. dot
17. dress
18. ear
19. egg
20. elbow
21. fairy

22. fork
23. frog
24. gloves
25. grape
26. jar
27. juice
28. lamb
29. leg
30. lip
31. milk
32. monkey
33. mouse
34. mouth
35. nose
36. oven
37. pants
38. pea
39. pig
40. pillow
41. pond
42. rabbit
43. rug
44. shed

45. sheep

46. shirt

47. shoe

48. sink

49. sleeve

50. soap

51. socks

52. spoon

53. stool

54. thumb

55. toe

56. tongue

57. tooth

58. turtle

59. wool

60. worm

61. plate

62. cloud

63. deer

64. boot

65. salt

66. bowl

67. sugar

68. kitten

69. mud

70. duck

71. lemon

72. lion

73. chin

74. smoke

75. tree

76. leaf

77. butter

78. cheek

79. dirt

80. carrot

81. bacon

82. doll

83. bell

84. goat

85. puppy

86. coat

87. knee

88. toilet

89. knife

90. finger

Late AoA Words

1. ankle
2. ape
3. beaver
4. beer
5. beet
6. blood
7. bosom
8. bra
9. brain
10. canoe
11. cedar
12. chapel
13. chest
14. cube
15. drug
16. fawn
17. fig
18. garlic
19. garter
20. girdle
21. gown
22. heart

23. hip
24. jaw
25. lime
26. liver
27. lizard
28. lung
29. maze
30. menu
31. minnow
32. moose
33. octopus
34. olive
35. pouch
36. radish
37. ranch
38. salad
39. scarf
40. shawl
41. skin
42. skunk
43. statue
44. steak
45. stew

46. suit
47. swan
48. sword
49. tie
50. tower
51. turnip
52. veil
53. vest
54. vine
55. walrus
56. wax
57. weasel
58. whale
59. wheat
60. wine
61. silk
62. comet
63. spine
64. skull
65. soil
66. shrub
67. mist
68. dome

69. dusk
70. tomb
71. planet
72. kidney
73. veil
74. pelvis
75. dawn
76. trout
77. liquid
78. elm
79. blade
80. copper
81. apron
82. stew
83. mop
84. bomb
85. bench
86. raft
87. pistol
88. mirror
89. crow
90. grenade

Non-words

1. aptle
2. varn
3. belm
4. blandet
5. bulton
6. sheese
7. coomie
8. liaper
9. drels
10. elg
11. fuiry
12. frob
13. graxe
14. juipe
15. lem
16. mirk
17. monkel
18. pouse
19. bouth
20. noxe
21. oken
22. panfs

23. vea
24. pij
25. pallow
26. ranbit
27. sned
28. shirm
29. vink
30. boap
31. snoon
32. shumb
33. tondue
34. purtle
35. borm
36. kedar
37. chost
38. frug
39. kig
40. garmer
41. gorn
42. hiq
43. hime
44. lipard
45. yaze

46. minlow

47. poose

48. ochopus

49. olire

50. houch

51. padish

52. banch

53. sakad

54. scorf

55. sharl

56. voil

57. vife

58. waz

59. thale

60. jine

Appendix B

Statistical Analyses

Analysis of Variance

Error: Subject

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
List	1	18503	18503	0.303	0.586
Residuals	32	1954681	61084		

Error: Subject:Age.of.Acquisition

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Age.of.Acquisition	1	100802	100802	37.55	7.49e-07 ***
Age.of.Acquisition:List	1	967	967	0.36	0.553
Residuals	32	85890	2684		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Error: Subject:Visual.Field

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Visual.Field	1	3485	3485	1.040	0.315
Visual.Field:List	1	5235	5235	1.562	0.220
Residuals	32	107206	3350		

Error: Subject:Age.of.Acquisition:Visual.Field

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Age.of.Acquisition:Visual.Field	1	894	894.0	0.480	0.493
Age.of.Acquisition:Visual.Field:List	1	848	847.8	0.456	0.505
Residuals	32	59550	1860.9		

Paired t-tests

Early and Late AoA words presented to the LVF/RH

data: FinalData$EarlyLVF and FinalData$LateLVF
t = -6.1945, df = 33, p-value = 5.45e-07
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -65.52118 -33.12251
sample estimates:
mean of the differences
 -49.32185

Early and Late AoA words presented to the RVF/LH

data: FinalData$EarlyRVF and FinalData$LateRVF
t = -4.2224, df = 33, p-value = 0.0001782

```
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -88.28414 -30.87045
sample estimates:
mean of the differences
              -59.5773
```